

Catcher in the Sky: Galactic X-ray Binaries in the Era of eROSITA and Beyond

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Zusammenfassung

Röntgendoppelsterne (Engl. Äquivalent: X-Ray Binaries, XRBs) sind die Endpunkte der stellaren Entwicklung massereicher Sterne, und stellen einzigartige Weltraumlaborare für die Hochenergieastrophysik dar. Forschungsarbeiten zu XRBs können sowohl umfangreiche Studien der XRB-Population, als auch Analysen einzelner Doppelsternsysteme umfassen. Populationsstudien von XRBs sind der Schlüssel zum Verständnis der Entwicklung massereicher Sterne und der Eigenschaften der Host-Galaxie. Zudem können sie auch Licht auf die physikalischen Prozesse werfen, welche in engen Doppelsternsystemen ablaufen. Beobachtungsanalysen und theoretische Modellierungen wiederum bieten die Möglichkeit, das Verhalten spezifischer Systeme zu verfolgen, spezifische Mechanismen zu erforschen und grundlegende Fragen der modernen Hochenergieastrophysik zu beantworten.

In Bevölkerungsstudien besteht eine der Hauptaufgaben darin, eine repräsentative Stichprobe zu bilden, d.h. in unserem Fall, einen wesentlichen Teil aller XRBs zu beobachten und zu identifizieren. Im Rahmen dieser Studie umfasst dies zwei Aufgaben: 1) sorgfältige Sammlung der Informationen über alle entdeckten XRBs in unserer Galaxie; 2) Suche nach neuen (bisher unbekannten) galaktischen XRBs. Diese beiden Aufgaben stellen eine Reihe von Herausforderungen dar.

Erstens waren zu Beginn dieser Arbeit die letzten Kataloge der galaktischen Röntgendoppelsternen mit geringen Massen (Engl. Äquivalent: Low-Mass X-Ray Binaries, LMXBs) und hohen Massen (Engl. Äquivalent: High-Mass X-Ray Binaries, HMXBs) stark veraltet (Liu et al., 2006, 2007, Ritter and Kolb, 2003). Seitdem wurden viele neue transiente und persistente Objekte entdeckt. In diesem Zusammenhang haben wir zwei neue Kataloge der galaktischen LMXBs und HMXBs zusammengestellt, die in den Papieren I und II vorgestellt werden. Sie bieten eine aktuelle Bestandsaufnahme der bekannten XRBs in unserer Galaxie mit einer Vielzahl von Multi-WellenLängen (MWL) Informationen (beste verfügbare Astrometrie, Zeitmessung, Photometrie und andere Daten), die aus aktuellen Röntgen-, optischen und IR-Durchmusterungen stammen. Unsere Kataloge enthalten zusammen mehr als 500 XRBs und haben damit ein um mehr als 70% größeres Volumen als die umfangreichsten Kataloge der Vergangenheit.

Zweitens, wird die Suche nach neuen XRBs durch die Tatsache erschwert, dass die meisten von ihnen eine relativ geringe Röntgenleuchtkraft $L_x \lesssim 10^{34-35}$ erg/s (Doroshenko et al., 2014a, Grimm et al., 2002, Lutovinov et al., 2013, Mineo et al., 2011, Revnivtsev et al., 2008, Voss and Ajello, 2010). Daher entgingen sie wahrscheinlich der Entdeckung in aktuellen großräumigen Röntgendurchmusterungen mit mäßiger Empfindlichkeit und/oder starker Absorption in der galaktischen Ebene (wo sich die meisten XRBs befinden). Die Situation begann sich jedoch dank der himmelsweiten Durchmusterung durch das Extended ROentgen Survey Imaging Telescope Array (eROSITA, Merloni et al., 2012, Predehl et al., 2021) zu ändern, dessen erste Datenveröffentlichung (eRASS DR1) Anfang 2024 erfolgte. Im Paper III haben wir eine Suche nach neuen galaktischen XRBs unter den eRASS DR1-Quellen durchgeführt und zwei Kataloge von galaktischen XRB-Kandidaten vorgestellt. Die Katalogtabellen enthalten Röntgeneigenschaften von eRASS DR1 und Merkmale der identifizierten optischen/IR-Gegenstücke für insgesamt 192 XRB-Kandidaten. Die Auswahl der Gegenstücke und die endgültige MWL-Klassifizierung wurden beide mit überwachten Methoden des maschinellen Lernens als Teil eines einzigen Verfahrens durchgeführt, das speziell auf die Suche nach XRBs abgestimmt ist.

Darauf aufbauend berichten wir in Paper IV über die Nachbeobachtungen von

zwei XRB-Kandidaten (1eRASS J061330.8+160440 und 1eRASS J161201.9-464622) mit der X-ray Multi-Mirror Mission (XMM-*Newton*, [Jansen et al., 2001](#)). Die XRB-Kandidaten wurden auf der Grundlage der vorläufigen Analyse der ersten eROSITA-Röntgendurchmusterung (eRASS1) als solche ausgewählt. Mit XMM-*Newton*-Beobachtungen wurden die Röntgenpositionen verfeinert und entsprechende optische/IR-Gegenstände identifiziert. Basierend auf der detaillierten Spektral-, Zeit- und MWL-Analyse, die in dieser Arbeit durchgeführt wurde, kommen wir zu dem Schluss, dass beide unserer Kandidaten wahrscheinlich keine XRBs sind. 1eRASS J061330.8+160440 wurde als chromosphärisch aktiver Unterriese vom M-Typ mit ausgeprägter H_{alpha}-Emission und einer optischen Periodizität von 7,189 Tagen identifiziert, die wahrscheinlich auf Sternflecken zurückzuführen ist. Andererseits wurde 1eRASS J161201.9-464622 als das zweite von eROSITA entdeckte nichtmagnetische novaartige kataklysmische Veränderliche mit einer vorläufigen Umlaufperiode von 4,832 Stunden bestimmt. Wir betonen, dass die Auswahl dieser Kandidaten hauptsächlich auf den relativ hohen Röntgenfluss in eRASS1 zurückzuführen ist (der auf der Grundlage der damals verfügbaren vorläufigen eROSITA-Verarbeitungspipeline (c946) überschätzt wurde). Mit anderen Worten: Obwohl wir bereits gezeigt haben, dass eROSITA in der Lage ist, neue XRBs zu identifizieren, gibt es noch Raum für eine Verbesserung der Genauigkeit.

Was die Analyse einzelner Quellen betrifft, so untersuchen wir in Paper V die viskose Entwicklung einer Akkretionsscheibe in Gegenwart des thermischen Windes, der von ihrer Oberfläche ausgeht. Aus diesen Gründen wurde eine numerische Methode entwickelt und als Teil des von uns geschriebenen öffentlichen Codes FREDDI ([Avakyan et al., 2019, 2021](#), [Lipunova and Malanchev, 2017](#), [Lipunova et al., 2022](#)) implementiert, die die 1-D Evolutionsgleichung der Shakura-Sunyaev ([Shakura and Sunyaev, 1973](#)) Akkretionsscheibe löst. Unter Verwendung des implementierten thermischen Windmodells von [Woods et al. \(1996\)](#) haben wir die Entwicklung des LMXB 4U 1543–47-Ausbruchs von 2002 simuliert und angepasst. Die Anpassung erfolgte auf der Grundlage der archivierten Beobachtungen des Rossi X-ray Timing Explorer Observatoriums (RXTE, [Jahoda et al., 1996](#)). Es wurde festgestellt, dass der Beobachtungswert des turbulenten Viskositätsparameters α für den betreffenden Ausbruch um etwa den Faktor 1,6 überschätzt wird, wenn der thermische Wind ignoriert wird. Es wurde auch festgestellt, dass der V-Band-Fluss zwar mit unserem Modell erklärt werden konnte, es jedoch nicht vollständig mit dem J-Band-Fluss übereinstimmt. Dies könnte ein Zeichen für das Vorhandensein einer von uns nicht berücksichtigten Quelle zusätzlicher optischer/IR-Strahlung sein, möglicherweise ein Jet. Abschließend kommen wir zu dem Schluss, dass die Modellierungen und Beobachtungen für das Vorhandensein des Akkretions-Scheibenausflusses sprechen, der thermische Wind jedoch die Entwicklung der Ausbrüche nicht vollständig erklären kann.

Letztendlich bietet diese Dissertation eine breit angelegte Studie in den Bereichen Population, Beobachtung, Theorie, Simulation und Archivanalyse von XRBs in unserer Galaxie, die eine breite Grundlage für zukünftige Arbeiten in verschiedenen Bereichen der Hochenergie-Astrophysik bietet.

Abstract

X-ray binaries (XRBs), being the endpoints of the stellar evolution of massive stars, represent unique space laboratories for high-energy astrophysics. XRB research can include both extensive studies of their population as a whole, and in-depth analysis of individual binary systems. Population studies of XRBs play key role in understanding both the evolution of massive stars and the properties of the host galaxy, showing how high-energy physical processes appear on a large scale. Observational analysis and theoretical modellings of individual systems, in turn, while tracking the behaviour of specific XRBs, provide an opportunity to dig deep into specific mechanisms, and answer fundamental questions of modern astrophysics.

One of the main goals of population studies is to form a representative sample, i.e. to detect and identify a substantial fraction of existing sources, XRBs in our case. This includes two tasks: 1) careful collection of the information regarding all discovered XRBs in our Galaxy; 2) search for new (previously unknown) Galactic XRBs. Both of these tasks present a number of challenges.

First of all, existing archives of known XRBs might be incomplete. At the time this work has started, the latest catalogues of Galactic low-mass (LMXBs) and high-mass (HMXBs) X-ray binaries, were vastly outdated (Liu et al., 2006, 2007, Ritter and Kolb, 2003). Since their latest updates, many new transient and persistent objects have been discovered. In this context, we have compiled two new catalogues of the Galactic LMXBs and HMXBs, as presented in the Papers I and II, respectively. They provide an up-to-date census of known XRBs in our Galaxy along with various multiwavelength (MWL) information (best astrometry available, timing, photometry and other data) extracted from current X-ray/optical and infrared (IR) surveys. Our catalogues together contain more than 500 XRBs, which represents $\approx 70\%$ increase in volume with respect to the most extensive catalogues of the past.

Secondly, the search for new XRBs is complicated by the fact that the majority of them are expected to have relatively low X-ray luminosities $L_x \lesssim 10^{34-35}$ erg/s (Doroshenko et al., 2014a, Grimm et al., 2002, Lutovinov et al., 2013, Mineo et al., 2011, Revnivtsev et al., 2008, Voss and Ajello, 2010). Thus, they likely escaped detection in current wide-area X-ray surveys with moderate sensitivity and/or strong absorption in the Galactic plane (where most XRBs are located). The situation, however, began to change thanks to the all-sky survey performed by the extended ROentgen Survey Imaging Telescope Array (eROSITA, Merloni et al., 2012, Predehl et al., 2021), which had it's first data release (eRASS DR1) in the beginning of 2024. In the Paper III we conducted a search for new Galactic XRBs among eRASS DR1 sources and presented two catalogues of Galactic XRB candidates. Catalogue tables include X-ray properties from eRASS DR1 and characteristics of the identified optical/IR counterparts for 192 XRB candidates in total. The selection of the counterparts and final MWL classification were both accomplished using supervised machine-learning methods as part of a single procedure tuned specifically to XRBs search.

Building upon that work, in the Paper IV we report on the follow-up observations of two XRB candidates (1eRASS J061330.8+160440 and 1eRASS J161201.9-464622) with X-ray Multi-Mirror Mission (XMM-Newton, Jansen et al., 2001). The XRB candidates were selected for follow-up based on the preliminary analysis of the first eROSITA X-ray survey (eRASS1). With XMM-Newton observations the X-ray positions were refined, corresponding optical/IR counterparts were identified. Based on the detailed spectral, timing and MWL analysis conducted in the work, we concluded that both of our candidates are

unlikely to be XRBs. 1eRASS J061330.8+160440 is found to be an M-type chromospherically active subgiant with rich H_{α} emission and optical periodicity of 7.189 days likely attributed to starspot(s). On the other hand, 1eRASS J161201.9-464622 is defined as a second eROSITA-discovered nonmagnetic novalike cataclysmic variable with a tentative orbital period of 4.832 h. We emphasise, that now clarified to be erroneous selection of these candidates was mainly due to the relatively high X-ray flux in eRASS1 (derived based on preliminary eROSITA processing pipeline (c946) available at the time, not a part of the public release). In other words, while we have already demonstrated the ability of eROSITA to identify new XRBs, there is room for improving the accuracy.

Regarding the observational and theoretical analysis of individual sources, in the Paper V we study the viscous evolution of an accretion disc in the presence of the thermal wind occurring from its surface. A numerical method was developed and implemented as a part of the open code FREDDI written by us (Avakyan et al., 2019, 2021, Lipunova and Malanchev, 2017, Lipunova et al., 2022), which solves 1-D evolution equation of Shakura-Sunyaev (Shakura and Sunyaev, 1973) accretion disc. Using the implemented thermal wind model from Woods et al. (1996), we have simulated and fitted the evolution of the LMXB 4U 1543–47 outburst of 2002. Model was applied to the analysis of the archival observations made by Rossi X-ray Timing Explorer observatory (RXTE, Jahoda et al., 1996). It was found, that if the thermal wind is ignored, the observational value of the turbulent viscosity parameter α for the particular outburst is overestimated by about a factor of 1.6. It was also found that while V band flux could be explained within our model, it still cannot fully match for J band flux. This may be a sign of the presence of some, yet unaccounted, source of additional optical/IR radiation, possibly a jet. Finally, we conclude that the modellings and observations are in favour of the disc outflow's presence, however thermal wind cannot fully explain the evolution of the outbursts.

Ultimately, this dissertation provides a wide study in areas of population, observational, theoretical, simulation and archival analysis of XRBs in our Galaxy, giving a large basis for future works in different parts of high-energy astrophysics science.

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Abbreviations

AGN	Active Galactic Nucleus
ASM	All-Sky Monitor (RXTE)
BAT	Burst Alert Telescope (<i>Swift</i>)
BeXB	Be-type donor X-ray Binary
BH	Black Hole
BW	Black Widow binary
CCD	Charge-Coupled Device
CMD	Color-Magnitude Diagram
CRSF	Cyclotron Resonant Scattering Feature
CV	Cataclysmic Variable
CXO	<i>Chandra</i> X-ray Observatory
DFG	Deutsche Forschungsgemeinschaft
DIM	Disc Instability Model
DT	Decision Tree
EoS	Equation of State
eRASS	eROSITA All-Sky Survey
eROSITA	extended ROentgen Survey Imaging Telescope Array
eRO-STEP	eROSITA view of STellar EndPoints
EPIC	European Photon Imaging Camera (<i>XMM-Newton</i>)
ESA	European Space Agency
FRED	Fast-Rise Exponential-Decay
GCl	Global Cluster
HEXTE	High Energy X-ray Timing Experiment (RXTE)
HEW	Half-Energy Width
HID	Hardness-Intensity Diagram
HMXB	High-Mass X-ray Binary

HRS	High Resolution Spectrograph (SALT)
IMXB	Intermediate-Mass X-ray Binary
INS	Isolated Neutron Star
INTEGRAL	INTErnational Gamma-Ray Astrophysics Laboratory
IR	InfraRed
LMXB	Low-Mass X-ray Binary
MAXI	Monitor of All-sky X-ray Image
ML	Machine-Learning
MOS	Metal Oxide Semiconductor (<i>XMM-Newton</i>)
MWL	MultiWaveLength
NS	Neutron Star
NuSTAR	Nuclear Spectroscopic Telescope ARray
PCA	Proportional Counter Array (RXTE)
RB	RedBack binary
RF	Random Forest
RLOF	Roche Lobe OverFlow
ROSAT	ROentgen SATellite (RÖntgenSATellit)
RSS	Robert Stobie Spectrograph (SALT)
RXTE	<i>Rossi</i> X-ray Timing Explorer
SALT	Southern African Large Telescope
SFR	Star Formation Rate
SFXT	Supergiant Fast X-ray Transient
SGXB	SuperGiant donor X-ray Binary
SMOTE	Synthetic Minority Oversampling TEchnique
SRG	Spectrum-Roentgen-Gamma spacecraft
SyXB	Symbiotic X-ray Binary
TD	Training Dataset
tMSP	transitional MilliSecond Pulsar
UV	UltraViolet

WD	White Dwarf
WISE	Wide-field Infrared Survey Explorer
XLF	X-ray Luminosity Function
XMM	X-ray Multi-Mirror Mission
XRB	X-Ray Binary
XRBCats	X-Ray Binary catalogues (Paper I and Paper II)
XRP	X-Ray Pulsar
XRT	X-Ray Telescope (<i>Swift</i>)
YSO	Young Stellar Object

List of original publications

This dissertation is based on the following original journal publications (listed in order of mentioning in the dissertation):

Paper I "XRBcats: Galactic Low-Mass X-ray binary catalogue"

Avakyan A., Neumann M., Zainab A., Doroshenko V., Wilms J., Santangelo A., 2023, [A&A](#), **675**, [A199](#)

Paper II "XRBcats: Galactic High Mass X-ray Binary Catalogue"

Neumann M., **Avakyan A.**, Doroshenko V., & Santangelo A., 2023, [A&A](#), **677**, [A134](#)

Paper III "Hunting down new Galactic XRBs in eROSITA-DE DR1 using ML"

Avakyan A., Zainab A., Doroshenko V., Wilms J., Salvato M., Schwope A., Santangelo A., (2026 in progress)

Paper IV "XMM-*Newton* follow-up of two eROSITA X-ray binary candidates"

Avakyan A., Zainab A., Doroshenko V., Wilms J., Schwope A., Suleimanov V., Buckley D., Brink J., Santangelo A., 2025, [Experimental Astronomy](#), **60**, [6](#)

Paper V "The effect of thermal winds on the outbursts evolution of LMXB systems"

Avakyan A., Lipunova G., & Malanchev K., 2024, [MNRAS](#), **527**, [3709](#)

The listed original publications have been reproduced in this dissertation with the permission of the copyright holders.

List of publications not included in the thesis

The following original publications have not been included in the dissertation (listed in reverse chronological order):

- 1 "Multi-wavelength study of 1eRASS J085039.9–421151 with eROSITA, NuSTAR, and X-shooter"
Zainab A., **Avakyan A.**, Doroshenko V., et al., 2025, [A&A](#), 693, A260
- 2 "The SRG/eROSITA all-sky survey. First X-ray catalogues and data release of the western Galactic hemisphere"
Merloni A., Lamer G., Liu T., ... **Avakyan A.**, et al., 2024, [A&A](#), 682, A34
- 3 "Modelling outbursts of viscous accretion discs"
Lipunova, G., Malanchev, K., **Avakyan A.**, et al., 2022, in Astronomy at the Epoch of Multimessenger Studies, Proceedings of the VAK-2021 conference, p. 288—290
- 4 "Change in the Orbital Period of a Binary System Due to an Outburst in a Windy Accretion Disk"
Avakyan A., Lipunova G. , Malanchev K., Shakura N., 2021, [Astron. Lett.](#), 47, 377
- 5 "Influence of accretion disk wind on the evolution of LMXB outburst"
Avakyan A., Malanchev K., & Lipunova G., 2019, Proceedings of The Multi-Messenger Astronomy conference: Gamma-Ray Bursts, Search for Electromagnetic Counterparts to Neutrino Events and Gravitational Waves. p. 25—31

Declaration

The primary aim of this collective research is to identify and classify new XRB candidates within the Milky Way, utilizing data from the first public release of the eROSITA survey. This objective focuses on detecting previously unknown members of the Galactic XRB population that are hidden amidst millions of X-ray sources of various origins. The identification of these faint XRBs is essential for understanding the distribution and properties of their population within our Galaxy. The second focus of this dissertation is to investigate the role of thermal winds emanating from accretion discs and their impact on the evolution of X-ray nova outbursts. This aspect addresses the broader question of accretion dynamics, specifically by examining how these winds influence the progression of outbursts during high accretion states. Understanding the complex interaction between accretion flows and disc winds is vital for resolving key uncertainties in disc viscosity parameters and for explaining the rapid evolutionary phases observed in many X-ray novae.

In this context, the core contributions of the dissertation enhance the broader comprehension of the Galactic XRB population, particularly its less luminous segment. Furthermore, this work establishes a foundation for future follow-up observations of high-probable XRB candidates using X-ray and optical telescopes. These follow-up studies are critical for confirming the nature of the identified candidates and for conducting more detailed analyses of their properties. The investigation into accretion disc winds offers additional insights into the mechanisms driving X-ray nova outbursts. By addressing the challenges related to the high evolution rates of these outbursts and the uncertainties surrounding viscosity in accretion discs, this study aims to fill gaps in our theoretical models of accretion processes. The results have the potential to contribute to a more comprehensive framework for understanding the long-term behaviour and variability of XRBs.

I hereby declare that all findings and conclusions presented in this dissertation are the result of my independent research efforts. The ideas and discoveries discussed herein are based on original work, with proper acknowledgment given to collaborators whose contributions are documented in the respective articles. To the best of my knowledge, no additional sources have been used beyond those cited in the bibliography sections and corresponding papers.

Tübingen, January 24, 2025

Artur Avakyan

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1 Introduction

From the very beginning of observational X-ray astronomy, accreting compact objects have been one of the primary sources for study and exploration. It all started in June 1962, when an Airforce Aerobee rocket with three Geiger-Müller detectors onboard was launched with a purpose of surveying the lunar surface for X-rays (before launching astronauts to the Moon) and potentially detect Galactic X-ray emitters. However, while no X-rays from the Moon were detected during the observation, the first X-ray source outside our solar system was discovered (Giacconi et al., 1962, see Fig. 1). The object was later revealed to be located in the Scorpius constellation, and thus given a name of Scorpius X-1 (Sco X-1). Later on, the following studies showed that the X-ray emission from Sco X-1 cannot be explained by conservative means (such as optically thin hot plasma). Therefore, based on X-ray features and the properties of identified optical counterpart (Sandage et al., 1966, see also Fig. 10 in the Sect. 4.1) it was first suggested in Hayakawa and Matsuoka (1964) and then confirmed by Shklovsky (1967) that the source of radiation is an accreting neutron star (NS) in a binary system, making it the first X-ray binary (XRB) to be found. For a detailed review of the history of X-ray astronomy, see the "Handbook" (Bambi and Santangelo, 2024, Santangelo et al., 2023a,b, Volume 1).

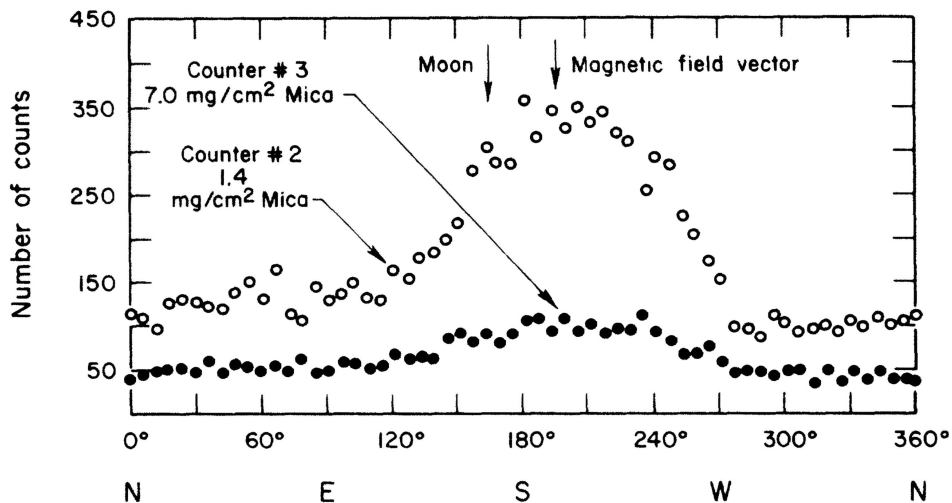


Figure 1: The azimuthal distribution of the count rates of the Geiger-Müller detectors, June 1962. Image is taken from Giacconi et al. (1962).

Since then, many other XRBs have been revealed, which host not only NSs, but also black holes (BHs) as an accreting component, showcasing the endpoints of stellar evolution of massive stars. Even today, new sources continue to be discovered and the number of known XRBs is ever growing. Therefore, systematically maintaining an up-to-date census of XRB population and the properties of its members is essential for understanding the evolution of massive stars and of our Galaxy as a whole. It is especially important in today's landscape of extensive surveys such as *Gaia* (Gaia Collaboration et al., 2016, 2023), Wide-field Infrared Survey Explorer (WISE, Cutri et al., 2021, Wright et al., 2010)

and extended ROentgen Survey Imaging Telescope Array (eROSITA, Merloni et al., 2012, 2024, Predehl et al., 2021), which provide many new and ever deeper observational data.

In light of this constant discovery process, it is clear that the latest catalogues of Galactic XRBs by 2023 (at the time this work took place), namely Liu et al. (2006, 2007), Ritter and Kolb (2003), were vastly outdated (by more than 16 years). Since then, hundreds of new persistent and transient objects have been unveiled. Surveys such as the Monitor of All-sky X-ray Image (MAXI, Matsuoka et al., 2009), X-ray Multi-Mirror Mission (XMM-Newton, Jansen et al., 2001), INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL, Winkler et al., 1993), Nuclear Spectroscopic Telescope Array (NuSTAR, Harrison et al., 2013), *Swift* X-ray and Burst Alert Telescopes (XRT and BAT) (Barthelmy et al., 2005, Gehrels et al., 2004), *Ross*i X-ray Timing Explorer observatory (RXTE Jahoda et al., 1996) and *Chandra* (Weisskopf et al., 2000) continued to improve our knowledge of physics and properties of XRBs. Moreover, follow-up studies allowed to identify optical/IR counterparts for many objects and study them in detail. Of course, the results of those investigations are also mostly not reflected in old catalogues. In this light, we have compiled two up-to-date catalogues of Galactic low-mass and high-mass X-ray binaries (LMXBs and HMXBs) showing about 500 XRBs as presented in **Papers I** and **II** respectively¹ (see the list of included papers on the page 12).

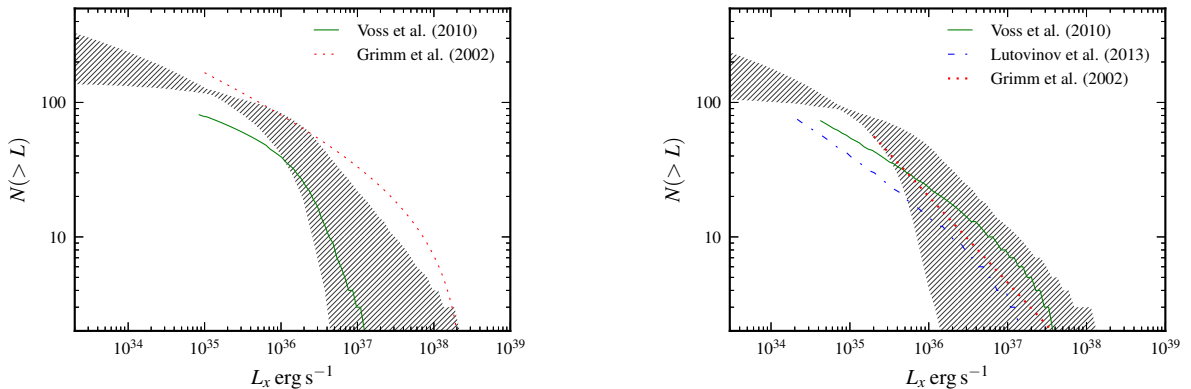


Figure 2: Cumulative X-ray luminosity functions for low-mass (left panel) and high-mass (right panel) XRBs from Doroshenko et al. (2014a).

It is also import to emphasise that XRB discoveries will not stop anytime soon. According to the population synthesis modellings there are several thousand XRBs in our Galaxy alone (Iben et al., 1995a,b, Lü et al., 2012, Portegies Zwart and Verbunt, 1996, van Haaften et al., 2015, Zhu et al., 2012). It means that potentially only a small part of suspected Galactic XRB population is discovered. This fact is supported by the form of the observed X-ray luminosity function (XLF, see Fig. 2) of XRBs in our and other galaxies (Doroshenko et al., 2014a, Grimm et al., 2002, Lutovinov et al., 2013, Mineo et al., 2011, Revnivtsev et al., 2008, Voss and Ajello, 2010). This implies, that the majority of XRBs are relatively faint in X-rays ($\lesssim 10^{34-35}$ erg/s), and thus escaped detection. Today, generally, only a few of such sources are known. Specifically, the majority of long-term faint XRBs have been discovered either during the outbursts (which make them bright, but happen once in years-decades) or in deep observations of other targets. This all underscores the necessity of expanding the faint part of known XRBs to comprehend the properties of their entire population, to come up with better constrains on XLF. Ultimately, studies on XLF allow to track accretion physics at low and high states, as well to

¹catalogues could be accessed on the <http://astro.uni-tuebingen.de/~xrbcat>

reveal interesting phenomena such as the propeller effect (Illarionov and Sunyaev, 1975, Shtykovskiy and Gilfanov, 2005) and the cold disc accretion (Tsygankov et al., 2017), happening in some XRBs (see more about that in the Sect. 3).

The reason why we are still missing most of the faint XRBs is related to the moderate sensitivity of wide-area X-ray surveys and the strong absorption in the Galactic plane (where XRBs are mostly located). Fortunately, the landscape started to shift with the implementation of the all-sky survey by the extended ROentgen Survey Imaging Telescope Array (eROSITA, Merloni et al., 2012, 2024, Predehl et al., 2021) aboard the Spectrum-Roentgen-Gamma (Spektra-RG, SRG) mission. With given eROSITA characteristics, it was predicted that the full survey will reveal up to several hundred of new XRBs in our Galaxy (Doroshenko et al., 2014a), effectively almost doubling the known sample. Crucially, most of the newly identified XRBs are expected to be relatively faint ($L_x \lesssim 10^{34-35}$ erg/s), a range where XRB XLF constraints are currently the weakest (see Fig. 2). This year (31st of January 2024), data from the first survey has been released as part of the public data release, covering half of the sky in X-rays (Merloni et al., 2024, eRASS, DR1, first six months scan, western Galactic hemisphere). In this light, we made a search for Galactic XRB candidates among almost a million of eRASS DR1 sources, which resulted in two catalogues of selected HMXB and LMXB candidates, as shown in the **Paper III**. Furthermore, two of XRB candidates identified in eROSITA data (however, with older pipeline version and much simpler approach used in comparison with the **Paper III**) were after observed with XMM-Newton. These follow-up observations together with eROSITA data are analysed (astrometry, spectral, timing properties) in the **Paper IV** in order to better constrain the origin of those candidates.

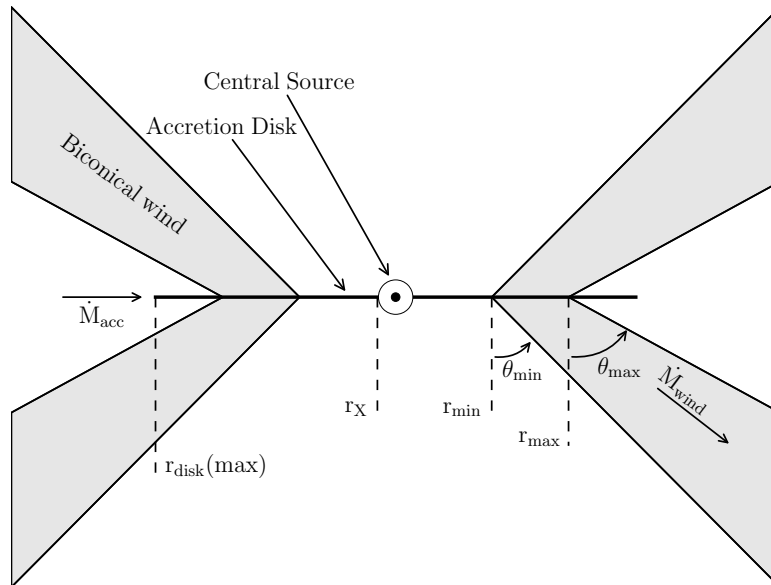


Figure 3: Representation of an accretion disc with the outflowing wind. Image is taken from Higginbottom et al. (2013).

Naturally, the science surrounding XRBs is not limited to the population, archive, and purely observational studies. The field also encompasses theoretical research aimed at solving the puzzles posed by deep and detailed observations of individual sources. One of such puzzles concerns the outbursts happening in XRBs, typically in LMXBs.

In a LMXB, material falling onto a BH/NS generally forms an accretion disc, with the outbursts themselves resulting from instability within this disc. To describe the complex behaviour of LMXB transient nature and the evolution of accretion discs, [Shakura \(1972\)](#), [Shakura and Sunyaev \(1973\)](#) introduced the dimensionless parameter of the turbulent viscosity $\alpha \lesssim 1$, which characterises the angular momentum transfer rate and the viscous time of the disc.

So, the puzzle here is that the observational analysis of LMXB outbursts require α to lie within $\sim 0.2 - 1$ range ([Lipunova and Malanchev, 2017](#), [Lipunova and Shakura, 2002b](#), [Martin et al., 2019](#), [Suleimanov et al., 2008](#), [Tetarenko et al., 2018a](#)). However, modern 3D simulations, employing magnetorotational instability as a source of angular momentum and matter transport in the disc, indicate values significantly lower: $\alpha \lesssim 0.1$ ([Balbus and Hawley, 1991](#), [Hirose et al., 2014](#)). This discrepancy to some extent may be explained by an incorrect estimation of α parameter values from observations, potentially influenced by the presence of another mechanism responsible for angular momentum transport, such as an accretion disc wind (see Fig. 3). In **Paper V** we consider the model in which the disc's material is thermally heated by central radiation (through inverse Compton processes) in the optically thin regions ([Begelman et al., 1983](#), [Shields et al., 1986](#), [Woods et al., 1996](#)). Namely, we implement the analytical Compton-heated wind into our code FREDDI which calculates X-ray and optical light curves of soft X-ray transients outbursts ([Avakyan et al., 2019, 2021](#), [Lipunova and Malanchev, 2017](#), [Malanchev and Lipunova, 2016](#))².

In the next chapter I will go a bit deeper into the topics outlined above and briefly describe the family of XRBs, their origin and evolution, key observational properties and how they are represented in our Galaxy. Going further, I will show how the accretion processes could be characterised through the means of observations of faint (propeller mode systems, cold disc accretion) and bright sources (such as X-ray novae). Description of the LMXB outbursts modelling taking into account the presence of the disc wind will also be given. Next, the methods to identify new XRBs using MWL data will be discussed, with special emphasis on machine-learning (ML) algorithms and eROSITA. Finally, I will outline potential applications of the results from this dissertation in future studies, illuminating the path forward for XRB population science.

²FREDDI can be freely downloaded from the web page <https://github.com/hombit/freddi>

2 X-ray binaries

Many stars in the universe are born as part of multiple stellar systems, such as pairs, triples or even higher multiplicities. Moreover, the probability of a star to be a member of a system increases with its mass (Kouwenhoven et al., 2007, Mason et al., 2009, Moe and Di Stefano, 2017). Therefore, BHs and NSs, being the endpoints of massive star evolution (supernova II progenitors), are generally expected to end up forming in binary systems. However, since the supernova explosion is a drastic phenomena itself, the probability that the system will remain gravitationally bound, much less become a close binary, depends on many conditions, such as the mass ratio of the components, mass and momentum loss rate, and even asymmetry in the core-collapse (which drives star kicks).

2.1 Origin and evolution

An X-ray binary (XRB) is a 'successful result' of such one-component collapse process, namely, it is a close binary system where one of the stars evolved into a neutron star (NS) or a black hole (BH), with the other companion still being a main-sequence star (in rare cases dwarf/giant). These systems are some of the most dynamic objects, which emit enormous amounts of energy, mostly in the form of X-rays. The main source of such high-energy radiation is the accretion of matter onto a compact object from a donor star. In fact, accretion is the process whose presence makes the system 'compact object+star' considered as an XRB. However, it should be noted that binaries with white dwarf (WD) accretors are not generally considered as XRBs, despite their emission of soft X-rays through accretion. These systems are historically attributed to a different Galactic population known as cataclysmic variables (CVs). Additionally, 'spider'-type sources such as Black Widows and RedBacks (BW and RBs, respectively; see e.g. Chen et al., 2013, Roberts, 2013), which are believed to be 'NS+star' binaries, are also generally not considered as XRBs, unless they are classified as transitional millisecond pulsars (tMSPs, see Archibald et al., 2009, Papitto et al., 2013). The reason is that although 'spider'-type systems are similar to XRBs as binaries (contain NS components) and some of them emit detectable X-rays, their radiation is not powered by accretion (however, in the case of tMSPs accretion occurs from time to time).

The characteristics of XRBs are primarily determined by the mass-transfer process driving the accretion, which can occur either directly from the wind of the secondary star (Lamb et al., 1973) or via Roche lobe overflow (RLOF) when donor fills it (Pringle and Rees, 1972). This mechanism mainly depends on the mass ratio M_x/M_{opt} and distance between the compact object and its optical counterpart. In principle, XRBs are divided into two major categories: high-mass X-ray binaries (HMXBs) and low-mass X-ray binaries (LMXBs). Systems where the compact object mass (M_x) is lower than the optical counterpart mass (M_{opt} , usually $M_{\text{opt}} \gtrsim 5M_{\odot}$), matter transfer generally occurs directly from strong stellar wind of early-type star component. Such binaries are categorised as HMXBs. In turn, when $M_x > M_{\text{opt}}$ and mostly $M_{\text{opt}} \lesssim 1M_{\odot}$, mass transfer goes primarily via RLOF (usually from a late-type star), identifying these systems as LMXBs. These two cases of accretion flow in XRBs are shown on the Fig. 4. The substantial discrepancies in the observed properties of LMXBs and HMXBs, along with their belonging to different

parts Galactic population and/or stellar evolution stages, require separate consideration for each class.

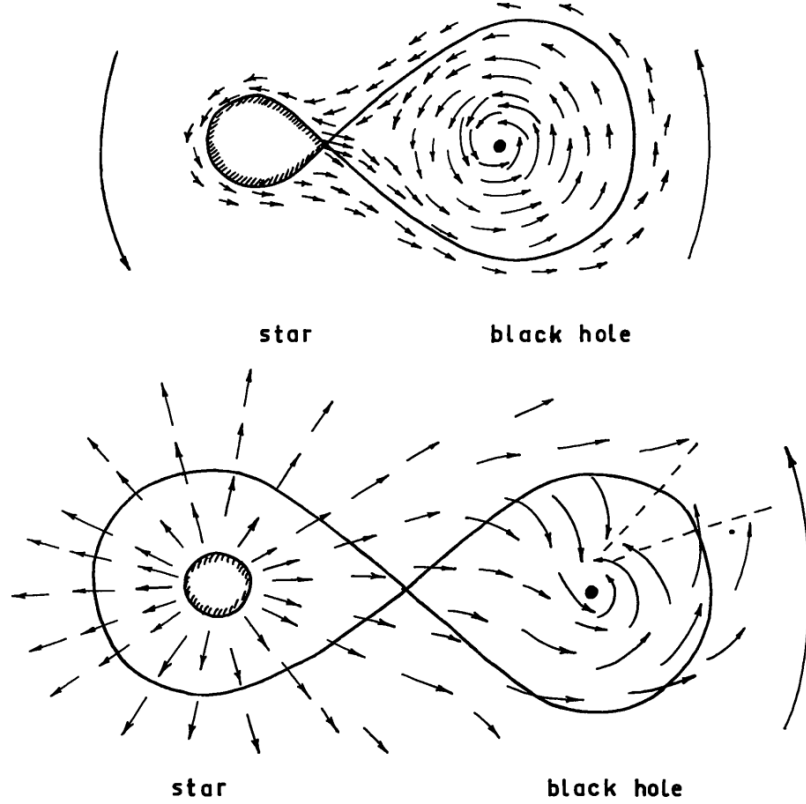


Figure 4: Schematic view on two regimes of the accretion onto a compact object: RLOF with the creation of an accretions disc (top drawing) and stellar wind from a massive early-type star component (bottom drawing). Image credit: [Shakura and Sunyaev \(1973\)](#).

2.2 High-mass X-ray binaries

Based on the simulations, a BH/NS progenitor component of the binary system with a mass above $20M_{\odot}$, expands during the evolution and fills its Roche lobe, transferring most of its hydrogen-rich material to the less-massive early-type main-sequence counterpart ([Hilditch, 2001](#)). This transfer of matter causes the mass ratio between binary members to change in the opposite direction, and initially less massive component begins to dominate in the mass of the system. If the binary remains intact after core-collapse supernova of the original primary, with the created compact object accreting the matter from the secondary, a HMXB may be formed.

As the result, HMXBs host early type (typically O-B) donor stars, which masses generally above $5 - 10M_{\odot}$ ([Bhattacharya and van den Heuvel, 1991](#), [Kretschmar et al., 2019](#)). Given the relatively short lifespans of such stars (around a few million years), HMXBs are considered to be young systems and are often found in the regions with high Star Formation Rate (SFR), such as spiral arms of the Milky Way. Therefore, population of HMXBs could be a good tracer for star forming activity in the host galaxy ([Grimm et al., 2003](#), [Kudritzki and Puls, 2000](#)). As of now, more than 170 of such sources are known in our Galaxy alone (see Paper II). The majority of currently known HMXBs

host a NS (instead of a BH) with a strong magnetic field, typically having $B \approx 10^{12}$ G (Staubert et al., 2019), which is mainly measured via detection of cyclotron resonant scattering features (CRSFs). It is also believed that high B values are related to the young age of HMXBs, since the magnetic field is expected to decay over time and would therefore be weaker in older NSs. The fact that the majority of observed HMXBs contain NSs rather than BHs is at least partly caused by selection effects. Since BHs have no surfaces, they can only be detected through radiation from the accretion disc, which in turn rarely forms in HMXBs.

Based on the type of the massive companion, HMXBs can be further subdivided into two groups: systems with supergiant counterparts (SGXBs, Corbet, 1986), and XRBs with Be type companions (BeXBs, Reig, 2011). The main difference between the two sub-classes is in the mechanism driving the accretion. In SGXBs matter is accreted from a radially outflowing stellar wind, while the compact object in BeXB accretes matter directly from the circumstellar disc of a fast rotating donor (Balona and Ozuyar, 2020). However, RLOF or disc-fed accretion is also possible for HMXBs on rare occasions (such as SS 433 or Cen X-3). Since supergiants have dense and powerful stellar wind (mass-loss rate could be up to $\dot{M}_{\text{wind}} \approx 10^{-5} M_{\odot} \text{ yr}^{-1}$, see Martínez-Núñez et al., 2017), SGXBs consistently exhibit high X-ray luminosity by persistently maintaining high accretion rates. On the other hand, in BeXBs accretion does not go constantly at relatively same level, and the X-rays mainly emitted when the compact object passes through the secondary’s circumstellar disc when it is present. As a result, the SGXBs are persistent sources, whilst the BeXBs are very variable, with their variability tracking the orbital period. You can see the schematic view of such two cases on the Fig. 5.

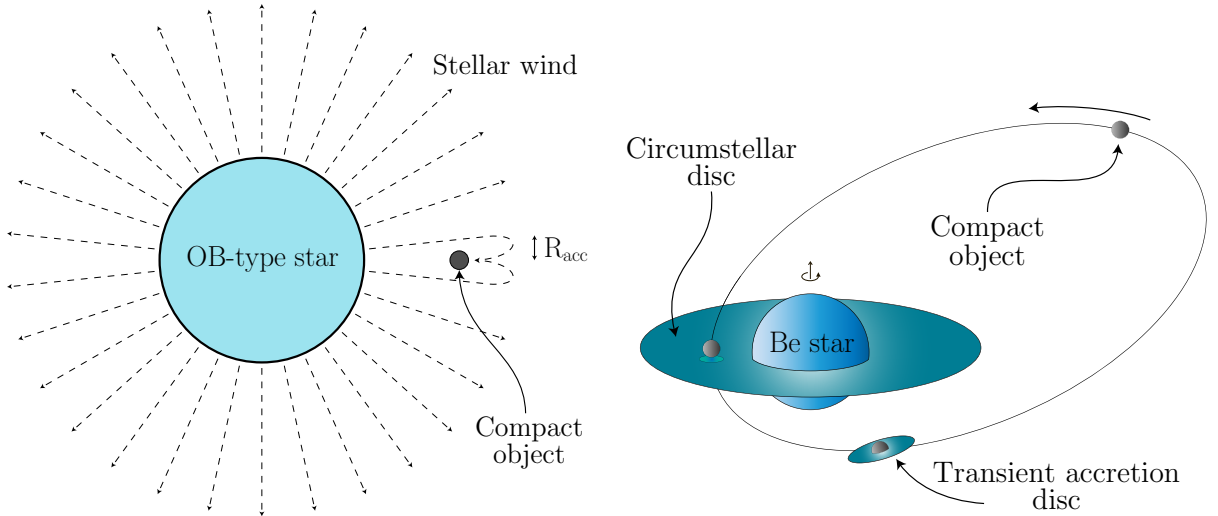


Figure 5: Schematic representation of the two main HMXB sub-classes: SGXB (left panel) and BeXB (right panel).

However, even in the category of SGXBs there are also highly variable subtype of sources: supergiant fast X-ray transients (SFXTs, Negueruela et al. 2006). These systems are known for their sudden and intense X-ray outbursts, which can increase their luminosity by several orders of magnitude (going from 10^{32-34} up to 10^{36-37} erg/s) but only within a short period, typically lasting from a few minutes to a few hours. This is short-lived compared to BeXBs, where bursts typically last for weeks. The source of the rapid variability in SFXTs is believed to be the clumpy nature of the supergiant companion’s stellar wind, however, other mechanisms are also considered. BeXBs, on the other hand, also show different kinds of outbursts, mainly divided into two types. Type I outbursts

are regular events of increased luminosity (up to 10^{37} erg/s), normally correlated with the passage of the compact object through equatorial decretion disc. In turn, the Type II outbursts happen irregularly, last longer and generally less frequent than Type I outbursts. These outbursts probably arise from a dramatic expansion of circumstellar disc. Peak luminosity during Type II outburst can reach up to 10^{39} erg/s (Doroshenko et al., 2020), thus even exceeding the Eddington luminosity limit for a NS.

2.3 Low-mass X-ray binaries

On the other hand, in the progenitor binary systems for LMXBs, only one member is a massive early-type star. This star eventually undergoes core-collapse supernova, leaving behind a NS or a BH. The other component in such systems is typically a low-mass star ($M_{\text{opt}} \lesssim 1M_{\odot}$): late-type (M-K, G or A on rare occasions) main-sequence star, degenerate dwarf, or a red giant, depending on the system’s evolutionary stage. Such stars do not have strong stellar winds or circumstellar discs, so any potential accretion may occur primarily via RLOF. If the system remains gravitationally bound after supernova explosion of the primary, it can evolve into a LMXB. Basically, after several billion years (typical age of a LMXB is about $10^9 - 10^{10}$ years) the secondary star (following the primary) also evolves and fills its Roche lobe, therefore, material begins to fall onto the compact object and RLOF accretion starts. Since the matter flowing out of the Roche lobe of the secondary component has significant angular momentum, it does not fall directly onto the compact object but rather revolves around it. Due to the redistribution of angular momentum caused by turbulent viscosity, the rotating stream of matter forms an accretion disc (Shakura and Sunyaev, 1973). If the compact object’s magnetic field is weak or absent, a large amount of gravitational energy is released as the accretion flow moves towards the central object. As a result, the brightest part of the system in X-rays is the central regions of the accretion disc around the compact object.

As was mentioned before, LMXBs are evolutionary old systems and trace low-mass star density in the Galaxy. Therefore, they can locate relatively high above the Galactic plane (far from the regions of high SFR). The majority of about 350 known Galactic LMXBs (see Paper I) are concentrated in the bulge and thick disc of the Milky Way, as well as could be frequently found within Global Clusters (GCs). Therefore, LMXB population could be used as a tool in order to track the overall mass of the host galaxy (Gilfanov, 2004).

One of the key observational features of LMXBs is their X-ray variability. Only a small number of LMXBs are persistent X-ray sources, while the majority of them exhibit transient behavior. Some bursts arise from thermonuclear explosions on the neutron star surface, triggered by the accumulation of hydrogen or helium from the donor star. These bursts (called Type-I bursts) are characterised by the overall relatively short duration ($\sim 10 - 10000$ s) and exhibit rapid rises in X-ray luminosity followed by exponential decays, providing insights into the nuclear processes occurring on the neutron star’s surface. They can also be used to measure the compactness of a NS as well as to constrain the corresponding equation of state (EoS), see Suleimanov et al. (2020).

However, the major source of a long-term variability of LMXBs is the instability of accretion flow in disc around compact object. Due to such instabilities, LMXBs show periods of intense X-ray outbursts (called ‘X-ray Novae’, which last weeks-months) followed by quiescent phases (with duration up to decades). X-ray Novae are some of the brightest objects on the X-ray sky (with luminosities up to $10^{38} - 10^{39}$ erg/s). According to the disc instability model (DIM, Lasota, 2016), during the quiescence state, mass from the secondary component accumulates in the disc. As the mass of the disc increases, its temperature rises until it becomes sufficient for hydrogen ionisation. In this region of

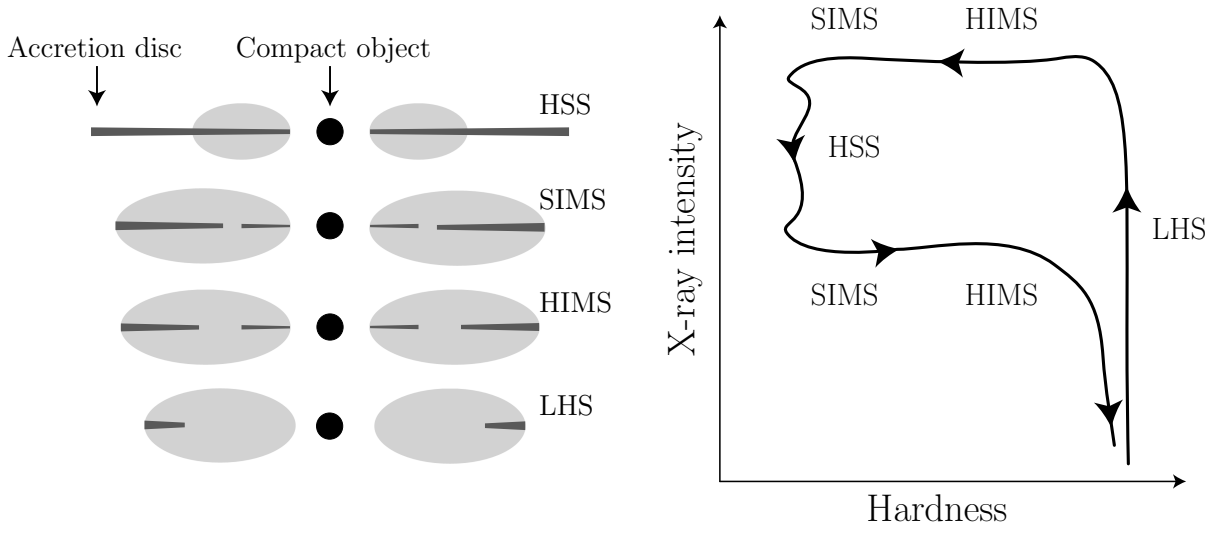


Figure 6: The structure of the accretion flow (left panel) during different states of LMXBs. A hardness-intensity diagram (HID) for typical LMXB outburst/quiescence evolution (right panel). Left image is drawn based on the figure from [Liu and Qiao \(2022\)](#).

the disc, thermal-viscous instability is activated, leading to further heating. This process results in a sharp increase of the central accretion rate onto compact object, consequently, increasing luminosity.

This type of evolution is shown on the Fig. 6, where the system after accumulating the mass exhibits an outburst, entering the high-soft state (HSS). This state is characterised by the soft spectrum and really high X-ray luminosities (usually reaching sub-Eddington level). After the peak of the outburst, when the accretion processes are sufficiently suppressed, the decay rate changes and the binary switches first to the soft-intermediate (SIMS) and then to the hard-intermediate state (HIMS). In these states LMXBs show significantly lower luminosities, and harder spectra compared to the HSS. However, SIMS and HIMS are transitional phases, and soon after the system ends up in the low-hard state (LHS), where it could stay for years after the accumulation of mass into the disc restarts. It is important to emphasise that LMXB outburst properties and evolution are phenomenologically very rich and cannot be fully discussed here, so please refer to the "Handbook" ([Bahramian and Degenaar, 2023](#), [Bambi and Santangelo, 2024](#), Volume 6) for the recent review.

Boundary type cases

Naturally, the division of mass ranges for HMXBs and LMXBs is not fully strict, and the existence of boundary cases is unavoidable. Currently there are two main additionally highlighted types of XRBs which don't fully fit into canonical H/LMXB class definition: symbiotic (SyXBs) and intermediate-mass X-ray binaries (IMXBs).

SyXBs mostly host NSs as a primary, which accrete matter from an evolved red late-type giant companion star with a mass less than $1M_{\odot}$. The accretion process in SyXBs is similar to the one in HMXBs, namely, it is primarily wind-fed. SyXBs also exhibit significant variability, which can be attributed to changes in the wind density and/or accretion flow properties. Only a handful number of SyXBs are known today. However, even though they are usually considered as a part of the LMXBs population (based on the type and age of the donor), their timing and spectral behaviour in the X-rays strongly resembles that of the HMXBs. SyXB systems typically have long orbital periods, often

spanning several years. In many cases, the NSs in these systems are highly magnetized, with the strength $B \approx 10^{12}$ G (as HMXBs, SyXBs also show CRSFs). This is somewhat surprising because, over time, especially during accretion (Shibazaki et al., 1989, Taam and van den Heuvel, 1986), a NS’s magnetic field generally weakens. Given that a typical SyXB is at least several billion years old, the presence of such strong magnetic fields is unexpected. The old age is actually the main reason why the majority of LMXBs host weakly magnetised NSs (Tauris, 2015). In this context, an alternative origin for such XRBs is generally assumed. It is proposed that a NS in a SyXB progenitor system is not formed directly from a core-collapse supernova of a massive star, but rather through the delayed collapse of a WD via accretion (Ablimit, 2023, Tauris et al., 2013). Namely, it means that some SyXRBs were originally CV systems, however, accretion of mater onto a WD led it to collapse into a NS less than a few million years ago. Consequently, the recently formed NS remains ‘young’ and is able retain its high magnetic field up to the point when the system appears as a SyXB. However, the WD-to-NS collapse process is not yet fully understood, and other mechanisms for maintaining a highly magnetised NS in old age are being considered (Bozzo et al., 2008, 2018, Shakura et al., 2012).

IMXBs, on the other hand, represent a more transitional category, literally placed between HMXBs and LMXBs in terms of mass. In IMXBs, the donor star is typically a main-sequence star of (B,A classes), with masses ranging from about $1.5M_{\odot}$ to $5M_{\odot}$ solar masses. Such XRB share characteristics with both LMXBs and HMXBs, making them important for understanding the full spectrum of X-ray binary evolution. Mass transfer in IMXBs usually occurs via the RLOF or in rare cases via the stellar wind, depending on the evolutionary stage of the donor star. One of the best known members is Her X–1, where the accretion occurs via RLOF, similar to the majority of classical LMXBs. However, the donor in the system is a B3-type star (which more resembles HMXBs) with relatively low mass (closer to the mass range of LMXBs) of $\sim 2.2M_{\odot}$ (Middleditch and Nelson, 1976, Tananbaum et al., 1972). On top of that, the compact object here is a strongly magnetised NS, making it similar to HMXBs in that sense.

Even though SyXBs and IMXBs sort of ‘bridge’ the HMXB and LMXB classes, as binary star systems they are evolutionarily closer to LMXBs. Considering that and the fact that the total number of SyXBs and IMXBs is relatively small, in this dissertation we consider these type systems as a part of the LMXB population (see more in the Paper I, II and III). Nevertheless, both SyXBs and IMXBs provide important test boundary cases for theories of binary evolution and accretion physics, such as NS propeller modes, RLOF and wind-fed mass transfer, binary stellar evolution at late stages. Taken together, all these subclasses of binaries deepen our understanding of the complex interactions that govern the dynamical behavior of such systems, highlighting the continuous spectrum of properties that span across all XRB population, ultimately giving us a better look at the endpoints of stellar evolution.

In the next chapter, a short description of the physics behind the accretion and disc winds will be provided, focusing on magnetospheric accretion onto NSs and X-ray novae-like sources. This will include an exploration of the mechanisms driving accretion and disc winds, the analytical models behind these processes, and their role in the evolution of XRBs.

3 Accretion physics in XRBs

Accretion of matter onto a compact object (BHs, NSs or WDs) is one of the most efficient energy release processes in the Universe. It dominates in the observational appearance of sources such as: young stellar objects (YSOs), XRBs, CVs and active galactic nuclei (AGNs). Fundamentally, accretion is the process of converting the potential energy into radiation. As a result of such process, accreting sources are detectable across the whole electromagnetic spectrum. However, the energy peak range (while varying based on the nature of the accreting object) is in most cases focused in X-rays, especially for NS or BHs located in XRBs. Analysing the behavior of such objects gives the insights into the ongoing physical processes and their long-term evolution.

3.1 Accretion in HMXBs

As mentioned in the previous chapter, known HMXBs tend to host strongly magnetised NSs, which leads to some interesting modifications of the accretion physics in this case. Accretion onto a NS involves complex interactions between the stellar wind of the massive companion and the NS's gravitational and magnetic fields.

Donor star's material falling onto the NS (with a mass of M_{NS}) at the relative speed v_{rel} accretes within a cylindrical radius, known as the accretion radius $R_{\text{acc}} = 2GM_{\text{NS}}/v_{\text{rel}}^2$ (see Fig. 5, left panel). Given that the binary separation is significantly larger than the accretion radius R_{acc} , only a small fraction of the total wind from the companion star will be accreted onto the NS (Martínez-Núñez et al., 2017). Consequently, assuming a spherically symmetric mass loss from the companion, the accretion rate onto the NS can be calculated as (Davidson and Ostriker, 1973):

$$\dot{M} = \dot{M}_{\text{wind}} \times \frac{\pi R_{\text{acc}}^2}{\Omega a^2}, \quad (3.1)$$

where a is the separation between binary components, $\dot{M}_{\text{wind}}$ is the mass loss in the stellar wind and Ω is solid angle (equal to 4π for isotropic stellar wind). Pressure of the strong magnetic field, however, affects the infalling material, inducing the presence of specific accretion modes, depending on the system's parameters.

Magnetosphere and the mass inflow

When the ionised accretion flow approaches a highly magnetised NS, at some point, it gets disrupted by the NS's strong magnetic field. This distance is called magnetospheric radius (R_{M}). At this distance, the magnetic field pressure balances the pressure exerted by the infalling material. In order to calculate R_{M} one can examine the equilibrium between magnetic and plasma pressures. Assuming a spherically symmetric accretion inflow with the free-fall velocity $v_{\text{ff}} = \sqrt{2GM/R}$ and density ρ , the ram pressure of the infalling matter could be calculated as:

$$P_{\text{ram}} = \frac{\rho v_{\text{ff}}^2}{2} \sim \frac{\dot{M}}{4\pi} \sqrt{\frac{GM}{2R^5}}, \quad (3.2)$$

and then equated to the magnetic pressure:

$$P_{\text{mag}} = \frac{B^2}{8\pi} = \frac{\mu^2}{8\pi R^6}, \quad (3.3)$$

where R and M are the distance from the NS and its mass respectively, and $\mu = BR^3$ and B are the dipole magnetic momentum and the magnetic field itself. If one solves the equation, the so called Alfvén radius at which the equilibrium is reached, could be obtained:

$$R_A = \left(\frac{\mu^2}{\dot{M}\sqrt{2GM}} \right)^{2/7}. \quad (3.4)$$

However, the accretion flow onto the NS is not generally spherical, and more accurate formula for R_M would look as:

$$R_M = \Lambda \times R_A = \Lambda \times 3 \cdot 10^8 \mu_{30}^{4/7} \dot{M}_{17}^{-2/7} M_{1.4\odot}^{-1/7} \text{ cm}, \quad (3.5)$$

where μ_{30} is the magnetic momentum in terms of 10^{30} G cm^3 , $\dot{M}_{17}$ is the accretion mass rate in the units of 10^{17} g/s and $M_{1.4\odot}$ is the mass of the NS in units of $1.4M_\odot$. The coefficient Λ here is responsible for the geometry of the accretion mass inflow. In the case of a stellar wind accretion $\Lambda \approx 1$, whilst for disc accretion it is $\Lambda = 0.5$ (Doroshenko et al., 2014b, Ghosh and Lamb, 1978, 1979). It should be noted, that for an accretion disc, this radius corresponds to magnetospheric truncation radius, at which the disc is disrupted (truncated) by the magnetic field. According to equations (3.4) and (3.5) the magnetospheric radius shrinks when the mass accretion rate increases, so the accretion flow penetrate closer to the surface of the NS. This has some important consequences for many observed properties of NS HMXBs, some of which will be discussed further in this chapter.

Transfer of the angular momentum to a NS via accretion implies that it must inevitably spin. In turn, the strong magnetic field of a NS channels the accretion matter straight down to its magnetic pole through the magnetic field lines. Since the magnetospheric and rotational axes are usually not aligned these two processes together lead to the phenomenon of an X-ray pulsar (XRP, Caballero and Wilms, 2012, Davidson and Ostriker, 1973, Giacconi et al., 1971, Lamb et al., 1973, Mushtukov and Tsygankov, 2022). However, the fact that the NS spins also affects the accretion process itself. For accretion to proceed onto the surface of a NS, the inflowing matter at the magnetospheric boundary must have an angular velocity which is above that of the magnetosphere. The magnetosphere rotates at the same angular velocity as the NS itself, while the inner disc plasma is expected to rotate at the local Keplerian velocity. At a specific distance, known as the corotation (or co-rotating) radius (R_{co}), the angular velocity of the magnetosphere Ω_{NS} equals the Keplerian angular velocity of the matter Ω_{K} :

$$\begin{aligned} \Omega_{\text{NS}} = \Omega_{\text{K}}(R_{\text{co}}) &= \sqrt{\frac{GM}{R_{\text{co}}^3}}, \\ R_{\text{co}} &= \left(\frac{GM}{\Omega_{\text{NS}}^2} \right)^{1/3} = \left(\frac{GMP^2}{4\pi^2} \right)^{1/3}, \end{aligned} \quad (3.6)$$

where P is the spin period of the NS.

Propeller mode

Ultimately, the behaviour of the NS HMXB system depends on the sizes of the magnetospheric radius R_M and the co-rotating radius R_{co} . If R_M is close or smaller than R_{co} , the

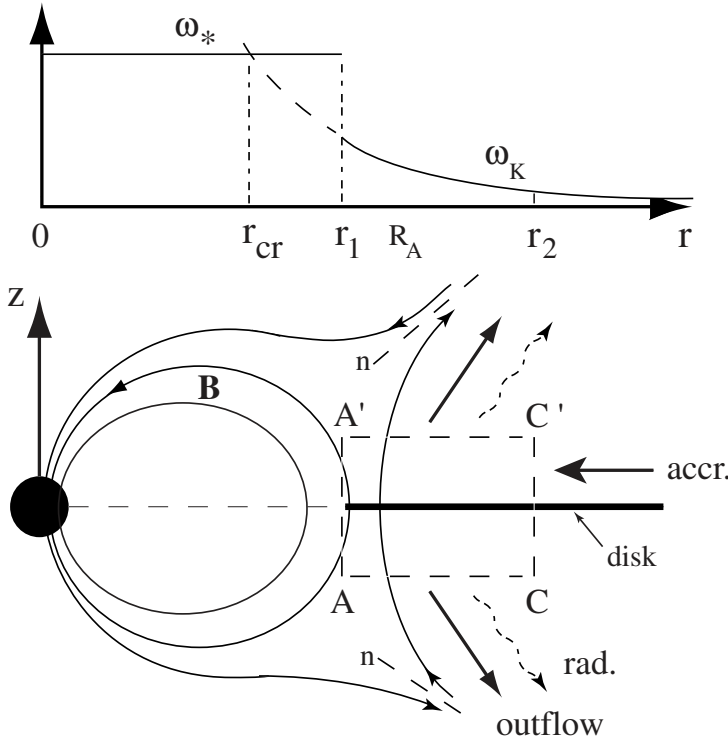


Figure 7: Geometry of disc accretion to a rapidly rotating star with an aligned dipole high magnetic field. *Top panel:* radial distribution of angular velocities of the star and of the accretion disc. *Bottom panel:* the structure of the magnetosphere in the propeller regime. Here, R_A is the effective radius where the outflow begins, ω_* is the star's rotation rate, ω_K is the Keplerian rotation rate of the accretion disc, r_{cr} is the corotation radius. The dashed lines marked by the letters 'n' indicate neutral surfaces along which re-connection occurs. Image is taken from [Lovelace et al. \(1999\)](#).

system maintains equilibrium accretion. Here, the angular velocity of the magnetosphere is less than the Keplerian velocity, allowing matter to be accreted, making the binary detectable as an XRB. However, if R_M is larger than R_{co} , accretion is halted by centrifugal forces, entering what is known as the 'propeller' regime ([Illarionov and Sunyaev, 1975](#), [Lovelace et al., 1999](#), [Ustyugova et al., 2006](#)), shown on the Fig. 7. Here, in turn, the infalling matter is basically expelled by the centrifugal barrier, stopping accretion at R_{co} . Some systems actually can switch from one mode to another due to the change of the magnetospheric radius (with the accretion rate), which allows its calculation ([Tsygankov et al., 2016](#)).

As a result, it seems clear that with a constant magnetic field and rotation speed of the NS, there should exist some limit on the accretion mass rate, below which the binary system goes into propeller mode. It can be calculated from (3.5) (considering (3.4)) and (3.6), by equating one with the other, as follows:

$$\dot{M}_{prop} = \frac{\Lambda^{7/2} \mu^{2/3}}{(2GM)^{5/3}} \left(\frac{2\pi}{P} \right)^{7/3} \approx 3.75 \times 10^{17} \Lambda^{7/2} B_{12}^2 R_{NS,6}^6 M_{1.4\odot}^{-5/3} P^{-7/3} \text{ g/s}, \quad (3.7)$$

where B_{12} is the magnetic field in the terms of 10^{12} G and $R_{NS,6}$ is the radius of the NS in the units of 10^6 cm. Therefore, the limiting X-ray luminosity L_{prop} could be obtained via $L_X = G M_{NS} \dot{M} / R_{NS}$:

$$L_{prop} \approx 5 \times 10^{37} \Lambda^{7/2} B_{12}^2 R_{NS,6}^5 M_{1.4\odot}^{-2/3} P^{-7/3} \text{ erg/s}. \quad (3.8)$$

Some NS HMXBs actually show the transition behaviour between propeller and accretion regimes ([Campana et al., 2001](#), [Lutovinov et al., 2017](#), [Tsygankov et al., 2016](#)). This effect was even showcased to have an impact of the picture of HMXB population in the Large Magellanic Cloud (LMC) and respective XLF ([Shtykovskiy and Gilfanov, 2005](#)). However, it was later revealed that some systems can actually avoid the transition to the propeller regime even at low accretion states, exhibiting behaviour similar to that of LMXBs, as will be discussed below.

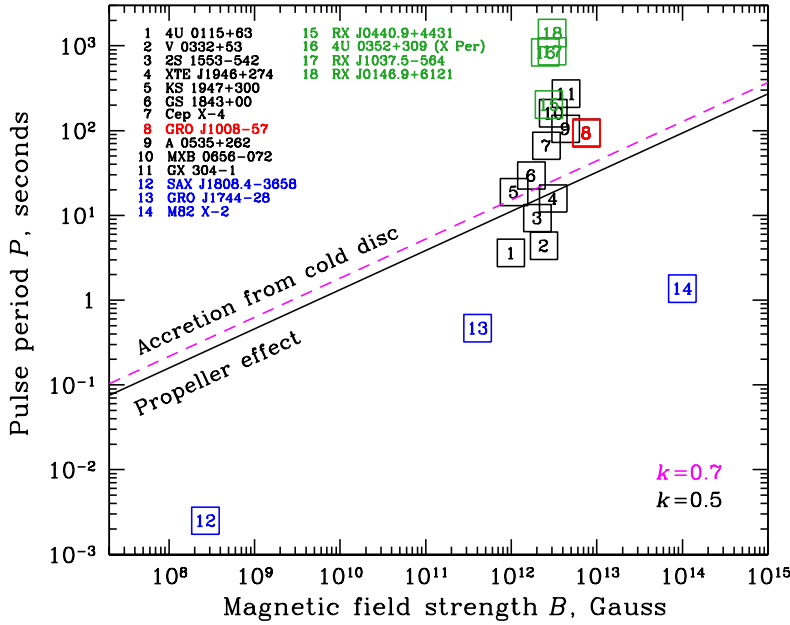


Figure 8: Spin period/magnetic field diagram showing several known BeXBs (black squares), as well as SAX J1808.4–3658, GRO J1744–28, and M82 X–2 (all three as blue squares). Persistent low-luminous BeXRBs are shown in green, while GRO J1008–57 is shown in red. Image is taken from [Tsygankov et al. \(2017\)](#).

Cold accretion mode

Typically, the transition to the propeller regime in a NS HMXB goes after the outburst decay. Specifically, after the peak of the flare, the accretion rate exponentially decreases, dropping below the $\dot{M}_{\text{prop}}$, therefore, the inflow of matter stops. Such behavior is usually associated with NS BeXPs due to their transient/variable nature. However, if the spin period of a NS is long enough, the system may not turn into propeller and accretion continues. This is also strongly connected to the ionisation state of the disc around the NS, which is usually created after NS passes through circumstellar disc of Be counterpart (see Fig. 5, right panel).

As mentioned before in the Sect. 2.3, when the matter is accumulated into the disc and temperature inside rises, at some point hydrogen gets ionised, forcing the disc to switch to the hot state as the result of the thermal-viscous instability. Given higher viscosity, the accretion rate rapidly rises, allowing the accumulated matter (the majority of it) to be transferred onto the NS. Accretion from such a hot, viscous disc is, in fact, the main accretion regime for all XRBs where a disc is presented. However, if the accretion disc is not replenished at a sufficient rate, it may lose the material and cool down below the hydrogen ionisation temperature, starting recombination and making the accretion process stable at the low rate calculated as ([Lasota, 1997, 2001](#)):

$$\dot{M} < \dot{M}_{\text{cold}} \approx 3.5 \times 10^{15} R_{10}^{2.65} M_{1.4\odot}^{-0.88} \text{ g/s}, \quad (3.9)$$

where R_{10} is the inner disc radius in units of 10^{10} cm. At this point the accretion rate drops and stabilises at some low but persistent value. It means that R_M stops increasing, which may prevent onset of the propeller regime. In principle, if one considers the inner radius to be equal to the magnetospheric radius, the transition to the cold disc accretion rate/luminosity could be found as :

$$L < L_{\text{cold}} \approx 9 \times 10^{33} \Lambda^{3/2} M_{1.4\odot}^{0.28} R_6^{1.57} B_{12}^{0.86} \text{ erg/s}. \quad (3.10)$$

Below this level, the accretion disc is in the cold state at the distances above the magnetospheric radius R_M .

In most NS XRBs, the limit luminosity (which corresponds to the propeller regime transition, Eq. 3.8) is higher than the cold disc accretion luminosity (Eq. 3.10), i.e. $L_{\text{prop}} >$

L_{cold} . Therefore, the accretion rate decay after the peak of the outburst at some point will stop, transitioning to the propeller mode. However, if the spin period P of a NS is relatively long, it results in a lower centrifugal barrier, making it possible for the accretion disc to switch to the cold state before the propeller regime arises. In such scenario, L_{prop} is, in opposite, lower than L_{cold} , allowing the accretion process to continue at low rate. Thus, the final state the system enters after an outburst in this case is determined by the NS's spin period P and magnetic field B (Tsygankov et al., 2017). By equating the expressions for the luminosities L_{cold} and L_{prop} , the critical value for the spin period as a function of the magnetic field can be derived as:

$$P^* = 36.6 \times \Lambda^{6/7} B_{12}^{0.49} M_{1.4\odot}^{-0.17} R_6^{1.22} \text{ s}. \quad (3.11)$$

One can use this equation to predict the transient evolution of any NS XRB which appear as an XRP (thus, with known spin period and magnetic field). Specifically, if the spin period of a NS is below P^* , the system will end up in the propeller regime. In turn, if $P > P^*$ the system will end up in cold accretion state. The latter scenario was revealed to be especially important for BeXBs (Tsygankov et al., 2017), since such systems are known for their transient behaviour (see Sect 2.2). This was further showcased for Be-transient XRP GRO J1008–57, which went to the steady accretion from the cold disc after Type I outburst (Tsygankov et al., 2017, see also Fig. 8).

Both of these processes, the propeller regime and steady cold disc accretion, influence the shape of the HMXB XLF and can be monitored through its analysis without the need for in-depth studies of specific sources. Consequently, archival and population studies are crucial for understanding and demonstrating how such complex physics operates on a global scale across the entire XRB population.

After we've discussed the main processes responsible for different transient/evolution behaviour of HMXBs, which affect the picture of their population as whole, we will move to LMXBs. In the next section, I will provide the description of how the accretion disc evolves during the quiescence and X-ray nova outburst (especially relative to BH systems). Such flares happen in majority of LMXBs, making them variable, ultimately affecting the population observational appearance. Since in the Paper V, however, I study the impact of accretion disc wind on the evolution of outbursting LMXBs, a significant part of the upcoming subsection will be devoted to the disc wind description.

3.2 Accretion in LMXBs

In the Sect 2.3, it was mentioned that LMXB systems exhibit recurrent outbursts (X-ray nova events) caused by the instabilities in the accretion disc and/or unstable matter flow between the binary components. In most cases the outburst is the only time when LMXB system is solidly detectable in X-rays, showing the accretion physics as such high states. Moreover, X-ray novae are such bright and dynamic phenomena that they can be observed from almost anywhere in the Galaxy, making them one of the most studied source classes in high-energy astrophysics. In this subsection we will focus on the physics happening during such outbursts. One of the main issues concerning LMXB outbursts is the strong outflow of matter and angular momentum from the system during the X-ray nova event. Therefore, in the next paragraphs, I will discuss the arguments supporting the presence of disc wind, followed by a description of accretion disc theory relevant to this dissertation.

Evidence for wind's presence

Presumably, during outbursts there is an material outflow in the form of a wind from the accretion disc around the compact object. The existence of such a wind in LMXBs is supported by observations indicating the presence of expanding ionised matter. The outflows are observed in the X-rays as blue-shifted absorption lines (e.g., [Díaz Trigo and Boirin, 2016](#), [Ueda et al., 2009](#)), and in the optical band as emission lines broadening (see, e.g., [Casares et al., 2019](#), [Charles et al., 2019](#), [Muñoz-Darias et al., 2019](#)). In some cases, the fact of the wind's presence is also supported by the detection of P-Cygni profiles ([Fijma et al., 2023](#), [Miller et al., 2016](#), [Miškovičová et al., 2016](#)). Moreover, in most cases, the wind's features are observed in systems with an inclination above 50° . Consequently, the absorbing plasma most probably has a higher density towards to the equatorial plane, therefore, suggesting that the wind is launched from the accretion disc ([Higginbottom and Proga, 2015](#)).

The nature and physical characteristics of such accretion disc winds remain an open question. In general, there are 4 mechanisms considered today. The first model suggests that the outflow arises from thermal heating of matter by central radiation in optically thin regions of the disc ([Begelman et al., 1983](#), [Shields et al., 1986](#), [Woods et al., 1996](#)). The second model proposes hydromagnetic winds ([Blandford and Payne, 1982](#), [Fukumura et al., 2010, 2017](#), [Pelletier and Pudritz, 1992](#), [Scepi et al., 2024](#)), while the third is focused on radiation pressure at super-Eddington accretion rates ([Proga and Kallman, 2002](#), [Shakura and Sunyaev, 1973](#)). Additionally, the radiation pressure in spectral lines ('line-driven' winds) is also being considered as the fourth mechanism ([Feldmeier and Shlosman, 1999](#), [Murray et al., 1995](#), [Proga and Kallman, 2004](#), [Shlosman et al., 1985](#), [Suleimanov, 1995](#)). Nevertheless, most observational and theoretical studies indicate that accretion disc winds are relatively powerful and, in most cases, surpass the corresponding accretion rates ([Higginbottom et al., 2017, 2019](#), [Kosec et al., 2020](#), [Luketic et al., 2010](#), [Ponti et al., 2012](#)).

Given such a strong wind, it will inevitably affect the long-term dynamical evolution of the accretion disc. Therefore, it is necessary to study in detail what the exact consequences of the presence of such wind on the accretion disc theory and the features observed during LMXB outbursts.

Accretion disc with wind

The evolution of an accretion disc, accounting for the wind, is described by a diffusion-type differential equation with an inhomogeneous term ([Shields et al., 1986](#)):

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{4\pi} \frac{(GM_x)^2}{h^3} \frac{\partial^2 F}{\partial h^2} - \dot{\Sigma}_w(F, h), \quad (3.12)$$

where r is a given disc's radius, Σ is the surface density, F is the torque of the viscous forces, which is expressed as $F = 2\pi W_{r\varphi} r^2$ in terms of the viscous stress height-integrated tensor $W_{r\varphi}$ (positive, see, e.g., [Lyubarskij and Shakura, 1987](#)) and $h = \sqrt{GM_x r}$ is the specific angular momentum of the accretion disc's material. The function $\dot{\Sigma}_w$ represents the local mass loss rate via disc wind, indicating the outflow of mass per unit disc surface area per unit time, with $\dot{\Sigma}_w > 0$ when a wind is active.

The relationship between surface density Σ and viscous torque F in a Keplerian disc is expressed as follows (e.g., [Shakura et al., 2018](#), chapter 1):

$$F = 3\pi h \nu_t \Sigma, \quad (3.13)$$

where ν_t denotes the kinematic coefficient of turbulent viscosity, dependent on radius r and surface density Σ due to underlying physical processes. This relationship derives from the conservation of angular momentum:

$$\dot{M} = \frac{\partial F}{\partial h} . \quad (3.14)$$

In order to describe turbulent viscosity effectively, [Shakura \(1972\)](#) introduced the dimensionless parameter α , linking the total pressure P_{tot} in the disc to the viscous stress tensor component:

$$w_{r\varphi}^t = \alpha P_{\text{tot}} , \quad (3.15)$$

where P_{tot} comprises gas pressure P_{gas} and radiation pressure P_{rad} . The integrated viscous stress tensor $W_{r\varphi}$ over disc height z is given by:

$$W_{r\varphi}(t, r) = \int_{-z_0}^{+z_0} w_{r\varphi}^t(t, r, z) dz , \quad (3.16)$$

where z_0 is the disc half-thickness at radius r .

To solve equation (3.12), it is necessary to specify certain boundary conditions (both outer and inner) as well as initial condition. At the inner disc boundary (corresponding to the last stable orbit), the viscous torque F in the case of a BH is zero ([Shakura and Sunyaev, 1973](#)):

$$F(h_{\text{in}}, t) = 0 , \quad (3.17)$$

where h_{in} is the specific angular momentum at the inner edge of the disc. The outer boundary condition looks as follows:

$$\left. \frac{\partial F}{\partial h} \right|_{h=h_{\text{out}}} = \dot{M}_{\text{out}} , \quad (3.18)$$

where $\dot{M}_{\text{out}}$ is the mass inflow rate into the disc from the secondary (through the second Lagrange point), and h_{out} is the specific angular momentum at the outer edge. Finally, the initial distribution of the viscous torque must satisfy initial some conditions (see, for example, quasi-stationary disc condition in [Lipunova and Shakura, 2002a](#)):

$$F(h, 0) = F_0(h) . \quad (3.19)$$

Details of the numerical solution for equations listed above are given in the Paper V (see the appendix). One also needs to specify the form of the function $\dot{\Sigma}_w$. Since in the Paper V we work with thermally-heated accretion disc wind, its brief description and implementation is given in the following sections.

Compton-heated wind

Theoretical models of accretion discs, along with observational data, indicate that radiation from the central regions of the disc can irradiate its outer surfaces. In the standard accretion model proposed by [Shakura and Sunyaev \(1973\)](#), the disc exhibits a concave geometry and becomes progressively thicker with increasing radius. This structure causes the surface of the accretion disc, particularly its outer parts, to be exposed to radiation from the central region, resulting in the heating of the disc material. A schematic illustration of a disc in a binary system is depicted in Fig. 9.

In Begelman et al. (1983) this heating of the disc is mostly defined by the introduced ‘inverse Compton temperature’ (the term ‘Compton temperature’ is also used), which is defined as:

$$T_{\text{IC}} \equiv \frac{1}{4k} \langle \epsilon \rangle = \frac{1}{4k} L^{-1} \int_0^{+\infty} h\nu L_\nu d\nu, \quad (3.20)$$

where $\langle \epsilon \rangle$ is the mean photon energy, h is the Planck constant, k is the Boltzmann constant, ν is the radiation frequency, L_ν is the luminosity per frequency interval and L is the bolometric luminosity.

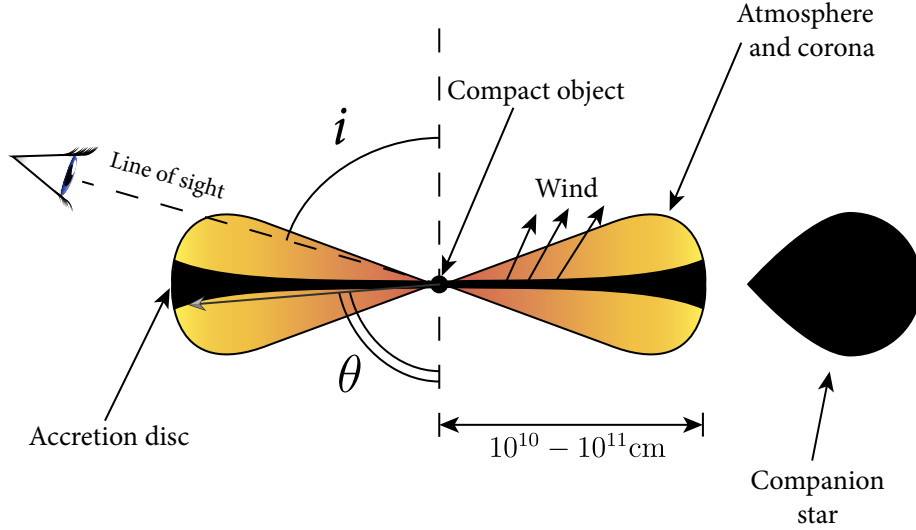


Figure 9: Representation of a LMXB system with a donor and accretion disc with wind. Angles i and θ are the disc inclination and polar angle, respectively. Image is taken from the Paper V.

Begelman et al. (1983) also introduced the concept of ‘escape temperature’: $T_g \equiv GM_x \mu m_p / (kr)$, derived from equating the thermal velocity of a particle to its local escape velocity. Here, M_x denotes the mass of the compact object, r is the radial distance from the center of the disc, m_p is the proton mass, and μ is the average mass per particle, accounting for ions and electrons (assumed to be 0.61 for solar abundances). If the temperature of the medium exceeds T_g , it will expand. Consequently, the characteristic ‘Compton radius’ is defined as follows:

$$R_{\text{IC}} \equiv \frac{GM_x \mu m_p}{kT_{\text{IC}}} = \frac{1.0 \times 10^{10}}{T_{\text{IC}8}} \left(\frac{M_x}{M_\odot} \right) \text{ cm}, \quad (3.21)$$

with $T_{\text{IC}8} = T_{\text{IC}}/10^8$ K. It was suggested that matter begins to flow out of the disc in the form of a wind at radii greater than $0.1 \times R_{\text{IC}}$, where the corona’s height is already substantial. The upper layer, heated to the Compton temperature T_{IC} , expands at the sound speed $c_{\text{IC}} = \sqrt{kT_{\text{IC}}/(\mu m_p)}$.

In the same work by Begelman et al. (1983) the critical luminosity was introduced:

$$L_{\text{cr}} \equiv \frac{1}{8} \left(\frac{m_e}{\mu m_p} \right)^{1/2} \left(\frac{m_e c^2}{kT_{\text{IC}}} \right)^{1/2} L_{\text{Edd}} = 0.030 \times T_{\text{IC}8}^{-1/2} L_{\text{Edd}}, \quad (3.22)$$

where m_e is the mass of an electron, c is the speed of light, L_{Edd} is the Eddington limit luminosity:

$$L_{\text{Edd}} \equiv \frac{4\pi G M_x \mu_e m_p c}{\sigma_T} \approx 1.5 \times 10^{38} \left(\frac{M}{M_\odot} \right) \text{ erg/s}, \quad (3.23)$$

where μ_e is the mean molecular weight per electron and σ_T is the Thomson cross section. Therefore, while the ratio L/L_{Edd} indicates the effectiveness of radiation pressure in overcoming gravity, the ratio L/L_{cr} characterises the efficiency of electromagnetic radiation in overcoming gravity by heating the matter through Compton processes. Conversely, at smaller radii and/or lower luminosity, most of the disc material remains gravitationally bound, forming a hydrostatic corona (Jimenez-Garate et al., 2002).

Thermal wind model

As said before, in order to solve the equation (3.12), it is essential to determine the specific form of the function $\dot{\Sigma}_w(h)$. In the context of this dissertation, it means to find how thermal wind affects the disc. Fortunately, the dynamics of the Compton-heated wind and corona have been analytically explored in Begelman et al. (1983), where authors estimated the mass loss rate as a function of distance along the disc's radius. They treated the wind flow as a set of streamlines and solved the equations of momentum and energy conservation along these lines. Shields et al. (1986) provided an analytical approximation for the results obtained by Begelman et al. 1983 (see more in related papers and Paper V).

In subsequent work, Woods et al. (1996) performed two-dimensional magnetohydrodynamic calculations, generalizing the results of Begelman et al. (1983) and Shields et al. (1986). Woods et al. (1996) considered various processes contributing to X-ray heating and radiation cooling, whereas Begelman et al. (1983) focused only on heating and cooling through Compton processes. Additionally, while Begelman et al. (1983) assumed a geometrically thin disc, Woods et al. (1996) accounted for the structure of the disc's upper layers in an optically thin approximation. Therefore, the function $\dot{\Sigma}_w(h)$ according to these studies is formulated as follows:

$$\begin{aligned} \dot{\Sigma}_w = 2 \eta_{\text{wind}} \dot{m}_{\text{ch}} \times & \left(\frac{1 + ((0.125l + 0.00382)/\xi)^2}{1 + (l^4(1 + 262\xi^2))^{-2}} \right)^{1/6} \times \\ & \times \exp \left[-(1 - (1 + 0.25\xi^{-2})^{-1/2})^2 / (2\xi) \right], \end{aligned} \quad (3.24)$$

where η_{wind} is a dimensionless wind's strength parameter, $\dot{m}_{\text{ch}}$ is the characteristic mass-loss rate per unit area, $\xi = r/R_{\text{IC}}$ and $l = L/L_{\text{cr}}$, see equations (3.21) and (3.22). The characteristic mass-loss rate per unit area $\dot{m}_{\text{ch}}$ looks here as follows:

$$\dot{m}_{\text{ch}} = \frac{1}{2^{8/3} \Xi} \frac{m_e c}{\sigma_T R_{\text{IC}}} \left(\frac{\mu_e}{\mu} \right)^{2/3} l^{2/3} \xi^{-5/3}. \quad (3.25)$$

Here, Ξ is the pressure ionisation parameter defined in Begelman et al. (1983) as follows:

$$\Xi \equiv P_{\text{rad}} / P_{\text{gas}} = \mathcal{F} / (c P_{\text{gas}}), \quad (3.26)$$

where P_{rad} and P_{gas} are the radiation and gas pressure, respectively, $\mathcal{F}$ is the radiative flux.

Ultimately, by incorporating the wind term (3.24) into the differential equation (3.12), while taking (3.25) into account, it becomes possible to solve the equation and calculate the evolution of the accretion disc with the thermal wind impacting its surface. Naturally, it cannot be done analytically, especially if the accretion rate is not stationary,

and the wind’s presence was incorporated into the open-source code FREDDI³. I was one of the three main contributors to the code and was primarily responsible for the part that implemented the wind effect on the disc structure and evolution, as well as the irradiation of the disc and the donor star. This code solves the above evolution equations with given by the user conditions and simulates fast-rise exponential-decay (FRED) light curves (X-ray/optical and IR).

By analysing the physics of accretion discs and taking into account disc wind outflows, the evolution of X-ray novae and LMXBs can be examined in greater detail and better understood. This approach enables predictions on how their dramatic variable behaviour impacts the overall picture of Galactic LMXBs. Ultimately, it helps in understanding the evolution of the XLF, which is a crucial task in its own right, since the population of XRBs is ever changing.

In this section, our focus was on the behavior of known (already identified) HMXBs and LMXBs hosted by our Galaxy. Their properties are shaped by the physics we discussed above as well as the other effects, making the appearance of XRBs extremely diverse. Moreover, the variability and transient nature of XRBs influence our perception of their population (and consequently, the XLF). However, the population studies of XRBs are even more complicated by the relatively small sample of known sources, as was briefly mentioned in the introduction (see Sect. 1). Consequently, in the next chapter, I will dig into methods used for classifying unidentified X-ray sources on the sky to find new faint XRBs hidden among them.

³see <https://github.com/hombit/freddi/>

4 Classification of X-ray sources

In the previous sections of the dissertation, we’ve discussed (among other things) the nature, properties and evolution of already identified XRBs, which determine the view on their known demographic. However, as was stated in the introduction (see Sect. 1), currently discovered XRBs in our Galaxy represent only the small high-luminous tail of their population. Therefore, the vast majority of XRBs are likely to be relatively faint and may have thus escaped identification/detection. In the current era of wide-area surveys such as *Gaia*, INTEGRAL, *Swift*, etc, it becomes even more essential to study those data to find new XRBs. And those missions did indeed contribute to the substantial increase of known XRBs as discussed in the Sect. 1 and Papers I and II. This goes even further, considering the all-sky X-ray survey made by eROSITA, which provides ever deep and sensitive observations of the whole sky. One major issue here is, however, that the fraction of XRBs among millions of eROSITA source is tiny. One needs, therefore, to first identify XRBs as such before population studies become possible. That is, to solve the problem of X-ray source classification. We will begin by describing the traditional methods historically used to identify XRBs. This will be followed by the discussion of similar but modified classification methods applied to large datasets, such as those of eROSITA and *Gaia*.

4.1 Historical approach to the identification of XRBs

Naturally, the discovery of a new XRB starts with the detection of its X-ray emission, as this is the range in which XRBs are most active. Respectively, one may try to identify the origin of an unknown X-ray source (and check for its possible XRB nature, for example) based purely on the X-ray data. This, in principle, could be done since accreting compact objects behave in a specific way even in X-rays, distinguishing them from other type X-ray sources. For instance, one can try to fit the X-ray spectra of an unknown source with a power-law and/or comptonisation models (typical for an accreting NS/BH) and look on the result parameters, comparing them with data from known XRBs. Other characteristics could also be checked via X-rays: timing analysis for the presence of spin/orbital period modulation, spectral measurements of the iron line, check for FRED-like light curves behaviour typical for LMXB outburst, etc. However, the majority of undiscovered XRBs are assumed to be faint (with $L_x < 10^{34}$ erg/s, see Doroshenko et al., 2014a), meaning that there is just not enough X-ray information to analyse for specific behaviour, especially so in a relatively shallow survey like eROSITA. Therefore, additional data from other bands should be considered in order to come out with the most robust classification possible.

In practice, understanding of the multiwavelength (MWL) behaviour of an X-ray source necessitates the identification of corresponding band counterparts. This process mainly concerns optical and infrared (IR) bands, where the source sky density (therefore the number of potential associations) is the highest. Counterpart identification involves several steps, including accurate localisation of an X-ray source, selection of potential counterpart stars, and final association with the specific optical/IR object through various observational techniques. In reality the identification of optical/IR (sometimes even

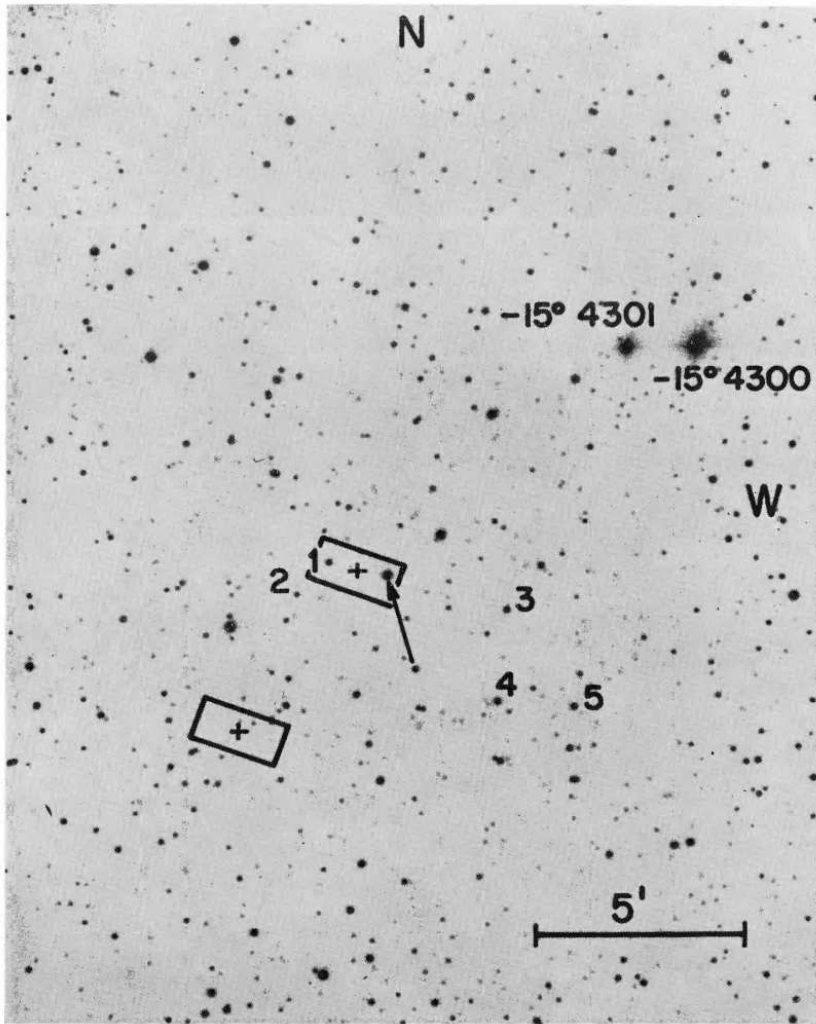


Figure 10: Figure from Sandage et al. (1966) regarding Sco X-1 optical counterpart. Photograph of the region containing the new X-ray position of Sco X-1 refined by Gursky et al. (1966). Image is reproduced from the Palomar Sky Survey prints. The two equally probable new X-ray positions are showed by crosses surrounded by a rectangle of 1x2 arcminutes. The true counterpart associated by Sandage et al. (1966) is marked with an arrow. The numbers represent identifications of other stars for which photoelectric photometry existed at the time of the observation.

radio) counterparts is conducted even for relatively bright X-ray objects, since it makes the classification more solid and provides additional insights into the physics of XRBs, which cannot be obtained based on the X-ray data alone.

This was actually a big problem even for the brightest extrasolar persistent X-ray source, NS LMXB Sco X-1 (for the history of its discovery see Sect. 1). As was mentioned in the introduction, Sco X-1 was first detected in X-rays by an Airforce Aerobee rocket experiment in 1962. However, those early detections had large positional uncertainties, often exceeding several arcminutes. Therefore, repeated and more accurate observations were made and the X-ray position was gradually refined (Gursky et al., 1966). Soon after that, the corresponding region of the sky (narrowed by the more accurate X-ray observations) was searched for potential optical counterparts by Sandage et al. (1966, see Fig. 10). Ultimately, based on the spectral (large change in the strength of Balmer lines, and overall appearance as an old novae), timing (the suggested counterpart was highly unstable in its continuum radiation), and photometric (counterpart had very peculiar colours) analysis, authors identified the true optical counterpart of the Sco X-1. This, eventually, led to its classification as the first known XRB (Shklovsky, 1967).

Even now, the general algorithm for testing the XRB nature of an unidentified source looks pretty much the same way. 1) A new X-ray source is found during a flare with wide area X/ γ -ray telescope with poor astrometry such as *Swift*/BAT, INTEGRAL, MAXI, etc. 2) Follow-up observations are conducted with more sensitive facilities like *Chandra* and *XMM-Newton* to localise the source. 3) Optical/IR association is either unambiguously

found based on the good X-ray astrometry, or (in more vague cases, star crowded sky areas) is selected additionally based on the optical/IR behaviour of counterpart candidates (colours are more blue, shows variability, specific lines in the spectra, etc). The basic idea here is that X-ray sources in general (XRBs included) appear differently from regular star-like sources. Ultimately, based on the MWL data analysis, the final classification for an X-ray source is given.

However, when large datasets (such as eROSITA, *Gaia* and WISE) are considered, the classification of a big number of X-ray objects cannot be done in the same way. This is mainly due to the huge number of sources ($\sim 10^6$ in eROSITA and about $\sim 10^9$ in *Gaia*/WISE) and potential survey-to-survey cross-correlations. Moreover, when searching for faint XRBs, many distinctive features specific to this source class become undetectable, forcing to use more MWL data. Therefore, in the next section I discuss the implementation of classical identification methods when working with such large datasets. And since Papers III and IV are dedicated to eROSITA sources, the following description will be biased towards its survey data.

4.2 Large datasets and MWL analysis

In the current realm of astronomical research, analysing large datasets of the ongoing survey missions like eROSITA and *Gaia*, provides rare opportunity to discover new different type objects. And in special interest for us, objects of the XRB origin. Naturally, most of the sources presented in corresponding large-survey archives have not been classified or studied. Given the vastness of those surveys and the limited availability of detailed spectral and/or timing data for the most sky sources, their classification primarily relies on the photometric measurements in multiple bands rather than more detailed spectral and timing information (at least for the first step).

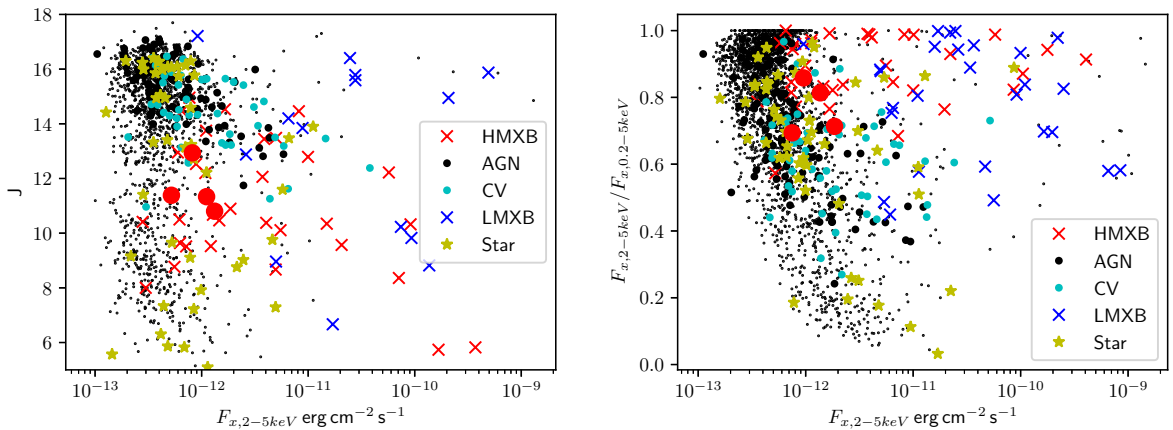


Figure 11: Examples of inter-dependence for some of the features that can be used for MWL classification. Various source classes considered shown with different symbols and unclassified sources as small points. *Left panel:* observed X-ray 2 – 5 keV flux (eROSITA) and apparent NIR *J*–band magnitude (2MASS) diagram. Counterparts are the brightest 2MASS object in the eROSITA error circle. *Right panel:* X-ray flux hardness ratio (2 – 5 vs 0.2 – 5 keV, eROSITA) dependence on the observed X-ray 2 – 5 keV flux. It is seen that the ratio of fluxes in X-ray and IR band is a powerful discriminating feature between XRBs and AGNs/CVs, while XRBs also tend to have harder spectra.

Similar how it was shown for the case of the Sco X–1, the classification approach here

hinges on exploiting distinctive MWL signatures that different types of X-ray objects exhibit. Early-type stars, for example, typically appear bluer in optical and ultraviolet (UV) bands, while late-type stars and AGNs emit more in the IR spectrum. XRBs usually exhibit harder X-ray spectra than CVs. And so on. Therefore, practical methods employed in classification typically rely on examining various 2D plots in the MWL parameter space: colour-colour diagrams, colour-magnitude diagrams (CMDs), X-ray hardness dependencies, X-ray-to-optical/IR flux ratios, etc. (see [Kaplan et al., 2006](#), [Misanovic et al., 2010](#), [Yang et al., 2021](#)). Such plots are being analysed in order to pinpoint sources with unique features indicative of specific origin type. For example, X-ray-to-optical/IR flux ratios can highlight objects with enhanced X-ray emission relative to their optical counterparts, generally distinguishing accreting sources from regular stars (see Fig. 11 as an example).

Unfortunately, classification challenges start right from the beginning, specifically when trying to gather the necessary MWL data. Similar to the scenario of Sco X-1 discussed earlier, current wide-area X-ray telescopes often do not provide precise positional information needed for unambiguous MWL counterpart identification. The situation is even more troublesome in the optical and IR bands, where the density of objects is significantly higher compared to X-rays (by a factor of a thousand). For instance, even eROSITA all-sky survey (eRASS), known for its high sensitivity and precision, typically has a $3\text{-}\sigma$ error circle radius of about $15''$. This results in about a dozen of potential optical/IR counterparts (depending on the source position), making purely geometric cross-match unfeasible. Therefore, additional prior knowledge about properties of X-ray sources in other bands must be considered to identify their true counterparts and corresponding origin. However, when considering billions of sources and potential survey-to-survey cross-correlations, the traditional classification approach becomes both inhumanly time-consuming and tedious, often lacking clear guidelines on how to assign confidence to these classifications. In other words, there is no clear understanding which explicit thresholds should be specified for any considered MWL parameter, since different type sources in any case strongly overlap on 2D plots (see Fig. 11).

4.3 Implementation of ML methods

An effective solution to both of these challenges (counterpart identification and source origin classification) is the implementation of an automated classification system. In scientific context, one of the most efficient methods involves using supervised machine-learning (ML) techniques to analyse large datasets. In the setting of X-ray sources, the application of ML methods was firstly done by [McGlynn et al. \(2004\)](#). Authors utilised a supervised ML algorithm, specifically oblique decision trees ([Murthy et al., 1994](#)), to categorise approximately 80000 sources from ROSAT data. Since then, ML techniques have been implemented in numerous works in order to classify X-ray sources based on MWL data. Some studies rely on Bayes metric methods ([Broos et al., 2011](#), [Hand and Yu, 2001](#)), which have shown to perform well on XMM-Newton and Swift/XRT data ([Tranin et al., 2022](#)). However, currently, one of the fastest and most effective methods in use are Random Forest (RF) algorithms ([Breiman, 2001](#)), which have been utilised to classify sources in Chandra ([Yang et al., 2022](#)) and XMM-Newton serendipitous catalogues ([Farrell et al., 2015](#), [Lo et al., 2014](#)), and even to specifically find unidentified XRBs among sources detected by Chandra in the Andromeda (M31) galaxy ([Arnason et al., 2020](#)).

Therefore, since in the Paper III we conduct RF classification to find new Galactic XRBs in eROSITA data, the following paragraphs will briefly describe how RF algorithm generally work. Additionally, the application of RF methods for identifying optical/IR counterparts and classifying X-ray sources using MWL data will be explored.

Random forest algorithm

Random Forest (RF) is a robust supervised ML algorithm that leverages the concept of ensemble methods to improve classification accuracy. During the training phase, RF uses the properties (so called features) of known sources to build a collection of decision trees (DTs, see Fig. 12). These trees are created through a process called bagging, where each tree is trained on a different subset of the training dataset (TD). Each DT divides the feature space using a loss function, ensuring that each leaf node ideally contains samples of a single type. During the classification phase, each DT in the RF algorithm independently makes its prediction. The final prediction is determined by aggregating the votes (predictions) from all the trees in the forest.

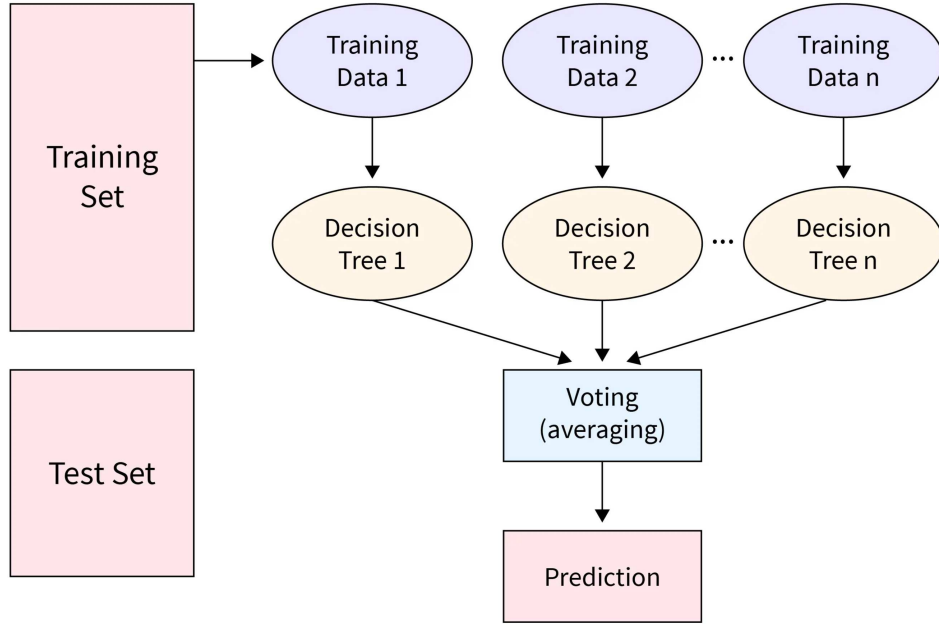


Figure 12: Schematic representation of the RF algorithm. Each DT votes (provides classification) based on corresponding part of the TD. The votes are then averaged to come up with final classification prediction. Image is taken from <https://www.scaler.com/topics/machine-learning>.

Like other ML algorithms, RF uses a set of pre-labelled TD to classify new data into several specified by the user classes. However, in most real-world applications with astronomical data, the classes exhibit significant imbalance. This imbalance introduces a bias in the model, causing it to predominantly classify unknown sources as the majority class members, despite the specific interest in rarer classes. To address this bias and mitigate the impact of class imbalance, the Synthetic Minority Oversampling Technique (SMOTE, Chawla et al., 2002) is often employed. SMOTE generates synthetic samples for the minority classes by selecting feature values (MWL parameters) based on the k -nearest neighbours method within the parameter space of real sources belonging to a particular class (see Fig. 13). By leveraging SMOTE, one ensures that all data subsets dedicated to each class of sources reach the same size, equal to that of the most populous source class. Ultimately, this procedure compensates for class imbalance and creates a more balanced TD, improving predictions. In the context of this dissertation, this issue is particularly significant, as XRBs are severely outnumbered by other classes of X-ray sources detected in the sky, such as AGNs and stars (see Figure 14, left panel).

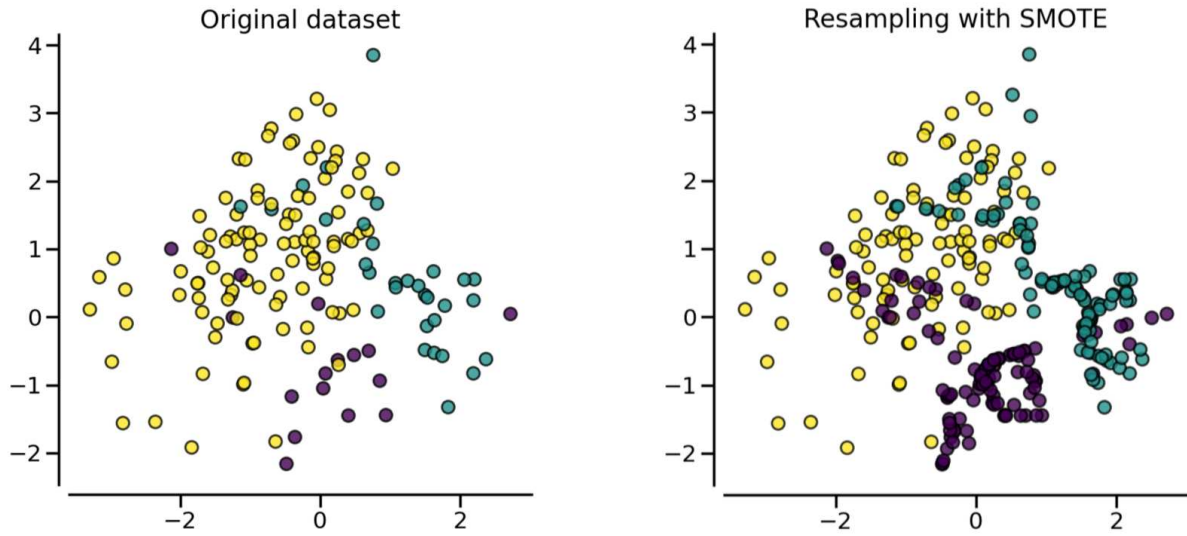


Figure 13: *Left panel:* Schematic example of a 2D MWL feature plot, representing the original dataset with three classes indicated by colour. *Right panel:* The same data sample but augmented with SMOTE. It's clearly seen that the number of the two underrepresented classes (purple and cyan) is increased to match the most abundant class (yellow). Image credit: https://imbalanced-learn.org/stable/over_sampling.html.

Counterpart identification and source classification

Naturally, cross-matching X-ray and optical/IR catalogues is essential to obtain MWL data used for classification. Therefore, proper counterpart identification is a must have to ensure that the majority of X-ray sources got the most appropriate MWL properties assigned. However, as mentioned earlier, purely geometrical cross-matching becomes unreliable due to the high object density in optical/IR bands and the limitations of X-ray astrometry, bringing us to the usage of MWL data once more. Therefore, in this dissertation, counterpart identification is also carried out using ML methods which analyse optical/IR data to identify objects that are likely to be X-ray emitters based solely on their optical/IR properties.

Respectively, in order to accomplish this, RF classification should be used on all potential optical/IR counterparts of given X-ray sources. Classification here goes into two classes: class of interest (for example, 'X-ray emitter', see Fig. 14, right panel) and class of other origin sources. Again, at this step, only optical and IR properties of the counterparts themselves are used, since at this point it is unknown if corresponding optical/IR object is the true counterpart to an X-ray source. It is done in order to find the optical counterpart which resembles the behavior of a typical X-ray source (of a given type) the most, knowing that X-ray emitters appear differently from regular stars even in in optical/IR bands. As the result, photometrically based RF prior probabilities for each optical/IR potential association are obtained.

In principle, such prior photometrical probabilities have to be taken into account along with corresponding geometrical-match likelihoods. One of the most commonly used solutions to do so, is to rely on Bayesian statistics (Budavári and Szalay, 2008) implemented in NWAY⁴, a cross-matching ML tool for astronomical catalogues and surveys (Salvato et al., 2018). It takes into account not only positional information, but also source sky-density distribution in each catalogue respectively. Moreover, NWAY is also able to incorporate

⁴<https://github.com/JohannesBuchner/nway>

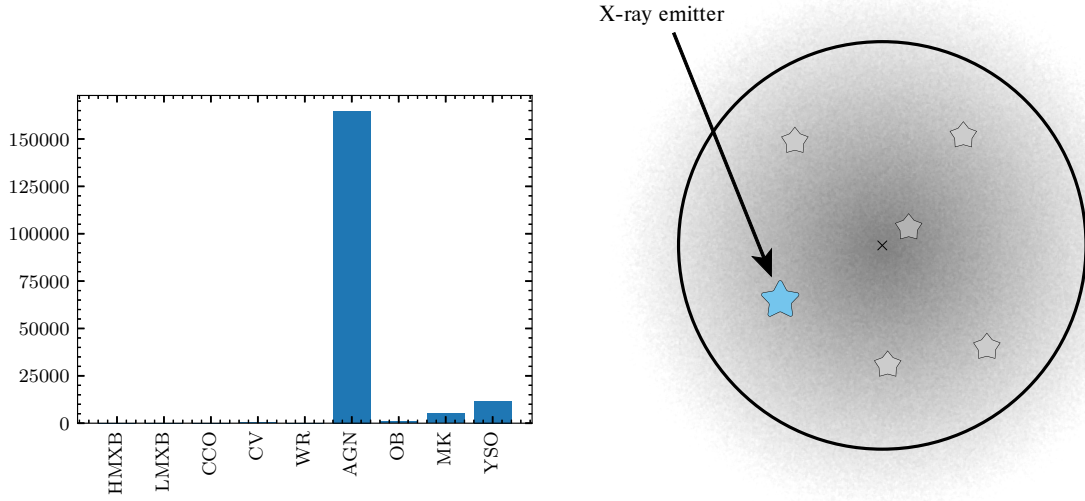


Figure 14: *Left panel:* Histogram distribution of different classes of X-ray sources detected by eROSITA. For X-ray types description see Paper III. *Right panel:* Schematic representation of the view on an X-ray source with several potential counterparts. Black circle represents $3\text{-}\sigma$ error of the X-ray source position. Shading shows geometrical probability of association with the X-ray source. Blue star is the optical/IR counterpart which behaves like an X-ray source and all other grey stars are the background 'X-ray emitter' probability optical/IR sources.

MWL information (such as magnitudes, colours, prior RF probabilities in our case) about the potential counterparts, refining the cross-match probabilities.

At the second step, the list of selected by NWAY counterparts and their optical/IR properties together with X-ray information are to be used as a MWL data input for source origin classification. Here, another RF machine should be trained to classify all X-ray sources based on the obtained MWL features. At this step, the corresponding list of source classes is usually expanded to include all relevant object types, and not simply discriminate sources between two classes. This is done to enhance the performance of the RF algorithm and to prevent potential contamination of the class of interest, since characteristic properties of different type sources largely overlap. The outcome of this final RF classification yields probabilities for each X-ray source considered, indicating the likelihood of belonging to any class within the specified classes set. Typically, a threshold is then applied to these probabilities to select final, most reliable candidates of the specific class of interest. Such candidates can later be studied in more detail with dedicated follow-up observations as presented in the Paper IV.

Determining the appropriate probability threshold for considering an object a reliable candidate is challenging, as these probability values are not calibrated for individual source classes. A common approach involves using purity and completeness metrics, which can be computed for any chosen probability threshold based on the labeled dataset. Purity measures the proportion of sources from other classes (excluding H/LMXBs in the context of this dissertation) that surpass the selected probability threshold, therefore, "polluting" the candidate pool. Conversely, completeness represents the fraction of pre-labeled sources belonging to the target class (H/LMXBs in this case) that have probabilities exceeding the chosen threshold. That is, purity and completeness (for a given *class*) are defined as follows:

$$Purity \equiv \frac{N_{\text{class}}(P_{\text{class}} > P_{\text{class}}^{\text{cut}})}{N_{\text{all}}(P_{\text{class}} > P_{\text{class}}^{\text{cut}})} \quad (4.27)$$

$$Completeness \equiv \frac{N_{\text{class}}(P_{\text{class}} > P_{\text{class}}^{\text{cut}})}{N_{\text{class}}} \quad (4.28)$$

where N_{class} is the number of pre-labelled sources of the class considered, P_{class} – produced by a ML model probability that source is a member of the corresponding class, $P_{\text{class}}^{\text{cut}}$ — selected cut on this probability, above which sources are considered as candidates, N_{all} is the number of all class pre-labelled sources. With these 3 numbers ($P_{\text{class}}^{\text{cut}}$, purity and completeness) one can estimate the whole amount of the considered class candidates in a given sample.

In principle, all the steps need to be performed independently for each target X-ray source class (like LMXB, HMXB, AGN, CV, etc), followed by a procedure to combine the results for a cohesive classification of the entire X-ray sample. Optical/IR counterparts for potential LMXBs, for instance, may differ from those for HXMBs, stars, or AGNs, resulting in varying classification outcomes. However, given the focus of this dissertation on XRBs, Paper III specifically addresses HMXB and LMXB classes separately. The methodology is tailored to maximise identification of these classes, even if it means potentially lower classification accuracy for other types of celestial objects. The methods described in the Paper III are then used to find as much of XRBs as possible in the X-ray sample presented by the eROSITA all-sky survey first data release (Merloni et al., 2024, eRASS DR1, first six months scan, western Galactic hemisphere,), discussing potential effects they may have on XLF appearance. In the Paper IV I also analyse in detail two XRB candidates found in eRASS DR1 using similar but simpler approach to those described above. They are analysed based on the XMM-Newton follow-up observations obtained for both candidates.

Naturally, in Papers I–V included in this dissertation, I use data not only from eROSITA, but also from other facilities. Their brief description is given in the next chapter, which is then followed by the summary of the incorporated into the thesis Papers.

5 Observational Facilities

Observations across the electromagnetic spectrum have played a pivotal role in advancing our understanding of the Universe. For instance, X-rays — typically ranging from 0.1 to 100 keV — cannot penetrate the Earth’s atmosphere, making them inaccessible to ground-based instruments. The advent of space-based detectors in the latter half of the 20th century revolutionised X-ray astronomy by unveiling high-energy phenomena that were once unreachable. Nonetheless, ground-based optical telescopes have proven indispensable for follow-up observations of X-ray discovered sources, providing spectral and complementary data essential for a comprehensive modern MWL analysis.

In this section, I briefly describe the characteristics of the observatories whose data have been analysed in this dissertation and related papers. Emphasis is placed on the facilities whose data analysis I have been directly involved in — whether through observation proposals or consortium participation — even though this work incorporates a wide variety of other surveys and instruments.

5.1 eROSITA

The extended ROentgen Survey Imaging Telescope Array (eROSITA, [Merloni et al., 2012](#), [Predehl et al., 2021](#)), launched aboard the Spectrum-Roentgen-Gamma (Spektra-RG, SRG) spacecraft in July 2019, is designed to conduct all-sky X-ray survey with unprecedented depth. Its primary goal is to map the X-ray universe with high sensitivity, providing critical insights into the distribution of dark matter, the growth of supermassive black holes, and the large-scale structure of the cosmos.

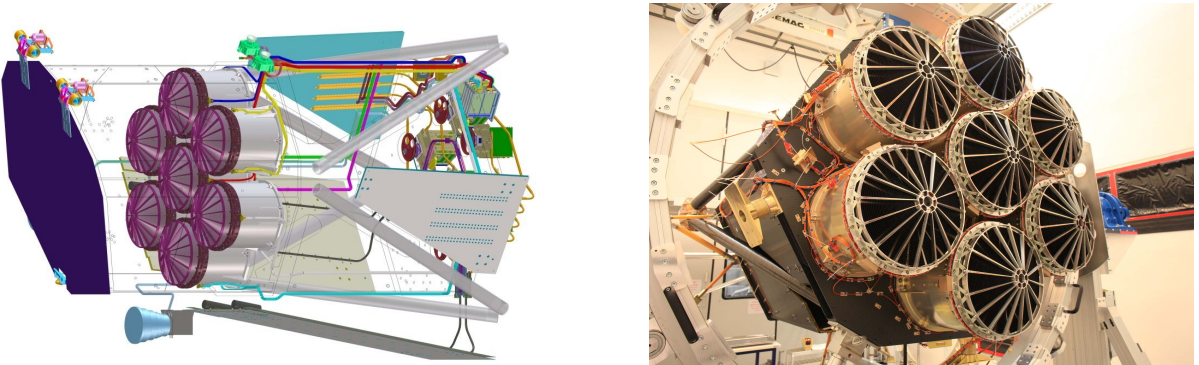


Figure 15: View on eROSITA. *Left panel:* Schematic view of the eROSITA telescope: 7 mirror assemblies (MAs, baffle, mirror, electron deflector), and 7 camera assemblies (CAs, filter wheel, camera, electronics box). Each MA includes a mirror module, an X-ray baffle located at the front, and a magnetic electron deflector positioned at the rear. *Right panel:* Photo of the telescope (front view) with all seven MAs installed. Images are taken from [Predehl et al. \(2021\)](#).

eROSITA surpasses the capabilities of the earlier soft X-ray all-sky survey conducted by the Roentgen Satellite (ROSAT, abbrev. from ger. Röntgensatellit, [Boller et al., 2016](#), [Truemper, 1982](#), [Voges et al., 1999](#)) by a factor of forty ([Merloni et al., 2012](#)). This

enhancement is coupled with a broader energy range coverage of 0.2-10 keV, compared to the ROSAT's relatively narrow 0.2-2 keV range. This wider energy range allows eROSITA to be less affected by absorption effects in the Galactic plane, where the majority of Galactic X-ray sources are situated. eROSITA is also more sensitive than coded-mask hard X-ray surveys like *Swift*/BAT and INTEGRAL. Additionally, eROSITA offers superior positional accuracy and provides extensive spectral and timing information across various timescales. As an instrument, eROSITA consists of seven identical mirror modules (see Fig. 15), each paired with its own charge-coupled device (CCD) camera. The aggregate effective area of the telescope is approximately 9600 cm². eROSITA also offers an angular resolution of about 15'' on average (half-energy width, HEW) and a field of view of a 1°. Its positional accuracy is around 2–5'' (1- σ confidence level) ensuring precise localisation of X-ray sources for such wide-area instrument. The timing resolution of eROSITA is about 50 milliseconds, which allows for detailed studies of variability in X-ray sources (providing that enough photons can be detected).

During its surveys, eROSITA aims to detect and catalogue around 100,000 clusters of galaxies, millions of active galactic nuclei, and various other X-ray sources such as stars, binaries, and supernova remnants. Up to now, eROSITA has successfully completed 4.5 out of the planned eight all-sky surveys, with each survey lasting six months. The data from the first half-year survey has been made public at 31st of January 2024, as part of the first public data release, covering half of the sky (Merloni et al., 2024, eRASS, DR1, the first six months scan, western Galactic hemisphere) in X-rays. Thus, eROSITA's characteristics make it an ideal instrument for searching for faint X-ray sources across the entire sky (see Paper III).

5.2 XMM-Newton

Launched by the European Space Agency (ESA) in December 1999, X-ray Multi-Mirror Mission (XMM-Newton, Jansen et al., 2001) is one of the most sensitive X-ray observatories ever built. It provides high-sensitivity observations of cosmic X-ray sources, covering a wide range of astronomical objects from nearby stars to distant quasars.

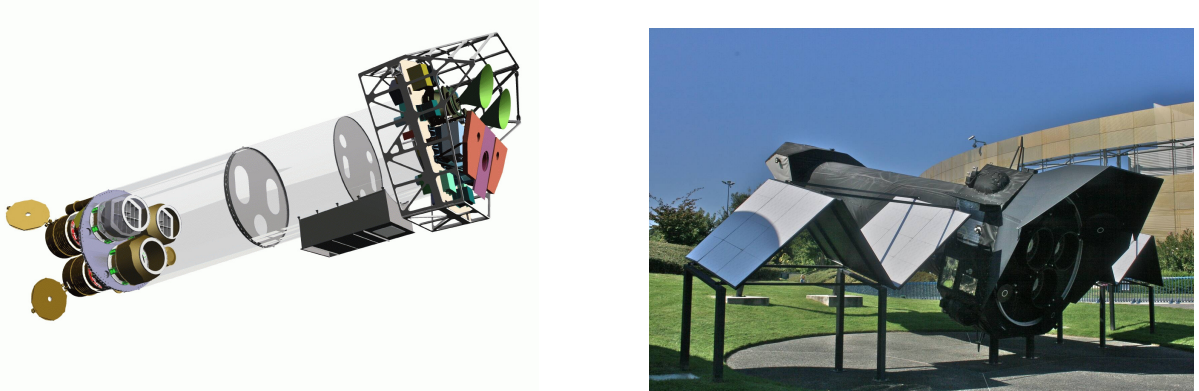


Figure 16: XMM-Newton payload and view on. *Left panel:* Focal Point Assembly (FPA) with the EPIC MOS (green/black) and pn (violet) detectors as well as the Reflecting Grating Spectrometer (RGS, light blue) are located in the top right. The optical monitor (OM), Mirror Support Platform (MSP), and Reflecting Grating Arrays (RGA) are also shown. *Right panel:* Mock-up of XMM-Newton at the Cité de l'espace, Toulouse. Credit: Image courtesy of Dornier Satellitensysteme GmbH.

XMM-Newton carries three advanced X-ray telescopes (see Fig. 16), each with 58

concentric mirrors, providing a large collecting area. Its cameras cover an energy range from 0.1 to 15 keV. The European Photon Imaging Camera (EPIC) consists of three detectors: two Metal Oxide Semiconductor (MOS, [Turner et al., 2001](#)) CCD arrays and one pn-CCD array ([Strüder et al., 2001](#)), offering imaging, timing, and spectroscopy capabilities with an effective area of about 1500 cm² at 1.5 keV. The resolution of XMM-*Newton*'s mirrors is around 6'' (HEW). The timing resolution of EPIC-pn can reach up to 30 microseconds in timing mode, and EPIC-MOS has a timing resolution of 2.6 seconds in full frame mode.

In addition to the EPIC cameras, XMM-*Newton* includes two Reflection Grating Spectrometers (RGS, [den Herder et al., 2001](#)) for high-resolution spectroscopy in the 0.35 – 2.5 keV range. The observatory also features an Optical Monitor (OM, [Mason et al., 2001](#)), a 30 cm optical/ultraviolet telescope covering the 170 – 650 nm range. XMM-*Newton*'s positional accuracy is approximately 1-2 arcseconds (1- σ confidence level), allowing it to unambiguously identify corresponding optical counterparts in most cases. XMM-*Newton*'s high sensitivity, broad energy coverage, and excellent timing resolution make it perfect for studying in detail faint and intriguing sources revealed by eROSITA during its surveys (more about that in Paper IV).

5.3 SALT

The Southern African Large Telescope (SALT, [Buckley et al., 2006](#), see Fig. 17, left panel) is one of the largest ground-based optical telescopes in the southern hemisphere. It is designed to cover a broad range of wavelengths from the near-UV to the near-IR. Its primary mirror consists of 91 hexagonal segments, yielding an effective aperture of approximately 9.2 m. SALT's design features a fixed primary mirror with a movable tracker (see Fig. 17, right panel) — which, although imposing some limitations on continuous tracking time per object, enables efficient sky coverage and rapid follow-up observations of transient phenomena.

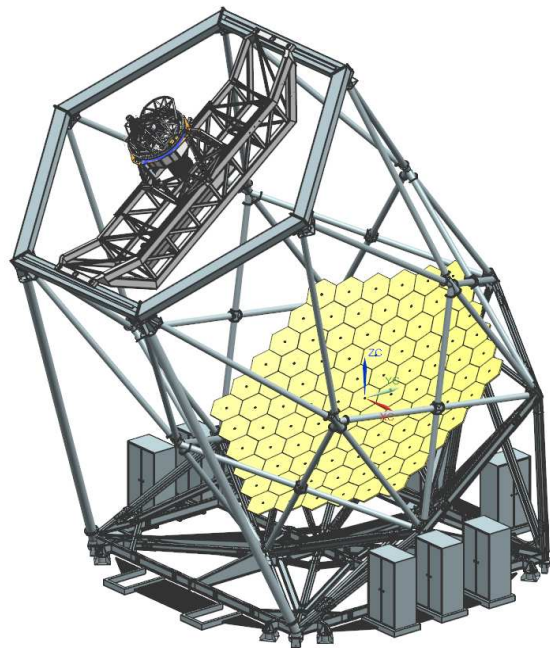


Figure 17: *Left panel:* View on SALT telescope in the Karoo, South Africa. *Right panel:* SALT telescope structure with instrument payload and tracker on the top of image. The image is taken from here⁵.

SALT is equipped with several versatile instruments. The Robert Stobie Spectrograph (RSS, formerly known as the Prime Focus Imaging Spectrograph, PFIS, [Burgh et al., 2003](#), [Kobulnicky et al., 2003](#)) serves as the workhorse for low- to medium-resolution spectroscopy ($R \sim 5000\text{--}9000$) and imaging⁵. RSS covers a wavelength range roughly between 320 and 900 nm and offers multiple observing modes — including long-slit, multi-slit, and polarimetric configurations — allowing for flexible setups tailored to diverse scientific objectives.

Complementing the RSS, the High Resolution Spectrograph (HRS, [Barnes et al., 2008](#), [Bramall et al., 2010, 2012](#), [Crause et al., 2014](#)) provides high-resolution spectroscopy over a similar spectral range (approximately 370—900 nm). HRS is a dual-beam, fibre-fed échelle spectrograph designed for precise radial velocity measurements and detailed chemical abundance studies. It operates in two distinct modes: a high-resolution mode with a resolving power of about $HR \sim 65\,000$, and a lower resolution mode ($LR \sim 16\,000$) that offers increased throughput when higher sensitivity is required⁵. The HRS is housed in a thermally controlled environment to ensure stability and optimal performance for precision studies.

Together, these instruments make SALT a versatile facility for a wide array of astronomical investigations — from detailed follow-up spectroscopy of transient events to systematic studies of stellar and galactic properties — thus providing essential complementary optical data to space-based observations. In the context of this thesis, SALT spectroscopic observations (combined with eRSOITA and XMM-*Newton*) led to a discovery of a new bright novalike CV (see more in Paper IV).

5.4 RXTE

The Rossi X-ray Timing Explorer (RXTE, [Swank, 1999](#)) was a NASA satellite dedicated to studying the variability of X-ray sources. Launched in December 1995 and operational until January 2012, RXTE was designed to provide crucial insights into the dynamics of compact objects.

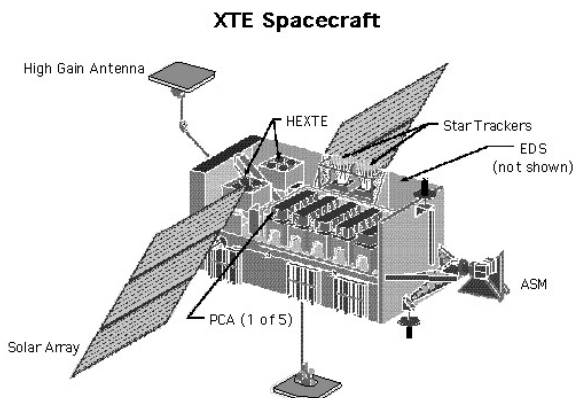


Figure 18: Outlook in RXTE. *Left panel:* Sketch image showing the RXTE final configuration with three primary instruments. *Right panel:* Technicians work on RXTE in 1995. Credits: NASA’s Goddard Space Flight Center.

RXTE featured three primary instruments (see Fig. 18): the Proportional Counter Array (PCA, [Jahoda et al., 1996](#)), the High Energy X-ray Timing Experiment (HEXTE,

⁵https://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html

[Rothschild et al., 1998](#)), and the All-Sky Monitor (ASM, [Levine et al., 1996](#)). The PCA consisted of five proportional counter units sensitive to X-rays in the $2 - 60$ keV range, with a combined effective area of about 6500 cm^2 . It offered moderate energy resolution and exceptionally high time resolution on the order of microseconds, with a specific timing resolution of 1 microsecond. HEXTE extended the energy coverage to $15 - 250$ keV, with an effective area of 1600 cm^2 and a time resolution of 8 microseconds. The ASM provided continuous monitoring of bright X-ray sources, covering an energy range of $2 - 10$ keV and scanning about 80% of the sky every orbit (~ 90 minutes), with a timing resolution of 90 seconds.

RXTE's unique capability to observe rapid X-ray variability contributed significantly to the understanding of the behaviour and properties of compact objects in X-ray binaries and other variable X-ray sources. Its legacy includes numerous discoveries about the timing properties of X-ray sources, which have been instrumental in advancing the field of high-energy astrophysics. In the context of this dissertation, RXTE's properties make it clear why it is particularly suitable for investigating variable and energetic phenomena such as X-ray nova (see Paper V).

6 Short summary of the original publications

This chapter provides a summary of the original research papers, both published and submitted, that are included in this cumulative dissertation. For each paper, a concise overview of its key contributions and findings will be presented. Additionally, my specific role and contributions to each work will be explicitly outlined, acknowledging that these studies are the result of collaborative efforts among all co-authors. See the results and discussion of these works presented in the next Chapter 7, as well as the full versions of Papers I-V in Appendix A.

6.1 Paper I — XRBcats: Galactic low-mass X-ray binary catalogue

In the Paper I we introduced a new catalogue of LMXBs in the Milky Way. This catalogue includes the names, coordinates, types, fluxes, distances, system parameters, and other key properties of 349 LMXBs. The purpose of this catalogue is to offer a comprehensive list of all currently known Galactic LMXBs, along with basic information for each system, including X-ray and optical/IR properties where available. It was also done to form a learning sample for eROSITA ML classification pipeline used in the Paper III. We have incorporated literature published up to May 2023 in compiling this data. That is, the new catalogue presented here represents a more than 71% increase in volume with respect to the two most extensive catalogues of the past (Liu et al., 2007, Ritter and Kolb, 2003). The catalogue includes references for all listed properties and provides finding charts across several energy bands for all LMXBs. The table is updated regularly, especially to include new objects discovered through ongoing large-scale surveys like *Gaia* and eROSITA. The catalogue of LMXBs (together with finding charts and additional features/information) can be accessed on the dedicated website⁶ and/or Vizier⁷.

Author's contribution

The author of the dissertation found in the literature the overall majority of all LMXBs presented in the catalogue, did the archive manual and code data search for each source. Author also contributed to the idea, creation of the dedicated website, finding charts and wrote most of the manuscript.

6.2 Paper II — XRBcats: Galactic high-mass X-ray binary catalogue

In this work, similar to the Paper I, a newly enhanced catalogue of Galactic HMXBs is presented. This updated compilation includes newly discovered HMXBs since the previous publications and reclassifies several objects that were earlier identified as HMXBs or candidates. The catalogue offers fundamental information, similar to those in Paper I, such as MWL data, best astrometry possible, and other characteristic properties for

⁶<http://astro.uni-tuebingen.de/~xrbcat>

⁷<https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/675/A199>

the 169 catalogued HMXBs. This work also provided the basis to build the learning sample for eROSITA ML classification pipeline (see Paper III). Additionally, we provide finding charts across multiple bands from IR to hard X-rays for each object same as in the Paper I. Our aim was to gather a broader set of relevant HMXB properties in a more standardised manner compared to previous catalogues. The catalogue of HMXBs (together with finding charts and additional features/information) can be accessed on the same (as LMXBs) website⁶ and/or Vizier⁸.

Author’s contribution

Similar to Paper I, however, the work here was led by Marvin Neumann, with the dissertation author (as the second co-author) contributing $\sim 30\%$ — writing parts of the search code and manuscript’s text, as well as conducting literature reviews on selected HMXBs.

6.3 Paper III — Hunting down new Galactic XRBs in eROSITA using ML

Paper III presents the results of a search for new Galactic XRBs among almost a million of eRASS DR1 sources and offer two catalogues of HMXB and LMXB candidates. These catalogues include X-ray properties from eRASS DR1 and details of the identified optical and IR counterparts for a total of 192 XRB candidates. The objective of this study is to provide the first coherent estimate of XRB numbers observable by eROSITA, expand the sample of low-luminosity XRBs, and lay the groundwork for subsequent dedicated follow-up observations. Candidate selection was based on their X-ray properties observed by eROSITA and the MWL characteristics of plausible counterparts in other bands. The selection of MWL counterparts and the final classification of sources were achieved using ML methods, specifically tailored for XRB identification. In the paper we specifically address the methods used to cross-match and classify X-ray sources which gave us an opportunity to come out with the largest sample of XRBs (together with XRBcats catalogues) possible today.

Author’s contribution

In this paper, the author led the corresponding sub-project (P5, accreting NSs/BHs) of the DFG funded research unit of eROSITA view of Stellar Endpoints (eRO-STEP) under supervision of Dr. Victor Doroshenko and Prof. Dr. Andrea Santangelo. Author made most of the ML analysis, compiled MWL datasets, conducted crossmatch and classification of eRASS DR1 sources and wrote most of the manuscript.

6.4 Paper IV — XMM-Newton follow-up of two eROSITA XRB candidates

In this study, we followed-up two XRB candidates with XMM-Newton, 1eRASS J061330.8+160440 and 1eRASS J161201.9-464622 (J061331 and J161201 respectively), which were both identified in eRASS1 preliminary survey data. Obtained observations refined X-ray positions and confirmed corresponding optical counterparts. Analysis of the X-ray spectra and timing did not reveal characteristics typical of accreting sources

⁸<https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/677/A134>

but rather resembled double temperature thermal plasma emission models. Despite their high initial X-ray fluxes in the early eROSITA pipeline, subsequent reprocessing showed lower flux levels, challenging their classification as XRB candidates based on eROSITA data alone. Therefore, based on archival LAMOST spectral data and ZTF/TESS photometry, J061331 was classified as an M-type chromospherically active subgiant with rich H_{α} emission and optical periodicity of 7.189 days likely attributed to starspot(s). In turn, requested SALT optical spectroscopy firmly defines J161201 as a nonmagnetic novalike CV with a tentative orbital period of 4.832 h, found in each TESS observation available (2019, 2021, 2023). This study highlights the variability in XRB detections and the ongoing need to refine candidate selection criteria. Nonetheless, the overall success in identifying other XRB candidates from eROSITA data suggests significant potential for future discoveries, which we aim to enhance with improved classification pipelines and forthcoming data releases.

Author’s contribution

The author of the dissertation conducted the majority of the study presented in the paper, including X-ray/optical timing, spectral, and astrometrical analysis. In addition to contributing to the paper’s conclusions, the author wrote most of the manuscript. As a member of eROSITA_DE consortium, the author also applied for and obtained optical spectroscopic observations with SALT. Candidate selection and planning of the XMM-*Newton* observations were carried out by Dr. Victor Doroshenko.

6.5 Paper V — The effect of thermal winds on the outbursts evolution of LMXBs

In Paper V, we explored how a thermal wind affects the evolution of accretion discs in XRBs using numerical simulations within the FREDDI code⁹. Incorporating various thermal wind models, we found that the presence of a wind accelerates the evolution of accretion discs during outbursts, particularly in brighter events where the wind’s power scales with higher accretion rates and disc sizes. Neglecting the thermal wind can lead to an overestimation of the Shakura-Sunyaev viscosity parameter α derived from observations, potentially by a significant factor depending on the X-ray spectral characteristics. Our application of the thermal wind model successfully fitted the accretion rate during the 2002 outburst of the BH LMXB 4U 1543–47, revealing an approximately 1.6 times overestimation when the wind effect was ignored. Furthermore, we also simulated optical/IR light curves from the 2002 4U 1543–47 outburst and identified discrepancies in the J band flux, suggesting additional unaccounted sources of optical/IR radiation, possibly including a jet. Lastly, we examined the evolution of wind column density N_H along the line of sight, predicting changes once the wind ceases due to the disc’s hot-zone radius shrinking below the wind launch radius.

Author’s contribution

In this paper, the author was one of the key contributors behind the entire concept, conducting most of the analytical, numerical, observational, and theoretical analysis. Author also contributed significantly to the writing and improvement of the open-source code FREDDI (including most of the code dedicated to the modelling of disc winds) and wrote the majority of the text.

⁹FREDDI code is fully available at <https://github.com/hombit/freddi/tree/dev>

7 Results and discussion

In this chapter, I will summarize the methods and key results presented in Papers I–V, with the full journal versions available in Appendix A. However, in the context of Paper IV, some of the results presented below have yet to be incorporated into the respective manuscript. Paper IV, under review as of March 2025, awaits time-resolved spectroscopy with SALT to confirm or challenge the conclusions reached.

The primary focus of this dissertation is the study of XRBs as a Galactic population. To achieve this, I will discuss the methodology and underlying concepts of the two-stage approach designed to maximize the identification and characterization of the entire XRB population.

The first stage involves the creation of two comprehensive catalogues of high-mass and low-mass XRBs (Papers I and II), incorporating over half a century of discoveries and studies on HMXBs and LMXBs conducted by various authors. The second stage builds upon these results to identify new XRBs within eROSITA data using a ML approach (Paper III).

Beyond population-level studies, this dissertation also includes investigations of specific X-ray sources, as presented in Papers IV and V. These works focus on characterizing XRB candidates through optical/X-ray spectral and timing analyses, as well as modelling the thermal wind from the accretion disc of a known LMXB during X-ray nova events.

7.1 Modern X-ray binary catalogues

The X-ray binary catalogues (XRBcats), presented in two similar works (Paper I and Paper II), are landmark contributions to the study of XRBs in our Galaxy. These comprehensive catalogues focus on two respective populations: LMXBs and HMXBs, addressing a long-standing need for updated, detailed resources in high-energy astrophysics. Together, these works integrate a wealth of new observational and literature data, reclassify numerous systems, and provide key insights into the populations and properties of accreting binaries.

Paper I detailed the creation of a catalogue for LMXBs, featuring about 350 systems — a substantial 71% increase from previous compilations (Liu et al., 2007, Ritter and Kolb, 2003). This expansion reflects an immense effort to incorporate data from large-scale surveys such as *Gaia*, *XMM-Newton*, *Swift*, etc., combined with public databases like SIMBAD and VizieR. Each entry in the catalogue table includes critical parameters such as flux measurements, distances, orbital periods, accurate astrometry, and far more. Additionally, the publication provides finding charts for each LMXB across multiple wavelengths (see an example on Fig. 19, taken from Paper I).

The main focus was on increasing the depth and accuracy of the catalogue data, while expanding the number of known systems. This catalogue is instrumental in studying the diverse subclasses of LMXBs, which include persistent systems, X-ray transients, burst sources, millisecond pulsars and others to name a few. By refining classifications and integrating modern data for each source, the catalogue serves as a vital resource for our understanding of compact object formation, accretion physics at low and high states, and Galactic structure and evolution in future works.

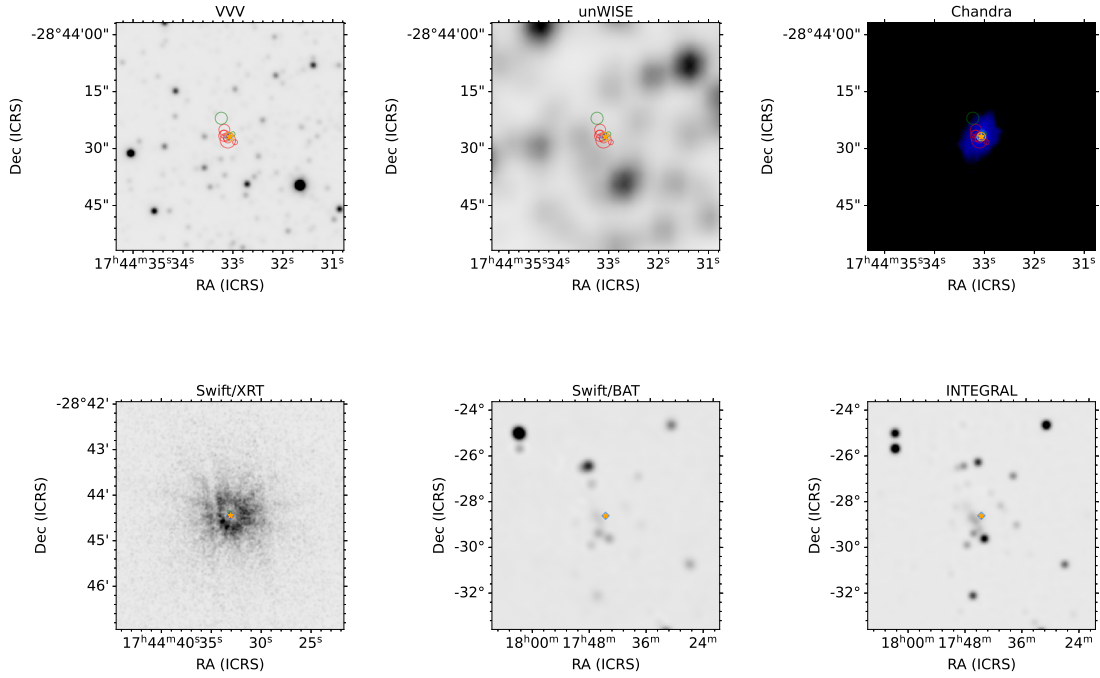


Figure 19: Finding chart of GRO J1744–28. The finding charts display markers and error circles representing observations made by different instruments. The error circles are used for soft X-ray observations to prevent overcrowding, with a yellow circle indicating *Chandra* and a green circle representing *Swift*/XRT. The red cross and the blue diamond indicate the positions reported by SIMBAD and that found in the literature, respectively. An orange star denotes the position of the LMXB used in this catalogue. The image is taken from Paper I.

Paper II complements this effort by cataloguing 169 HMXBs, replacing [Liu et al. \(2006\)](#), with a similarly meticulous approach to data collection and validation as in Paper I. It includes important subcategories such as Be-type and supergiant XRBs, highlighting the diversity of these systems and their evolutionary pathways. The HMXB catalogue also benefits from cross-survey integration, ensuring the inclusion of newly discovered systems and the reclassification of existing ones. These high-mass systems provide a crucial window into massive star evolution, stellar wind dynamics, and the Galactic star formation rate.

The updated catalogues provide a lot of crucial information which is already being used by other authors, specifically:

- **Standardised datasets:** A major improvement in the XRBcats is the shift towards more standardised X-ray flux measurements in defined energy bands, with soft and hard X-ray fluxes now reported separately. By improving the reporting of X-ray fluxes, the catalogue allows for more precise studies of variability, outbursts, and long-term evolution in these systems, which are driven by processes such as accretion instabilities and magnetic activity. Furthermore, the catalogue table has added several new fields — such as stellar temperatures, optical luminosities, and hydrogen column densities — which offers more detailed insights into the stellar and circumstellar environments of these systems, helping to refine models of their evolution and the interstellar medium.
- **New Discoveries and Revisions:** The XRBcats feature numerous reclassifica-

tions based on new data from literature. In particular, sources that were once thought to belong to the HMXB or CV class have been currently identified as LMXBs and vice versa, driven by the reclassification of their companions, accretion signatures or distance estimates. This has led to a reevaluation of the relative populations of HMXBs and LMXBs, as well as a better understanding of the diversity within each group. In the end, this reclassification process reflects the growing accuracy of observational techniques, such as more precise optical and X-ray spectroscopy, as well as a deeper understanding of the physical processes within these systems. Furthermore, the inclusion of newly discovered systems address some long-standing questions regarding the population distribution of XRBs.

- **Cyclotron Line and Spectral Features:** A particularly important result in this update is the inclusion of more detailed data on CRSFs for HMXBs. By reporting both fundamental and harmonic energies for sources with detected CRSFs, the catalogue enhances our understanding of the magnetic properties of the compact objects in these systems. These observations offer a direct probe of the environment around neutron stars, allowing researchers to test theoretical models of accretion, magnetic field geometry, and emission processes on a much more global scale.
- **Luminosity and Variability:** The catalogues also shed light on the luminosity distribution of both HMXBs and LMXBs. By reporting fluxes in different energy bands and over varying time scales, the catalogues highlight the significant variability in X-ray output, driven by factors such as accretion rate changes, orbital motion, and intrinsic activity of the compact objects. Understanding these variability patterns is crucial for constraining models of accretion physics, particularly the role of magnetic fields in shaping the observed X-ray spectra and variability.
- **Outreach to MWL Studies:** A notable outcome of the updated catalogues is their ability to facilitate MWL studies based on enormous amount of publications incorporating data from *Gaia*, WISE, etc. By providing optical and near-infrared data from a number of facilities, these catalogues serve as valuable resources for researchers studying the broader properties of XRBs. Future work using infrared and optical telescopes, in combination with high-energy X-ray observatories, will be instrumental in expanding the understanding of the long-term behaviour of these systems.

To summarise, both works together fill a critical gap left by earlier, outdated catalogues. Previous compilations often lacked the scope and precision needed to capture the dynamic nature of these populations. The XRBcats catalogues overcome these limitations by integrating MWL high astrometry observations, addressing classification ambiguities, and including previously under-represented systems, such as transitional millisecond pulsars and symbiotic XRBs. Moreover, XRBcats, while being publicly available on the VizieR website^{10,11}, also have their own dedicated webpage¹² hosted by the Tübingen University. The corresponding citation offers additional details about the sources, features fast updates, and provides a user-friendly *Aladin*¹³-based interface.

As a part of this dissertation, HMXB and LMXB catalogues provide a wealth of data that enables a statistical analysis of the XRB population. This is specifically of a great

¹⁰<https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/675/A199>

¹¹<https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/677/A134>

¹²<http://astro.uni-tuebingen.de/~xrbcat/>

¹³<https://aladin.cds.unistra.fr/>

importance in the context of the Paper III, where ML algorithms are directly trained based on the MWL data collected in the Papers I and II. This is done in order to find new Galactic XRBs in the first eROSITA data release (see Sect. 7.2). Moreover, these two catalogue publications will significantly influence the future of this dissertation as a scientific study. They will serve as one of the primary foundations for constructing the most accurate, time-variable XLF of XRBs in the Milky Way.

The release of these two catalogues also came at the right time in the field of high-energy astrophysics. Given the rapidly evolving nature of observational techniques and the increasing sensitivity of X-ray telescopes, researchers were in urgent need of updated and more reliable resources to classify and study these systems. This need is evident in the fact that both papers combined garnered over 80 citations within just a year since their publication. This widespread acknowledgment underscores the importance of these catalogues in advancing the field and supporting future investigations into compact objects and stellar evolution. The citations reflect a wide range of works, from population synthesis studies (Heinke, 2023, Kim et al., 2023, Zhang et al., 2023) to computational analysis of accretion processes (Lančová, 2023, Shui et al., 2024), and even as reference datasets for revising nature of some sources (Sidoli et al., 2025, Trumic et al., 2024). By standardizing and enriching the available data, the catalogues enable collaborative research and foster a deeper understanding of XRBs. Furthermore, the catalogue data is also used to monitor the activity of bursting XRBs on the optical observatories such as ZTF.

As new observational tools such as eXTP, XRISM, THESEUS and ATHENA come online, the catalogues will continue to evolve. These updates not only refine our understanding of individual systems but also help improve statistical models of X-ray binary populations, providing a more nuanced picture of their role in the universe. The ongoing development of these catalogues will be critical for future studies of accreting compact objects, the interstellar medium, and stellar evolution.

In conclusion, the XRBcats catalogues represent a transformative step in the study of Galactic X-ray binaries. By providing an unprecedented level of detail and accuracy, these works have redefined our understanding of these systems and their place in the cosmos. Their widespread adoption and citation reflect their importance as essential tools for researchers, laying the groundwork for continued advancements in high-energy astrophysics and stellar evolution.

7.2 Searching for new XRBs in eROSITA with ML

The Paper III presents an extensive description of the methods used to search for XRB candidates in the eROSITA first data release (eRASS DR1) using ML techniques. The primary goal is to identify new HMXB and LMXB candidates by leveraging MWL data and supervised RF classification models. The identification process is refined using machine learning approaches, which take into account X-ray flux properties, optical and infrared characteristics, and various statistical measures to classify X-ray sources and distinguish XRBs from the large pool of detected objects. The main motivation behind the Paper III is the fact that according to the current models of XLF, the population of XRBs is dominated by its fainter part. In other words, we expect that the majority of XRBs have X-ray luminosities $L_x \lesssim 10^{34-35}$ erg/s and therefore, they remain poorly sampled due to sensitivity limits of past wide-area surveys like ROSAT and *Swift*. In turn, eROSITA, which provides a ~ 40 -fold sensitivity improvement over ROSAT, enables the first systematic search for low-luminosity XRBs across the X-ray sky.

Challenges in identification of XRBs

The Galactic plane's high source density and interstellar absorption complicate counterpart identification for any given source, especially in high-energy bands. eROSITA has typical $3\text{-}\sigma$ positional error circle of $\approx 15''$, which, while much better than ROSAT, still allows multiple potential counterparts to be considered. Thus, traditional methods relying on colour-magnitude diagrams or X-ray-to-optical flux ratios (see given description of those methods in Sect. 4.2) struggle with eROSITA's all-sky large sample, especially considering potential MWL cross-correlation. ML offers a scalable solution, but requires careful handling of class imbalances (AGNs and stars dominate) and missing data (see Sect. 4.3 for a review).

As was stated in Sect. 4.3, in order to cross-match eROSITA with optical/IR surveys, NWay is used, a Bayesian cross-matching algorithm. Specifically, it is employed to determine the most probable counterparts for each X-ray source. Since NWay is able to take into account prior information for plausible counterparts (aside of geometrical coincidence), user can apply it to find more probable "user-preferred-like" counterparts. If the majority of X-ray sources in a given dataset are AGNs, it is reasonable to prioritise IR-bright objects as potential counterparts within the given positional uncertainty. This is because most X-ray luminous AGNs also exhibit strong IR emission. In such cases, an AGN-like source can be regarded as a likely X-ray emitter, and the IR magnitudes of possible counterparts can serve as a weighting factor or prior in the selection process. Objects with lower IR magnitudes would then have a higher probability of being selected as right counterparts to X-ray sources. More sophisticated selection criteria can also be implemented. For example, in addition to requiring a source to appear red, one might also impose the condition that it lacks a significant *Gaia* parallax, among other constraints. Unfortunately, it is not possible to determine in advance whether a given X-ray source is an AGN, an HMXB, or another type of object, as their X-ray properties can be nearly indistinguishable without deep observations. As a result, assigning counterparts with complete certainty for each source is not feasible.

A straightforward strategy to address this issue is to optimise for the highest overall fraction of correct associations by adjusting priors based on the characteristics of a typical X-ray-emitting source. However, by definition, this approach inherently favours counterparts that align with the most common source class, leading to a bias in counterpart selection and subsequent classification. In the case of eROSITA, the vast majority of detected point sources are either AGNs or normal stars (see Fig. 14, left panel). As a result, if priors are set according to the average X-ray source, less common objects such as XRBs and CVs are more likely to be misidentified with AGN- or star-like counterparts. While this may not be a major concern for studies focused on dominant source populations — where minor contamination from rarer objects is negligible — it poses a significant challenge when the goal is to identify a small number of XRBs hidden among hundreds of thousands of AGNs and stars.

Methods

The classification of eROSITA X-ray sources heavily depends on the MWL characteristics of their potential counterparts, particularly in the optical and IR bands. In general, the process of identifying the origin nature of X-ray sources can be divided into two main steps:

- Counterpart identification: Selecting plausible counterparts in other wavelength bands based on spatial coincidence with the X-ray source, while incorporating priors

derived from the optical and IR properties of potential counterparts (NWAY+RF), optimised for the target source class (XRBs in our case, L/HMXBs separately).

- X-ray source classification: Determining the nature of the X-ray source using the MWL properties of the assigned counterparts.

The first step ensures that objects belonging to the target class are matched with the most suitable MWL counterparts, thereby improving the completeness of the candidate list. However, this approach also increases the likelihood of misassigning counterparts to sources of other types, making them appear more similar to the target class (HMXBs or LMXBs in our case). As a result, while completeness improves, the purity of the final sample—i.e., the fraction of correctly classified objects—may be reduced (see more regarding completeness and purity in Sect 4.3). Therefore, it should be addressed accordingly, as done in the Paper III.

Step 1: Counterpart Identification

Objective: Train a RF classifier to distinguish "XRB-like" counterparts from other type sources using known, previously identified XRBs (from Paper I and Paper II). Since HMXBs and LMXBs have different types of counterparts, two of these XRB categories are treated separately. At this stage only optical and IR features are used for training RF machine models, such as magnitudes, colours and distances. Resulting RF probabilities are used as priors for NWAY.

- **Data in use:**

- Positive class: 149 HMXBs + 197 LMXBs with confirmed *Gaia* and CatWISE counterparts (all-sky is used). Another condition: no other XRBs shall be found within 1' radius of selected ones. Additionally, Global cluster and some very Galactic central Galactic are excluded due to high number of X-ray accreting emitters.
- Negative class: All optical/IR contaminants within 1' radius of the selected on the previous stage "positive class" identified XRBs. Assumption: no unknown XRBs exist within 1' areas around "positive class" XRBs.
- Features: $G, BP, RP, J, H, K, W1, W2$ band magnitudes, distances with corresponding errors

- **Test and Train:**

The resulting labelled dataset is divided into train (75%) and test (25%) sub-samples

- **Class Balancing:**

SMOTE ratio = 1 : 1 (XRBs : contaminants) is used for all sub-datasets

- **RF Configuration:**

- For the training and classification an RF model implemented in `RandomForestClassifier()`¹⁴ class from the `sklearn.ensemble` module with 500 decision trees is used, max depth = 20

¹⁴<https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestClassifier.html>

- Feature importance dominated by the magnitudes and distance significances for HMXBs and colours for LMXBs (see Fig. 20)

- **NWAY Cross-Matching:**

- The probability of a cross-match association P_{match} with a given optical/IR source is calculated by NWAY as:

$$P_{\text{match}} \propto P_{\text{spatial}} \times P_{\text{RF prior}} \times P_{\text{source density}} \quad (7.29)$$

where P_{spatial} is a classic geometrical cross-match likelihood, $P_{\text{RF prior}}$ is the probability determined by a RF algorithm for a given optical/IR source to be a positive class member ("XRB-like"). In turn, $P_{\text{source density}}$ is a likelihood, which takes into account different source densities in provided X-ray and optical/IR catalogues.

- Match threshold for cross-match to be selected: $P_{\text{match}} > 0.65$, calculated from generating fake X-ray catalogue with sources positions much shifted from their original coordinates, see more on that in NWAY description¹⁵. In cases, when 2 potential association are above the threshold level for a singular source, both are considered and classified independently (look for `match_flag` description in the NWAY readme file)

Step 2: Source Classification

Objective: Classify all eROSITA sources using combined X-ray + MWL features. At this stage, the data collected from the selected by NWAY counterparts to X-ray sources from eRASS DR1 is used for origin classification. Corresponding RF algorithm is trained on a pure sample of identified eRASS DR1 sources with known counterparts (no bias towards "XRB-like" optical associations). Specifically, optical/IR counterparts to the eROSITA sources of known nature were selected inside 3'' radius from their archive positions.

Classification is conducted into 8 classes instead of 2 like in the Step 1. This is done to avoid more contamination of other type sources with XRBs. Basically, some isolated NSs (INs), or CVs, for example, could appear similar in MWL space to XRBs, so distinguishing them from other sources by forming separate classes improves the work of ML algorithm.

- **Data in use:**

- 127,811 labeled eROSITA-detected sources (46 HMXBs, 63 LMXBs, 26 INS, 613 CVs, 127811 AGNs, 655 OB-type stars, 4325 MK-type coronal active stars and 9500 YSOs, 8 classes in total). Wolf-Rayet type stars are included into OB class due to similar MWL behaviour.
- Expanded features: In addition to what was used to train NWAY-prior RF models on the previous step, several other features are utilised: $\{F_{0.2-2.3 \text{ keV}}, F_{2-8 \text{ keV}}, HR, N_H\}$, variability index and excess noise from *Gaia* DR3.

- **Test, Train and Verification:**

¹⁵<https://github.com/JohannesBuchner/nway?tab=readme-ov-file>

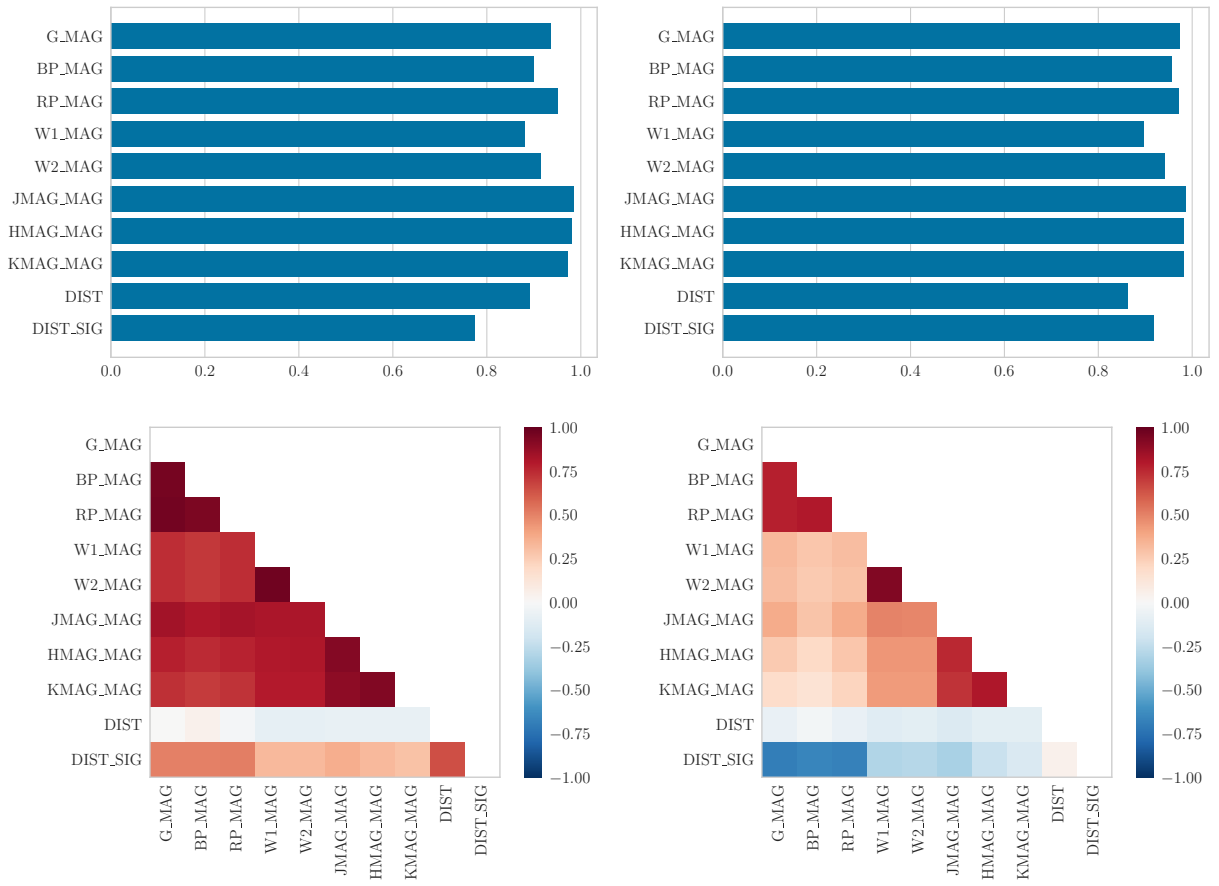


Figure 20: 1D (top panel) and 2D (bottom panel) feature importance rankings for RF trained to identify 'HMXB-like' (left) and 'LMXB-like' (right) optical/IR counterparts (pre-NWAY) based on the augmented (SMOTE) training/test sets. Figure is taken from Paper III.

- All labelled data is divided into the verification and the rest datasets — 25% and 75%, respectively. Verification sample is not visible to classifier at any point and is only used for final assessment of the classifier performance.
- The rest dataset is further divided to train (75%) and test (25%) sub-samples.
- **Class Balancing:**
SMOTE ratio = 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 (all 8 classes balanced) is used for all sub-datasets
- **RF Configuration:**
 - The same `sklearn.ensemble` RF classifier but with 1000 trees and a maximum depth of 25
 - Feature importance picture looks similar to the Fig. 20, with X-ray fluxes and hardness ratios also be dominant.
- **Thresholds and Candidates Selection:**
In order to select the candidates, one needs specified selection criteria on given by a RF corresponding probabilities. This is done based on selected completeness and purity values (see the description in Sect 4.3).

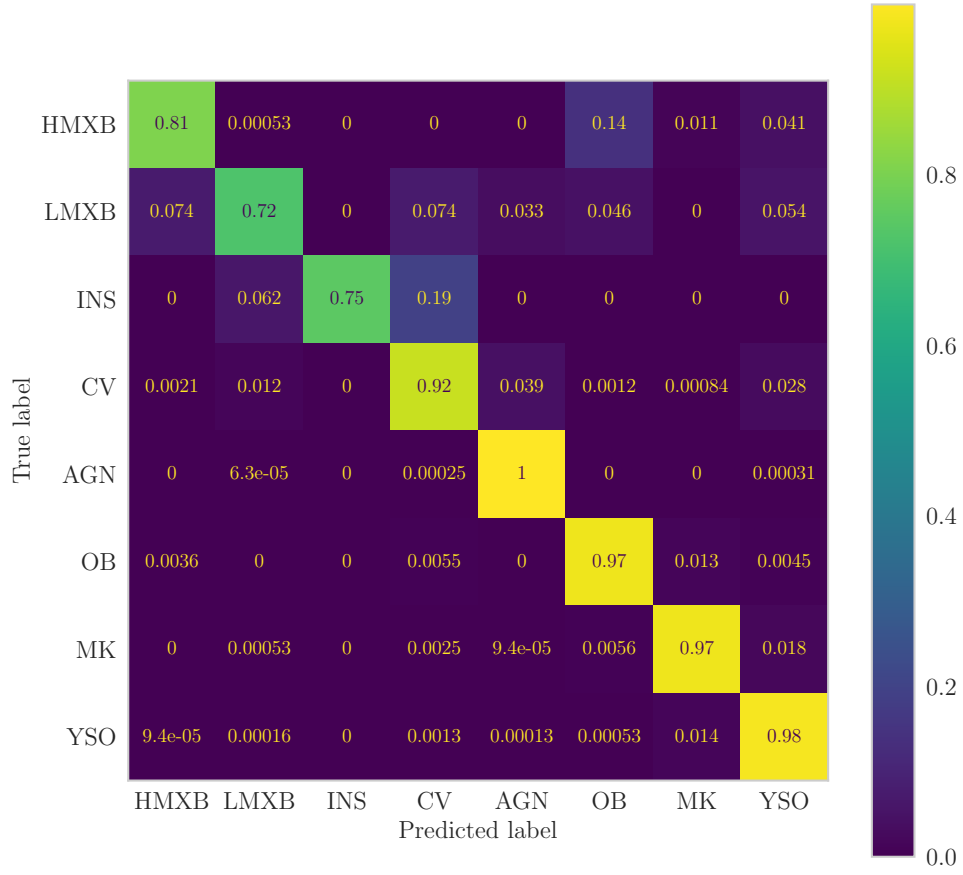


Figure 21: Confusion matrix for MWL source classification RF machine. Figure is shown for augmented (SMOTE) verification sample data. Figure is taken from Paper III.

- The completeness of both XRB candidate samples was set to be 0.7 (70%). This resulted in the probabilistic threshold cuts:

$$P_{\text{HMXB}} > 0.472 \text{ (70\% completeness)}$$

$$P_{\text{LMXB}} > 0.476 \text{ (70\% completeness)}$$

- Resulting candidates sets:

HMXBs — 94 candidates; Purity: 0.83

LMXBs — 98 candidates; Purity: 0.76

At both steps (counterpart identification and source classification) missing values in MWL feature space (corresponding source is not detected in a given survey) are handled through a combination of data imputation techniques, including interpolation for missing distances and magnitude-based extrapolation for undetected sources in specific bands. In general, data imputation is done via replacing missing values with the simulated, randomised and physically justified estimations with given corresponding high errors. The whole procedure is conducted in order to not miss any potential XRB candidates. This is especially important while considering potential LMXBs or highly absorbed HMXBs, since they often lack optical associations due to fainter counterparts, while being relatively bright in X-rays.

Classifier evaluation is performed using standard metrics, including precision, recall, F1-score, accuracy, and log-loss. The trained model is applied to the full MWL

Table 1: Performance of the MWL classification RF algorithm on the augmented (SMOTE) verification sample data.

Class	Precision	Recall	F1-score	Accuracy	Log_Loss
HMXB	0.91	0.81	0.86	0.889	0.495
LMXB	0.90	0.72	0.80		
INS	0.97	0.75	0.81		
CV	0.77	0.92	0.84		
AGN	0.93	1.00	0.96		
OB	0.83	0.97	0.90		
MK	0.96	0.97	0.97		
YSO	0.87	0.98	0.92		

eRASSDR1 based dataset, yielding probability scores for each source belonging to each class. Key performance metrics are presented in Table 1. Probability thresholds are optimized to balance completeness and purity, ensuring the selection of high-confidence XRB candidates. The classifier’s performance varies across different classes, with some being more effectively distinguished than others (see Fig. 21). As expected, the RF model performs better on larger classes, such as AGNs, coronal active stars, and YSOs, due to the significant class imbalance present in the dataset. Even with SMOTE augmentation, the available training data remains insufficient for certain under-represented classes.

However, the classifier’s performance for the target classes (HMXBs and LMXBs) appears reasonable. This is supported not only by standard evaluation metrics (accuracy, F1 score, and precision, Table 1) but also by an analysis of the confusion matrix (Fig. 21)). Notably, despite being among the smallest classes, HMXBs and LMXBs show relatively low misclassification rates with other categories. Although the methods used are not flawless — which should always be approached with caution in ML research — the results indicate that they are functioning as intended.

The RF classifier, trained on the pure MWL dataset, was then independently applied to classify 767,597 previously unlabeled X-ray sources in eRASS1M (excluding spurious detections) that had NWAY-identified counterparts. This classification was conducted on 1,025,967 MWL associations for HMXBs (optics/IR biased) and 996,206 MWL associations for LMXBs (optics/IR biased). It is important to note that the number of associations exceeds the actual number of X-ray sources. This occurs because NWAY can assign multiple counterparts to a single X-ray source (see the description above). Additionally, the slight variation in MWL association numbers between the HMXB and LMXB optics/IR biased cases arises from differences in the adopted priors, which influence the final association probabilities estimated by NWAY and, consequently, the selection of counterparts.

Selected XRB Candidates

Similar to the approaches taken in Papers I and II, the findings of Paper III are compiled into a structured catalogue to facilitate easy access and usability of the data. Presenting the results in this format allows for streamlined analysis and comparison while ensuring that key classifications are readily available to researchers.

The final catalogue includes a total of 192 XRB candidates, with 94 sources classified as HMXBs and 98 as LMXBs. These classifications are based on the selected probability thresholds, ensuring a balance between purity and completeness. The catalogue provides

all essential information about each candidate, including classification probabilities, MWL counterparts, and relevant observational parameters.

To account for possible detections of the selected candidates by other X/ γ -ray facilities, their positions were cross-matched ($3\text{-}\sigma$ coincidence) with archival data of *Chandra*, *XMM-Newton*, *Swift*, INTEGRAL, MAXI and others. All relevant identifications are incorporated into both of XRB candidate catalogues. Although X/ γ -ray associations with the selected XRB candidates are not definitively established, they are provided as a reference for future follow-up studies.

Challenges and Future Directions

The application of machine learning to eROSITA DR1 has successfully identified 192 high-confidence XRB candidates, providing a valuable resource for future studies. The number of detected XRBs goes in line with the pre-launch predictions (Doroshenko et al., 2014a), suggesting small deviations from expected XLFs. Therefore, we still expect an even larger number of XRBs hidden among faint X-ray sources within our Galaxy.

The study identifies several key challenges in XRB classification while considering large all-sky survey datasets:

- **Contamination from extragalactic sources:** Certain XRBs share similar MWL characteristics with AGNs, occasionally resulting in misclassification. This underscores the need for a cautious and meticulous approach when identifying optical/IR counterparts to ensure accurate classification.
- **Effects of Galactic absorption:** Uncertain absorptions and distance constraints obscure many faint X-ray sources, reducing the purity and completeness of the test and train samples. Therefore, developing new models for Galactic structure and dust absorption, as well as improved methods for managing poor distance priors, is crucial for future XRB population studies.
- **Limited training data:** The small number of confirmed XRBs in the training dataset constrains model accuracy. Therefore, most thorough data imputation and class balancing methods, alongside with the expansion of XRBs sample are required in order to maximise the performance of ML classification.

The results demonstrate the power of MWL classification in XRB identification, while also highlighting the problems associated with source confusion and observational biases. Upon that, candidates found nearly double the number of known XRB in the surveyed region (western Hemisphere), creating a new playground for subsequent observations with X-ray and optical observatories such as *XMM-Newton*, NuSTAR, SALT, etc. Future eROSITA data releases, combined with targeted follow-up observations, will enable a more comprehensive understanding of the Galactic XRB population and its role in stellar and binary evolution.

7.3 Analysis of previously selected XRB candidates

As discussed in the subsection above, identifying faint XRBs among millions of other sources is challenging due to the similarity of their X-ray properties to those of AGNs and stars dominating the survey. However, before previous part dissertation work started (Papers I–III), several XRB candidates were identified based on the analysis and classification of X-ray sources detected in a preliminary, non-public version of eRASS1 back in

2020. In particular, the combination of eROSITA X-ray fluxes and near/mid IR properties from 2MASS and WISE (CMD analysis, similar to that described in Sect. 4.2) was used to identify XRB candidates for follow-up observations with XMM-*Newton* and NuSTAR. Such works are essential to test classification techniques as well as to widen the MWL space of the Galactic X-ray point-source population for future studies.

Four out of the six XRB candidates proposed for X-ray follow-up have actually been observed — the two brighter ones by NuSTAR and the remaining two by XMM-*Newton*. Detailed follow-up results of the first of the two objects observed by NuSTAR, SRGA J124404.1–632232 (which turned out to be a NS HMXB), were presented in Doroshenko et al. (2022). Analysis of NuSTAR observations of the second candidate, 1eRASS J085039.9–421151, which was identified as a SyXRB, is presented in Zainab et al. (2025, thesis’s author is a second co-author of the paper, not a part of this dissertation). Paper IV, in turn, reports on the MWL spectral, photometric and timing analysis of the two remaining eROSITA-selected XRB candidates observed with XMM-*Newton*, namely, 1eRASS J061330.8+160440 and 1eRASS J161201.9–464622, (hereinafter J061331 and J161201).

X-ray data: XMM-*Newton* and eROSITA

The inherent limitations in counting statistics associated with all-sky surveys restrict the positional accuracy of the eROSITA survey. Consequently, deeper pointed XMM-*Newton* observations were employed to significantly enhance this accuracy. X-ray coordinates were calibrated using data from the XMM-*Newton* Optical Monitor (OM) camera, and positions were refined to achieve uncertainties of approximately $0.98''$ for J061331 and $0.94''$ for J161201 at the $1-\sigma$ confidence level. Both sources were found to have unique optical/IR counterparts in available catalogues such as *Gaia*, 2MASS, etc.

The X-ray spectral modelling was performed using commonly applied phenomenological models for XRBs and active stars. Along with that, X-ray timing analysis for both XRB candidates was conducted in order to find modulations which could be associated with a spin of a potential compact object. The key steps and findings are summarised as follows:

- Initial attempts were made using absorbed cutoff power law (`constant*tbabs*cutoffpl`) and absorbed black body models typical for accreting XRBs, but neither provided a statistically acceptable fit for either source.
- A better fit was achieved using a two-temperature optically thin thermal plasma emission model (Raymond and Smith, 1977, Smith et al., 2001), represented as `constant*tbabs*(apec+apec)`. Such models are widely used for both hot (Nazé et al., 2014) and cool (Robrade and Schmitt, 2005, Stelzer et al., 2022) stars, as well as some CVs (Ramsay et al., 2004, Worpel et al., 2020). Fig. 22 shows both spectra.
- In general, two candidates have similar X-ray observational appearance, being both variable with relatively close X-ray 0.2–10 keV luminosities around $\sim 10^{31-32}$ erg/s.
- However, J161201 displays a harder X-ray spectrum compared to J061331 ($kT_{\text{hot}} \approx 5.8$ keV instead of ~ 3.4 keV) and, more notably, exhibits iron emission line features around 6–7 keV found in PN-camera data (Fig. 22, right image, green plot). Such features are rarely observed in active stars but are commonly associated with binary systems exhibiting hard X-ray emission, such as CVs and XRBs. However, poor statistics do not allow us to resolve each iron line separately.

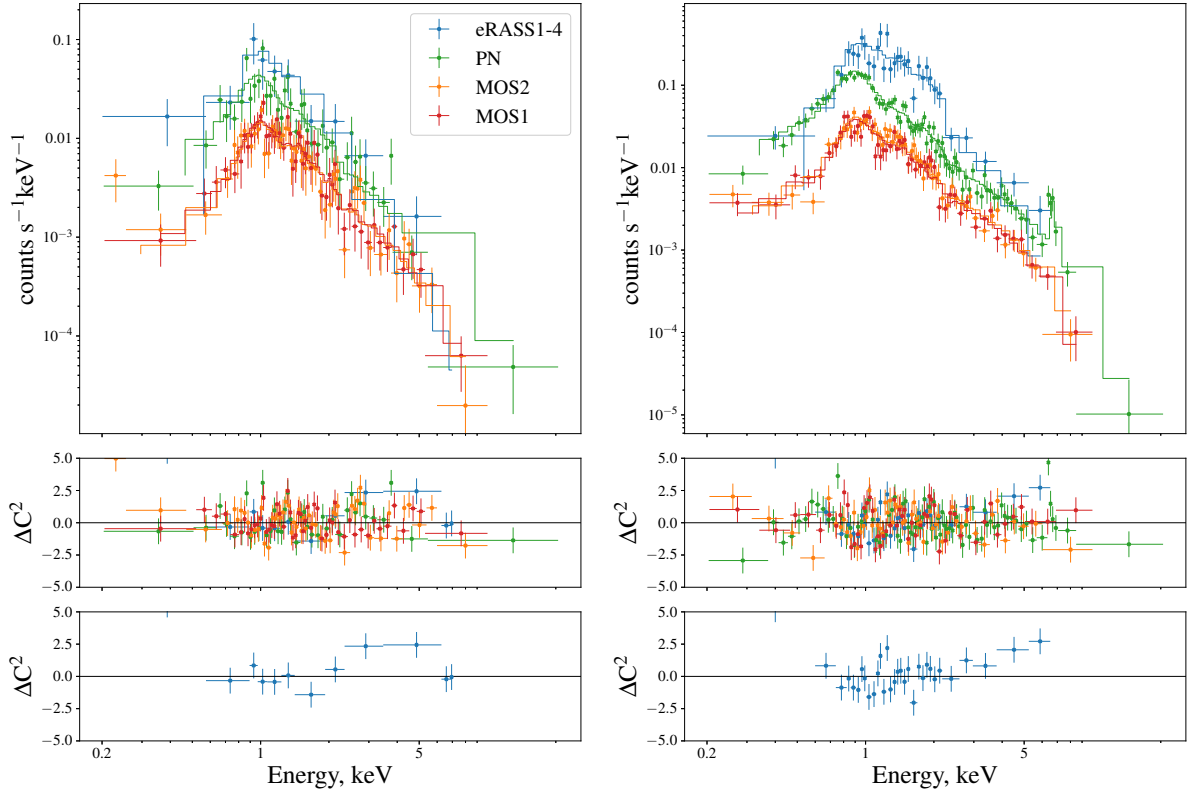


Figure 22: XMM-*Newton* and eROSITA spectra of J061331 (left image) and J161201 (right image) fitted with double *apec* (`const*tbabs*(apec+apec)`) model. *Top panels*: spectra themselves and the fit; *Middle panels*: all corresponding residuals; *Bottom panels*: eROSITA residuals only. Figures are taken from Paper IV.

- A periodicity search using XMM-*Newton* was conducted by implementing Z^2 statistics (de Jager et al., 1989) from *Stingray* package (Huppenkothen et al., 2019)¹⁶, with event arrival times corrected to the Solar system barycentre. Unfortunately, no significant X-ray periodicity was detected for either source, though this may be due to insufficient counting statistics.

Ultimately, the X-ray data analysis did not provide a definitive conclusion regarding the nature of either XRB candidate. While the spectral fitting and timing analysis yielded valuable insights into their X-ray properties, no unique signatures were found that could conclusively determine their origins. However, the identification of optical/IR counterparts, opened the opportunity for a deeper MWL investigation. Given this, an extensive search for archival optical/IR spectroscopic and photometric observations of J061331 and J161201 was conducted.

Optical spectra: LAMOST and SALT

A search for archival optical spectral data of J061331 and J161201 was made to further characterise their nature. While no spectra were available for J161201, LAMOST archival data provided valuable spectral insights for J061331. Therefore, as a member of eROSITA_DE consortium I proposed and got the observations with SALT (see Sect. 5.3) for J161201 optical counterpart. Observations were made with HRS on February 5, 2025 in low-resolution (LR ~ 15000) mode. The analysis of both spectra (see Fig. 23 and Fig. 24

¹⁶<https://docs.stingray.science/>

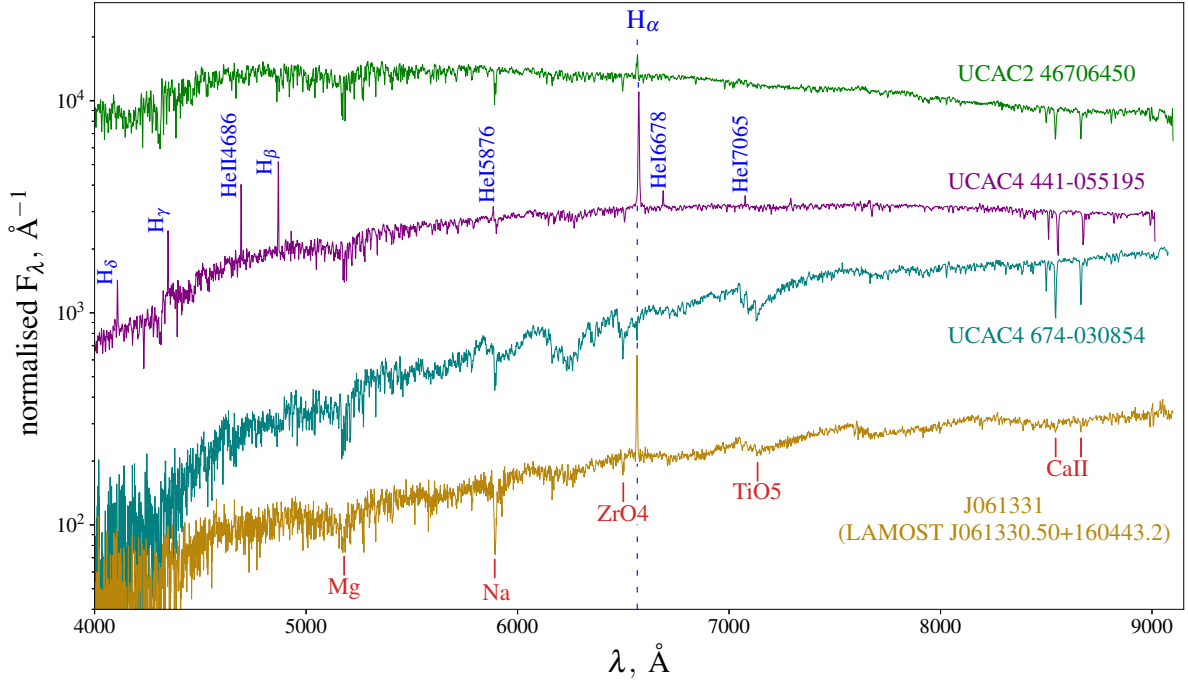


Figure 23: From the bottom to the top: LAMOST DR9 low resolution ($\lambda/\Delta\lambda = 1800$) optical spectra of the counterpart to J061331, UCAC4 674–030854 (S-type giant), UCAC4 441–055195 (Symbiotic CV with K-type giant) and UCAC2 46706450 (K-type subgiant with non-accreting WD). Spectra of UCAC4 674–030854 and UCAC4 441–055195 were rescaled for ease of plotting. Strong emission and absorption lines are marked with blue and red coloured text, respectively. Figure is taken from Paper IV.

for J061331 and J161201, respectively), including emission and absorption features, comparison with known stellar types, and spectral classification, led to the following key findings:

- **LAMOST spectral features of J061331:**

- The spectrum of J061331’s optical counterpart exhibits a strong H_α emission line at $6564.6 \text{ \AA}$, which is indicative of chromospheric and coronal activity in late-type stars (Douglas et al., 2014, Strassmeier et al., 1990).
- The FWHM of the H_α line was measured to be $7.4 \pm 0.3 \text{ \AA}$ ($\sim 330 \text{ km/s}$), while its equivalent width, $EW = -9.2 \pm 0.9 \text{ \AA}$.
- H_α FWHM exceeds the expected rotational width by a factor of nine. Assuming that H_α is bound with the star, FWHM estimation suggests that a part of the emission may come from a circumstellar region reaching up to 8-10 stellar radii (Kővári et al., 2019, Ramsey et al., 1981, Short et al., 1998, Zboril et al., 2004).
- No additional emission features such as H_β , H_γ , or He lines, which are characteristic of accreting binaries, were detected (Koljonen et al., 2023, Miszalski et al., 2013).
- The presence of TiO, Mg, and Na absorption lines suggests a photospheric origin, and their relative weakness implies that J061331 is more likely a subgiant

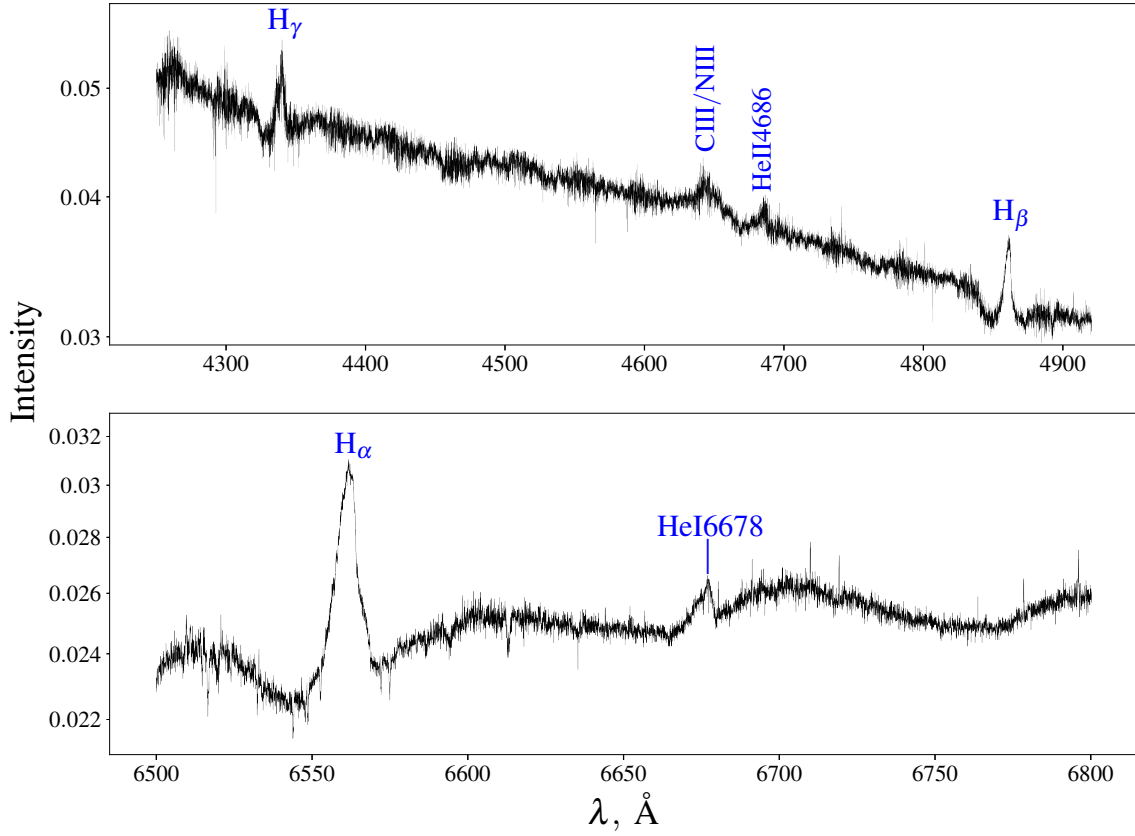


Figure 24: Blue (top panel) and red (bottom panel) arms of J161201’s SALT spectrum. Wavelength regions are selected to showcase identified emission lines.

rather than a giant star.

- The spectral type of J061331’s counterpart was further refined using TiO band indices as described by [Kenyon and Fernandez-Castro \(1987\)](#).
- TiO index measurements from the LAMOST spectrum were used to calculate spectral type indicators ST_1 and ST_2 , yielding values close to 1.9, which corresponds to an M2-type star.
- This classification is slightly later than the archival LAMOST estimates (K7–M0) but remains consistent within uncertainties.

• SALT spectral analysis of J161201:

- The obtained SALT spectrum of J161201’s has a very blue continuum that still grows up to the short-wavelength cutoff at around 3500 Å.
- The spectrum itself reveals a bunch of Balmer emission lines, such as H_α , H_β , H_γ (see Fig. 24). In addition to H-Balmer emission lines the source displays He-emission lines (neutral HeI6678 and ionised HeII4686) as well as C III/N III Bowen fluorescent blend around 4640 Å.
- The overall optical spectrum indicates that the source is a CV.
- Each H-emission line displays absorption wings potentially caused by a linear Stark effect coming from an optically thick high-gravity accretion disc observed at low inclination.

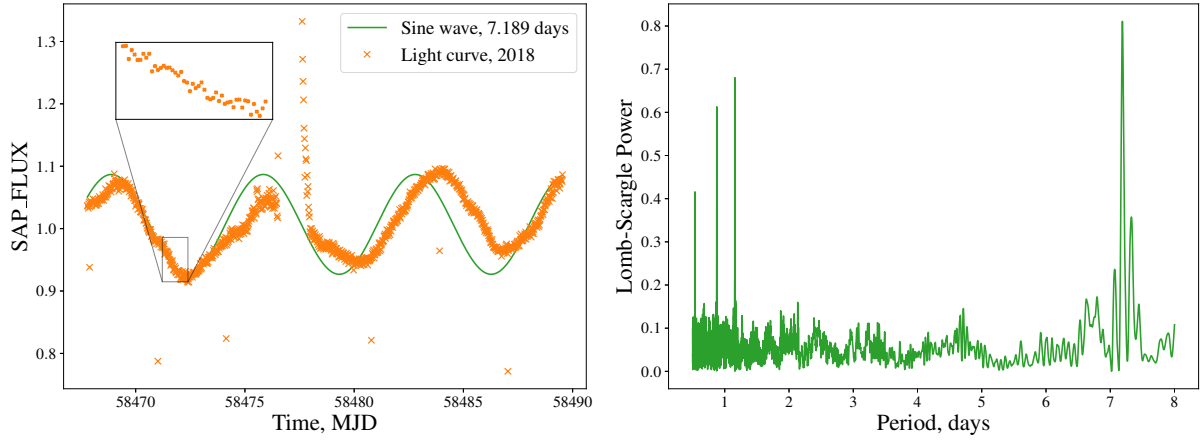


Figure 25: *Left panel:* TESS light curve taken in 2018 (~ 21.7 days duration) of the J061331 optical counterpart along with the sine wave having a period of 7.189 days obtained from ZTF Lomb-Scargle periodogram. *Right panel:* Band-combined ZTF Lomb-Scargle periodogram itself, showcasing the real 7.189-days period and beat tones.

- The typical FWHM of the emission lines correspond to $\sim 360 \text{ km s}^{-1}$, suggesting the presence of particles moving well beyond typical thermal velocities in an optically thin region, likely located above the accretion disc. Moreover, all emission lines have EWs well above $-10 \text{ \AA}$ ($\text{EW} > -10 \text{ \AA}$, or $|\text{EW}| < 10 \text{ \AA}$) with the HeII4686 to the Balmer H_β ratio below 0.2.
- Such emission line features make it unlikely for the source to be a magnetic CV, such as a polar or IP (van Paradijs and Verbunt, 1984).
- The overall spectral analysis, colours and low for a typical CV X-ray to optical flux ratio ($\log(F_x/F_{\text{opt}}) \approx -2.5$, source is really bright in optics) strongly suggest that J161201 is a weakly magnetised novalike CV.

In the end, the LAMOST and SALT spectra enabled the determination of the nature of both sources. Specifically, J061331 was identified as an M0–M2 coronal active subgiant, while J161201 was classified as a novalike CV. In the absence of time-resolved spectroscopy during the writing of this dissertation (J161201 is still awaiting the SALT series spectral observations with RSS), the photometric data for both objects were examined in order to search for the orbital period of a potential binary.

Optical variability: ZTF, ASAS-SN, and TESS

To investigate periodic behaviour in the optical bands, archival data from ZTF, ASAS-SN, and TESS were analysed. Periodicity searches were performed using epoch folding and Lomb-Scargle periodograms, implemented via the `gatspy` package¹⁷ (Lomb, 1976, Scargle, 1982, VanderPlas and Ivezić, 2015).

The optical periodicity analysis of J061331 and J161201 yielded the key findings listed below this paragraph. It should be noted that J061331 is relatively faint for ASAS-SN, therefore I focus on ZTF and TESS data results for this candidate. On the other hand, J161201 is outside the ZTF survey coverage, therefore, only ASAS-SN and TESS data were utilised.

• ZTF and TESS data results for J061331:

¹⁷<https://github.com/astroML/gatspy>

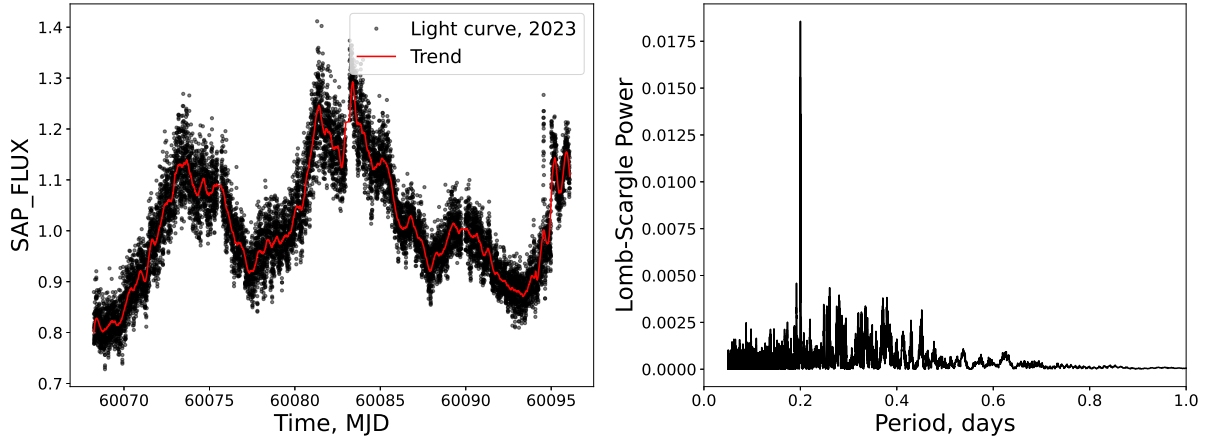


Figure 26: *Left panel:* TESS optical light curve (~ 27.9 days duration) of the J161201’s optical counterpart taken with the shortest among available data cadence (~ 3 min). The plot shows the raw light curve itself, as well as the Savitzky-Golay trend which captures any quasi-periodic signals above 1-day periodicity. *Right panel:* The combined (2019, 2021 and 2023 TESS observations) Lomb-Scargle periodogram based on the de-trended photometric data.

- Significant periodic signals were detected at 1.158 (along with multiplicities and aliased peaks around) and 7.189 days in ZTF, consistent with archival findings from ATLAS and ZTF (Fig. 25, right panel).
- The same 7.189-days sinusoidal periodicity is seen in TESS data (2018 observation, see Fig. 25, left panel), matching the ZTF based findings.
- All signals below ~ 7 days were identified to be just beat tones resulting from the 7.189-days periodicity and Earth’s rotation harmonics.
- A flare event occurred around MJD 58475–80 in TESS data, briefly disrupting the periodic behaviour before returning to a stable sinusoidal pattern.
- In principle, observed 7.189-days signal could be caused by starspots rather than orbital modulation.

• **ASAS-SN and TESS data results for J161201:**

- The overall ASAS-SN periodogram and light curves for J161201 do not look very promising, even though the source’s variability is high.
- TESS observations from 2019, 2021 and 2023 (left panel of Fig. 26 presents the latter, it has the best cadence among the three) show different quasi/a-periodic variations on timescales of several days, which is consistent with the ASAS-SN data.
- Due to the high variability and quasi-periodic nature of J161201’s photometry, it was decided to de-trend TESS light curves before searching for an orbital period.
- Since J161201 is a novalike CV (as comes from SALT data), one expects the orbital period to be found on a level of several hours. Therefore, by using Savitzky-Golay filter (Savitzky and Golay, 1964, Schafer, 2011) all quasi/a-periodic signals above 1 day level were captured and then de-trended from the original light curve (see left panel of Fig. 26).

- Each de-trended TESS light curve (2019, 2021, 2023) shows the same stable peak in its periodogram around 4.8 hours (see the combined Lomb-Scargle periodogram on the right panel of Fig. 26). This provides strong evidence that the orbital period of J161201 is indeed 4.8 hours.

Implementations and future studies

The MWL investigation of the two XRB candidates underscores the complexity of identifying faint X-ray sources amid a dominant background of other type objects. X-ray observations with *eROSITA* and *XMM-Newton* provided key spectral and timing insights, yet they did not alone yield a definitive classification for the sources. Crucially, optical spectroscopy from LAMOST and SALT enabled a more precise characterization, with LAMOST data indicating that J061331 is an active M-type subgiant and SALT spectra confirming that J161201 is a novalike CV. In addition, extensive optical variability studies using ZTF, ASAS-SN, and TESS revealed a robust 7.189-day periodic modulation in J061331 — likely linked to stellar rotation — and a tentative 4.8-hour orbital period for J161201. These findings emphasise that while X-ray data offer essential initial clues, it is the subsequent optical and infrared follow-ups that are vital for resolving ambiguities in source classification.

The initial selection of J061331 and J161201 as XRB candidates was based on their relatively high X-ray flux as estimated from eRASS1 using an early version of the *eROSITA* processing pipeline. Subsequent analyses — including *XMM-Newton* observations and reprocessing with the updated *eROSITA* pipeline (eRASS1, c020) — revealed that both sources now exhibit much lower fluxes, such that they would not currently qualify as likely XRB candidates using eRASS1 data alone. This outcome highlights the opportunity to refine the classification pipeline further, particularly by incorporating data from eRASS1-4. Moreover, considering that two other XRB candidates identified using *eROSITA* data have ultimately been confirmed as XRBs, the simplified selection criteria applied to eRASS1 data have already proven effective, and efforts are underway to develop an improved identification pipeline, with a final catalogue to be released alongside the first public data set (Paper III).

In turn, the identification of J161201 as a novalike CV marks only the second instance of such a system uncovered by *eROSITA*, following SRGt 062340.2–265751 (Schwope et al., 2022). This milestone underscores *eROSITA*’s expanding role in revealing more CVs of different subclasses. In particular, pairing *eROSITA*’s X-ray surveys with large-scale spectroscopic follow-up programs — such as *eROSITA*/SDSS (Kollmeier et al., 2017) — will continue to advance the Galactic census of accreting binaries. By contributing new discoveries, *eROSITA*-driven identifications offer valuable insight into the broader evolutionary paths and diversity of CVs in the Milky Way.

7.4 Thermal disc winds and their role in LMXB outbursts

Paper V investigates the role of thermal winds in shaping the evolution of X-ray outbursts in LMXB systems. By incorporating wind-driven mass loss into the standard viscous disc evolution framework (see Sect. 3.2), the study explores how thermal winds modify the accretion rate evolution, disc structure, and affect the inferred viscosity parameter (α). The work builds upon previous theoretical models (Begelman et al., 1983, Shields et al., 1986, Woods et al., 1996) and observational studies (Done et al., 2018, Tetarenko et al., 2018b), aiming to resolve discrepancies between inferred and simulated α -values.

Using an updated version of the FREDDI code¹⁸, the study modelled outbursts with and without wind, systematically varying parameters such as the peak accretion rate ($\dot{M}_{\text{acc},0}$), turbulent viscosity (α), disc self-irradiation parameter (C_{irr}), etc. In addition to simulating various outburst scenarios and disc evolution, the code was employed to fit the 2002 outburst of the BH LMXB 4U 1543–47. To achieve this, observational X-ray data from RXTE/PCA (see Sect. 5.4) were employed, enabling the model predictions to be compared with actual LMXB behaviour. Subsequently, optical light curves in the V and J bands were incorporated to further constrain the irradiation parameters. This combined observational approach enables a detailed comparison between theoretical predictions and real LMXB behaviour, shedding light on the role of thermal winds in the transient evolution of these systems.

Thermal Wind Model and Its Implementation

To properly incorporate wind-driven mass loss into LMXB outburst simulations, the study modifies the standard viscous evolution equation by introducing an additional wind-loss term. The modelling approach consists of:

- **Wind mass-loss prescription:** Based on Compton-heated wind models, the mass-loss rate depends mainly on the Compton temperature (T_{IC}), the mass of a BH and ionization parameter (Ξ). Therefore, spectral modellings were performed in order to find the exact value of those parameters.
- **Time-dependent accretion disc evolution:** Simulations performed track the evolution of the central accretion rate ($\dot{M}_{\text{acc}}$), hot disc radius (R_{hot}), and wind-to-accretion mass-loss ratio ($C_{\text{w}} = \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$), and other disc parameters under different wind strengths.
- **Revised viscosity estimates:** Since mass loss due to winds removes angular momentum, α -values inferred from standard disc models may be overestimated. The study quantifies this correction for different wind efficiencies.
- **Checking for the solution’s stability:** The stability of the numerical method was tested with a new wind-related function. I employed an implicit finite-difference scheme to ensure robust time integration. The stability tests were carried out by comparing the numerical results with analytical benchmarks and by verifying that the solutions remain consistent across different time steps and spatial grid resolutions. In the end, the solution was found to be stable within physically justified wind parameters.

Simulations are conducted for different set of disc and system parameters. In turn, 4U 1543–47 outburst fitting was performed by varying viscosity α and irradiation C_{irr} parameters to determine their impact on outburst evolution. Moreover, different types of initial/boundary conditions and wind models were implemented in both cases to test the work of the method and the resulting code.

Key results and findings of simulations

To investigate the impact of the thermal disc wind, outbursts of two peak accretion rate scenarios were simulated: $\dot{M}_{\text{acc},0} = \dot{M}_{\text{Edd}}$ and $\dot{M}_{\text{acc},0} = 0.1 \times \dot{M}_{\text{Edd}}$, where $\dot{M}_{\text{Edd}} =$

¹⁸<https://github.com/hombit/freddi>

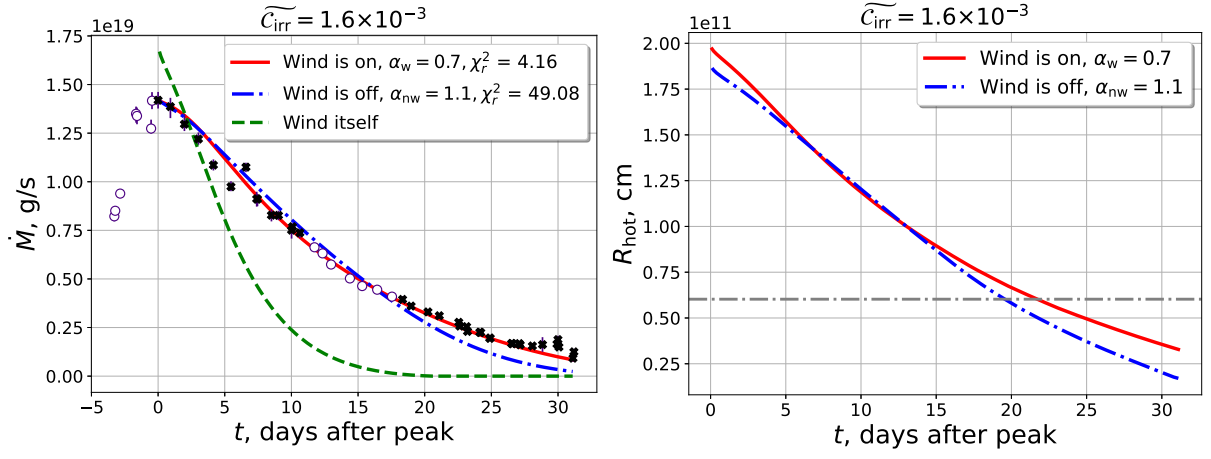


Figure 27: *Left panel:* Central accretion rate evolution $\dot{M}_{\text{acc}}(t)$ during the 4U 1543–47 outburst (2002). Empty circles are excluded from the fitting due to them not being a part of the decay. The ‘Wind itself’ curve shows the rate of the mass-loss in the thermal wind ($\dot{M}_{\text{wind}}(t)$). *Right panel:* Modelled evolution of hot zone radius during the 2002 outburst of 4U 1543–47. Grey dash-dotted line represents wind launching radius $0.1 R_{\text{IC}}$. Both figures are taken from Paper V.

$1.4 \times 10^{18} (M_{\text{x}}/M_{\odot})$ g/s for a compact object with mass $M_{\text{x}} = 10 M_{\odot}$. In addition, variations in the turbulent viscosity parameter α and the disc’s self-irradiation coefficient C_{irr} were explored. The Compton temperature is fixed at $T_{\text{IC}} = 10^8$ K, and the parameter Ξ is set to 7.53, as determined from heating and cooling process simulations (Higginbottom et al., 2017). The results are as follows:

- **Winds shorten outburst duration and accelerate decay**

- The presence of a thermal wind causes the accretion rate to decline more rapidly than in wind-free models.
- The effect is more pronounced for higher peak accretion rates, where stronger irradiation leads to greater mass loss.
- The hot, ionized region of the disc (R_{hot}) remains larger in high- $\dot{M}_{\text{acc}}$ models, enhancing wind-driven outflows.

- **Mass-loss efficiency quantified by wind-to-accretion ratio**

- The study tracks the evolution of $C_{\text{w}} = \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$ to assess the fraction of disc material lost to winds. The mass-loss rate via wind increases at higher values self-irradiation parameter and doesn’t really depend on α .
- The results indicate that for strong winds, C_{w} can reach values close to unity, meaning nearly as much mass is lost via thermal wind as is accreted. And the ratio is higher for higher accretion rates.
- This highlights the importance of outflows in regulating accretion efficiency and LMXB evolution.

- **Correction to the viscosity parameter**

- The inferred α -values from standard light-curve fitting are systematically over-estimated when the presence of disc winds is ignored.

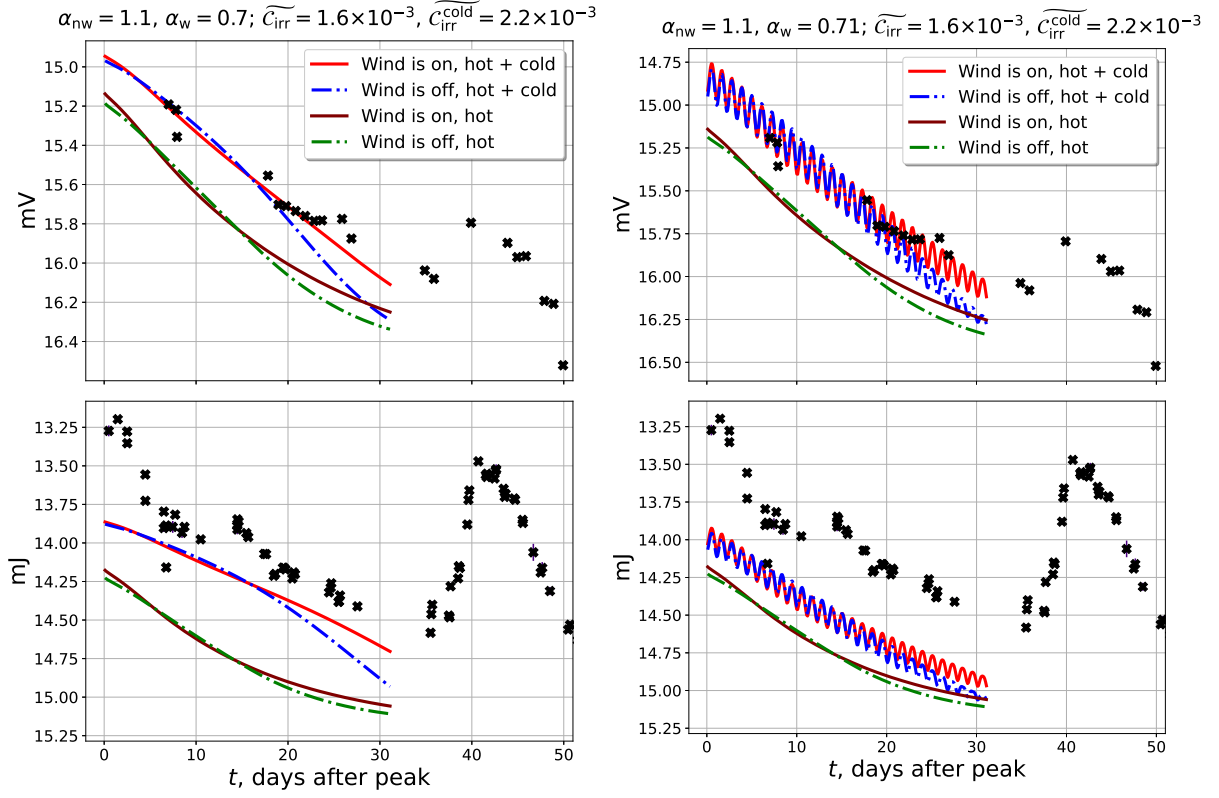


Figure 28: *Left panel:* Observed and modelled optical/IR light curves in V and J bands during the 2002 outburst of 4U 1543–47. The model consist of two parts: hot and cold impact coming from the accretion disc. *Right panel:* Similar modelled light curves but the cold component here is the irradiated by X-rays donor star. Both figures are taken from Paper V.

- The study quantifies this correction using the ratio α_{nw}/α_w (wind-free vs. wind-included models), showing that α can be overestimated by a factor of 1.5–10 depending on wind’s efficiency.
- The impact of winds depends on the outer radius of the accretion disc: larger discs allow winds to remove more mass, but beyond a certain size, wind efficiency saturates.
- The degeneracy between α and η_{wind} can be resolved by examining the overall shape of the outburst decay curve.

The case study: 4U 1543–47 (2002 outburst)

To demonstrate the impact of the wind in a real transient LMXB outburst, the evolution of both the central accretion rate and the optical flux during the 2002 outburst of the X-ray nova 4U 1543–47 was modelled. The results include:

- **Better fit to the observed X-ray light curve:** The decline of $\dot{M}_{acc}$ is used to fit observational data from the 2002 outburst of 4U 1543–47, showing that the inclusion of the wind component leads to a better match with the observed light curve (see Fig. 27).

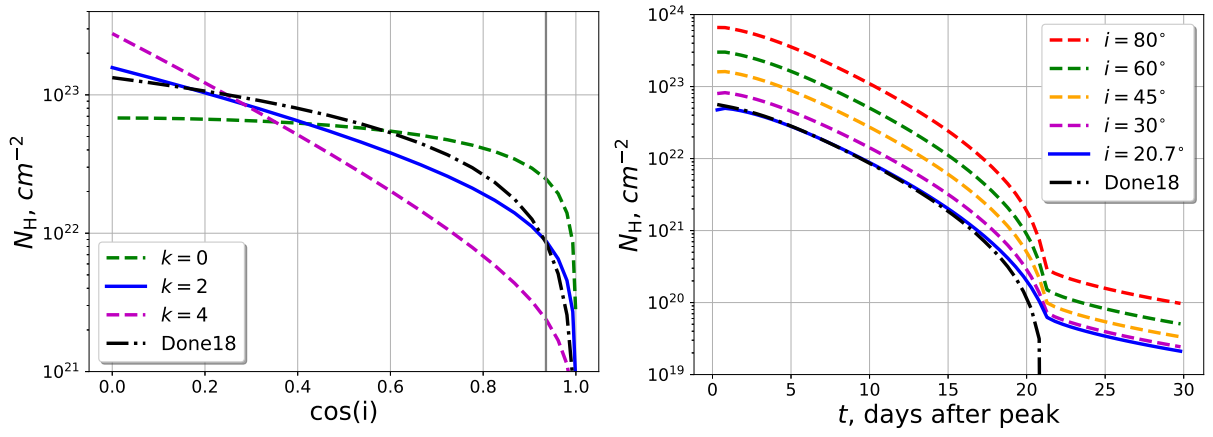


Figure 29: *Left panel:* Column density at the 10th day of an outburst as a function of the binary inclination for different values of the damping coefficient k in the wind density distribution. The black dash-dotted line shows the dependence calculated following Done et al. (2018), while the grey line marks the adopted inclination of 4U 1543–47 (20.7°). *Right panel:* Evolution of column density N_{H} over time after the peak of the 2002 outburst of 4U 1543–47, shown for $k = 2$. The black dash-dotted line represents the calculation from Done et al. (2018) for $i = 20.7^\circ$.

- **Winds shut down after ~ 21 days:** As the outburst decays, the hot zone shrinks. The hot disc radius R_{hot} falls below the wind-launching threshold, naturally ending the wind phase (Fig. 27, right panel).
- **Optical light curve constraints on irradiation:** The modelled optical/IR light curves in the V and J bands were compared with observations to constrain the disc’s irradiation properties. The analysis revealed that the emission from the hot disc alone cannot fully account for the observed optical flux. Including contributions from either the cold outer disc or the irradiated donor star improves the agreement with the data (see Fig. 28). However, a residual excess in the J band suggests additional emission components, possibly from a jet.
- **Evolution of hydrogen column density:** The study tracks the evolution of $N_{\text{H}}(t)$, showing that wind material initially contributes significantly to absorption but rapidly disperses after the wind shuts down. Figure 29 illustrates how N_{H} varies with the binary inclination and time. Notably, N_{H} drops more rapidly than the accretion rate, reflecting the fast dispersion of wind material once the wind shuts down.

Implications and Future Work

The analysis of simulated light curves and spectral properties demonstrates the significant role of thermal winds in shaping the evolution of outbursts in LMXBs. The inclusion of a wind component in disc evolution models leads to a more rapid decline in the central accretion rate, effectively shortening the outburst duration. This effect is particularly pronounced in high-luminosity outbursts, where irradiation-driven mass loss is more efficient. As the hot zone in the accretion disc contracts, the wind-launching region gradually disappears, leading to the natural termination of the outflow approximately 21 days after the outburst peak in the case of 4U 1543–47. The findings suggest that wind activity is

closely linked to the extent of the ionized region in the disc, reinforcing the necessity of considering wind dynamics when interpreting XRB light curves.

A key outcome of this study is the revision of the turbulent viscosity parameter α when wind effects are taken into account. Observational estimates of α have traditionally ranged from 0.2 to 1, significantly exceeding the values predicted by magneto-hydrodynamic simulations, which typically suggest $\alpha \lesssim 0.1$. The results indicate that ignoring thermal wind effects leads to an overestimation of α by a factor of up to four. This finding provides a possible resolution to the long-standing discrepancy between observationally inferred and theoretically predicted viscosity values. Since the wind efficiently removes mass and angular momentum from the disc, it mimics the behaviour of a system with higher viscosity in wind-free models, fundamentally altering the interpretation of LMXB outburst evolution.

The efficiency of the thermal wind, parametrized by η_{wind} , is identified as a crucial factor in determining both the rate of outburst decay and the correction required for α . Models with $\eta_{\text{wind}} \sim 1$, corresponding to the standard wind prescription, yield the best fit to the observed light curve of 4U 1543–47. Furthermore, the influence of the wind is strongly regulated by the size of the hot disc, which is initially governed by irradiation. Once cooling processes limit the hot zone, the wind efficiency saturates, restricting further mass-loss impact. The evolution of the wind column density N_{H} and the ionization parameter ξ offers a key observational signature of this process. As the outburst decays, N_{H} declines more rapidly than the accretion rate, indicating that wind material disperses quickly once the wind ceases. This trend suggests that absorption features associated with the wind should be most prominent in high-inclination systems during the early phases of an outburst, before the wind shuts down and the ionized material disperses.

These findings emphasize the necessity of incorporating wind-driven mass loss into standard disc evolution models to obtain accurate physical parameter estimates in LMXBs. Future high-resolution X-ray spectroscopic observations will provide crucial insights into wind-driven angular momentum removal, particularly in systems where outflows persist throughout the outburst cycle. Additionally, understanding the role of winds in modifying accretion processes has broader implications for the long-term evolution of XRBs, including their transition into compact object mergers. By refining wind models and integrating them with observational constraints, ongoing and future studies will enhance the understanding of the interplay between accretion, mass loss, and disc instability in these systems. This research lays the foundation for improved theoretical frameworks that will be vital for interpreting current and upcoming observational data from next-generation X-ray missions.

8 Future research

The outline presented in the above chapters only gives a broad key overview of the concept studied in detail by the authors in the Papers I–V forming the bulk of my cumulative thesis as described in the next sections after bibliography list. Future studies will aim to construct the most detailed view of the Galactic XRB population possible today. Considering the enormous amount of manual work done to create catalogues of known HMXBs and LMXBs presented in Papers I and II, their results provide an ideal basis for future population studies and the analysis of peculiar and/or candidate XRBs highlighted within.

Along with the candidate catalogues of XRBs found in eRASS DR1 and presented in Paper III, they will serve as a foundational resource for placing necessary constraints on the X-ray luminosity function (XLF). This will, in the future, allow to track specific characteristics and modes occurring in XRBs, as well as studying accretion physics at both low and high states. Additionally, it will provide insights into the spatial distribution of XRBs within the Milky Way, offering a deeper understanding of their evolutionary processes and contributions to the Galactic X-ray emission.

Machine learning methods, particularly RF algorithms described and used in Paper III on eRASS1 to specifically find XRBs, can play a crucial role in classifying X-ray sources in other surveys. This is particularly important in the context of the next upcoming eROSITA data releases (eRASS1–4, eRASS:4), as well as considering the numerous unidentified sources in *XMM-Newton* and *Chandra*. There is also room for improvement in relation to the ML methods used, as partly already discussed in the Paper IV. One major consideration is the long-term X-ray variability of sources in eROSITA. While this was impossible to accomplish with data from eRASS DR1, the publication of eRASS1–4 will enhance classification results. Additional eRASS:4 catalogues will also provide four times more exposure, thus expanding the potential XRB candidate catalogue list.

Finally, the physics of accretion disc winds could be better understood, as demonstrated in Paper V. Obtained results indicate that additional mechanisms of mass and angular momentum transfer in the accretion disc should be considered to understand the behaviour of transient XRBs. However, the paper clearly shows that in some cases, thermal wind alone is probably not powerful enough to explain the fast evolution of some X-ray nova outbursts, suggesting that other types of winds should be additionally considered. This will be of great importance in future studies analysing the outburst nature of XRBs.

In summary, the future work outlined here aims to significantly advance our understanding of the Galactic XRB population. By leveraging MWL data, advanced ML methods, high-precision astrometric information, and better theoretical understanding, substantial contributions to the field of X-ray astronomy are anticipated. The results of these efforts will enhance our knowledge of XRBs, provide valuable insights into the broader population of high-energy astrophysical sources, and refine our understanding of their roles in Galaxy evolution.

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Appendix A: Original Publications

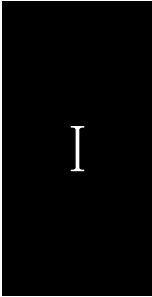
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Paper I

A. Avakyan, M. Neumann, A. Zainab,
V. Doroshenko, J. Wilms, A. Santangelo
"XRBcats: Galactic Low-Mass X-ray binary catalogue"

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XRBcats: Galactic low-mass X-ray binary catalogue^{*}

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ABSTRACT

We present a new catalogue of low-mass X-ray binaries (LMXBs) in the Galaxy. The catalogue contains source names, coordinates, source types, fluxes, distances, system parameters, and other characteristic properties of 349 LMXBs, including systems that have been newly discovered or reclassified since the most recently reported LMXB catalogues. The aim of this catalogue is to provide a list of all currently known Galactic objects identified as LMXBs with some basic information on each system (including X-ray and optical/IR properties where possible). Literature published before May 2023 has been taken into account where possible when compiling this information. References for all reported properties as well as object-finding charts in several energy bands are provided as part of the catalogue. We plan to update the catalogue regularly, in particular to reflect new objects discovered in the ongoing large-scale surveys such as *Gaia* and eROSITA.

Key words. catalogues – binaries: close – stars: late-type – X-rays: binaries

1. Introduction

X-ray binaries (XRBs) are among the brightest objects in the sky in the X-rays. They represent the endpoints of the stellar evolution of massive stars. Understanding the physical processes defining the observational appearance of individual objects and the properties of the XRB population as a whole is therefore essential for understanding massive star evolution and the evolution of the Galaxy in general. To this end, it is important to maintain an up-to-date census of known XRBs and their properties, especially in the era of the current generation of large-scale surveys such as the extended ROentgen Survey Imaging Telescope Array (eROSITA, Merloni et al. 2012; Predehl et al. 2021) on board SRG, *Gaia* (Gaia Collaboration 2016, 2023) and the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010; Cutri et al. 2021), which are able to unveil ever fainter objects.

However, the identification of XRBs among millions of other objects requires up-to-date knowledge of the properties and locations of already known sources, and the large-scale surveys mentioned above are providing vast amounts of new observational data for these objects. The compilation of such an updated database is the primary goal of this work, although many other uses can of course also be envisaged.

The main source of high-energy radiation in XRBs is the accretion of matter onto either a neutron star (NS) or a black hole (BH) from a companion star. The observed properties of XRBs are largely defined by the mass-transfer mechanism powering the accretion, which can occur either directly from the wind of a

secondary or via Roche lobe overflow (RLOF), which primarily depends on the mass ratio between the compact object and the optical counterpart (M_x/M_{opt}). Based on this ratio, XRBs are subdivided into two large groups: high- and low-mass X-ray binaries (HMXBs and LMXBs, respectively). For objects with $M_x > M_{\text{opt}}$; $M_{\text{opt}} \lesssim 1 M_{\odot}$, the mass is usually transferred to the compact object via RLOF. Such objects are classified as LMXBs. Those with $M_x < M_{\text{opt}}$; $M_{\text{opt}} \gtrsim 5 M_{\odot}$ typically accrete directly from the stellar wind and are classified as HMXBs. The rather dramatic differences in the observed properties of LMXBs and HMXBs warrant the treatment of each subclass separately. Here, we focus on the properties of LMXBs. In turn, updated catalogues of HMXBs are presented by Neumann et al. (2023) and Fortin et al. (2023)^{1,2}.

As follows from the definition of an LMXB, the donor is (in most cases) a late-spectral-type star filling its Roche lobe. However, A-type stars, F-G-type subgiants, or even white dwarfs (WDs) can also act as donors in LMXBs. The optical properties of LMXBs can also be affected by emission from the accretion disc around the compact object, where the disc can be heated by itself or illuminated by X-ray emission from the compact object. Nevertheless, LMXBs are generally intrinsically faint objects in the optical and IR bands. The main way to analyse features of known LMXBs in detail or to detect new ones is to observe them during outbursts (Lasota 2016). New sources continue to be discovered in this way, and the population of known LMXBs is ever growing.

The latest catalogue of Galactic LMXBs, which was published by Liu et al. (2007), is now nearly 16 years old. Since that time, many new transient and persistent objects have been discovered. Some LMXB candidates have been reclassified, while

^{*} The catalogue is available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/675/A199>, and the catalogue table, along with the corresponding finding charts and other useful information is also publicly accessible at <http://astro.uni-tuebingen.de/~xrbcat>

¹ <https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=J/A+A/671/A149>

² <https://binary-revolution.github.io/HMXBwebcat>

other sources have gained LMXB status. Moreover, missions such as the X-ray Multi-Mirror Mission (*XMM-Newton*, Jansen et al. 2001), the INTERNATIONAL Gamma-Ray Astrophysics Laboratory (INTEGRAL, Winkler et al. 1993), and *Gaia* have resulted in a quantitative and qualitative improvement in our knowledge of XRB properties. In this context, we have compiled a revised catalogue of the Galactic LMXBs that incorporates multi-wavelength information and encompasses the inclusion of new sources identified since the publications of Liu et al. (2007) and Ritter & Kolb (2003; Liu07 and RK03 hereinafter). Our final catalogue contains 349 LMXBs and candidates, of which 204 were contained in the two catalogues mentioned above (the content of Liu07 and RK03 overlaps but neither includes the other completely). That is, the new catalogue presented here represents a more than 71% increase in volume with respect to the two most extensive catalogues of the past. We aim to compile a comprehensive and up-to-date database containing information such as optical/IR magnitudes, X-ray fluxes, distances, and so on, for the current catalogue, which will hopefully help to facilitate the identification of new LMXBs in current and future X-ray surveys, as well as population studies.

The structure of the paper is as follows: in Sect. 2, we describe how the LMXB sample was compiled and list data sources used to provide extra information on known objects. In the same section, we list relevant X-ray and optical properties, and characterise methods used for identification of known and candidate optical/IR counterparts in large-scale surveys. In Sect. 3, a description of the table fields and finding charts is provided, as well as a comparison of our catalogue with works of RK03 and Liu07. Finally, we summarise our results in Sect. 4. One can also find a list of identified archive optical/IR counterparts for some LMXBs based on the literature in Appendix A. A description of the columns of the catalogue table is presented in Appendix B.

2. Definition of the sample and data sources

The bulk of the objects in the catalogue consists of LMXBs reported by the catalogues of RK03 and Liu07, and so we started our compilation of the sample by merging these two catalogues. During this process, a number of duplicate objects both within and across the two catalogues were identified and removed from the sample. In addition, several sources in RK03 and Liu07 were found to be extragalactic (in some cases, this possibility was already indicated in the original catalogues and sometimes reported in the literature afterwards). Such objects were also excluded from our final list. The same applies to the satellite galaxies of the Milky Way. To this end, the two LMXBs known to be located in the Large Magellanic Cloud (LMC), namely, LMC X-2 and RX J0532.7–6926 (which were included in both RK03 and Liu07) are not listed in our catalogue. All objects that were removed, as well as other problematic cases, are listed and described in detail in Sect. 3.2.

In addition to Liu07 and RK03, we also considered all Galactic objects classified as possible LMXBs in the SIMBAD³ and VizieR⁴ databases hosted by the Centre de Données astronomiques de Strasbourg (CDS) databases. We include these objects in the catalogue, giving appropriate references for classification. We conducted a thorough literature search (including Astronomer’s Telegrams⁵) to identify any newly discovered

LMXBs. Most of the new LMXBs reported in the literature between 2006 and 2020 were discovered by the INTEGRAL (Winkler et al. 2003), MAXI (Matsuoka et al. 2009), *Swift* (Gehrels et al. 2004), or *Gaia* (Gaia Collaboration 2016) missions, as summarised by Bahramian & Degenaar (2023). The latter publication can therefore also be considered as another major data source used in this work. In addition, the catalogue of Galactic LMXBs detected by INTEGRAL (Sazonov et al. 2020) also proved to be a valuable resource for expanding our list of LMXBs. Finally, we used the recently published catalogue of ultracompact X-ray binaries (UCXBs) made by Armas Padilla et al. (2023)⁶ to cross-check the completeness of our sample in the context of UCXBs (no missing sources were found). It should be noted that although efforts have been made to find all LMXBs identified to date, it is possible that some may have been missed. Therefore, we kindly ask readers to report any omissions found, so that those can be included in updated versions of the catalogue.

We note that systems in which a WD acts as an accretor are not generally considered as XRBs for historical reasons (despite the fact that they also emit in the X-ray band), and so those systems (namely cataclysmic variables or CVs) are not included in the current catalogue. We also do not include rotation-powered pulsars, even if they are members of binary systems and emit in X-rays, unless the observed emission is accretion powered; that is, ‘spider’-type pulsars including Black Widows (BW) and Redbacks (RBs; see e.g. Chen et al. 2013; Roberts 2013) are omitted unless they are also classified as transitional millisecond pulsars (tMSP; see e.g. Archibald et al. 2009; Papitto et al. 2013; Knight et al. 2023). All tMSPs and their candidates included in the catalogue are listed in Table 1 in Sect. 3.2.

The mass ranges quoted in Sect. 1 for XRBs are of course approximate, and there are some boundary cases, such as Her X-1, where accretion to a NS occurs via the RLOF of a B3 type $\sim 2.2 M_{\odot}$ donor (Tananbaum et al. 1972; Middleditch & Nelson 1976). This system is most often classified in the literature as an intermediate mass X-ray binary (IMXB) rather than as an LMXB because the NS appears as an X-ray pulsar and is therefore strongly magnetised, which is not typical for NS LMXBs. As the total number of IMXBs is relatively small, and despite the additional fact that they ‘bridge’ the HMXB and LMXB classes, they are evolutionarily closer to LMXBs as binary systems, and so we opt to include them as a part of the current LMXB catalogue. This decision is also clearly communicated in the publication describing the HMXB catalogue released in parallel to the current work (Neumann et al. 2023) in order to avoid any confusion or source duplication, except for one specific case (Cir X-1), which is described in Sect. 3.2.

2.1. Main properties and features

In order to reflect the huge variety of LMXB properties, we incorporate all accessible and relevant information concerning the donor star and compact object, including data on their properties, variability, and other pertinent details. Besides the quantitative properties (such as positions, fluxes in various bands, orbital or spin periods, and so on), some of these properties or features can be incorporated as a set of flags defined to characterise several LMXB subclasses, as was already done by Liu07 and RK03. Here, we extend the classification adopted by these authors to account for extra features added to the current catalogue. In order

³ <http://simbad.cds.unistra.fr/simbad>

⁴ <https://vizier.cds.unistra.fr/viz-bin/VizieR>

⁵ <https://astronomerstelegram.org>

⁶ <https://research.iac.es/proyecto/compactos/UltraCompCAT>

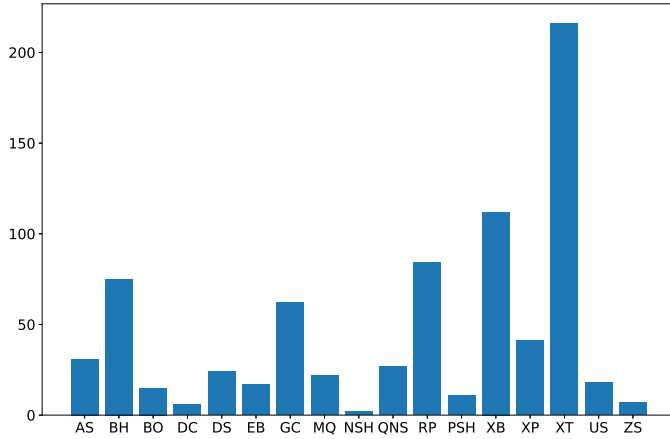


Fig. 1. Population of LMXBs of each type in the Galaxy.

to provide a broad overview of the Galactic LMXB properties, we also show the frequency of the occurrence of the individual type flags in graphical format in Fig. 1. It is important to note that these flags are not intended to serve as a basis for systematic classification, but rather to reflect the characteristics of individual systems to ease the selection of objects exhibiting specific observational features. Each source in the catalogue may therefore have one or more of the following flags, which are listed alphabetically:

1. AS: Atoll X-ray binary hosting a weakly magnetised NS as a main component. The spectrum is soft and no significant pulsations are present. The majority of the points on the colour–colour diagrams (‘hard’ versus ‘soft’) from atoll sources usually form a band at constant hard colour.
2. BH: System contains a black hole candidate.
3. BO: X-ray burster (see XB definition below) with coherent burst oscillations at the NS spin period.
4. DC: System with an accretion disc corona.
5. DS: ‘Dipping’ source. System shows periodic but irregular dips in the X-ray intensity, which are generally connected with the partial obscuration of the NS by a thickened region of the accretion disc.
6. EB: Eclipsing or partially eclipsing binary system.
7. GC: Source within a globular cluster.
8. MQ: Microquasar, a source with reported evidence for relativistic jets.
9. NSH: Negative (nodal) superhumps are present in the system. These negative superhumps are periodic optical signals, the periods of which are smaller than the orbital period of the binary.
10. QNS: Quiescent NS.
11. RP: Compact object acts as a radio pulsar.
12. PSH: Positive superhumps (permanent or transient) present in the system. The same as the NSH type (see above), but the time period of the signal is larger than the orbital one.
13. XB: X-ray burst source. This type collects X-ray binary systems with a NS, which exhibit thermonuclear (type-I) X-ray bursts.
14. XP: Compact object in the binary acts as an X-ray pulsar.
15. XT: Transient X-ray source. System shows dramatic changes in luminosity (mostly in the X-ray band). Energy is produced by means of a non-stationary accretion process.
16. US: Ultrasoft X-ray spectrum. In some catalogues, this type is denoted ‘super soft’. These binaries also include some ‘extreme ultrasoft’ (EUS) sources.

17. ZS: Z-type source. This type of X-ray binary is similar to the atoll type (also contains weakly magnetised NS), but the plot on the colour–colour diagram is different (Z-letter shape).

We note that the ‘XB’ (X-ray burster) flag – originally introduced by RK03 – in our catalogue specifically refers to thermonuclear (type-I) bursts only. Type-II X-ray bursts likely caused by instabilities in the accretion flow are relatively rare, and to the best of our knowledge have only been detected from two LMXBs: MXB 1730–335 (‘rapid burster’; [Bagnoli et al. 2015](#)) and GRO J1744–28 (‘bursting pulsar’; [Court et al. 2018](#)), and one HMXB: SMC X–1 ([Rai et al. 2018](#)), and are therefore not flagged separately. The MXB 1730–335 is known to exhibit bursts of both types, and is therefore still flagged. On the other hand, type-I bursts have been suggested to be present but have never been unambiguously detected from the bursting pulsar ([Giles et al. 1996](#); [Lamb et al. 1996](#); [Doroshenko et al. 2015](#)), and so this source is not flagged.

2.2. X-ray properties

Considering that X-ray emission dominates the bolometric luminosity of XRBs, one of their main characteristics is their X-ray flux and spectrum. In our catalogue, we therefore tried to compile information on X-ray fluxes in soft and hard X-ray bands for all LMXBs in a uniform way. For the soft X-ray band, we report fluxes observed by *XMM-Newton*⁷ ([Schartel et al. 2022](#); [Webb et al. 2020](#)), the *Chandra* X-ray Observatory⁸ (CXO, [Weisskopf et al. 2000](#); [Evans et al. 2010](#)), and *Swift*/XRT⁹ ([Burrows et al. 2005](#); [Evans et al. 2020](#)) throughout their lifetime. In particular, we report the 0.2–12 keV energy band flux (equivalent to the EPIC_8 band used in *XMM-Newton* catalogues) and/or the X-ray flux in similar energy bands of CXO and *Swift*/XRT, that is, the 0.3–10 keV observed flux for *Swift*/XRT, and either the broad ACIS band (0.5–7.0 keV) or the wide HRC band (0.1–10.0 keV) for CXO. We note that although the difference in energy bands for various instruments might result in a factor of ~ 1.5 difference for a given source, here we only report the range of fluxes detected over a long period. This range is therefore dominated by intrinsic variability and differences in source spectra, and so the difference in energy range between the various instruments is not really relevant to our purposes. In the hard X-ray band, fluxes from INTEGRAL¹⁰ ([Krivonos et al. 2012](#)) and *Swift*/BAT¹¹ ([Oh et al. 2018](#); [Barthelmy 2004](#)) are reported. Here, we report fluxes in the energy range of 14–145 keV for *Swift*/BAT and in the energy range of 17–60 keV for INTEGRAL. We note that these bands are largely equivalent as the flux above 60 keV is comparatively small for most sources, and the variability argument still applies.

Another key property provided by X-ray observations is the localisation that is essential to identify or assess the reliability of the identified optical counterparts. We therefore also include information on the most accurate X-ray position available either from the literature or directly from soft (*Chandra*, *XMM-Newton*

⁷ <https://heasarc.gsfc.nasa.gov/W3Browse/xmm-newton/xmmssc.html>

⁸ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=IX/57/csc2master>

⁹ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=IX/58/2sxps>

¹⁰ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=J/A%2bA/545/A27>

¹¹ <https://heasarc.gsfc.nasa.gov/W3Browse/swift/swbat105m.html>

or *Swift*/XRT) and hard (INTEGRAL, *Swift*/BAT) catalogues as described in the following section.

2.3. Astrometry and identification of the optical counterparts

Considering that the properties of XRBs are largely defined by the properties of the donor star, the identification of the optical counterparts and the characterisation of their multi-wavelength properties are essential. Some of the LMXBs in the sample already have robustly identified optical counterparts; however, the optical positions (as well as other optical data) reported in Liu07 and RK03 are in many cases outdated, and lack accuracy by current standards. We therefore attempted to improve position accuracy using the latest astrometry data from *Gaia* DR2¹², eDR3¹³, DR3¹⁴ (Gaia Collaboration 2018, 2021, 2023), Two Micron All Sky Survey¹⁵ (2MASS, Skrutskie et al. 2006; Cutri et al. 2003b,a) and the mid-IR CatWISE2020 catalogue¹⁶ (Marocco et al. 2021).

We started the process of identifying counterparts in these catalogues by verifying whether the SIMBAD database already had any pre-existing matches with *Gaia* DR3 (eDR3, DR2), 2MASS, and/or WISE and checking their correctness manually. It should be noted that in some cases, the associations provided by SIMBAD were indeed incorrect, and we list such cases in Sect. 3.2. In cases where no SIMBAD optical/IR identifiers were provided, we attempted to find counterparts reported in the literature. In some cases where precise optical, IR, or radio coordinates were available, these coordinates were used to find the corresponding counterparts in *Gaia* DR3, 2MASS, and CatWISE2020. All solid cross-matches and relevant data were added to the catalogue. In particular, identifications by Arnason et al. (2021) proved to be useful, and so these are considered as the main references for the cases marked in Table A.1. This table lists all sources for which optical/IR counterparts are available, except those correctly listed in SIMBAD.

As mentioned above, some LMXBs have been classified as such only based on their X-ray properties, and have no uniquely identified optical counterparts in the literature. In most cases, these are relatively poorly studied sources (sometimes only detected once with X-ray monitors during an outburst). However, in some cases, accurate X-ray positions obtained at a later time are available. For those objects, we used CXO, *XMM-Newton*, or *Swift*/XRT positions (in order of preference). The search radius was set to match the full positional uncertainty (i.e. statistical plus systematic) reported in the respective X-ray catalogue. The final identification of plausible optical counterparts was done manually by inspection of the finding charts also released as part of the current catalogues and by searching for tentative counterparts in the literature based on their properties. In all cases where it was possible to identify a plausible counterpart, we list it as such; however, the optical position is only assigned as primary if a unique counterpart is identified.

2.4. Additional information

For all optical counterparts identified as described above, we include information on IR and/or optical magnitudes wherever possible. In particular, we include *Gaia* *G*-band or *V*-band magnitudes in the optical band, near-IR photometry either from 2MASS or Visible and Infrared Survey Telescope for Astronomy (VISTA, Emerson et al. 2006; Dalton et al. 2006) Variables in the Via Lactea (VVV) DR4 catalogue (VVV¹⁷, Minniti et al. 2010) surveys, or from the literature. Finally, we also include magnitudes in the W1 and W2 bands reported in the CatWISE2020, AllWISE, or WISE (in that order of preference) catalogues (Marocco et al. 2021; Cutri et al. 2021; Wright et al. 2010). In all cases, we provide the references to the sources where the *V*-band, *G*-band, JHK, and WISE magnitudes were taken from and show them in ‘Vmag_Ref’, ‘Gmag_Ref’, ‘JHK_Ref’, and ‘WISE_Ref’ columns, respectively. It should be noted that we mainly tried to include the optical/IR magnitudes during the quiescent state of the corresponding binary (to represent the LMXB population in the state in which it is found most of the time). However, in some cases, ‘quiescent’ magnitudes were not available, and so we list magnitudes during the outburst, if any.

Besides more accurate positions and photometry, we also include some additional information unavailable at the time of publication of Liu07 and RK03. For all LMXBs for which a *Gaia* counterpart was ultimately identified, we provide distance estimates from *Gaia* DR3, those based on *Gaia* eDR3¹⁸ (Bailer-Jones et al. 2021) or *Gaia* DR2¹⁹ (Bailer-Jones et al. 2018), and estimations from StarHorse1^{20/21} (Anders et al. 2019, 2022). In addition, we manually searched the literature for any distance estimations, especially in cases where *Gaia*/StarHorse data were unavailable.

We were also interested in the spectral type of the optical counterpart, and we therefore attempted to include this information based on either *Gaia* DR3, SIMBAD, or the literature search. We note that the list of X-ray pulsars maintained by Mauro Orlandini²² was found to be a useful resource in this regard (and also for reported spin and orbital periods) and we would like to acknowledge it here. For sources where the reported spectral type and corresponding reference were published before 2007, the spectral information in RK03 or Liu07 was used.

Finally, for convenience, we also provide the X-ray absorption neutral hydrogen column density (N_{H}) estimates, which might be relevant to estimate some additional LMXB properties such as X-ray to optical luminosity ratios in order to facilitate searches for new LMXBs with similar properties. We report values based either on *Swift*/XRT data (Evans et al. 2020) or on results reported in the literature (all references are listed). In cases where one of the two (N_{H} or A_{G}) was unknown, we calculated the other one through the $N_{\text{H}}(A_{\text{G}})$ relation reported by Foight et al. (2016).

¹² <https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=I/345>

¹³ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/350/gaiaedr3>

¹⁴ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/355>

¹⁵ <https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=II/246>

¹⁶ <https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=II/365>

¹⁷ <http://vvvsurvey.org>

¹⁸ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/352>

¹⁹ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/347>

²⁰ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/349/starhorse>

²¹ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/354/starhorse2021>

²² http://www.iasfbo.inaf.it/~mauro/pulsar_list.html

3. Catalogue content and quality assurance

3.1. Description of the fields

There are 349 entries in the catalogue, each of which corresponds to a single Galactic source. The objects are sorted by right ascension (the second column) in increasing order. There are a total of 62 columns listing various parameters and corresponding references. The content and format of individual columns is described in detail in Table B.1.

3.2. Finding charts and problematic cases

We provide finding charts for all sources in our catalogue, which includes up to six different images, covering bands from mid-IR to hard X-rays. Corresponding charts can be found on a dedicated website²³ or obtained via CDS system²⁴. The top row of each finding chart includes images from the VVV DR4 catalogue²⁵ (Minniti et al. 2010) or 2MASS²⁶ (left, in order of preference), an image of unWISE²⁷ (Schlafly et al. 2019; middle), and an RGB-image of either *Chandra*²⁸, *XMM-Newton*²⁹, or the Roentgensatellit (ROSAT³⁰, Truemper 1982; Boller et al. 2016; Voges et al. 1999; right, in order of preference).

The bottom row includes the soft X-ray image of *Swift*/XRT (SwiftXRTint in astroquery.skyview) in the left corner, and hard X-ray images from *Swift*/BAT³¹ and INTEGRAL³² in the middle and right corners, respectively. The field of view for VVV, 2MASS, unWISE, *XMM-Newton*, and *Chandra* images was set at 1 arcmin, while for *Swift*/XRT and ROSAT it was set at 5 arcmin and 15 arcmin, respectively. The field of view for *Swift*/BAT and INTEGRAL was chosen to be 10°, with the size of the region chosen based on the field of view and angular resolution of the given instrument.

Each panel of the finding chart includes the coordinates and uncertainties of all detected sources within the respective regions, with position uncertainties represented by error circles. A red cross indicates the position listed in SIMBAD for the source, while a dark-blue diamond represents the coordinates described in the literature (Liu07 or RK03). The position used for this catalogue is indicated with an orange star. In the case of soft X-ray instruments, observation positions are indicated by error circles to prevent overcrowding. A golden circle indicates the *Chandra* position, a red circle indicates the *XMM-Newton* position, a green circle indicates the *Swift*/XRT position, and a navy-blue circle indicates the ROSAT position. *Swift*/BAT and INTEGRAL are indicated as a deep-pink pentagon and a lime-green triangle, respectively. In the optical band, we indicate CatWISE2020 with an orange ‘X’, 2MASS with a cyan ‘+’, and *Gaia* DR3 data with a purple square. From a technical perspective, we used the Hierarchical Progressive Surveys (HiPS) data from Fernique et al. 2015, using SkyView Query only for *Swift*/XRT to obtain images. Both

services were queried using astroquery.hips2fits³³, and astroquery.skyview³⁴ modules.

As an example, the finding chart of GRO J1744–28 can be seen in Fig. 2. We also note that imaging in more bands with a catalogue overlay is available via the Aladin lite interface (Baumann et al. 2022) on the website hosting the catalogue³⁵.

Based on the literature search and inspection of the finding charts described above, we identified several problematic cases:

- The X-ray source SAX J0840.7+2248, which is classified as a LMXB in Liu07, is excluded from our catalogue. This transient is more likely to be the X-ray-rich gamma-ray burst GRB980429 rather than an XRB (Sidoli et al. 2007).
- J0732.6–1330, which is listed as a LMXB in SIMBAD, is also not presented in our catalogue due to the fact that the source is an intermediate polar (accreting magnetised white dwarf, IP; Butters et al. 2007).
- Peng & Shen (2021) find the LMXB candidate OGLE BLG511.6 25872 to be of the same polar nature. We therefore do not include it in our catalogue.
- The X-ray transient Swift J061223.0+701243(.9), listed as LMXB in Liu07, could also be an IP (Butters et al. 2011). In this case, the authors suggest that an LMXB nature cannot be ruled out, and so the source can still be found in our catalogue; however, we urge caution when considering the classification of this source.
- 2E 1613.5–5053 (listed as 1E 161348–5055.1 in Liu07 LMXB catalogue) is an X-ray source located close to the centre of the supernova remnant RCW 103. Based on XMM observations, it was discovered that the source has a 6.67 h periodicity, which may originate from either an orbital period of a LMXB or a spin period of an isolated neutron star (INS; De Luca et al. 2006). After some time of searching for an optical/IR counterpart to confirm or refute a binary nature origin, Tendulkar et al. (2017) finally reported the detection of an IR counterpart, the properties of which clearly indicate that the IR emission was coming from an INS, ruling out an LMXB origin scenario.
- V* V934 Cen, another SIMBAD LMXB, seems to possess no XRB characteristics (the corresponding link in SIMBAD for the suggested LMXB type does not provide any data regarding the source), and so it is excluded from our catalogue as well.
- The same also goes for the binary TWA 22 (TWA 22AB), which is considered to be a LMXB in the SIMBAD database. SIMBAD refers to Bonnefoy et al. (2009) as the source of the corresponding classification. However, these authors estimated the total mass of the binary to be about a 220 M_{Jup} , which is far too low for the XRB. Although the system emits X-rays via coronal activity (Stelzer et al. 2022), it cannot be classified as an XRB.
- 4U 1745–203 (H 1745–203) is a transient that was considered to be a separate LMXB, but the source appears to simply be a counterpart of SAX J1748.9–2021 (NGC 6440 CX1), which has already been noted in Liu07.
- The same goes for bursting source MXB 1742–29. Following Martí et al. (2007), we consider it to be the counterpart of LMXB 1A 1742–294.

²³ <http://astro.uni-tuebingen.de/~xrbcat>

²⁴ <https://cdsarc.cds.unistra.fr/cgi-bin/qcat?J/A+A>

²⁵ http://alasky.cds.unistra.fr/VISTA/VVV_DR4/VISTA-VVV-DR4-J

²⁶ <http://alasky.cds.unistra.fr/2MASS/J>

²⁷ <http://alasky.cds.unistra.fr/unWISE/W1>

²⁸ <https://cdfatp.cfa.harvard.edu/cxc-hips>

²⁹ <http://skies.esac.esa.int/XMM-Newton/EPIC-RGB>

³⁰ <http://alasky.cds.unistra.fr/RASS>

³¹ http://cade.irap.omp.eu/documents/Ancillary/4Aladin/BAT_14_20

³² http://cade.irap.omp.eu/documents/Ancillary/4Aladin/INTEGRAL_17_60

³³ <https://astroquery.readthedocs.io/en/latest/hips2fits/hips2fits.html>

³⁴ <https://astroquery.readthedocs.io/en/latest/skyview/skyview.html>

³⁵ <http://astro.uni-tuebingen.de/~xrbcat>

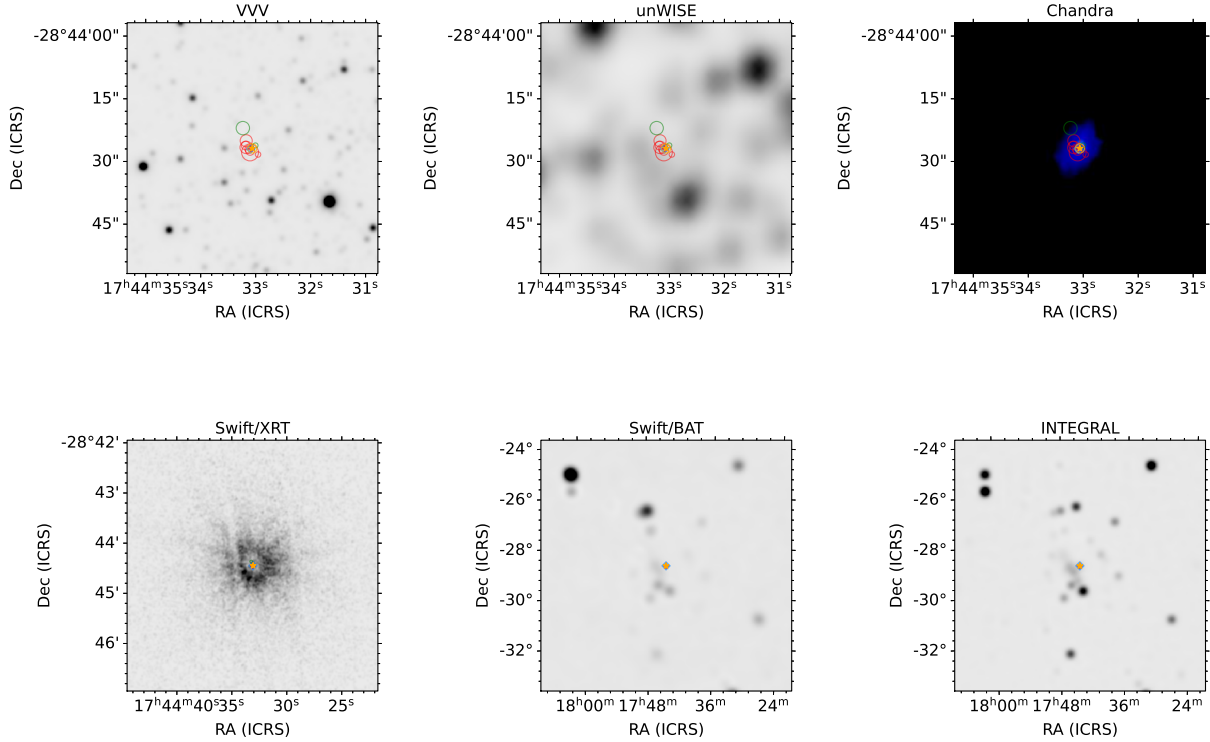


Fig. 2. Finding chart of GRO J1744–28. The finding charts display markers and error circles representing observations made by different instruments. The error circles are used for soft X-ray observations to prevent overcrowding, with a yellow circle indicating *Chandra* and a green circle representing *Swift*/XRT. The red cross and the blue diamond indicate the positions reported by SIMBAD and that found in the literature (Liu07 or RK03), respectively. An orange star denotes the position of the LMXB used in this catalogue.

- AX J1620.1–5002 is also an X-ray transient, which for a long time was considered to be a separate XRB, but it is now strongly associated with the bursting transient LMXB MAXI J1621–501 (Chenevez et al. 2018; Gorgone et al. 2018).
- 4U 0614+09 (4U 0614+091) is an UCXB with an uncertain orbital period, which is only constrained to be greater than 1 h (Baglio et al. 2014). However, following Liu07 and RK03 in the catalogue, we provide a value of 51.3 min based on Shahbaz et al. (2008).
- The nature of IGR J17404–3655 is not well constrained, because it is unclear whether the source is a LMXB or a HMXB, and is potentially a BeXRB (Coleiro et al. 2013). However, Fortin et al. (2018) used *K*-band spectroscopy for the source, and revealed that the object is more likely to be a CV with a K3–5V donor star. Consequently, we made the decision to not include it.
- CXOGBS J174623.5–310550 is an accreting binary, and is presented in our catalogue. However, its exact classification, that is, as either LMXB or CV, is still unknown (Torres et al. 2019).
- 1RXS J180431.1–273932 was at first considered a symbiotic LMXB system (Nucita et al. 2007) hosting a NS with a M5 III donor star. However, based on optical observations, Masetti et al. (2012) excluded a possible symbiotic LMXB nature and identified the source as a magnetic CV. Therefore, despite the fact that 1RXS J180431.1–273932 is listed as a symbiotic X-ray binary in Kuranov & Postnov (2015), we do not include it.
- Based on IR observations of 4U 1556–60 made by Revnivtsev et al. (2013), we associated an optical counterpart to this source, namely *Gaia* DR3 583304229928809907

- (see Table A.1), which lies well inside the position error circle of $0''.3$. However, according to the provided parallax, the distance to this source should not exceed 1 kpc (Bailer-Jones et al. 2021), which is 3–4 times less than the distance estimations to 4U 1556–60 (Christian & Swank 1997; Grimm et al. 2002). We decided to leave this association with the *Gaia* DR3 source, but this discrepancy should be borne in mind.
- For the source IGR J17597–2201, Walter et al. (2006) proposed 2MASS J17594556–2201435 as a potential counterpart. However, based on Very Large Telescope (VLT) observations conducted by Fortin et al. (2018), we can exclude this possibility.
 - The persistent X-ray-bright LMXB 4U 1624–49 seems to have incorrect coordinates and optical/IR associations in the SIMBAD database. The source was localised by *Chandra* with $0''.6$ uncertainty at the position $\alpha_{J2000.0} = 16^{\text{h}}28^{\text{m}}02^{\text{s}}.825$, $\delta_{J2000.0} = -49^{\circ}11'54''.61$ (Wachter et al. 2005), which corresponds to the known XMM source 2XMM J162802.8–491154, which is located $\approx 53''$ away from the position of 4U 1624–49 in SIMBAD. In our table, we provide the *Chandra* coordinates and uncertainty, as well as the *K*-band data obtained by Wachter et al. (2005). In the corresponding *Chandra* error circle, there are no *Gaia*, 2MASS, or CatWISE2020 sources. We also label 2XMM J162802.8–491154 as an alternative name for 4U 1624–49 due to the fact that this name is not listed as an identifier for this source in any other databases to the best of our knowledge.
 - There is also an incorrect SIMBAD association with optical/IR archives for the LMXB GX 5–1 (4U 1758–25). At the position provided by SIMBAD, there is a bright star

located ≈ 200 pc away (Gaia Collaboration 2023), a distance which is totally inconsistent with distance estimations for GX 5–1 (4.2–5.6 kpc, according to Clark 2018). Jonker et al. (2000) found an IR counterpart of the X-ray source at the position $\alpha_{J2000.0} = 18^{\text{h}}01^{\text{m}}08^{\text{s}}.222$, $\delta_{J2000.0} = -25^{\circ}04'42''.46$ with $0'.35$ uncertainty, leading to it being located $\approx 20''$ away from the position of GX 5–1 in SIMBAD. As in the case of 4U 1624–49, there are no *Gaia*, 2MASS, or CatWISE2020 counterparts. However, in the error circle, we find a VVV source, for which the JHK magnitudes are provided in the table.

- We also decided to add the object named AX J1659.0–4208 as a LMXB in our catalogue. The source was detected during the Advanced Satellite for Cosmology and Astrophysics (ASCA) Galactic plane survey (Sugizaki et al. 2001). At the time, the X-ray flux of the source was at the level of $6 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ (0.7–10 keV), but its coordinates were not well constrained. Its accurate position was then derived by *Chandra*, which led to identification of a near-IR counterpart by Revnivtsev et al. (2013). These latter authors suggested that the source is likely to be a symbiotic LMXB or a CV. However, based on high extinction towards this area, and distance estimations of about 5–10 kpc (Revnivtsev et al. 2013), unabsorbed X-ray luminosity can be estimated to be $10^{34} \text{ erg s}^{-1}$ at the very least (most likely even $10^{35} \text{ erg s}^{-1}$), which is significantly greater than expected for a typical CV. We therefore suggest that the source is very likely to be a LMXB and it is added to our catalogue table.
- We add an X-ray source IGR J19308+0530, which seems to be an IMXB hosting an NS and s F4V-type donor star (Fortin et al. 2018). At first it was not clear whether the object is a CV or a L/IMXB (Ratti et al. 2013), and even the SIMBAD database presents the source as a CV. However, based on the spectral analysis (Ratti et al. 2010) and *K*-band spectroscopy (Fortin et al. 2018), we suggest that IGR J19308+0530 is most likely not a CV but an IMXB. It should also be noted that the star TYC 486–295–1 is a counterpart of IGR J19308+0530 (Rodríguez et al. 2008; Ratti et al. 2010), but it is considered to be a separate source (also a CV type instead of XRB) by SIMBAD, $\approx 88''$ away from the INTEGRAL position for IGR J19308+0530 listed in SIMBAD.
- The source LMXB 4U 1728–34 was given an orbital period of ~ 11 min (Galloway et al. 2010), and this value is also given for the binary in RK03. However, in an analysis of other X-ray observations, no further evidence was found for a periodic signal at 11 min. Subsequently, based on an analysis of its type-I X-ray burst, Vincentelli et al. (2020) stated that the orbital period should be much higher, probably ~ 66 min or even $\gtrsim 2$ h. In our catalogue, the value of 66 min is quoted, but readers should be aware of the lack of robust confirmation.
- The X-ray source J2039–5617 (listed as [SMD2015] 3 in SIMBAD) is presented in the RK03 catalogue as a LMXB. However, due to a likely association with the known RB source 1FGL J2039.4–5621 (Salveti et al. 2015), it is excluded from our catalogue.
- XB 1832–330 is a globular cluster LMXB (in NGC 6652) that was tentatively assigned a 43.6 min orbital period (Deutsch et al. 2000). However, Engel et al. (2012) argue that the 43.6 min candidate period is probably spurious and suggest a longer period (by a factor 3) of about 2.15 h (this value is quoted in our catalogue).

Table 1. tMSP candidates presented in our catalogue.

Source name	References
1FGL J1417.7–4407 (J1417–4402 in RK03)	[1]
CXOG1b J183544.5–325939 (NGC 6652B)	[2]
4FGL J0427.8–6704	[3], [4]
4FGL J0407.7–5702	[5]
CXOG1b J174804.5–244641 (Terzan 5 CX1)	[6]
CXOU J110926.4–650224	[7], [8]
3FGL J1544.6–1125	[9], [10], [11]
4FGL J0540.0–7552	[12]
RX J1739.4–2942 (GRS 1736–297)	[13]

Notes. Along with the candidates, all three confirmed tMSPs: XSS J12270–4859, IGR J18245–2452 and PSR J1023+0038 are also included in the catalogue.

References. [1] Swihart et al. (2018), [2] Paduano et al. (2021), [3] Kennedy et al. (2020), [4] Li et al. (2020), [5] Miller et al. (2020), [6] Bahramian et al. (2018), [7] Coti Zelati et al. (2019), [8] Coti Zelati et al. (2021), [9] Bogdanov & Halpern (2015), [10] Britt et al. (2017), [11] Jaodand et al. (2021), [12] Strader et al. (2021), [13] Tetarenko et al. (2016).

- There is uncertainty over the orbital period of the tMSP candidate 4FGL J0540.0–7552. Strader et al. (2021) identified a consistent periodic signal at 2.7 h in their photometry. However, this signal could represent either the orbital period, half the orbital period (if due to ellipsoidal variations), or could even be spurious. We decided to keep the 2.7 h orbital period value in our catalogue table for this source, but other possibilities may be worth consideration.

As mentioned in Sect. 1, we decided to add all three known tMSP: XSS J12270–4859, IGR J18245–2452, and PSR J1023+0038 (all three are also listed in RK03 by the names J1227–4853, J1824–2452, and AY Sex, respectively). In addition, we include some tMSP candidates identified as such in the literature, which can be found in Table 1 with references. In the catalogue table itself, one can find a corresponding flag column named ‘tMSP_Flag’ (see Table B.1).

Several objects originally listed in the HMXB catalogue of Liu et al. (2006) are now moved to the current LMXB catalogue as their preferred classification changed:

- According to Karasev et al. (2008), XTE J1901+014 was suggested to be the first low-mass fast X-ray transient. However, the exact nature of this source remains unclear. Nevertheless, according to Sato et al. (2019), it appears to be more similar to a LMXB, hence its inclusion in our catalogue.
- IGR J16358–4726 was initially identified as an HMXB by Chaty et al. (2008). However, Nespoli et al. (2010) later invalidated this identification, and now the source is classified as a symbiotic X-ray binary, which we consider to be a LMXB subclass based on the typical donor mass.
- The situation is similar for IGR J17407–2808. This source was first classified as part of a supergiant fast X-ray transients (SFXT, Sguera et al. 2006), which are all HMXBs. However, subsequent works (Heinke et al. 2009; Greiss et al. 2011) ruled out the presence of a supergiant companion, and showed that this source is more likely to be a LMXB with an F-type dwarf. Kaur et al. (2011) also found that a few days after the outburst, the IR counterpart was 1 mag brighter. Such behaviour is more expected during the LMXB outburst due to the exposure of the optical component to the X-rays emitted by the compact object.

- After analysing the X-ray spectra and near-IR observations of SAX J1452.8–5949, [Kaur et al. \(2009\)](#) were able to estimate the distance to SAX J1452.8–5949 (≤ 10 kpc). This estimation eliminated the possibility of the system being a HMXB, as it would have to be an extragalactic source in that case. Consequently, the authors suggested that the binary has a low-mass companion and could either be a LMXB or an IP. Therefore, we classify SAX J1452.8–5949 as a LMXB candidate.
- It has been unclear for some time whether 4U 1807–10 is a HMXB or a LMXB. However, based on the ratio of spin and orbital periods ([Blay et al. 2008](#)), as well as the fact that the system shows type-I X-ray bursts ([Chelovekov et al. 2017](#)), we conclude that an LMXB origin is more likely for this source, despite the fact that 4U 1807–10 is marked as a HMXB candidate in [Blay et al. \(2008\)](#), and therefore we add 4U 1807–10 to our LMXB catalogue.

In addition, there is one source that is present in both of our catalogues, in this one, and in the one dedicated to HMXBs ([Neumann et al. 2023](#)). This is due to the presence of conflicting results and the absence of any final decision on the true nature of the source:

- Cir X–1 was originally classified as a LMXB after its discovery. However, [Heinz et al. \(2013\)](#) were able to determine that the system is only about 4500 yr old, which led to a revision of its classification. Additionally, [Jonker et al. \(2007\)](#) reported that Cir X–1 contains a supergiant companion of A0 to B5 type. However, Cir X–1 has also exhibited type-I X-ray bursts ([Tennant et al. 1986](#)), which are characteristic of LMXBs. Furthermore, the fact that the companion star in Cir X–1 has yet to be decisively detected at optical wavelengths supports a possible LMXB nature for the system. [Johnston et al. \(2016\)](#) concluded that the optical counterpart in Cir X–1 could either be an unevolved low-mass star or a giant star that is still in the process of recovering from the supernova explosion that occurred less than 5000 yr ago. Due to the ambiguity surrounding the nature of Cir X–1, the source has been included in both our LMXB and HMXB catalogues.

As mentioned previously, several objects included in RK03 and Liu07 have been removed from our catalogue. Sometimes this was necessary because objects reported as independent in RK03 and Liu07 represented the same source (in either of the catalogues). This was mainly due to large positional uncertainties at the time of the catalogue compilation, or in some cases because the objects are extragalactic. In the case of the former, we include only the element from the pair in our LMXB list with the most used name, omitting the other, and summing up all known data. In the extragalactic origin scenario, the corresponding source is removed as we only consider Galactic LMXBs. Our initial source list was therefore modified as follows:

- The relatively bright source 2A 0521–720, which is more commonly referred to as LMC X–2, is located in the LMC (as the name suggests). As we consider only Galactic objects, we exclude it from our catalogue.
- The same is true for RX J0532.7–6926 (located in LMC), and so it is also not included in the current catalogue.
- Two sources AX J1745.6–2901 and 1A 1742–289 listed in Liu07 actually correspond to the same LMXB, and as the name ‘AX J1745.6–2901’ is more commonly used, we combine information regarding the two from Liu07 under this name.

- The second case of identical sources is 1E 1743.1–2852 and SAX J1747.0–2853, and so again we gave the most popular name to the object, SAX J1747.0–2853.

3.3. Summary of other differences with respect to the Liu07 and RK03 catalogues

In addition to the problematic cases described above, and the overall expansion of the sample, several other changes have been made compared to Liu07 and RK03:

- To standardise the reported X-ray fluxes, we revised the energy ranges used in the Liu07 study. Instead of using a single range of 2–10 keV, we now present ‘soft’ and ‘hard’ X-ray fluxes separately, each in well-defined energy ranges.
- In addition, X-ray fluxes (absorbed) in our table are represented in cgs units ($\text{erg s}^{-1} \text{cm}^{-2}$, instead of Jy reported in Liu07), which are more commonly used and meaningful for X-ray sources. We also now report both maximum and minimum flux values for each of the two energy bands instead of only reporting the maximum, as done in Liu07.
- To better reflect various phenomenological features reported in the literature, we increased the number of flags used to describe the properties of the sources. In comparison to Liu07, where 11 flags were used, we use 17.
- Our new version of the LMXB catalogue has additional (in comparison with Liu07) columns for hydrogen column density, near- and mid-IR data (from 2MASS, VVV, WISE, literature, etc.), BP-RP colour, optical *Gaia*/StarHorse/literature data, and distances.
- In addition, we include up to six finding charts (from mid-IR images to hard X-ray bands) for each object, instead of just a reference to a finding chart.
- Finally, our catalogue now includes 349 objects, which is a 71% increase from the 204 objects listed in Liu07 and RK03 combined.

4. Summary and conclusions

In this paper, we present a new LMXB catalogue, which provides an up-to-date census of known LMXBs in the Galaxy with a variety of corresponding multi-wavelength information extracted from current optical/IR surveys. In total, the catalogue contains 349 sources and has 62 columns. Descriptions of the columns are presented in Table B.1. The full version of the catalogue can be obtained through the VizieR database³⁶, and can also be found on a dedicated website³⁷. We ask authors who use our catalogue in their research to refer to us by citing this article, as well as by referring to the website link in either the acknowledgements or a footnote.

We would like to emphasise here that the origin of some of the sources listed in the catalogue is not yet certain; some sources have only been tentatively classified as LMXBs due to the similarity of their X-ray properties to those of the systems identified, with no counterparts found in other bands. Along with this article, a new similar catalogue of HMXBs is being published ([Neumann et al. 2023](#)). We hope that both catalogues will be useful tools for future studies, which includes (but is not limited to) population studies of various types of X-ray-emitting objects (especially XRBs), searches for new XRBs in ongoing and upcoming surveys, classification of unidentified

³⁶ <https://cdsarc.cds.unistra.fr/cgi-bin/qcat?J/A+A>

³⁷ <http://astro.uni-tuebingen.de/~xrbcat>

X-ray sources, and as training data-sets for machine learning classification algorithms (Yang et al. 2021, 2022). In particular, our catalogue be relevant in the context of the ongoing analysis of eROSITA survey data, which is expected to substantially increase the number of known XRBs (Doroshenko et al. 2014). We therefore plan to update our catalogues to the best of our ability to keep the ever-increasing census of the Galactic LMXBs up to date and accessible to the community.

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Appendix A: Optical/IR counterparts**Table A.1.** Identified archive optical/IR counterparts of LMXBs.

Source name	<i>Gaia</i> DR3	2 <i>MASS</i>	<i>CatWISE</i> 2020
Based on optical/IR/radio follow-ups:			
MAXI J0556–332	2890346074897001216		
4FGL J0427.8–6704	4656677385699742208	J04274958–6704350	J042749.64–670435.0
IGR J17494–3030	4056028099172996352		
1FGL J1417.7–4407	6096705840454620800	J14173057–4402574	J141730.57–440257.5
XTE J1637–498	5940421734427982336	J16370267–4951401	
MAXI J1807+132	4497207964419829632		
3A 1837+049	4283919201304278912	J18395759+0502113	J183957.57+050210.5
MAXI J1828–249	4076998775244833280		
1RXS J180408.9–342058	4042163562572848384		
IGR J17091–3624	5976921951382731520		J170907.75–362425.0
IGR J17585–3057	4044163406621956992		J175829.80–305702.3
4U 1543–624	5826501373348972288		
Swift J1858.6–0814	4203799300867262720		
MAXI J1305–704	5843823766718594560		J130655.74–702704.2
IGR J17329–2731	4061336747511224704	J17325067–2730015	J173250.54–273003.4
IGR J16358–4726		J16355369–4725398	J163553.75–472541.0
XMMU J174445.5–295044		J17444541–2950446	J174445.43–295044.5
IGR J17454–2919		J17452768–2919534	
4U 1705–250	4112450294268643456		
4FGL J0540.0–7552	4648562676357022208		J054001.80–755419.7
3FGL J1544.6–1125	6268529198286308224		J154439.38–112804.5
CXOU J110926.4–650224	5240167590731178624		J110926.21–650227.1
4FGL J0407.7–5702	4682464743003293312		J040731.65–570025.1
1RXH J173523.7–354013	5974787971132982144		
IGR J16287–5021	5934583950467938304		
4U 1556–60	5833042299288099072		
EXO 1846–031	4258794192383316864	J18491710–0303559	J184917.08–030355.3
AX J1735.8–3207	4055019091071763712	J17354627–3207099	
IGR J16293–4603	5942210433690960640	J16291285–4602506	J162912.85–460250.4
4U 1626–67	5809528276749789312		
SAX J1810.8–2609	4064636102946481408		
XTE J1709–267	4108865783346597760		
XTE J1710–281	4108449755564592256		
IGR J19308+0530	4294249387962232576	J19305075+0530582	J193050.75+053058.0
Swift J2037.2+4151		J20370560+4150051	J203705.60+415005.2
GS 1826–238	4077372536242802944		
SRGA J181414.6–225604	4066460746608630912	J18141475–2256195	J181414.78–225619.4

Table A.1. continued

Source name	<i>Gaia</i> DR3	<i>2MASS</i>	<i>CatWISE</i> 2020
Based on Arnason et al. (2021) :			
GRO J1655–40	5969790961312131456	J16540014–3950447	J165400.13–395044.7
SWIFT J061223.0+701243	1107229825742589696		J061222.63+701243.1
1A 1246–588	6059778089610749440		J124939.17–590516.3
MXB 1659–29	6029391608332996224		
SAX J1711.6–3808	5973177495780065664	J17113714–3807073	J171137.14–380707.4
4U 1724–307	4058208396397618688	J17273315–3048076	J172733.28–304809.0
EXO 1747–214	4118590585673834624		
4U 1755–33	4042473487415175168		
HETE J1900.1–2455	4074363039644919936		
4U 1915–05	4211396994895217152		
XTE J1901+014	4268294763113217152		

Appendix B: Catalogue format**Table B.1.** Description of columns in the LMXB catalogue table.

Nº	Column name	Unit	Description
1	'Name'		Object name, which is the most common name in the literature.
2	'RAdeg'	deg	Right Ascension in degrees (ICRS).
3	'DEdeg'	deg	Declination in degrees (ICRS).
4	'PosErr'	arcsec	Positional error in arcseconds.
5	'Coord_Ref'		The source from which the position of the object is taken.
6	'GLON'	deg	Galactic longitude in degrees.
7	'GLAT'	deg	Galactic latitude in degrees.
8	'Xray_Type'		List of the X-ray types assigned to the object. For more information see Sect. 2.1.
9	'Porb'	day	Orbital period of the binary system in days.
10	'Ppulse'	s	Pulsation period (spin) of a NS in seconds.
11	'Alt_Name'		Most frequently used alternative name.
12	'SpType'		Spectral type of the optical counterpart.
13	'Vmag'	mag	Optical magnitude in V-band according to SIMBAD database and literature.
14	'e_Vmag'	mag	Corresponding magnitude error in V-band.
15	'Gaia_DR3_ID'		Name in Gaia DR3(eDR3) catalogue.
16	'Gmag'	mag	Optical magnitude in G-band according to a Gaia catalogue or the literature.
17	'e_Gmag'	mag	Corresponding magnitude error in G-band.
18	'BP-RP'	mag	BP-RP colour.
19	'2MASS_ID'		Name in 2MASS catalogue.
20	'Jmag'	mag	IR magnitude in J-band according to 2MASS or the literature.
21	'e_Jmag'	mag	Corresponding magnitude error in J-band according to 2MASS or the literature.
22	'Hmag'	mag	IR magnitude in H-band according to 2MASS or the literature.
23	'e_Hmag'	mag	Corresponding magnitude error in H-band according to 2MASS or the literature.
24	'Kmag'	mag	IR magnitude in K-band according to 2MASS or literature.
25	'e_Kmag'	mag	Corresponding magnitude error in K-band according to 2MASS or the literature.
26	'WISE_ID'		Name in CatWISE, AllWISE, or WISE catalogue.
27	'W1mag'	mag	IR magnitude in W1 WISE band.
28	'e_W1mag'	mag	Corresponding magnitude error in W1 WISE band.
29	'W2mag'	mag	IR magnitude in W2 WISE band.
30	'e_W2mag'	mag	Corresponding magnitude error in W2 WISE band.
31	'N_H'	10^{22}cm^{-2}	Neutral hydrogen column density.
32	'MinSoftFlux'	$10^{-12}\text{erg/s/cm}^2$	Minimum flux (absorbed) from a source in soft X-ray.
33	'MaxSoftFlux'	$10^{-12}\text{erg/s/cm}^2$	Maximum flux (absorbed) from a source in soft X-ray.
34	'Soft_Xray_Var'		Ratio of maximal soft X-ray flux and minimal soft X-ray flux.
35	'Soft_Xray_Range'	keV	Soft X-ray flux energy range used.
36	'MinHardFlux'	$10^{-12}\text{erg/s/cm}^2$	Minimum flux (absorbed) from a source in hard X-ray.
37	'MaxHardFlux'	$10^{-12}\text{erg/s/cm}^2$	Maximum flux (absorbed) from a source in hard X-ray.
38	'Hard_Xray_Var'		Ratio of maximal hard X-ray flux and minimal hard X-ray flux.
39	'Hard_Xray_Range'	keV	Hard X-ray flux energy range used.
40	'AG'	mag	G-band absorption A_G .
41	'Mean_Dist'	pc	Mean estimate of the distance to the binary system.

Table B.1. continued

N ^o	Column name	Unit	Description
42	'Low_Dist'	pc	The lowest (minimum) estimate of the distance to the binary system.
43	'High_Dist'	pc	The highest (maximum) estimate of the distance to the binary system.
44	'Incl'	deg	Binary system inclination.
45	'Mx'	$M_{\odot}$	Mass of the compact object.
46	'Mopt'	$M_{\odot}$	Mass of the optical counterpart.
47	'B-V'	mag	B-V colour index.
48	'E(B-V)'	mag	E(B-V) colour excess.
49	'tMSP_Flag'		tMSP flag, which can take one of the two values, indicating that the source is: 1 – one of the three solidly considered tMSPs. 2 – a tMSP candidate.
50	'Liu07_IDX'		Ordinal number of the source in the table of Liu07 LMXB catalogue.
51	'RK03_IDX'		Ordinal number of the source in the table of RK03 LMXB catalogue.
52	'Orb_Ref'		Orbital period origin reference.
53	'Pulse_Ref'		Spin (pulsation) period of the NS origin reference.
54	'Spect_Ref'		Reference to the origin of the optical spectral type of the star.
55	'Vmag_Ref'		Reference to the origin of the V-band magnitude.
56	'Gmag_Ref'		Reference to the origin of the G-band magnitude.
57	'JHK_Ref'		Reference to the origin of the JHK information.
58	'WISE_Ref'		Reference to the WISE IR catalogue used (CatWISE, AllWISE or WISE).
59	'N_H_Ref'		N_{H} value origin reference.
60	'AG_Ref'		Reference to the origin of the G-band absorption A_{G} .
61	'Dist_Ref'		Reference to the origin of the distance estimations.
62	'Mass_Ref'		Reference to the origin of the mass estimations.

Paper II

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"XRBcats: Galactic High-Mass X-ray binary catalogue"

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II

XRBCats: Galactic High Mass X-ray Binary Catalogue^{*,**}

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ABSTRACT

Context. We present a new catalogue of high mass X-ray binaries (HMXBs) in the Galaxy that we call the Galactic High Mass X-ray Binary Catalogue (XRBCats), which improves upon the most recent of such catalogues. We include new HMXBs discovered since previous publications and revise the classification for several objects previously considered HMXBs or HMXB candidates. The catalogue includes basic information (e.g. source names, coordinates, types), other data (e.g. distance and X-ray flux estimates, binary system parameters), and other characteristic properties of the 169 HMXBs catalogued. We also present finding charts in several bands from the infrared to hard X-rays for each object.

Aims. The aim of this catalogue is to provide a list of all currently known Galactic HMXBs, including basic information on both compact objects and non-degenerate counterpart properties (where available). We also include objects tentatively classified as HXMBs in the literature and give a brief motivation for the classification in each case.

Methods. The catalogue is compiled based on a search of known HMXBs and candidates in all publicly available databases and literature published before May 2023. The relevant properties in various wavelength bands were collected for all objects, either from the literature or using data provided by large-scale surveys. For the latter case, the counterparts in each individual survey were found by cross-correlating positions of identified HMXBs with relevant databases.

Results. An up-to-date catalogue of Galactic HMXBs is presented to facilitate research in this field. Our goal was to collect a larger set of relevant HMXB properties in a more uniform way compared to previously published works.

Key words. catalogues – binaries: close – stars: early-type – X-rays: binaries

1. Introduction

X-ray binaries (XRBs) are still the focus of observational X-ray astronomy almost 60 yr after their discovery. These systems consist of a compact object, which can be a neutron star (NS), a black hole (BH), or a white dwarf (WD), and a non-degenerate companion providing matter for the accretion powering the X-ray emission. Depending on the mass of the optical companion, XRBs can be subdivided into two categories. Systems with low mass optical companions ($M_{\text{opt}} \lesssim 1 M_{\odot}$) are classified as low mass X-ray binaries (LMXBs; Chaty 2022), whereas those with higher mass optical companions ($M_{\text{opt}} \gtrsim 8 M_{\odot}$) are classified as high mass X-ray binaries (HMXBs; Chaty 2022). In the cases where the compact object is either a NS or a BH, accretion is usually assumed. However, systems in which the compact object is a WD are commonly considered separately from the first two cases, and are most often referred to as cataclysmic variables (CVs) rather than XRBs due to both physical and historical reasons. The mass gap between LMXBs and HMXBs is populated by a handful of sources (e.g. Her X-1 with an optical companion with a mass of $M_{\text{opt}} \approx 2 M_{\odot}$, Tananbaum et al. 1972), often referred to as intermediate-mass X-ray binaries (IMXBs, Pfahl et al. 2003). Despite the mass of the optical companion, all of these binaries host a compact object, and thus represent endpoints of stellar evolution. Understanding the properties of this population

is key to understanding the evolution of the Galaxy as a whole. Due to their short characteristic lifetimes of $\sim 2 \times 10^7$ yr, HMXBs can be considered young systems when compared to LMXBs ($\sim 10^{10}$ yr), and are thus good tracers for star forming activity (Grimm et al. 2003). Within the Milky Way such systems are concentrated around the Galactic plane and are often localised within the spiral arms. Similarly to other astrophysical sources, there are still large uncertainties in the spatial distributions, luminosity distributions, numbers, physics, and evolutionary cycles for XRBs. This issue is exaggerated by the fact that we only observe a fraction of the overall population of these systems. However, the number of known objects is ever increasing. It is therefore essential to keep the census of known XRBs and their properties up to date, especially in the era of new large-scale surveys such as eROSITA and Gaia that provide a wealth of new observational information across the entire sky. The goal of this paper is therefore to provide such an update for HMXBs. In parallel, similar efforts for LMXBs and IMXBs have been undertaken independently (Avakyan et al. 2023).

As already mentioned, HMXBs constitute a relatively broad class of objects defined based on the mass of the companion star. Depending on the properties of the companion, and the accretion mechanism, they can be divided into several sub-classes. Systems accreting via stellar winds of their optical companion with mass-loss rates of up to $\dot{M} \sim 10^{-6} \dots 10^{-5} M_{\odot} \text{ yr}^{-1}$ (Kudritzki & Puls 2000) are usually persistent sources of X-rays and are referred to as supergiant X-ray binaries (SGXBs, Corbet 1986). Within the category of SGXBs are also the highly variable supergiant fast X-ray transients (SFXTs, Negueruela et al. 2006), which are non-accreting most of the time, but show occasional bright flares

* The catalogue is available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/677/A134>

** A web version is publicly accessible at <http://astro.uni-tuebingen.de/~xrbcats/>

on timescales of minutes to days with peak fluxes comparable to other SGXBs. Depending on the mass ratio, accretion can be quasi-symmetric, or focused by gravity via the L1 point, as is the case of Vela X-1 (Kretschmar et al. 2021). In some cases Roche-lobe overflow (RLO) can also occur; the Galactic micro-quasar SS 433 and the first X-ray pulsar ever discovered, Cen X-3, are examples where this mechanism dominates. With mass-loss rates of $\dot{M} \sim 10^{-3} M_{\odot} \text{ yr}^{-1}$ (for a fully developed RLO) these systems have rather short lifetimes (of the order of the thermal timescale of the optical companion), and are thus rare. However, Savonije (1978) showed that an atmospheric RLO is feasible and could be sustained for thousands of years with mass-loss rates below $\dot{M} \sim 10^{-8} M_{\odot} \text{ yr}^{-1}$, and indeed more HMXBs of this type are known to exist outside of our own Galaxy. However, the known HMXB population is dominated by Be X-ray binaries (BeXBs, Reig 2011). In these systems the optical companion is either an early-type B star (earlier than B3) or a late-type O star (later than O8), with an equatorial decretion disc. This disc is formed by the material released at the equator of the optical companion due to its high rotation velocity (Balona & Ozuyar 2020). Decretion disc size is known to be variable and can be traced by the characteristic emission lines in the optical spectra of Be star. Passage of the compact object (in the vast majority of cases a NS) through the disc leads to enhanced accretion, especially if the disc is in an expanding state. From an observational point of view, this leads to the appearance of two different kinds of outbursts that are characteristic of BeXB systems. Type I outbursts are periodically occurring events with a typical peak luminosity below $10^{37} \text{ erg s}^{-1}$, normally coinciding with the periastron passage of the compact object. Type II outbursts are more irregular, less frequent events, and are apparently associated with the expansion of the circumbinary disc. Peak luminosity can reach up to $10^{39} \text{ erg s}^{-1}$ (Doroshenko et al. 2020), thereby exceeding the Eddington luminosity of the neutron star. Outbursts of this type are usually referred to as giant outbursts and do not show any preferred orbital phase, and usually last longer than their type I counterparts. Importantly, all BeXBs are transients with relatively low duty cycles and are mostly observable only during their outbursts. They continue, therefore, to be discovered at a steady rate, and contribute to the increase in the number of known HMXBs.

Prior to the recent catalogue Fortin et al. (2023), the most commonly used catalogue of HMXBs, and the starting point of this work, was Liu et al. (2006), which was published ~ 16 yr ago. Since then many new HXMBs have been discovered, and some previously categorised objects have lost their HMXB status. What is perhaps even more important, is that a wealth of additional observational data were collected with new facilities such as the X-ray Multi-Mirror Mission (*XMM-Newton*; Jansen et al. 2001), the International Gamma-Ray Astrophysics Laboratory (INTEGRAL; Winkler et al. 2003) or *Gaia* (Gaia Collaboration 2016), to name but a few. In this work we present an updated catalogue of Galactic HMXBs including multi-wavelength information as well as the new sources discovered since the publication by Liu et al. (2006). The current catalogue only includes Galactic HMXBs and does not include objects from the Small or Large Magellanic Clouds; candidates within these regions often have poorly identified or characterised optical counterparts. For Galactic HMXBs, a concerted effort has been made within the field to collect all relevant and current multi-wavelength information including distances, optical magnitudes, variability information in soft and hard X-rays, and information on detection in radio band, amongst others. Such information ensures that the catalogue can aid in the

identification of new HMXBs in the ongoing and future X-ray surveys, population studies, and other investigations.

2. Definition of the sample and data sources

As a first step, we compiled a sample of 169 HMXBs (123 confirmed and 46 candidates) by searching the SIMBAD¹ and VizieR² archives hosted by the Centre de Données astronomiques de Strasbourg (CDS) databases and the literature. The largest fraction of this sample (105 objects) originates from Liu et al. (2006), the catalogue this work is based on. We also systematically searched the literature (including Astronomer’s Telegrams³) for reports of new HMXB discoveries. A large fraction of new HMXBs reported in the literature were discovered between 2006 and 2020 by both the INTEGRAL mission and the Neil Gehrels Swift Observatory (Swift; Gehrels et al. 2004) (29 objects), as summarised in Kretschmar et al. (2019), which can therefore also be considered one of the main sources used in this work. As the next step, we considered all objects classified as HXMB or candidates in the SIMBAD and VizieR databases. Considering that the majority of objects not present in these databases or the literature are extragalactic, and the fact that HMXBs are strongly clustered towards the Galactic plane (Grimm et al. 2002), we restricted our search to the Galactic latitude between $\pm 15^\circ$ in the latter case. As an aside, the recent HXMB catalogue (Fortin et al. 2023) was published during the review process of this paper. We therefore utilised this catalogue as an additional source list, and cross-checked our own catalogue against this, which resulted in an additional five HMXBs. We note that although considerable effort was put into finding all possible HXMBs and candidates, it is still possible that some sources have been omitted, we therefore urge the reader to report such omissions to the corresponding author. We also note that some of the objects considered by Liu et al. (2006) as HMXBs or candidates are no longer accepted as such. In Sect. 3.2, we discuss these cases separately.

2.1. HMXB sample and classification

To reflect the variety among the properties of HMXBs, we include information on the origin of the donor star or compact object, system variability, and other relevant properties. These properties are then used to define a set of flags designed to represent the range of properties present in this catalogue. In general, the criteria for these flags are based on the classifications introduced in Liu et al. (2006). However, we have supplemented them with additional flags based on the information provided within Kretschmar et al. (2019), Staubert et al. (2019), and van den Eijnden et al. (2021, 2022). As a result, we converged on the set of flags listed below. The frequency of individual flags is provided in brackets and is also presented graphically in Fig. 1 to give a broad overview of the sample of known HMXBs. We note that the flags below are not meant as a basis for classification of HXMBs, but rather illustrate the range of different systems within the population considered in this catalogue, meaning a system may have multiple flags:

1. BH: black hole candidate (6);
2. EB: eclipsing or partially eclipsing binary system (9);
3. MQ: micro-quasar (4);
4. RS: radio emitting HMXB (13);

¹ <http://simbad.u-strasbg.fr/simbad/>

² <https://vizier.cds.unistra.fr/viz-bin/VizieR>

³ <https://astronomerstelegram.org/>

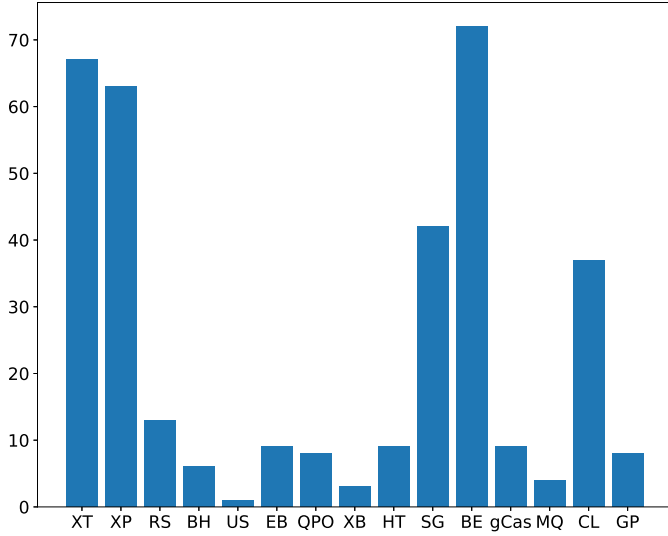


Fig. 1. HMXBs population of each type in the Galaxy.

5. XB: X-ray burst source (3);
6. XP: X-ray pulsar (63);
7. XT: transient X-ray source (67);
8. US: ultra-soft X-ray spectrum (1);
9. HT: hard transient (9);
10. Gcas: Gamma Cassiopeiae-like source (9);
11. QPO: quasi-periodic oscillation (8);
12. SG: supergiant optical companion (42);
13. BE: Be star companion (72);
14. CL: cyclotron resonance scattering feature in X-ray spectrum (37);
15. GP: high mass γ -ray binary (8).

2.2. X-ray properties

Considering that the prime feature of XRBs is their X-ray emission, we attempted to compile the relevant X-ray properties of the HMXBs in the catalogue. This includes fluxes in the soft X-ray band as observed by *XMM-Newton*, the *Chandra* X-Ray Observatory (*Chandra*; Weisskopf et al. 2000), and the *Swift* X-Ray Telescope (*Swift*/XRT; Burrows et al. 2005), and in the hard X-ray bands as observed by INTEGRAL and the *Swift* Burst Alert Telescope (*Swift*/BAT; Barthelmy et al. 2005). We also compiled X-ray positions, in order to assess the reliability of optical counterpart identification or identify plausible counterparts, as described below. In the case of *XMM-Newton* we report flux in the 0.2–12 keV energy band (corresponding to EPIC_8 band in the *XMM-Newton* catalogues⁴ Webb et al. 2020). For *Chandra*⁵ (Evans et al. 2010) we preferentially used the broad ACIS band (0.5–7.0 keV) or the wide HRC band (0.1–10.0 keV) depending on the availability. In the case of *Swift*/XRT we used data that is available in the *Swift* X-ray telescope point source catalogue⁶ (2SXPS; Evans et al. 2020), where for the flux we utilised the energy range 0.3–10.0 keV, calculated from an assumed power-law spectrum (Evans et al. 2020). In the hard X-ray regime we

used an energy range of 14–145 keV for *Swift*/BAT⁷ (Oh et al. 2018) data and an energy range of 17–60 keV for INTEGRAL data⁸ (Krivonos et al. 2012).

2.3. Optical position and astrometry

Most of the HMXBs in the sample have identified optical counterparts (an almost essential pre-requisite for HXMB classification). However, the optical positions reported in Liu et al. (2006) are often limited by the techniques of the time, and thus show discrepancies with modern observations. An effort was made to update these data with the updated astrometry provided by the *Gaia* mission. To achieve this, we first confirmed whether the SIMBAD database already contained identified *Gaia* DR3⁹ (Gaia Collaboration 2023) or Two Micron All Sky Survey¹⁰ (2MASS; Cutri et al. 2003) counterparts. If this was not the case, we matched the literature positions, which included *V*-band magnitudes, to *Gaia* DR3 using a large search radius of 10''. *Gaia* counterparts that matched the literature positions and magnitudes within the uncertainties were then selected. In most cases, this corresponded to an object closest to the literature position with *V*-band magnitude within 2 mag of the *G*-magnitude reported by *Gaia*. We note that most of the HMXBs are, to some extent, variable in the optical band so an exact comparison would be unfeasible. This meant that the threshold of two magnitudes was determined empirically by inspecting the observed difference between the literature and *Gaia* magnitudes for sources where the *Gaia* counterpart was already unambiguously identified.

For all HMXBs with a *Gaia* counterpart, we provide distance information from Gaia Collaboration (2023), Bailer-Jones et al. (2021)¹¹, and Anders et al. (2022)¹². In addition, for objects without an identified *Gaia* counterpart, but with available distance estimates in the literature, we give those estimates and their corresponding references. If multiple distance estimates were available, the mean distance was calculated by using the arithmetic mean on all available distance estimations linked to the given source. The range of possible distances, calculated by taking the lowest and highest estimations of all distance estimates for a given system (from the literature or from *Gaia*) is also reported.

2.4. Additional information

We also attempted to include some extra information related to the properties of the optical counterparts and the compact objects. For instance, in addition to the *G*-band magnitudes of *Gaia* published in Gaia Collaboration (2023), magnitudes in the *J*-, *H*-, and *K*-bands provided by Cutri et al. (2003) as well as magnitudes in the *W1*- and *W2*-bands of the Wide-field Infrared Survey Explorer mission (Wright et al. 2010) in CatWISE2020¹³

⁴ <https://heasarc.gsfc.nasa.gov/W3Browse/xmm-newton/xmmssc.html>

⁵ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=IX/57/csc2master>

⁶ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=IX/58/2sxps>

⁷ <https://heasarc.gsfc.nasa.gov/W3Browse/swift/swbat105m.html>

⁸ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=J/A%2bA/545/A27>

⁹ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/355>

¹⁰ <https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=II/246>

¹¹ <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/352>

¹² <https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/354/starhorse2021>

¹³ <https://vizier.cds.unistra.fr/viz-bin/VizieR?-source=II/365>

(Marocco et al. 2021) and available V-band magnitudes were included. Any luminosity estimates of the optical companions from Gaia Collaboration (2023) were also added. Since the spectral type of the counterpart is also pertinent information, we attempted to include this information by using the following sources: Kretschmar et al. (2019), Staubert et al. (2019), Liu et al. (2006), Mauro Orlandini’s website¹⁴, and SIMBAD. Due to the close connection between spectral type and effective stellar temperature, estimations of the temperatures provided by Anders et al. (2022) and Gaia Collaboration (2023) were included. The catalogue includes only the mean stellar effective temperature. One of the key properties of NS systems is the magnetic field strength of the compact object. This can be measured using observed energies of the cyclotron resonance scattering features (CRSFs, or cyclotron lines). We therefore included the literature values of the observed CRSF energies where such features were claimed to be detected. This includes the fundamental line as well as harmonics. The line energies and corresponding references were sourced from the recent review by Staubert et al. (2019) and the X-ray pulsar properties database by Mauro Orlandini, which appears to cover all X-ray pulsars where a detection of a CRSF was claimed in the literature.

3. Catalogue content and quality assurance

3.1. Description of the fields

The Galactic High Mass X-ray Binary catalogue (XRBcats) we present here contains a total of 169 HMXBs and candidates, sorted according to increasing right ascension (second column). The table consists of 66 columns, listing the various parameters and references for a given HMXB. The first column contains the source name, as decided by the most common name in the literature (number of mentions in NASA ADS system). The following seven columns are dedicated to the coordinates of the system, the second and third columns displaying the right ascension (RA) and declination (Dec) in degrees, followed by statistical uncertainties of the coordinates in arcseconds. The Coord_Ref column provides the reference of the catalogue or paper, which was used to extract the coordinates and uncertainties (e.g. Gaia Collaboration 2023 for Gaia DR3), given as a NASA ADS bibcode. The sixth column indicates whether the optical counterpart is solidly identified in the literature (0), if it is a tentative optical counterpart identified as such in the literature (1) or if it is not yet identified (2). In the seventh and eighth columns the galactic longitude (GLON) and galactic latitude (GLAT) in degrees can be found. The following column displays the different X-ray flags related to HMXB classification, which were discussed in Sect. 2. Columns 10 and 11 provide the orbital period of the compact object in days and the spin period of the pulsar (where appropriate) in seconds, respectively. For NS HMXBs with CRSFs reported in the literature, line energies are listed in Col. 12 in units of keV regardless of if it is reporting on the fundamental line or any harmonics. In the Alt_name column, the second most-used identifier in the literature was selected as an alternative name for the HMXB. Column 14 displays the spectral type of the optical companion. If it was possible to identify the Gaia counterpart, the Gaia-DR3-ID is listed in Col. 15. Columns 16 and 17 show the magnitude in the G-band as well as its uncertainty followed by the V-band magnitude in Col. 18 and its uncertainty in Col. 19. In

Cols. 20–29, the JHK-magnitudes as well as the W1- and W2-magnitudes with their respective uncertainties are shown. The neutral hydrogen column density in units of 10^{21} cm^{-2} is shown in Col. 30, which is available in Evans et al. (2020). In this reference hardness ratios were first taken and utilised to produce a power-law spectrum through interpolation; from this interpolated spectrum, the neutral hydrogen column density best fitting that spectrum was derived. The following 11 columns contain information on the X-ray flux. Columns 31 and 32 are the minimum and maximum flux values of the source in the *XMM-Newton* catalogue. Columns 33 and 34 are the flux values of the source in *Chandra*, due to the use of both *Chandra* HRC and ACIS; Col. 35 indicates which of these two instruments was used for the flux values. Columns 36 and 37 respectively display the minimum and maximum flux values of *Swift*/XRT of the source, Cols. 38 and 39 for *Swift*/BAT, and Cols. 40 and 41 for INTEGRAL. In cases where only one observation was taken the same value was adopted for minimum and maximum flux values. Columns 42–44 contain mass estimates of the compact object, in particular mean mass, as well as the upper and lower mass limits reported in the literature (in $M_{\odot}$). Columns 45–47 contain distance estimates (in parsec) to a given source, including the mean distance and the upper and lower limits given in the literature. The stellar effective temperature and the luminosity of the optical counterpart can be found in Cols. 48 and 49, where T_{eff} is in Kelvin and the luminosity of the companion is in $L_{\odot}$. All SIMBAD identifiers associated with HMXBs are quoted in Col. 50. The next seven columns are dedicated to the references of CRSF, pulsation period, orbital parameter, spectral type, distance-estimation (if literature values were used), mass estimation, and miscellaneous references. Column 58 is dedicated to comments (e.g. if the source is considered an HMXB candidate or similar). The final eight columns contain the source name given in the following catalogues: 2MASS All-Sky Catalogue of Point Sources, CatWISE2020 catalogue, Second ROSAT all-sky survey (2RXS) source catalogue, *XMM-Newton* Serendipitous Source Catalogue, *Chandra* Source Catalogue (CSC) Release 2.0, 2SXPS *Swift* X-ray telescope point source catalogue, *Swift*/BAT 105-Month All-Sky Hard X-Ray Survey catalogue, and INTEGRAL/IBIS 9-yr Galactic Hard X-Ray Survey catalogue.

3.2. Finding charts and problematic cases

As part of the catalogue we provide finding charts, which consist of up to six different images ranging from near-infrared (NIR) to hard X-rays for all sources. For the majority of the finding charts, we used the Hierarchical Progressive Surveys (HiPS; Fernique et al. 2015); only in the case of *Swift*/XRT did we use the SkyView Query. Both HiPS and SkyView offer the possibility to query data automatically with Python. To access HiPS, and SkyView we used the astroquery.hips2fits¹⁵ package and the astroquery.skyview¹⁶ package, respectively. In the following we give details of the surveys used and provide their corresponding links as footnotes. The finding charts consist of up to six different surveys, which are mentioned below, along with their corresponding links as footnotes. In the top row we include the image taken from the Visible and Infrared Survey Telescope for Astronomy (VISTA) from their Variables in the

¹⁵ <https://alasky.u-strasbg.fr/hips-image-services/hips2fits>

¹⁶ <https://astroquery.readthedocs.io/en/latest/skyview/skyview.html>

¹⁴ http://www.iasfbo.inaf.it/~mauro/pulsar_list.html

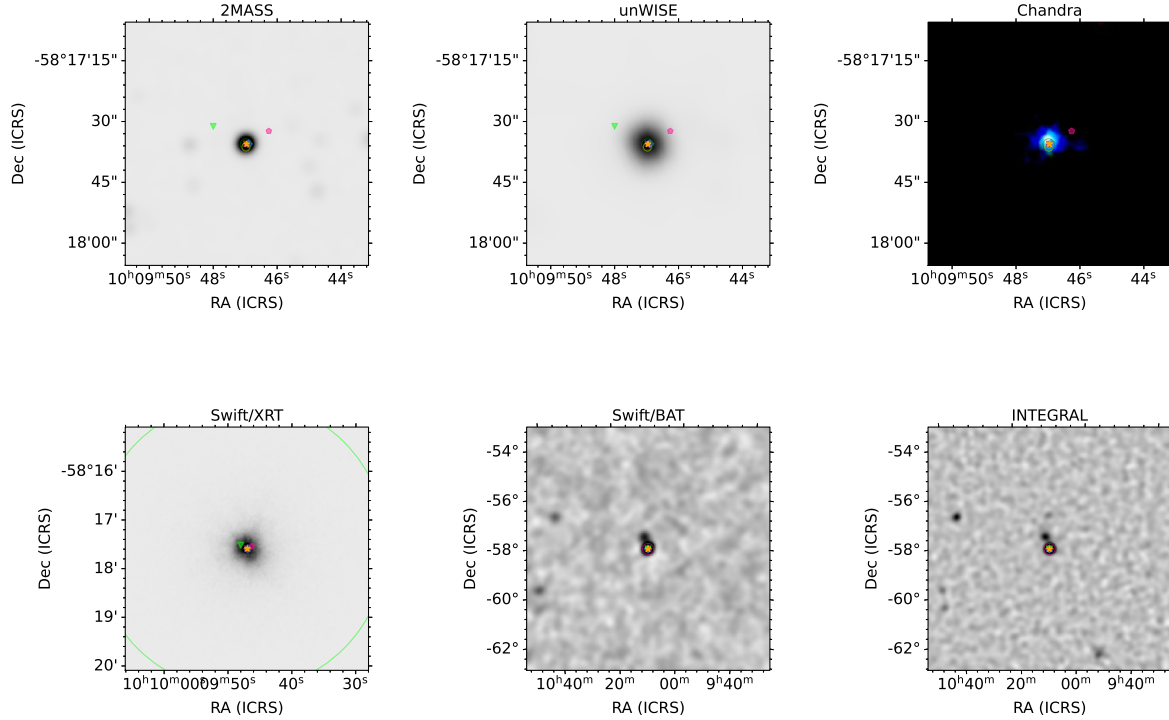


Fig. 2. Finding charts of GRO J1008–57. The finding charts are overlaid with symbols and error circles to indicate observations of different instruments. See text in Sect. 3.2 for an explanation of the finding charts and the symbols.

the Via Lactea (VVV¹⁷) DR4 catalogue (Minniti et al. 2010). Alternatively, for the top row image, where VVV was not available we utilised 2MASS¹⁸. The central image is taken from unWISE¹⁹ (Schlafly et al. 2019) and for the right-hand RGB image we utilised *Chandra*²⁰, *XMM-Newton*²¹, or the Roentgensatellit (ROSAT²²; Truemper 1982; Boller et al. 2016; Voges et al. 1999; listed here in order of preference). In the left-hand corner of the bottom row we provide a soft X-ray image of *Swift*/XRT (*Swift*XRTInt in astroquery.skyview). For hard X-rays we take images from *Swift*/BAT²³ (middle section of bottom row); and INTEGRAL²⁴ (right hand section of bottom row). A 1 arcmin field of view was used for the creation of the VVV, 2MASS, unWISE, *XMM-Newton*, and *Chandra* images. In the case of *Swift*/XRT and ROSAT, we used a field of view size of 5 arcmin and 15 arcmin, respectively. The field of view for *Swift*/BAT and INTEGRAL was chosen to be 10°. In each case, the size of the region was chosen considering the field of view and angular resolution of a given instrument. Every panel also shows the coordinates and uncertainties of all detected sources within their respective regions (position uncertainties are represented by error circles). A red cross indicates the position given by SIMBAD for the source, and a dodger-blue diamond for the coordinates described in the literature. The position of the source used by this catalogue is indicated with an orange

star. In the case of the soft X-ray instruments, the position of the observations is indicated by the error circles to prevent overcrowding, a golden circle indicates the *Chandra* position, a red circle *XMM-Newton*, a green circle *Swift*/XRT, and a navy blue circle ROSAT. *Swift*/BAT and INTEGRAL are denoted by a deep pink pentagon and a lime green triangle, respectively. In the optical band we indicate CatWISE with an orange X, 2MASS with a cyan plus sign, and *Gaia* DR3 data with purple square. As an example, Fig. 2 shows the finding chart of GRO J1008–57.

Based on visual inspection of the finding charts and literature research, several problematic cases were identified. We list these cases in their respective categories, in ascending order of their right ascension coordinates. Several sources initially assumed to be HMXBs were removed from the sample.

1E 1048.1-5937. 1E 1048.1-5937 is listed as an HMXB in SIMBAD; however, Dib et al. (2009) concluded that the source is actually a magnetar. The source is also listed as a magnetar in the McGill magnetar database²⁵ Olausen & Kaspi (2014).

IGR J18151-1052. IGR J18151-1052 was suggested to be an HMXB (Burenin et al. 2009); however, this was shown not to be the case by Lutovinov et al. (2012). The object might be associated with the magnetar candidate PSR J1845-0258 or be a CV, but in any case its identification as an HMXB is unlikely, so we decided not to include this source.

1E 2259+58.6. Another magnetar 1E 2259+58.6 (Gavril & Kaspi 2002) was excluded using the same logic as for 1E 1048.1-5937.

Several objects have tentative or known optical counterparts in the literature, but they could not be found automatically

¹⁷ http://alasky.cds.unistra.fr/VISTA/VVV_DR4/VISTA-VVV-DR4-J/

¹⁸ <http://alasky.cds.unistra.fr/2MASS/J/>

¹⁹ <http://alasky.cds.unistra.fr/unWISE/W1/>

²⁰ <https://cdaftp.cfa.harvard.edu/cxc-hips/>

²¹ <http://skies.esac.esa.int/XMM-Newton/EPIC-RGB/>

²² <http://alasky.cds.unistra.fr/RASS/>

²³ http://cade.irap.omp.eu/documents/Ancillary/4Aladin/BAT_14_20/

²⁴ http://cade.irap.omp.eu/documents/Ancillary/4Aladin/INTEGRAL_17_60/

²⁵ <https://www.physics.mcgill.ca/~pulsar/magnetar/main.html>

through the procedure outlined above. For these objects, the literature was searched manually and the known counterparts and their coordinates were added to the catalogue.

RX J0148.9+6121. Not much is known about RX J0148.9+6121 which was only referred to once by Wang et al. (2014) as having HMXB status. We therefore consider it to be a candidate rather than a confirmed HMXB.

PSR J0635+0533. Fortin et al. (2022b) compiled a list of galactic HMXBs that contain a NS as their compact object, and made an effort to identify optical counterparts for the systems in *Gaia* DR3. The study only lists objects with unambiguously identified counterparts both in *Gaia* DR3 and 2MASS catalogues that are within 0.5'' of each other. In the case of PSR J0635+0533, they identified *Gaia* DR3 3131755947406031104 as the counterpart.

1H 0749-600. For 1H 0749-600, Torrejón & Orr (2001) posited that the proposed optical counterpart HD 65663 is not the real counterpart, but rather a single Be star spatially coincident with an X-ray transient. Torrejón & Orr (2001) also considered the possibility that the system is not an X-ray binary at all. We therefore classify this association as tentative.

1FGL J1018.6-5856. For 1FGL J1018.6-5856 the same procedure was performed as in the case of PSR J0635+0533. Here Fortin et al. (2022b) identified *Gaia* DR3 5255509901121774976 as the *Gaia* counterpart for 1FGL J1018.6-5856.

1ES 1210-64.6. Based on the coordinates of the soft X-ray counterpart of 1ES 1210-64.6 (Revnivtsev et al. 2007), Masetti et al. (2009) identified the optical counterpart (*Gaia* DR3 6053076566300433920) This conclusion was confirmed by follow-up optical spectroscopy.

IGR J12341-6143. A soft X-ray counterpart for IGR J12341-6143 was discovered quite recently by Sidoli et al. (2020) with *Swift*/XRT, which also led to the identification of a tentative optical counterpart (*Gaia* DR2 6054778507172454912).

1A 1238-59. We suggest classifying 1A 1238-59 as an HMXB candidate, due to an error radius of 30'' (Dower et al. 1978) and because there is no detected optical counterpart.

IGR J14059-6116. We decided to classify IGR J14059-6116 as an HMXB candidate, due to a missing optical counterpart. Corbet et al. (2019) suggested that IGR J14059-6116 has a possible association with the HMXB 4FGL J1405.1-6119, and therefore we note that IGR J14059-6116 is likely to be the same source as 4FGL J1405.1-6119.

MAXI J1409-619. Kennea et al. (2010) located an uncatalogued X-ray source inside the MAXI error circle of MAXI J1409-619 using *Swift*/XRT. Inside the *Swift*/XRT error circle of this source, a catalogued IR source (2MASS J14080271-6159020) was also found which is considered a tentative optical counterpart.

IGR J14331-6112. *Gaia* DR3 5878377736381364608 is mentioned as the unambiguous optical counterpart of IGR J14331-6112 by Fortin et al. (2022b).

Cir X-1. Since its discovery, Cir X-1 has been referred to as an LMXB, until Heinz et al. (2013) determined the age of the system to be about 4500 yr. In addition, according to

Jonker et al. (2007) this system contains an A0- to B5-type supergiant companion. However, Cir X-1 has also shown type I X-ray bursts (Tennant et al. 1986), which indicates that source is an LMXB. The possible LMXB origin is also supported by the fact that the companion star itself in Cir X-1 still cannot be unambiguously detected at optical wavelengths. Johnston et al. (2016) concluded that the donor could either be a low mass star that has not had time to evolve or a giant star still recovering from the impact of a supernova blast that happened less than 5000 yr ago. Taking into account all this obscurity around Cir X-1's nature we decided to add it to both LMXB and HMXB catalogues.

XTE J1543-568. In March 2012, *Swift*/BAT detected an increased flux from XTE J1543-568, which led to a more accurate determination of the source position. This allowed Krimm et al. (2012) to identify a tentative counterpart (2MASS J15440515-5645425) within the error box provided by *Swift*/XRT.

2S 1553-542. With the help of *Swift*/XRT and *Chandra* observations, Lutovinov et al. (2016) were capable of identifying a likely infrared counterpart for 2S 1553-542 at RA(J2000) = 15 h 57 m 48.28 s Dec(J2000) = $-54^{\circ}24' 53.5''$.

IGR J16374-5043. Inside the error circle around the *Swift*/XRT position of IGR J16374-5043, Sguera et al. (2020) found only one infrared source. This source is not listed in the 2MASS catalogue but is in the catalogue of *Gaia* (*Gaia* DR3 5940285090075838848) and is likely to be the optical counterpart of IGR J16374-5043.

XTE J1716-389. Ratti et al. (2010) used *Chandra* for localisation of Galactic X-ray sources and did follow-up observations in the optical and NIR bands. One of the observed sources was XTE J1716-389. The refined *Chandra* position allowed Ratti et al. (2010) to identify the only possible optical counterpart, an infrared source 2MASS J17155645-3851537, that is thus considered to be XTE J1716-389's counterpart.

IGR J17375-3022. IGR J17375-3022 was a poorly studied source until Sguera et al. (2020) investigated it in the hard and soft X-ray bands, and in the infrared band. With an enhanced source position from *Swift*/XRT, the study found only one NIR object within the *Swift*/XRT error circle in the VVV survey. Therefore, Sguera et al. (2020) proposed that VVV J173733.74-302314.5 is the best counterpart candidate for IGR J17375-3022.

RX J1739.4-2942. RX J1739.4-2942, originally identified as an LMXB, could potentially be a Be/HMXB Bahramian et al. (2016). Therefore, we included RX J1739.4-2942 in the catalogue as an HMXB candidate (Number 67 in Liu et al. 2006).

IGR J18029-2016. Walter et al. (2006) proposed two possible NIR counterparts for IGR J18029-2016; they were 2MASS J18024194-2017172 and 2MASS J180242.0-201720.2, which were found in the 2MASS catalogue and the Second Guide Star Catalogue, respectively. The first candidate, 2MASS J18024194-2017172, was later confirmed to be the counterpart of the HMXB by Masetti et al. (2008).

IGR J18179-1621. With the refined position of IGR J18179-1621 reported by Li et al. (2012), Nowak et al. (2012) were able to observe the object with *Chandra* and identify a possible optical counterpart. 2MASS J18175218-1621316 was identified as a possible companion, due to it being the only NIR source in the 2MASS catalogue within a 1'' radius of the *Chandra* position.

IGR J18219-1347. Quite recently [O'Connor et al. \(2022\)](#) identified a bright IR counterpart for IGR J18219-1347 close to the *Chandra* localisation, at RA(J2000) = 18 h 21 m 54.821 s Dec(J2000) = $-13^{\circ}47'26.703''$, which appeared to be the combination of two point sources (Star A and Star B). They concluded that Star A is the Counterpart of IGR J18219-1347, because it is consistent with the SED of a Be star, and therefore the system was classified as a BeXRB.

AX J1841.0-0536. [Fortin et al. \(2022a\)](#) queried the confirmed HMXBs of their previous work ([Fortin et al. 2022b](#)) in *Gaia* DR3. For AX J1841.0-0536 the source *Gaia* DR3 4256500538116700160 was therefore identified as an optical counterpart.

Ginga 1839-04. For Ginga 1839-04 no optical counterpart has yet been identified. [Liu et al. \(2006\)](#) included this source in their catalogue due to a tentative pulsation detection of ~ 81 s ([Koyama et al. 1990](#)) by Ginga during an outburst in 1989. Since then no further X-ray detections have been reported ([Sguera et al. 2009](#)). Therefore, Ginga 1839-04 is classified as a candidate HMXB in this catalogue.

IGR J18482+0049. [Bodaghee et al. \(2012\)](#) observed five INTEGRAL sources towards the Scutum Arm, one of which was IGR J18482+0049. With the refined position, they found only one object in the 2MASS catalogue that was consistent with the *XMM-Newton* position. Based on this observation, IGR J18482+0049 has a possible association with 2MASS J18481540+0047332.

Ginga 1855-02. Within Ginga 1855-02, the positional error is $10'$ ([Koyama et al. 1990](#)). Like Ginga 1839-04, Ginga 1855-02 is a poorly studied source that does not have an identified optical counterpart, and therefore it is also classified as a candidate HMXB based on its transient behaviour.

XTE J1859+083. After an outburst of XTE J1859+083 detected by MAXI ([Negoro et al. 2015](#)), follow-up *Swift*/XRT observations by [Li & Kong \(2015\)](#) allowed the improvement of the position of the HMXB. No UVOT counterpart was detected, but with the enhanced position [Li & Kong \(2015\)](#) were able to find a possible counterpart in the USNO-B1.0 (USNO-B1.0 0982-0467424) and 2MASS catalogues (2MASS J18590163+0814444).

1E 1912.5+1031. [Bozzo et al. \(2011\)](#) identified 2MASS J19145680+1036387 as the most likely counterpart of 1E 1912.5+1031, based on the position inside the error circle of their estimated *Swift*/XRT position for 1E 1912.5+1031.

AX J1949.8+2534. For AX J1949.8+2534 the source 2MASS J19495543+2533599 was proposed to be the optical counterpart ([Sguera et al. 2017](#)). This was later confirmed to be the case by [Hare et al. \(2019\)](#).

W63 X-1. W63 X-1 is an X-ray binary within the supernova remnant W63, with a pulsation period of 36 s ([Rho et al. 2004](#)). Based on the pulsation period and spectrum, [Rho et al. \(2004\)](#) concluded that the companion is likely an isolated neutron star, HMXB, or LMXB. They found an optical counterpart with $H\alpha$ -excess emission typical for a Be companion, and thus classified the source as an HMXB.

Several objects present in [Liu et al. \(2006\)](#) were removed from the current catalogue as they are no longer classified as HMXBs:

1WGA J0648.0-4419. 1WGA J0648.0-4419, previously listed as source 18 in [Liu et al. \(2006\)](#), was removed because the optical star in the system has since been classified as a hot sub-dwarf ([Jaschek & Jaschek 1963](#)).

IGR J12349-6434. IGR J12349-6434 (source 35 in [Liu et al. 2006](#)) was initially classified as a new source. However, it is thought to be associated with RT Cru ([Tueller et al. 2005](#)), a symbiotic star containing a WD ([Luna & Sokoloski 2007](#)). It was therefore excluded from the catalogue.

1A 1246-588. 1A 1246-588, which was source 38 in [Liu et al. \(2006\)](#), is an LMXB ([Bassa et al. 2006](#)).

SAX J1452.8-5949. With the de-reddened magnitudes of their observations in the *JHK*-bands and the assumption of a black-body model, [Kaur et al. \(2009\)](#) made estimations of the distance of SAX J1452.8-5949 (source 46 in [Liu et al. 2006](#)). This ruled out the possibility of the object being an HMXB, due to the fact that the system would be an extragalactic source. They concluded that the binary system must have a low mass companion, and therefore is either an LMXB or an intermediate polar (IP, accreting magnetised white dwarf).

IGR J16358-4726. [Chaty et al. \(2008\)](#) classified IGR J16358-4726 (source 55 in [Liu et al. 2006](#)) as an HMXB; however, this classification was revoked by [Nespoli et al. \(2010\)](#) and the source is now considered to be a symbiotic X-ray binary.

AX J1700.1-4157. Based on NIR observations, [Kaur et al. \(2010\)](#) estimated that the companions of AX J1700.1-4157²⁶ (source 63 in [Liu et al. 2006](#)) should be a low mass star. In combination with a detected Fe emission line, [Kaur et al. \(2010\)](#) concluded that AX J1700.1-4157 is most likely an IP, and therefore AX J1700.1-4157 was removed from this catalogue.

IGR J17091-3624. IGR J17091-3624 (source 64 in [Liu et al. 2006](#)) is also now classified as an LMXB ([Grinberg et al. 2016](#)).

AX J1740.1-2847. AX J1740.1-2847 (source 68 in [Liu et al. 2006](#)) is a similar case to AX J1700.1-4157. [Kaur et al. \(2010\)](#) also estimated that the companion should be a low mass star, and due to a detected Fe emission line they concluded that AX J1740.1-2847 is most likely an IP as well, and hence it was removed from the catalogue.

4U 1807-10. 4U 1807-10 (source 75 in [Liu et al. 2006](#)) was detected by UHURU ([Forman et al. 1978](#)) within a large error of 1.3° . To date, it is not certain if 4U 1807-10 is an HMXB or an LMXB. However, it is more likely that 4U 1807-10 is an LMXB as the system shows type I X-ray bursts ([Chelovekov et al. 2017](#)). Therefore, we excluded it from this catalogue.

SAX J1819.3-2525. [MacDonald et al. \(2014\)](#) determined a mass of $2.9 M_{\odot}$ for the optical companion of SAX J1819.3-2525²⁶ (source 77 in [Liu et al. 2006](#)), which classifies this system as an IMXB, and therefore it was excluded from the catalogue.

²⁶ It can be found in the recently published catalogue of high mass X-ray binaries in the Galaxy by [Fortin et al. \(2023\)](#).

AX J1838.0-0655. AX J1838.0-0655²⁶ (source 82 in Liu et al. 2006) is currently classified as a supernova remnant. Malizia et al. (2005) does not exclude the possibility of AX J1838.0-0655 being an X-ray binary, but mentions that this scenario is unlikely due to the lack of strong X-ray and γ -ray variability, as well as the extension of the source to up to TeV energies. Therefore, AX J1838.0-0655 was removed from the catalogue.

XTE J1901+014. Karasev et al. (2008) proposed that XTE J1901+014 (source 94 in Liu et al. 2006) could be the first low mass fast X-ray transient. To date, the nature of this system is not completely clear (Sato et al. 2019); we therefore decided to exclude this source from the current version of this catalogue.

XTE J1906+09. XTE J1906+09 (source 96 in Liu et al. 2006) was not excluded, but the name was changed to XTE J1906+090 to match that commonly used in the literature.

A handful of sources that are included in the recently published catalogue of high mass X-ray binaries by Fortin et al. (2023) have been omitted from our catalogue. These sources have already been mentioned and are AX J1700.1-4157, SAX J1819.3-2525, AX J1838.0-0655, and GRS 1758-258. In the case of GRS 1758-258, there is a possibility that the system is an intermediate-mass X-ray binary, as proposed by Martí et al. (2016), and hence this source can be found in Avakyan et al. (2023) instead of this catalogue.

4. Conclusion

The Major changes with respect to Liu et al. (2006), in addition to the problematic cases, are described here:

- We homogenised the energy ranges of the reported X-ray fluxes. Liu et al. (2006) used an energy range of 2–10 keV for most sources, but in some cases the nominal energy range was different, and identifying these cases was not trivial. We now quote the soft and hard X-ray fluxes in well-defined energy ranges separately;
- Liu et al. (2006) only reported the maximum value of X-ray flux in units of Jy in most cases. In this work we report flux ranges in the two energy bands in the more commonly used cgs units, which are more accessible for X-ray sources;
- We increased the number of flags used to characterise source properties from 6 in Liu et al. (2006) to a total of 15 to better reflect the various features reported in the literature;
- While Liu et al. (2006) flags sources where a cyclotron line was detected, no information regarding the energy is available in most cases. We report both the observed energies and corresponding references. The number of objects where a line was detected also increased substantially due to the availability of new observations and publications;
- Effective stellar temperature and estimated optical luminosity, as well as the hydrogen column density are three completely new fields introduced in this version of the catalogue;
- Finally, we include up to six finding charts as part of the catalogue (from NIR images to hard X-ray bands) instead of referencing the existing finding charts.

Differences with respect to Fortin et al. (2023) are as follows:

- Fortin et al. (2023) utilised a flag to indicate the type of the optical companion. We used similar flags for the optical companion, but introduced additional flags for the compact object (e.g. CRSF to indicate if a neutron star has a detected cyclotron line);

- For sources with known cyclotron line energies we included both fundamental and harmonic energies;
- In addition to the cyclotron line energy, we also reported X-ray fluxes in different energy ranges for the compact object. This can be used to gauge the variability of the source and to make an estimation of the expected flux, although this cannot replace an in-depth analysis of individual sources;
- For the optical companions, we reported magnitudes in the optical and in the NIR bands. Some additional information regarding the properties of optical counterparts can be found in Fortin et al. (2023).

Together with the catalogues of Fortin et al. (2023) and Avakyan et al. (2023), this catalogue provides a useful tool for further studies of XRBs. With ongoing surveys like eROSITA, the number of known XRBs is expected to increase substantially (Doroshenko et al. 2014); therefore, we plan to keep the web version of our catalogue²⁷ up-to-date to the best of our ability.

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²⁷ <http://astro.uni-tuebingen.de/~xrbcat/>

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Appendix A: Catalogue format

Table A.1. Definition of columns in the HMXB catalogue. In total the catalogue contains **66** columns.

Nº	Column name	Unit	Description
1	'Name'		Object name, which is the most common name in the literature
2	'RAdeg'	deg	Right Ascension in degrees (ICRS).
3	'DEdeg'	deg	Declination in degrees (ICRS).
4	'PosErr'	arcsec	Positional error in arcseconds.
5	'Coord_Ref'		Reference of catalogue or literature, which was used to extract the coordinates and uncertainties
6	'ID_Flag'		Robust identification of the optical counterpart: 0 — solidly identified optical counterpart in the literature 1 — tentative optical counterpart identification in the literature 2 — no identified optical counterpart
7	'GLON'	deg	Galactic longitude in degrees.
8	'GLAT'	deg	Galactic latitude in degrees.
9	'Xray_Type'		List of the X-ray types assigned to the object. For more information see section above § 2.1.
10	'Porb'	day	Orbital period of the binary system in days if determined.
11	'Ppulse'	s	Pulsation period (spin) of the binary (with NS) in seconds if determined.
12	'CRSF'	keV	Cyclotron line energies in keV
13	'Alt_Name'		Second most used name in the literature.
14	'SpType'		Spectral type of the optical counterpart.
15	'Gaia_DR3_ID'		Source Name in the Gaia DR3 catalogue.
16	'Gmag'	mag	Optical magnitude in G-band according to a Gaia's catalogue.
17	'e_Gmag'	mag	Corresponding magnitude's error in G-band according to Gaia's catalogue.
18	'Vmag'	mag	Optical magnitude in V-band according to SIMBAD database.
19	'e_Vmag'	mag	Corresponding magnitude's error in V-band according to SIMBAD database.
20	'Jmag'	mag	IR magnitude in J-band according to 2MASS (Cutri et al. 2003).
21	'e_Jmag'	mag	Corresponding magnitude's error in J-band according to 2MASS (Cutri et al. 2003).
22	'Hmag'	mag	IR magnitude in H-band according to 2MASS (Cutri et al. 2003).
23	'e_Hmag'	mag	Corresponding magnitude's error in H-band according to 2MASS (Cutri et al. 2003).
24	'Kmag'	mag	IR magnitude in K-band according to 2MASS (Cutri et al. 2003).
25	'e_Kmag'	mag	Corresponding magnitude's error in K-band according to 2MASS (Cutri et al. 2003).
26	'W1mag'	mag	IR magnitude in W1 <i>CatWISE</i> 2020 band (Marocco et al. 2021).
27	'e_W1mag'	mag	Corresponding magnitude's error in W1 <i>CatWISE</i> 2020 band (Marocco et al. 2021).
28	'W2mag'	mag	IR magnitude in W2 <i>CatWISE</i> 2020 band (Marocco et al. 2021).
29	'e_W2mag'	mag	Corresponding magnitude's error in W2 <i>CatWISE</i> 2020 band (Marocco et al. 2021).
30	'N_H'	10^{21} cm^{-2}	Neutral hydrogen column density, assuming a power-law spectrum (Evans et al. 2020).
31	'XMM_min_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Minimum X-ray flux for XMM-Newton (0.2-12.0 keV).
32	'XMM_max_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Maximum X-ray flux for XMM-Newton (0.2-12.0 keV).
33	'Chandra_min_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Minimum X-ray flux for <i>Chandra</i> ACIS (0.5-7.0 keV) or HRC (0.1-10.0 keV).
34	'Chandra_max_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Maximum X-ray flux for <i>Chandra</i> ACIS (0.5-7.0 keV) or HRC (0.1-10.0 keV).
35	'Chandra_Instrument'		<i>Chandra</i> Instrument used for <i>Chandra</i> flux values.
36	'XRT_min_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Minimum X-ray flux for Swift/XRT (0.3-10.0 keV).
37	'XRT_max_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Maximum X-ray flux for Swift/XRT (0.3-10.0 keV).
38	'BAT_min_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Minimum X-ray flux for Swift/BAT (14-195 keV).
39	'BAT_max_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Maximum X-ray flux for Swift/BAT (14-195 keV).
40	'INTEGRAL_min_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Minimum X-ray flux for INTEGRAL (17-60 keV).
41	'INTEGRAL_max_flux'	$10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$	Maximum X-ray flux for INTEGRAL (17-60 keV).
42	'Mean_Mass'	$M_{\odot}$	Mean mass of the compact object.
43	'Low_Mass'	$M_{\odot}$	Lower limit of the compact object mass.
44	'High_Mass'	$M_{\odot}$	Upper limit of the compact object mass.
45	'Mean_Dist'	pc	Mean (between the two, minimum and maximum) estimate of the distance to the binary system according to Gaia Collaboration (2023); Bailer-Jones et al. (2021); Anders et al. (2022) or taken from literature. In every literature case only one source of information was taken.

Table A.1. continued

N ^o	Column name	Unit	Description
46	'Low_Dist'	pc	The lowest (minimum) estimate of the distance to the binary system according to Gaia Collaboration (2023) ; Bailer-Jones et al. (2021) ; Anders et al. (2022) or taken from literature. In every literature case only one source of information was taken.
47	'High_Dist'	pc	The highest (maximum) estimate of the distance to the binary system according to Gaia Collaboration (2023) ; Bailer-Jones et al. (2021) ; Anders et al. (2022) or taken from literature. In every literature case only one source of information was taken.
48	'Teff'	K	Effective stellar temperature provided by Gaia Collaboration (2023) ; Anders et al. (2022) .
49	'Lopt'	L _☉	Luminosity estimate of the optical companion provided by Gaia Collaboration (2023) .
50	'IDS'		List of all identifiers, that we found in SIMBAD and in the catalogues and articles.
51	'CRSF_Ref'		References to the articles, which providing the corresponding values for cyclotron line energies.
52	'Spin_Ref'		References to the articles, which providing the corresponding value for Pulsation Periods.
53	'Orb_Ref'		References to the articles, which providing the corresponding value for Orbital parameters.
54	'Spectral_Ref'		References to the articles, which providing the spectral type of the optical star.
55	'Dist_Ref'		Reference to the article, which provides the distance estimation, if literature values were used.
56	'Mass_Ref'		Reference to the article, which provides the mass estimation of the compact object.
57	'misc_Ref'		miscellaneous references regarding the object.
58	'comments'		Comments regarding the object.
59	'_2MASS_ID'		Source name in the 2MASS All-Sky Catalogue of Point Sources
60	'CatWISE_ID'		Source name in the CatWISE2020 catalogue
61	'ROSAT_ID'		Source name in the Second ROSAT all-sky survey (2RXS) source catalogue
62	'XMM_ID'		Source name in the XMM-Newton Serendipitous Source Catalogue
63	'Chandra_ID'		Source name in the <i>Chandra</i> Source Catalogue (CSC) Release 2.0
64	'XRT_ID'		Source name in the 2SXPS Swift X-ray telescope point source catalogue
65	'BAT_ID'		Source name in the Swift-BAT 105-Month All-Sky Hard X-Ray Survey catalogue
66	'INTEGRAL_ID'		Source name in the INTEGRAL/IBIS 9-year Galactic Hard X-Ray Survey catalogue

Paper III

A. Avakyan, A. Zainab, V. Doroshenko,
J. Wilms, M. Salvato, A. Schwope, A. Santangelo
"Hunting down new Galactic XRBs in eROSITA DR1 using ML"

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III

Hunting down new Galactic XRBs in eROSITA-DE DR1 using ML[★]

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ABSTRACT

The first data release (eRASS DR1) by the extended ROentgen Survey Imaging Telescope Array (eROSITA) mission containing the data obtained in the first six months of the operation (western Galactic hemisphere, eROSITA-DE Consortium) has been made public on 31st of January 2024. Here we report on a search for new Galactic X-ray binaries (XRBs) among eRASS DR1 sources and present two catalogues of Galactic high- and low-mass X-ray binary (HMXB and LMXB, respectively) candidates. Catalogue tables include X-ray properties from eRASS DR1 and characteristics of the identified optical and infrared counterparts for **192** XRB candidates in total. The aim of this work is to obtain the first self-consistent estimate of XRB numbers observable by eROSITA, expand the sample of low-luminosity XRBs and provide a basis for subsequent dedicated follow-up observations. The candidate selection was done based on their X-ray properties observed by eROSITA and multi-wavelength (MWL) properties of plausible counterparts in other bands. The selection of MWL counterparts among all potential associations, and final source classification were accomplished using machine learning (ML) methods as part of a single procedure tuned specifically to identification of XRBs. We plan to regularly update the list of XRB candidates to reflect results of ongoing follow-up observations and future eROSITA data releases, which will unveil further hitherto hidden parts of the XRB population in the Milky Way.

Key words. X-rays: binaries – methods: data analysis – methods: statistical – catalogs – astronomical data bases: miscellaneous – binaries: general

1. Introduction

Population studies of X-ray binaries (XRBs) are key to understanding the evolution of massive stars and the properties of the host galaxy. Naturally, detection and identification of a substantial fraction of all XRBs to form a representative sample is required for such studies. The observed X-ray luminosity function (XLF) of the Galactic XRBs (Grimm et al. 2002; Revnivtsev et al. 2008; Voss & Ajello 2010; Mineo et al. 2011; Lutovinov et al. 2013; Doroshenko et al. 2014) implies, however, that the majority of them have relatively low X-ray luminosities $L_x \lesssim 10^{34-35}$ erg/s, and thus likely escaped detection in current wide-area X-ray surveys with moderate sensitivity (Doroshenko et al. 2014). This makes the expansion of the faint XRB sample essential for understanding the properties of their entire population, as well as studying accretion physics at low states.

The extended ROentgen Survey Imaging Telescope Array (eROSITA, Merloni et al. 2012; Predehl et al. 2021) on board the Spectrum-Roentgen-Gamma (Spektra-RG, SRG) satellite with a factor $\gtrsim 10$ better sensitivity compared to previous surveys is an ideal instrument for this purpose. Indeed, it not only exceeds the sensitivity of the previous soft X-ray all-sky survey Roentgensatellite (ROSAT, Truemper 1982; Voges et al. 1999; Boller et al. 2016) by factor of forty, but also covers a wider energy range (0.2-10 keV compared to 0.2-2 keV covered by ROSAT). This makes it far less susceptible to absorption effects in the Galactic plane where most XRBs are located. Compared to ROSAT, eROSITA also offers higher positional accuracy, pro-

vides comprehensive spectral and timing information over several timescales, and operates in a new era of high-fidelity all-sky optical and infrared (IR) surveys enabling easier identification of counterparts to X-ray sources in other bands (essential for establishing their nature). Being a focusing instrument, eROSITA is also more sensitive than coded-mask hard X-ray surveys like *Swift* Burst Alert Telescope (*Swift*/BAT, Gehrels et al. 2004; Barthelmy et al. 2005) and INTERNATIONAL Gamma-Ray Astrophysics Laboratory (INTEGRAL, Winkler et al. 2003), and offers much better positional accuracy. Given these characteristics, up to several hundred new Galactic XRBs have been predicted to appear in full eROSITA survey (Doroshenko et al. 2014) thereby doubling the known sample. Crucially, most of the newly revealed XRBs are expected to be relatively faint ($L_x \lesssim 10^{34-35}$ erg/s), i.e. in the range where XRB XLF constraints are currently least robust. eROSITA has successfully completed four (six months each) out of eight planned all-sky surveys, and data from the first survey has recently been released as part of the first public data release for half of the sky (Merloni et al. 2024, eRASS DR1, first six months scan, western Galactic hemisphere).

Here we report on a search for XRB candidates among almost a million of eRASS DR1 sources and present two catalogues of identified high- and low-mass X-ray binary (HMXB and LMXB) candidates. The identification of a few dozens to hundreds of XRBs amidst hundreds of thousands of other X-ray sources (see Fig. 1) is non-trivial. Effectively disentangling XRBs from other source types and minimising contamination of the sample, can only be ensured by accurate classification. Moreover, any classification of X-ray sources is hardly feasible based on the soft X-ray information alone and requires the us-

[★] The table containing XRB candidates is available in electronic form at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via cdsarc.cds.unistra.fr/cgi-bin/qcat?J/A+A.

age of multi-wavelength (MWL) data. Therefore, identification of plausible optical and IR counterparts to X-ray sources is the first and integral part of the problem.

Practical methods employed in classification typically rely on examining various 2D plots in the MWL parameter space: colour-colour diagrams, colour-magnitude diagrams (CMDs), X-ray hardness dependencies, X-ray-to-optical/IR flux ratios, etc (see Kaplan et al. 2006; Misanovic et al. 2010; Yang et al. 2021). Such plots are analysed in order to pinpoint sources with unique features indicative of specific origin type. For example, X-ray-to-optical/IR flux ratios can highlight objects with enhanced X-ray emission relative to their optical counterparts, generally distinguishing accreting sources from regular stars. However, when considering billions of sources and potential survey-to-survey cross-correlations, the traditional classification approach becomes both inhumanly time-consuming and tedious, often lacking clear guidelines on how to assign confidence to these classifications.

An effective solution to these challenges is the implementation of an automated classification system. One of the most efficient methods involves using supervised machine-learning (ML) techniques to analyse large datasets. In the setting of X-ray sources, the application of ML methods was firstly done by McGlynn et al. (2004), where authors utilised oblique decision trees (Murthy et al. 1994) to categorise sources from ROSAT data. Since then, ML techniques have been implemented in numerous works in order to classify X-ray sources based on MWL data. Some studies rely on Bayes metric methods (Broos et al. 2011; Hand & Yu 2001), which have shown to perform well on XMM-Newton and Swift/XRT data (Tranin et al. 2022). However, currently, one of the fastest and most effective methods in use are Random Forest (RF) algorithms (Breiman 2001), which have been utilised to classify sources in Chandra (Yang et al. 2022) and XMM-Newton serendipitous catalogues (Lo et al. 2014; Farrell et al. 2015), and even to specifically find unidentified XRBs among sources detected by Chandra in the Andromeda (M31) galaxy (Arnason et al. 2020).

In this work, we use a combination of ensemble learning random decision forests classifiers implemented in sklearn package, version 0.23.2 (Pedregosa et al. 2011) for and identification of the plausible MWL counterparts and final classification. In order to obtain reliable counterpart associations, we incorporated NWAY¹ (Salvato et al. 2018) algorithm, employs a Bayesian statistical framework to probabilistically match sources from multiple astronomical catalogues in a multidimensional parameter space (positions, positional uncertainties, density of sources, magnitudes, colours, variability information, etc).

The structure of the paper is as follows: in Sect. 2 we discuss the motivation behind the adopted procedure for search and identification of XRBs among eROSITA sources followed by the simplified description of the procedure itself in Sect. 3. In Sect. 4 we describe X-ray, optical and IR catalogues used to select potential counterparts to eROSITA sources and their multi-wavelength (MWL) properties or “features” ultimately used for counterpart selection and subsequent classification. We also discuss there how missing data is treated (data imputation). In Sect. 5 we discuss details of the model implementation (algorithms used). In Sect. 6 we discuss results of the XRB search quest, assess purity and completeness of the derived XRB candi-

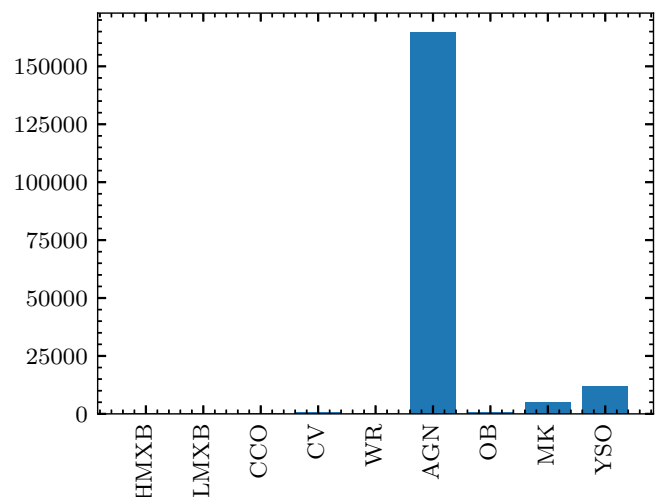


Fig. 1. Histogram distribution of different classes of X-ray sources detected by eROSITA. For X-ray types description see Sec. 5.2.

dates sample, and describe structure and auxiliary data included in final eROSITA XRB candidates catalogues. Finally, we summarise the main results of this work and discuss their possible implications for future research in Sect. 7.

2. A case for discrimination against AGNs

The NWAY cross-matching tool is widely used for counterpart identification, and is able to take into account not only geometrical coincidence between X-ray sources and objects detected in other catalogues, but also allows to incorporate available prior information for plausible counterparts. For instance, most X-ray bright AGNs are also bright IR sources, so if most X-ray sources in a catalogue are AGNs, it is sensible to prefer IR bright objects among potential counterparts allowed by the positional uncertainty. In this case one could say that an AGN-like source can be considered as a plausible “X-ray emitting source” and use IR magnitudes of potential counterparts as the weight or prior for their selection (the lower the magnitude, the higher the probability for this object to be selected as a counterpart to an X-ray source). Of course, more complex selection criteria can be applied, for instance, one could require that, besides being red, a source should not have a significant *Gaia* parallax, etc. This point becomes especially important for crowded fields or when accuracy of positions in any of the bands is not sufficiently high for unambiguous identification of counterparts based on positional coincidence alone. eROSITA has typical $3\text{-}\sigma$ positional error circle of $\approx 15''$, which, while much better than ROSAT, still allows multiple potential counterparts to be considered. Thus, using tools like NWAY is essential and became the standard for identification of the counterparts within the eROSITA_DE consortium.

The problem is, however, that priors for various types of X-ray objects are inherently different, and the assumed object type depends on the result of the classification procedure itself, which in turn, relies on the properties of the identified counterpart, i.e. we have a kind of a chicken or the egg problem. For instance, reliable selection of counterparts for true AGNs would require giving preference to red extra-Galactic objects, whereas for HMXBs blue early type star counterparts should be preferred. Unfortunately, we do not know a priori which of the X-ray sources is an AGN, which is HMXB (or other object type)

¹ github.com/JohannesBuchner/nway

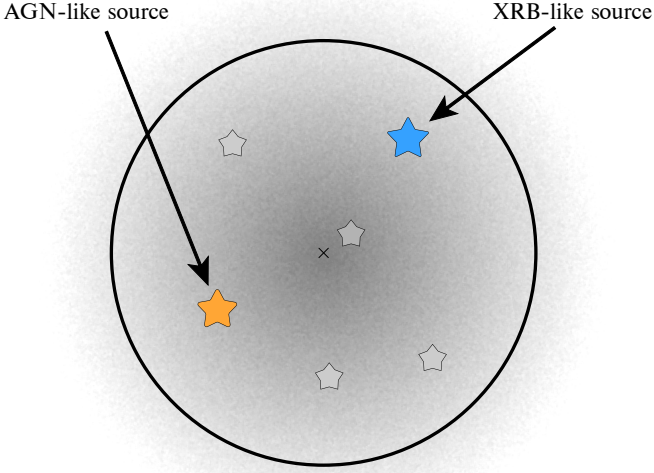


Fig. 2. Schematic representation of the case with two different ‘X-ray source-like’ plausible counterparts. Black circle represents $3\text{-}\sigma$ error of the X-ray source position. Shading shows geometrical probability of association with the X-ray source. Blue star is the potential optical/IR counterpart which behaves like an XRB, orange — optical/IR properties similar to those of an AGN, all other grey stars are the background low prior probability optical/IR sources.

because they can have virtually indistinguishable X-ray properties. The situation is illustrated in Fig. 2 where shading reflects geometrical probability of association for a given object with an X-ray source: the grey stars have MWL properties which imply they are unlikely to be X-ray emitting at observed level, and AGN-like and XRB-like optical/IR sources have same geometrical probability of association. Such a scenario results in the X-ray source with no clear path to select between the two potential counterparts.

One natural approach to this problem could be to aim for the highest fraction of correct associations on average, i.e. tune priors for the “average” X-ray-emitter object type. The problem is, however, that in this case, counterparts with properties of those in the dominating source class will always be preferred and counterpart selection for minority classes (and subsequent classification) will be biased towards the dominating class. In the case of eROSITA, large majority of all detected point sources are either AGNs or normal stars (see Fig. 1). Thus, if the priors are tuned to average “X-ray emitting” source, “not-so-average” X-ray sources (such as XRBs, CVs) will tend to get AGN/star-like counterparts. This is totally fine if one is interested in dominating source classes where small contamination by less numerous objects can generally be ignored. However, that becomes a real problem if one aims to find a needle in a haystack, i.e. few dozens of XRBs among hundreds of thousands of AGNs and normal stars.

3. Welcome to the machine(s)

As discussed above, classification of eROSITA X-ray sources relies heavily on MWL properties of their potential counterparts in other bands, most notably optical and IR. The task of searching for X-ray sources of a particular class can be separated in two steps:

- identification of plausible counterparts in other bands based on spatial coincidence with X-ray source and priors obtained

from optical/IR properties of the potential counterparts tuned for the particular source class of interest

- X-ray source classification based on MWL properties of the identified counterparts

The first step ensures that all target class objects have the most appropriate MWL counterparts and thus highest chance to be classified as such, i.e. increases completeness of the candidate list. Of course, this implies that some objects of other types will be assigned wrong counterparts making them more similar to target class, and ultimately incorrectly classified. That is, purity of the final sample identified as belonging to the target class is reduced. This reduction shall be assessed, and to some extent can be compensated, during the second classification step. Whether reduction in purity of the final target class sample is justified by increase of the completeness depends on the goals of the search, i.e. it could be problematic if number of identified candidates is unmanageably large for independent verification. In the context of the search for XRBs, we are however, willing to take this compromise as the total number of XRB candidates in eRASS1 is not expected to exceed few hundreds, so even manual screening of automatically identified XRB candidates is feasible. In practice we accomplish both steps (MWL counterpart identification and final classification), using the random forest (RF) supervised ML method.

In the first step we solve a task of RF classification of all potential optical/IR counterparts of all eROSITA sources in two classes: class of interest (i.e. HMXB-like or LMXB-like) and objects of other types. Here, we only use optical and IR properties of the counterparts themselves, and X-ray properties are not taken into account since we do not know at this point if the given optical/IR source is associated with an X-ray source. We cross-correlate eRASS1 catalogue with a set of optical and IR catalogues described in Sect. 4.1 and consider all optical/IR objects within $30''$ region around eROSITA sources to be potential counterparts. The size of the cutout region is chosen to exceed typical $3\text{-}\sigma$ eROSITA positional uncertainty while still keeping the number of potential candidates manageable. First, we train an RF classifier (the first “machine”) to discriminate between XRB-like and non-XRB-like objects. For that we use a sample of known optical/IR counterparts of XRBs (from Neumann et al. 2023 and Avakyan et al. 2023) and other optical/IR sources within $1'$ circle from the true counterpart as the training sample. The assumption is then that there are no other unknown XRBs within this region. Again, only properties of optical/IR sources are used at this step. The trained classifier is then used to infer probability that each optical/IR source within $30''$ from each eROSITA source belongs to the target source class (HMXB or LMXB). These probabilities are then normalised and used as an external prior to Nway for final identification of likely counterparts of the target class to all X-ray sources also taking spatial coincidence into account. Spatial coincidence actually dominates the choice of counterparts for cases when X-ray position is well constrained and/or in low-density sky fields. The process is then repeated for each of the two target classes (HMXB and LMXB) separately, which results in slightly different sets of preferred optical/IR counterparts.

The list of the selected counterparts and their optical/IR properties together with X-ray properties observed by eROSITA are then used as input for the second step. Here another RF classifier (the second “machine”) is trained to classify all eROSITA X-ray sources based on the obtained MWL features (X-ray & optical/IR/other properties of identified counterparts, see Table 1). However, while we use a similar set of MWL features as in

the first step (complemented by X-ray data from eROSITA and other information), the corresponding list of source classes is expanded to include all relevant object classes, and not simply discriminate between XRB-like and non-XRB-like objects. The list of X-ray type classes is presented and described in Sect. 4.2. The reason to use wide range of classes is that unlike the counterpart identification case which effectively has two classes (“H/LMXB-like” and “not H/LMXB-like” counterpart), here we are actually searching for members of particular source types (LMXB or HMXB) with specific characteristic properties which largely overlap with objects of other types. Considering all non-XRB sources a single class tends therefore, to blur its definition and degrade performance of the classifier.

In principle, both steps need to be done independently for each target source class (not only HMXB and LMXB), followed by some procedure to combine the results (or simultaneously) if one aims for homogeneous classification of the entire X-ray sample. Indeed, probable counterparts for potential LMXBs can generally be different than those for HXMBs, and so on, which means that different optical/IR counterparts are generally used for each source class. Thus, results of the classification will also vary. Here we do not attempt, however, to specifically classify all eROSITA sources as it goes far beyond the scope of the current work. Indeed, optimal selection of source classes to be considered, labeled object lists, subset of their properties, methods of training etc can also be different for various object types, so full classification of eROSITA sample is a far more challenging task than what we do here. Instead, we focus specifically on HMXB and LMXB classes separately and tune our methodology to identify as many of those as possible even if classification performance for other object classes might be degraded. Below we discuss the procedure, features used for counterpart selection and final classification, and catalogues used to identify sources of known origin in eRASS DR1 in more detail.

4. Features and labels

As already mentioned, we are using ML RF approach to identify counterparts and classify eROSITA sources. This implies that before proceeding we need to compile training, test and verification datasets consisting of clean samples of objects with known origin (“labels”), and MWL properties of their counterparts (or potential counterparts to X-ray sources of unknown origin) to be used as input for RF classifier (“features”). The labelled set shall include sufficient number of members of all relevant classes potentially present among sources of unknown nature (eROSITA sample), and list of “features” shall be suitable for task of classification, i.e. shall contain relevant information to allow efficient discrimination between various classes and training of the classifier. Note that both “label” and “feature” lists are specific to a particular problem and subjective to some extent, although the correctness of choices made may be assessed through quantitative metrics (such as feature importance diagrams) as we describe further here and in Sect 5.1, 5.2.

In the subsections below we describe the list of properties (“features”) and objects classes (“labels”) used in this work specifically for search of XRBs in eROSITA sample, and information sources. We start by discussing “features” as labelling X-ray sources already requires knowledge of their counterparts.

4.1. MWL and X-ray properties used for classification

Telling apart an XRB from a CV or an AGN might be tricky when using X-ray data alone, but becomes easier if also their

properties in other bands are considered. Similarly, high IR flux or an H_α emission line makes a probability that given optical source is an X-ray emitter much higher (AGN or BeXRB). This type of information is commonly referred to as “features” in ML context when used for classification or regression. The selection of features and their quality largely defines the result of the classification process and thus is extremely important. One of the main requirements here is that relevant information, i.e. full set of properties considered (i.e. features), is available for large majority of objects in the sample. For an all-sky survey like eROSITA this implies that mostly MWL information provided by other large-area surveys can be used, and that is what mainly motivated our choice of catalogues and surveys to extract features to be used for source classification and counterpart identification listed below and listed in Table 1. The table provides names of the features, corresponding units, their short description and data sources. The feature set is similar for both steps of the two-step ML RF classification analysis described above. It is with the exception that for a final classification we only use optical/IR features of identified counterparts to X-ray sources and complement them by X-ray and some other additional parameters.

Gaia DR3

Gaia Data Release 3 (DR3, [Gaia Collaboration et al. 2023](#))² catalogue containing impeccable astrometry, apparent optical magnitudes (close to visual, down to ~ 20 mag), colours and more for approximately 1.8 billion objects has become key dataset for most current research including this work. From its data, for our set of features we selected optical magnitudes (G , BP and RP band), as well as information on the distances, which are important to estimate luminosities in optical and other bands. Note that most of the XRBs are located beyond 3 kpc ([Avakyan et al. 2023](#); [Neumann et al. 2023](#)), where the fractional *Gaia* parallax uncertainties are sufficiently large to make direct inversion of parallaxes unfeasible. To overcome that, [Bailer-Jones et al. \(2021\)](#) used different models to estimate distances to sources in *Gaia* eDR3. Therefore, we add distance and distance error estimates from [Bailer-Jones et al. 2021](#) (BJ21 hereinafter) catalogue³. For objects where no *Gaia* counterpart and/or distance data were available, we resorted to alternative distance estimates (also using *Gaia* even if indirectly) as described further. In addition, we also use *Gaia* data in order to account for source variability and potential binary system orbital wobble (see later in this section 4.1).

2MASS and VVV

Absorption in the Galactic plane where most of the XRBs are located implies that near-IR data becomes essential for counterpart detection. Here we use JHK magnitudes and positions from Two Micron All Sky Survey⁴ (2MASS, [Skrutskie et al. 2006](#); [Cutri et al. 2003a,b](#)) and Visible and Infrared Survey Telescope for Astronomy (VISTA, [Emerson et al. 2006](#); [Dalton et al. 2006](#)) Variables in the Via Lactea Data Release 4 (VVV DR4) catalogues (VVV⁵, [Minniti et al. 2010](#)). 2MASS covers full sky containing almost half a billion sources on all-sky, but suffers from limited depth and confusion in the Galactic plane. On the other

² cdsarc.cds.unistra.fr/viz-bin/cat/I/355

³ vizier.cds.unistra.fr/viz-bin/VizieR?-source=I/352

⁴ vizier.cds.unistra.fr/viz-bin/VizieR?-source=II/246

⁵ cdsarc.cds.unistra.fr/viz-bin/cat/II/376

Table 1. Features used for counterpart identification and source classification*.

Feature	Unit	Definition	Source
X-ray and additional features			
<i>LOG_EFX</i>	$\text{erg s}^{-1} \text{cm}^{-2}$	Common logarithm of the observed 0.2 – 2.3 keV flux	eRASS1M
<i>LOG_EFX_SIG</i>		Common logarithm of the significance of 0.2 – 2.3 keV flux	eRASS1M
<i>LOG_EFX_HARD</i>	$\text{erg s}^{-1} \text{cm}^{-2}$	Common logarithm of the observed 2.0 – 8.0 keV flux	eRASS1M
<i>LOG_EFX_HARD_SIG</i>		Common logarithm of the significance of 2.0 – 8.0 keV flux	eRASS1M
<i>NH_GAL_22</i>	10^{22}cm^{-2}	Galactic neutral hydrogen column density	Doroshenko (2024)
<i>VAR_G_MAG</i>		G-band variability index	Gaia DR3**
<i>LOG_EPSI_SIG</i>		Common logarithm of <i>Gaia</i> excess noise significance	Gaia DR3
Optical/IR and distance features			
<i>G_MAG</i>	mag	Apparent <i>G</i> -band magnitude	Gaia DR3
<i>BP_MAG</i>	mag	Apparent <i>B</i> -band magnitude	Gaia DR3
<i>RP_MAG</i>	mag	Apparent <i>R</i> -band magnitude	Gaia DR3
<i>W1_MAG</i>	mag	Apparent <i>W1</i> -band magnitude	CatWISE/AllWISE/WISE
<i>W2_MAG</i>	mag	Apparent <i>W2</i> -band magnitude	CatWISE/AllWISE/WISE
<i>J_MAG</i>	mag	Apparent <i>J</i> -band magnitude	2MASS/VVV
<i>H_MAG</i>	mag	Apparent <i>H</i> -band magnitude	2MASS/VVV
<i>K_MAG</i>	mag	Apparent <i>K</i> -band magnitude	2MASS/VVV
<i>DIST</i>	kpc	Distance to the source	Gaia DR3/BJ21***
<i>LOG_DIST_SIG</i>		Logarithm of the distance significance	Gaia DR3/BJ21***

* For the cross-matching machine we use optical/IR and distance features only, whereas for source classification machine we use them combined with X-ray and additional features.

** Variability index is based on Barber & Mann (2023) and Riello et al. (2021) results and defined in the Eq. 1.

*** Detailed description of how the distance estimates (and corresponding significances) were obtained, see Sect 4.1.

hand, VVV covers only half of the Galactic bulge and part of its plane (western Galactic hemisphere), however, it is deeper and provides higher spatial resolution relieving source confusion. We used, therefore, VVV photometry and astrometry where available and 2MASS elsewhere. Note that VVV was extensively cross-validated with 2MASS so combining the data from two surveys is feasible for our purposes (Soto et al. 2013, see the equations in section 2.2).

CatWISE2020, AllWISE and WISE

The CatWISE2020 (Marocco et al. 2021)⁶ is an all-sky IR catalogue based on Wide-field Infrared Survey Explorer (WISE) surveys at mid-IR, and beats even *Gaia* DR3 by source count. What is important to us is that *CatWISE2020* provides in mid-IR *W1* and *W2* bands (3.4 and 4.6 μm , respectively) where even strongly absorbed sources invisible in the optical and near-IR bands can be detected. This information can also be useful to extend frequency range covered, which helps to better constrain spectral energy distributions also for objects detected by *Gaia*/2MASS, so we use both bands as features. In some rare cases, we found that even relatively bright objects are absent in CatWISE2020 catalogue, while being represented in AllWISE

and/or WISE (which are usually less deep), so *W1* and *W2* magnitudes from AllWISE and WISE (in the order of preference) were used where CatWISE2020 data were not available.

eRASS1

The eRASS DR1⁷ represents half of the sky in X-rays, namely the western Galactic hemisphere (whose proprietary data belong to the German eROSITA Consortium). We do not use here the data from the remaining 3.5 surveys as the processing and creation of X-ray catalogues beyond eRASS1 has not yet been fully finalised and similar work using this data will be published separately at a later point. As part of eRASS DR1 two main X-ray catalogues are released: the ‘main’ one (eRASS1M), which contains 930203 sources detected in the 0.2 – 2.3 keV band (the most sensitive eROSITA energy range), and the ‘hard’ catalogue (eRASS1H) with 5466 sources detected in ‘hard’ 2.3 – 5 keV band (Waddell et al. 2024). Here we aim to identify as many faint XRBs as possible, so eRASS1M is used as our main catalogue. The hard sample does contain some sources absent from the main catalogue, but also significant fraction of spurious detection, which made our classification process using this catalogue unreliable. We do use, however, hard flux estimates obtained for

⁶ vizier.cds.unistra.fr/viz-bin/VizieR?-source=II/365

⁷ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/682/A34

eRASS1M sources. In particular, we use positions, 0.2–2.3 keV flux (MLFlux1 column) and the aggregated flux of eROSITA P4 and P5 bands (MLFluxP4 and MLFluxP5 columns), in total covering 2.0–8.0 keV energy range. Using two bands ensures that not only brightness, but also hardness of X-rays are considered. Considering wide range of fluxes detected by eROSITA, we used common logarithm of the respective flux rather than fluxes directly. Along with the flux logarithms, we also took significances of the corresponding fluxes as features for classification. Significances were included in order to account for potential spurious sources, since those detections, although may have a high flux values itself, would still have low significances.

Additional features

Multi-band photometry by Gaia, 2MASS, VVV, and WISE is indirectly used by our classifier to discriminate between various stellar spectral/luminosity classes for optical counterparts of eROSITA sources. In presence of absorption there is, however, intrinsic degeneracy between temperature, luminosity and absorption column. To lift this degeneracy, we added an independent estimate of the absorption column N_H in the direction of a given source. In particular, we use results by Doroshenko (2024)⁸ combining reddening estimates based on analysis of dust emission observed by Planck (Planck Collaboration et al. 2016), modelling of electron density based on dispersion measure analysis (Yao et al. 2017) and extinction modelling based on Gaia and 2MASS data by Edenhofer et al. (2023).

Different classes of X-ray objects are also known to be variable. Thus, we decided to consider variability of sources in our study. Since we work with eRASS DR1 data only (one half-year scan and exposure for the majority of sources is relatively short), this cannot be done based on available X-ray data. It led us to instead utilise Gaia DR3 G-band variability information. However, just adding corresponding variability flag from Gaia DR3 (VarFlag column) to our model as a feature would simply be incorrect (RF would rather consider it as noise or in contrast to be very significant). Instead, we need some parameter that will reflect the degree of source’s variability. In this regard, we employ the method taken from Barber & Mann (2023). Authors constructed specific variability index metric (similar to Guidry et al. 2021) defined as follows (equation 2 in Barber & Mann 2023):

$$VAR_G_MAG = \log_{10} \left(\frac{2.5}{\ln 10} \times \frac{\sigma_{\langle FG \rangle}}{\langle FG \rangle} \right) - \log_{10}(\sigma_{G,p}), \quad (1)$$

where $\langle FG \rangle$ and $\sigma_{\langle FG \rangle}$ are the G-band mean flux and the corresponding uncertainty, respectively. In turn, $\log_{10}(\sigma_{G,p})$ is the logarithm of the predicted G-band magnitude uncertainty, which is a straight up result of Gaia photometric uncertainties tool code⁹ (Riello et al. 2021). This predicted uncertainty is a function of Gaia G-band flux/magnitude and number of corresponding observations. The variability index itself scales with the degree of source’s astrophysical variability.

Since we target XRBs, it would also be reasonable to account for potential orbital wobble in binaries. Based on Chandra and Gaia data, Gandhi et al. (2022) found out that Gaia excess noise (epsi Gaia DR3 column) is actually an effective tool in tracking orbital wobble behaviour in binaries. In general, they’ve shown that Gaia excess noise could be used to identify a diverse range

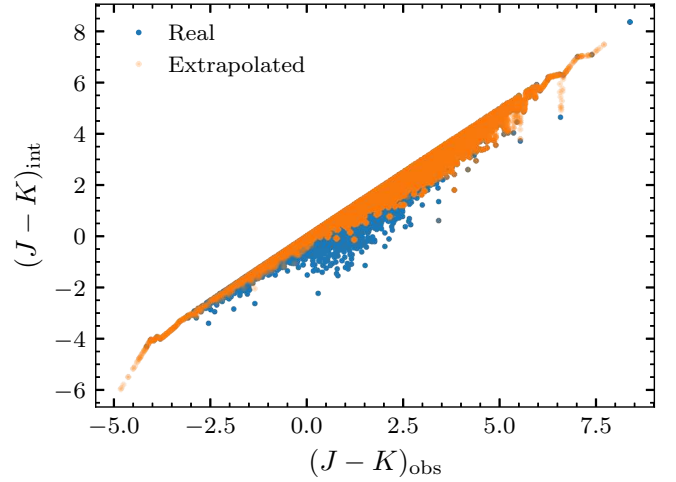


Fig. 3. Intrinsic $(J - K)_{\text{int}}$ colour versus observed $(J - K)_{\text{obs}}$ colour for all optical/IR objects around each eRASS1M source inside 30'' region. Blue circles correspond to the sources with known Gaia DR3/BJ21 distances and J & K -band magnitudes taken from 2MASS/VVV (1.5'' crossmatch radius between Gaia and 2MASS/VVV). Orange crosses, in turn, correspond to the objects with unknown distances, but having JK data from 2MASS/VVV and extrapolated $(J - K)_{\text{int}}$ based on blue circles.

of X-ray emitting class sources, especially binaries. We follow their approach and add logarithm of significance of the excess noise (logarithm of seps1 Gaia DR3 column) to our feature set. We chose the logarithmic significance instead of just using extra noise because the former revealed to be quite more impactful feature in our classification model.

Summarising everything above, the list of features used (both for counterpart identification and source classification), their short description and corresponding units are given in the Table 1.

Imputation of missing features

Despite use of all sky catalogues, it is clear that full feature set will not be available for all objects. For instance, given source can simply be not detected in a specific survey (i.e. not all WISE sources have Gaia counterparts and vice versa). The easiest strategy to treat such cases would be simple exclusion of such objects or features from the consideration. However, this comes at the price of losing a large number of potential counterparts and/or valuable information (features) about the objects. A better way to handle this, is to replace the missing values with some physically justified replacement values, i.e. impute missing data. The feature imputation strategy is obviously specific to concrete features and below we describe what was done in each individual case.

Missing photometry and/or fluxes. In cases where some (or even all) of optical/IR magnitudes were unavailable (i.e. source is not detected in given band), we replaced the corresponding fields with randomly selected values within a range that is below the sensitivity limit of the corresponding survey. That is, for Gaia (G , BP and RP) and CatWISE2020 ($W1$ and $W2$) missing values were filled with random ones within the range of 20.5 and 25 mag. For JHK data the upper limit of the range was selected to be 17 mag with the same 25 mag as the bottom. A similar

⁸ astro.uni-tuebingen.de/nh3d/nhtool

⁹ github.com/gaia-dpci/gaia-dr3-photometric-uncertainties

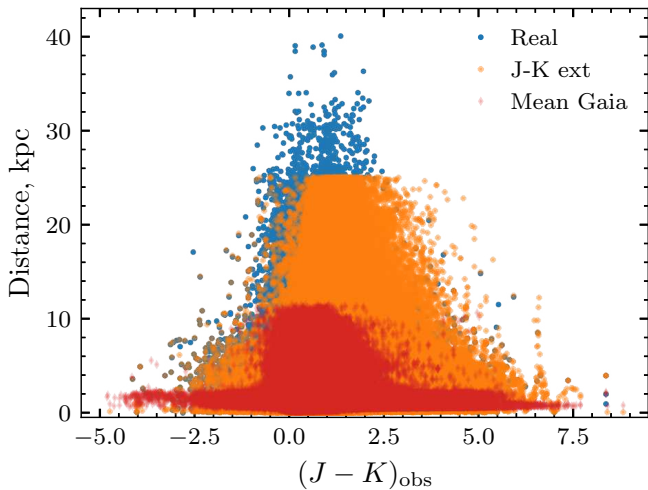


Fig. 4. Dependence of the distance on observed $(J - K)_{\text{obs}}$ colour for the same optical/IR as on the Fig. 3. Blue circles represent sources with known distances from *Gaia* DR3/BJ21, orange crosses — distances taken from $(J - K)_{\text{int}}$ colour extrapolation, red diamonds — distances equal to mean ones of *Gaia* DR3/BJ21 sources around with relative G -band magnitude. Distance's threshold of 25 kpc for orange crosses is caused by spatial limit of Doroshenko (2024) N_{H} map.

process was done for X-ray data, where if one of the two fluxes (LOG_EFX and LOG_EFX_HARD) values were missing, we replaced those with the logarithm of the randomised flux value in the range $10^{-17} - 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$. The latter value corresponds to a general sensitivity limit for eRASSIM. Note that replacing missing values with fixed value equal to sensitivity limit is not feasible as these values are then picked-up by the RF classifier as a very significant feature. Regarding the missing flux significances, they were replaced based on the corresponding flux values (even if those were imputed). The fluxes were converted to the net counts (based on eRASS DR1 exposure maps and energy conversion factors), and with assumed Poisson distribution (10000 events) for obtained number of counts, corresponding flux errors and thus significances were produced.

Missing variability index and/or excess noise. Since for sources with no *Gaia* identification we miss variability index (see Eq. 1) and excess noise significance estimations, they also should be imputed. Based on the analysis of sources with low/insignificant corresponding feature values, we decided to randomise the missing ones within specific ranges. For variability index we've chosen the range of $[-0.5, 0.5]$, while for logarithmic significance of the excess noise corresponding missing values were replaced with the logarithm of the value randomised in the range $10^{-16} - 10^{-14}$. The ranges were chosen to represent source with no significant variability/excess noise.

Missing distances. As already mentioned, distance estimates (i.e. by *Gaia* DR3 and BJ21) are very important source of information. Of course, *Gaia* distance estimates are not available for absolutely all sources. One strategy to circumvent this would be to use similar approach as for other missing features and randomise missing values (for example in the range of 3 – 20 kpc), giving such estimates relatively high uncertainties (i.e. decreasing corresponding distance significances). However, we found that this approach is not ideal. This is mainly caused by two

reasons: 1) *Gaia* in some cases does not provide parallax estimates even for relatively close objects ($< 1 \text{ kpc}$); 2) high absorption in the optical band in the Galactic plane implies that even known relatively nearby objects are often not detected by *Gaia* while being seen in near IR (especially evident in star forming regions). Just assigning large distances for such objects would significantly affect outcome of the classification and was found to produce large number of spurious XRB candidates.

We, therefore, explored several alternative strategies. First, to account for the selection effects for sources with known G -band magnitude but no distance estimate available, we substituted missing distances with mean distance value for all nearby *Gaia* objects with similar magnitude. The logic here is that for such objects missing distance estimate typically means that *Gaia* astrometric solution has not converged due to the partially missing data or processing issues unrelated to intrinsic faintness of the source (after all, it was possible to measure distances for similar objects around it). Of course, it can not be excluded that object is simply too far away or too close (so that large proper motion prevented convergence of astrometric solution), but on average we found that nearby stars with similar magnitudes are actually quite similar to one another and are located at similar distances.

To do that, we constructed a set of 14 healpix maps containing mean and dispersion values of distances for objects with the specific G -band magnitudes between 6–20 mag. The maps were constructed by querying the entire *Gaia* archive using ADQL and converted to healpix format using *healpy*¹⁰ package as shown in Appendix B. We then used the obtained maps to randomly sample distances for objects with missing distances taking mean and dispersion values from corresponding healpix map.

This method is, however, not applicable to sources not detected by *Gaia*. One could, of course, assume that the distance values should be close to the ones for sources from the last healpix 19–20 mag interval map, but we found that in some cases it leads to the underestimation of the distance. This happens mainly in high absorption areas, where the majority of all optically detected objects (for which we calculate mean distance) are located in the relative ‘front’ of the absorbing material. In this case we do not see stars which are optically faint because they are far away, but rather those which are intrinsically faint, mean distance even for faintest magnitude bin remains small. On the other hand, IR counterparts may be detected to much larger distances, and using this approach for them would yield incorrect estimates. This, for example, happens for HMXB IGR J16493–4348 which doesn't have a *Gaia* counterpart, but appears relatively bright in 2MASS/VVV. Here, distance estimated as described above provides a value of 735 pc, while literature values are in 6–22 kpc range (Hill et al. 2008; Nespoli et al. 2010; Pearlman et al. 2019).

To account for such cases, we attempted to derive additional distance information from J and K band colors and 3D reddening maps by Doroshenko (2024). First, we convert this map to $E(J - K)$ colour excess 3D map using relations from Savage & Mathis (1979). Keeping in mind that $(J - K)_{\text{int}} = (J - K)_{\text{obs}} - E(J - K)$ (where $(J - K)_{\text{int}}$ and $(J - K)_{\text{obs}}$ are intrinsic and observed colours respectively), $(J - K)_{\text{int}}$ could be easily obtained for sources with known JK -bands magnitudes (from 2MASS/VVV) and distances (from *Gaia* DR3/BJ21). We then calculate interpolated intrinsic $(J - K)_{\text{int}}$ for sources with known J and K and missing distance estimates using this relation. In

¹⁰ healpy.readthedocs.io

particular, we use `scipy.interpolate.interp1d`¹¹ function from `scipy` package (Virtanen et al. 2020) as presented in Fig. 3. Finally the interpolated $(J - K)_{\text{int}}$ values can be converted back to $E(J - K)$ and compared with a cumulative 3D reddening map to derive the distance. The uncertainty of the distance can be estimated based on J and K magnitude uncertainties and $E(B - V)$ uncertainties reported by Doroshenko (2024). As an example, for the same HMXB IGR J16493–4348 this $(J - K)_{\text{int}}$ approach gives an estimate of $9.1^{+3.7}_{-3.7}$ kpc, which is far closer to the literature estimates. Comparison of estimates obtained using both methods with actual distances reported by BJ21 is presented on the Fig. 4 and shows reasonably good agreement.

The actual missing distances and significances can finally be substituted with either of the two methods described above. Since HMXBs and LMXBs are the sources of interest in our study, we select the method which provides higher distance estimation in each specific case (the majority of XRBs are located beyond 3 kpc).

4.2. Sample of objects with known origin

Besides features, any classification problem requires also a set of classes to be defined. Of course, one could consider all types of astronomical objects, but this complicates the classification process and, moreover, not all object types are relevant in context of classification of eROSITA X-ray sources. After testing multiple combinations of classes, we settled on a balanced set of object classes including all relevant object types in eRASS1 which can be potentially confused with XRBs. The list of considered object classes is thus specifically optimised for XRBs search and not so much, for instance, for separating blazars from other AGNs or various classes of isolated neutron stars from each other (which is not our goal). We then searched the literature for catalogues of objects of relevant types and compiled the list of objects used for labelling eROSITA (along with the references to the catalogues used). The final list presented below thus contains objects which we consider to have known nature and use for training of the RF (second “machines”) classifiers:

- HMXB — high-mass X-ray binary. We used Neumann et al. (2023)¹² for labelling known HMXBs.
- LMXB — low-mass X-ray binary. Avakyan et al. (2023)¹³ catalogue was used for labelling known LMXBs.
- INS — isolated neutron stars. This class for our RF machine also encapsulates magnetars. The list of central compact objects (CCOs) maintained by Andrea De Luca (De Luca 2017)¹⁴ was found to be useful for labelling, as well the catalogue of pulsars by Manchester et al. (2005)¹⁵.
- CV — cataclysmic variable. Known CVs were labelled based on the data from Ritter & Kolb (2003)¹⁶, Downes et al. (2001, 2006)¹⁷, Hou et al. (2020)¹⁸, Inight et al. (2023a,b)^{19,20} and Canbay et al. (2023)²¹. Along with that

we used the catalogues of intermediate polars (IPs)²² and magnetic CVs²³.

- AGN — active galactic nuclei. For labelling known AGNs and blazars the catalogues used are Anderson et al. (2007)²⁴, Massaro et al. (2015)²⁵, Chang et al. (2019)²⁶, Arsioli et al. (2020)²⁷ and Lutz et al. (2018)²⁸. In addition, we utilised recently published Quia catalogue (Storey-Fisher et al. 2024)²⁹, clean AGN sample ($G < 20.0$).
- OB — O-B type star. This class includes O-B/Be, and even γ -Cas type stars labelled based on Jaschek & Egret (1982)³⁰, Reed (2003)³¹, Maíz-Apellániz et al. (2004)³², Maíz-Apellániz et al. (2016)³³, Nazé (2009)³⁴, Sota et al. (2011)³⁵, Raddi et al. (2015)³⁶ and Chen et al. (2019)³⁷. We also decided to add to this class Wolf-Rayet (WR) type stars. They were labeled based on van der Hucht 2001; Rosslowe & Crowther 2015 (see also the corresponding website³⁸).
- MK — M-K type star. By that we mean coronal active stars of late spectral types. Catalogues for labelling such sources are Pace (2013)³⁹, Gaidos et al. (2014)⁴⁰, Boro Saikia et al. (2018)⁴¹, Eker et al. (2008)⁴² and Žerjal et al. (2017)⁴³.
- YSO — young stellar object. Pillitteri et al. (2013)⁴⁴, Prisinzano et al. (2022)⁴⁵, Megeath et al. (2012)⁴⁶ and Zari et al. (2018)⁴⁷ catalogues were used for labelling YSOs.

To label eROSITA sources (to assign belonging to one of the classes listed above) for source classification (train, test and verification datasets, see Sect. 5.2), we first cross-correlated eRASSIM catalogue with all class source catalogues listed above in itemize within eROSITA $3\text{-}\sigma$ uncertainty ($30''\text{max}$). This resulted in $\sim 15.7\%$ of all eROSITA sources being labelled as some class members as summarised in Table 4. Then, we cross-matched obtained archive source positions with optical/IR surveys (see Sect. 4) in order to obtain all the features (see Table 1). Radius for cross-matching archive positions with those surveys was set to be $3''$.

5. Methods and procedures

Here we describe the procedures used to identify optical/IR counterparts to eROSITA X-ray sources and to conduct their fi-

¹¹ docs.scipy.org/doc/scipy/tutorial/interpolate/1D.html

¹² cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/677/A134

¹³ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/675/A199

¹⁴ www.iasf-milano.inaf.it/~deluca/cco/main.htm

¹⁵ cdsarc.cds.unistra.fr/viz-bin/cat/B/psr

¹⁶ cdsarc.cds.unistra.fr/viz-bin/cat/B/cb

¹⁷ cdsarc.cds.unistra.fr/viz-bin/cat/V/123A

¹⁸ vizier.cds.unistra.fr/viz-bin/cat/J/AJ/159/43

¹⁹ cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/525/3597

²⁰ cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/524/4867

²¹ cdsarc.cds.unistra.fr/viz-bin/cat/J/AJ/165/163

²² asd.gsfc.nasa.gov/Koji.Mukai/iphone/catalog/alpha.html

²³ www.picturerocksobservatory.org/mcv-catalog

²⁴ cdsarc.cds.unistra.fr/viz-bin/cat/J/AJ/133/313

²⁵ cdsarc.cds.unistra.fr/viz-bin/cat/VII/274

²⁶ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/632/A77

²⁷ cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/493/2438

²⁸ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/609/A9

²⁹ zenodo.org/records/10403370

³⁰ cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/500/3926

³¹ cdsarc.cds.unistra.fr/viz-bin/cat/V/125

³² cdsarc.cds.unistra.fr/viz-bin/cat/V/116

³³ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/620/A89

³⁴ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/506/1055

³⁵ cdsarc.cds.unistra.fr/viz-bin/cat/III/274

³⁶ cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/446/274

³⁷ cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/487/1400

³⁸ pacrowther.staff.shef.ac.uk/WRcat/index.php

³⁹ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/551/L8

⁴⁰ cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/443/2561

⁴¹ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/616/A108

⁴² cdsarc.cds.unistra.fr/viz-bin/cat/V/128

⁴³ cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJ/835/61

⁴⁴ cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJ/768/99

⁴⁵ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/664/A175

⁴⁶ cdsarc.cds.unistra.fr/viz-bin/cat/J/AJ/144/192

⁴⁷ cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/620/A172

Table 2. Numbers of datasets labelled for counterpart identification RF machines, which were SMOTEd (See 'S' in the brackets) and then got splitted into train and test subsets.

Class	All	All (S)	Train (S)	Test (S)
'HMXB-like'	149	50740	40620	10120
'not "HMXB like"	50740	50740	40564	10176
'LMXB-like'	197	128547	102772	25775
'not "LMXB like"	128547	128547	102903	25644

Table 3. Performance results of both optical/IR counterpart identification RF machines (pre-NWAY) on whole labelled data (column 'All' in Table 2).

Class	Precision	Recall	F1	Accuracy	Log_Loss
'HMXB-like'	0.75	0.98	0.86	0.99	0.014
not 'HMXB like'	1.0	1.0	1.0		
'LMXB-like'	0.73	0.96	0.84	0.98	0.016
not "LMXB like"	1.0	1.0	1.0		

nal classification. As already mentioned, we rely on random forest (RF) decision trees (DTs) supervising machine learning (ML) ensemble algorithm for both tasks. During the training step, object properties or features are used to construct a set of DTs through the process of bagging, where each tree is trained on a different subset of the training data. Each DT partitions the feature space using a loss function, ensuring that each leaf node contains only samples of one type. During the classification step, each DT in the RF algorithm independently provides its prediction. The final prediction is determined by aggregating the votes (predictions) from all the trees in the forest. We use RF implementation from `sklearn` package, version 0.23.2 (Pedregosa et al. 2011).

Like other ML algorithms, RF relies on a set of pre-labelled training data and depends on quality of pre-labeled samples and features of objects in them. One common issue with training which we also encounter here is a significant imbalance between various classes. Specifically, AGNs and stars vastly outnumber other types of objects such as XRBs or CVs (see Fig. 1). Both in general (i.e. within any training samples one can come up with), and in eRASS. If not taken care of, this leads to a natural bias towards more common objects (i.e. AGNs and stars in our case) if the division between various object types in feature space is not extremely clear. Basically, if we know that there is only one XRB for a thousand AGNs, it is safe to assume that all objects are AGNs, which is also what ML algorithms learn when trained on imbalanced samples. That is not a problem when one is interested in dominating class, however, for it is definitively an issue in context of our work. To overcome it, the most natural approach would be to train the classifier on a balanced sample, i.e. include comparable number of objects of all types so that only differences in their properties rather than relative abundance are learning during the training. The problem is, however, that total number of XRBs is quite low, so size of the training sample is artificially limited if the same number of other object types is used, and is rather inefficient (basically, we would have to neglect most of the available information about AGNs in this case).

Alternative way to balance the training sample is to expand minority classes either by additional observations or some kind of simulations. A popular approach to do that is the so-called Synthetic Minority Oversampling TEchnique (SMOTE, Chawla et al. 2002; Chawla et al. 2011). SMOTE generates synthetic samples for the minority classes by interpolating feature values (MWL parameters in our case) in feature space, which allows to at least partially compensate for the class imbalance and create a more balanced training dataset, although, obviously, expansion through inclusion of a larger number of real sources would be better. We did, in fact, make significant efforts to expand the sample of known XRBs (Neumann et al. 2023; Avakyan et al. 2023), but even then the size of the XRB sample (and some other classes) remains limited. To further improve class balance we use, therefore, `imblearn` SMOTE implementation (class `SMOTE()`⁴⁸ from `imblearn.over_sampling` PYTHON module). Let us now discuss in more detail the two main steps of the XRB search, i.e. counterpart identification and classification.

5.1. Counterpart identification

As already mentioned, MWL information is essential for X-ray source classification, so as a first step we need to identify counterparts of eRASS1M X-ray sources (in our case, optical/IR). Although the main criterion here is spatial coincidence, high source density of optical/IR surveys implies that typical eROSITA 3 σ error circle (15'') may contain many potential counterparts, so selecting the correct one is not straightforward. A common approach here is to exploit additional prior information for potential counterparts (such as magnitudes, colours, source density, etc) and use Bayesian statistics to incorporate that with the available positional information (Budavári & Szalay 2008). We use this approach here as implemented in `NWAY`⁴⁹ package (Salvato et al. 2018). Note that identification of optical/IR counterparts for eRASS DR1 sources is of course something essential to study any kind of source and was already done by several groups within eROSITA-DE consortium. In particular, Salvato et al, **in preparation**, identified eRASS1M counterparts using `NWAY` with a set of RF-derived priors based on *Gaia*/CatWISE2020 information. Their work is, however, optimised to identify counterparts of an "average" X-ray source, which effectively means AGNs and stars, whereas performance for minority classes like XRBs is compromised. For instance, counterparts for 30% of known HMXBs are identified incorrectly (AGNs on average have reddish companions, so with all things equal such counterparts are preferred, and there is never shortage of red stars in the Galactic plane). That is not an issue for AGN studies as few tens of XRBs among hundreds of thousands of AGNs are just a handful of outliers, but obviously this is an issue when one is looking specifically for the XRB needle in AGN haystack. Here we use, therefore, a similar approach, but with priors specifically optimised to identify XRB counterparts. To derive appropriate `NWAY` priors we use RF to classify potential counterparts to X-ray in two classes, i.e. "XRB-like" and "not XRB-like" based on their optical/IR properties, separately for HMXBs and LMXBs (as they generally have different properties).

To compile a training and test samples we use the updated catalogues of known HMXBs (Neumann et al. 2023) and LMXBs (Avakyan et al. 2023) and select all optical/IR objects form all optical/IR catalogues described in Sect. 4.1 within 1'

⁴⁸ imbalanced-learn.org/stable/references/generated/imblearn.over_sampling.SMOTE.html

⁴⁹ github.com/JohannesBuchner/nway/

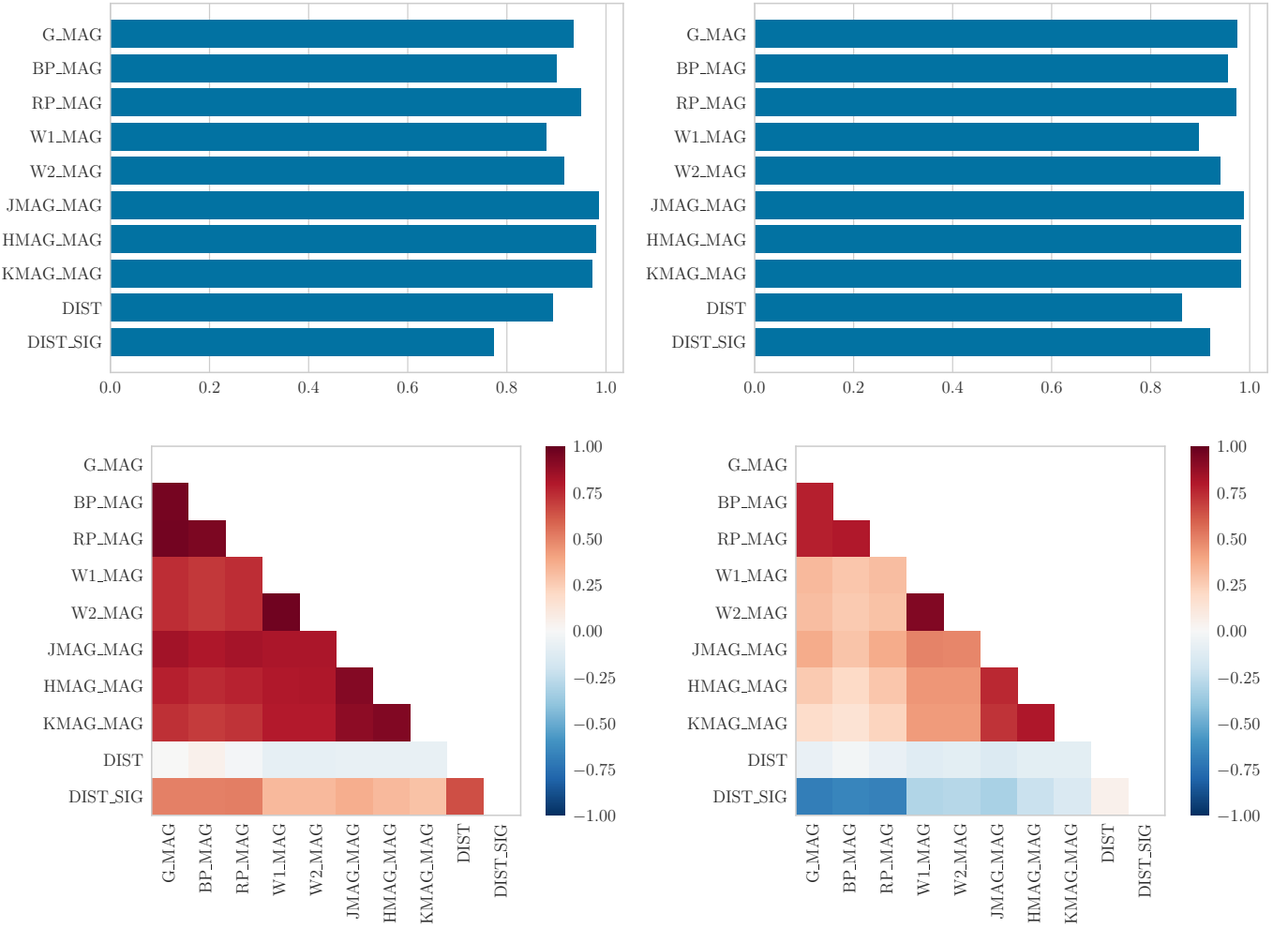


Fig. 5. 1D (top panel) and 2D (bottom panel) feature importance rankings for RF trained to identify ‘HMXB-like’ (left) and ‘LMXB-like’ (right) optical/IR counterparts (pre-NWAY) based on the augmented (SMOTE) training/test sets.

within XRBs. We then label known H/LMXB counterparts as “H/LMXB-like” objects and consider other nearby sources to be “not H/LMXB-like”. That is, we assume that there are no unknown XRBs within $1'$ from known ones. This assumption is well justified given the low sky density of XRBs and the fact that most of them have been extensively observed so any nearby XRBs would be identified. There are, in fact, couple of examples when there are two or more XRBs within $1'$, but these cases are easy to notice and were labelled appropriately. However, LMXBs located in Global Clusters (GC) were omitted for this procedure, since GCs are too stellar dense and only bring MWL noise to our RF operation. Note that at this stage we only consider optical/IR properties of sources located around true XRBs and do not use X-ray properties (eROSITA or otherwise), which allows to use also objects in eastern Galactic hemisphere for training. That is especially considering rather limited known XRB sample size. In fact, it is clear that training sample definition described above implies in any case that there are many more “not XRB-like” objects than “XRB-like” ones, i.e. the training sample is imbalanced, so SMOTE is to balance the two classes as described above (i.e. we add objects with properties similar to those of true H/LMXBs to increase “H/LMXB-like” samples size).

The resulting equal sized samples were then divided into train (in our case 75%) and test (25%) sub-

samples using command `train_test_split`⁵⁰ from `sklearn.model_selection` PYTHON module. The training subset is used to train the classifier (i.e. to optimise DT weights), and test sample to assess accuracy of the classification at each iteration. Note that test sample is used for evaluation of accuracy during the training and thus is not suitable for verification of final accuracy as the classifier. For this purpose a dedicated “verification” sample is normally used, which, however, requires that part of the labelled objects are removed from the training set thereby reducing amount of information available for training. Considering that the sample of known XRBs is already very limited, we decided not to remove any further objects to form a dedicated verification sample. This is expected to result in an “overtrained” model, i.e. classifier yielding higher accuracy for training data at the expense of accuracy for data previously not exposed previously to classifier.

For training and classification RF implemented in `RandomForestClassifier`⁵¹ class from the `sklearn.ensemble` module with 500 decision trees was used. Final sizes of each sample and performance of the classifier assessed by standard metrics is summarised in the

⁵⁰ scikit-learn.org/stable/modules/generated/sklearn.model_selection.train_test_split.html

⁵¹ scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestClassifier.html

Table 4. Numbers of sources labelled for classification RF machine, which were divided into verification (=Ver) and Rest datasets. Both datasets were augmented (or SMOTEd, see 'S' in the brackets) and the 'rest' sample was then splitted into train and test subsets.

Class	All	Ver	Ver (S)	Rest (S)	Train (S)	Test (S)
HMXB	46	11	32019	95792	71915	23877
LMXB	63	18	32019	95792	71825	23967
INS	24	6	32019	95792	71833	23959
CV	613	153	32019	95792	71729	24063
AGN	127811	32019	32019	95792	71979	23813
OB	655	162	32019	95792	71782	24010
MK	4325	1048	32019	95792	71904	23888
YSO	9500	2343	32019	95792	71785	24007

Table 2, and Fig. 5 (feature importances). For feature ranking we use functions Rank1D and Rank2D⁵² from Yellowbrick PYTHON package, which evaluate single features and their pairs respectively. For single feature we select the default Shapiro-Wilk algorithm (Shapiro & Wilk 1965) to assess the normality of the distribution of instances with respect to the feature. In the case 2D ranking the pairs of features are ranked using Pearson (Rank2D default) correlation score (Pearson 1895) to detect colinear relationships. In turn, confusion matrices were constructed using ConfusionMatrixDisplay function from sklearn.metrics module.

As evident from the accuracy scores (see Table 3), the classifier indeed appears to be “overtrained”. This behaviour is generally unwanted, however, in our case the training sample already mostly contains augmented data for “XRB-like” objects, so negative side of this effect is less obvious. We verified that introduction of a separate verification sample as expected leads to significant drop of estimated accuracy (depending on chosen sample size), however, classification results remain similar. Considering that we only use classification results to define priors for NWAY, we decided, therefore, to accept over-trained model. This limits general predictive power of the classifier but ensures that any optical/IR source similar to any true XRB counterpart will be ranked high among all potential X-ray source counterparts.

Both models (for LMXBs and HMXBs) trained separately as described above and referred as “pre-NWAY” further on. Then, they were used to calculate “HMXB-like” ($P_{\text{HMXB_CTPT}}$) and “LMXB-like” ($P_{\text{LMXB_CTPT}}$) probabilities for a massive set (15436727 optical/IR sources) of all potential optical/IR counterparts of eRASS 1M sources. This includes all Gaia DR3/CatWISE2020/2MASS/VVV sources within 30'' radius around each eRASS 1M source (excluding X-ray sources identified as spurious detections by eRSOITA-DE consortium, see flags in Merloni et al. 2024). We then used the obtained probabilities as NWAY priors to cross-match eRASS 1M and optical/IR counterpart catalogue based on the positional data to identify the most probable ‘HMXB-like’ (‘LMXB-like’) counterparts to all eRASS1M sources. As counterparts we selected matches with both match_flag=1 and match_flag=2 (see NWAY description⁵³) to not miss any potential associations. This resulted

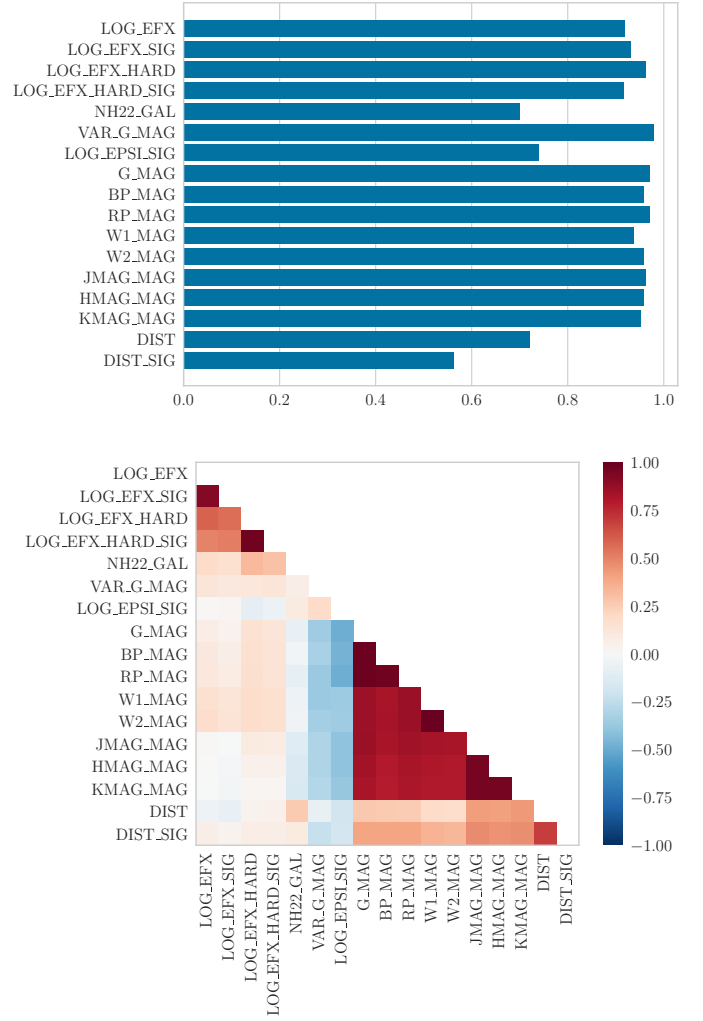


Fig. 6. 1D (top panel) and 2D (bottom panel) feature importance rankings for MWL source classification RF machine. Rankings are shown based on the augmented (SMOTE) test data subset (see Table 4)

in two tables of MWL features (all features from Table 1) containing 1195614 and 1154891 sources, with optical/IR features are biased towards HMXBs and LMXBs appearance respectively. The idea behind this is to pick counterparts which are most likely to be XRBs among all potential X-ray source counterparts to weaken general bias towards AGNs and increase chances of finding the few dozens XRBs expected to appear in the catalogue.

5.2. Source classification

Once the optical counterparts of X-ray sources are identified as described above, it is necessary to classify the nature of all objects based on their X-ray and MWL properties. Here we use similar process as for identification of the counterparts described above. The main differences here are: 1) in addition to optical/IR information, we also use X-ray and absorption data (see Table 1); 2) the classification of sources goes not just into two classes (‘H/LMXB-like’ and ‘not H/LMXB-like’), but into a wider range of classes; and 3) now accuracy of the classifier needs to be assessed more accurately as we are interested not only in finding new XRBs, but also to estimate total numbers of XRBs likely detected by eROSITA and contamination of final

⁵² www.scikit-yb.org/en/latest/api/features/rankd.html

⁵³ github.com/JohannesBuchner/nway/raw/master/doc/nway-manual.pdf

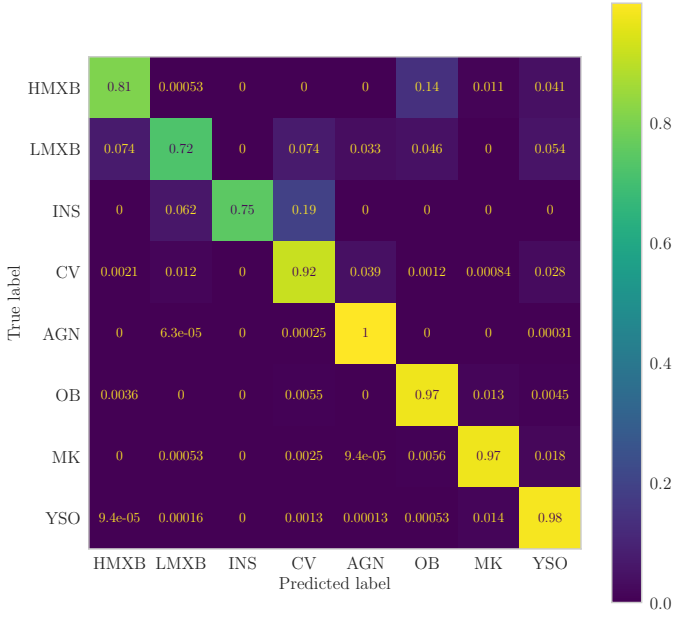


Fig. 7. Confusion matrix for MWL source classification RF machine. Figure is shown for augmented (SMOTE) verification sample data.

XR candidate sample, i.e. moving part of known objects to the verification sample can not be avoided.

Specifically, our verification sample includes 25% of all labelled objects which are not visible to classifier at any point and are only used for final assessment of the classifier performance. For rest of the objects we use a similar strategy as in Sect 5.1. Namely, we split data in training and test samples and use SMOTE procedure to augment both samples to counter class imbalances. Note that the verification sample is also augmented using SMOTE procedure as otherwise it would be too small, but neither original data nor interpolated values are exposed to classifier during training. Keep in mind that all labelled sources (verification, train, test) MWL data were obtained aside of NWAY optics/IR behaviour biased towards H/LMXBs procedure presented in Sect. 5.1. Specifically, optical/IR counterparts to the objects of known nature were selected inside 3'' radius from their archive positions (more on that, see Sect. 4.2). The results of each step are shown in the Table 4. Similarly to Sect 5.1, we present 1D and 2D feature rankings (see Fig. 6), as well as class confusion matrix (see Fig. 7). The corresponding values for precision, recall, f1-score and accuracy are presented in the Table 5. We note, that while feature rankings are plotted for augmented testing sample (as in Sect 5.1), confusion matrix and classification results (Table 5) are shown for the augmented verification subset.

It is clear that performance of the classifier is not uniform across the classes, i.e. some classes are better separated from others (see Fig. 7). Naturally, the RF performance on the large class sources (such as AGNs, coronal active stars, YSOs) is better than on other types. It was expected considering the amount of imbalance we work with. Even SMOTE augmentation is not sufficient enough to fully account for that, i.e. available training data is simply not adequate for some classes. On the other hand, the performance of the classifier for target classes (HMXBs and LMXBs) appears to be reasonable. This follows not only from formal metrics (accuracy, f1 score, precision), but also from inspection of the confusion matrix. In particular, overall confusion with other classes for HMXB and LMXB, although they

Table 5. Performance of the MWL classification RF algorithm on the augmented (SMOTE) verification sample data.

Class	Precision	Recall	F1-score	Accuracy	Log_Loss
HMXB	0.91	0.81	0.86		
LMXB	0.90	0.72	0.80		
INS	0.97	0.75	0.81		
CV	0.77	0.92	0.84	0.889	0.495
AGN	0.93	1.00	0.96		
OB	0.83	0.97	0.90		
MK	0.96	0.97	0.97		
YSO	0.87	0.98	0.92		

are among the smallest classes, is still relatively low. This indicates that our methods, although not working perfectly (which is always suspicious when dealing with ML methods), still work correctly.

RF classifier, trained on the pure MWL dataset, were then applied independently to classify all not-labelled by our procedure 767597 X-ray sources in eRASS1M (excluding spurious) with NWAY identified counterparts, i.e. to 1025967 (HMXBs optics/IR biased) and 996206 (LMXBs optics/IR biased) MWL associations. Note that corresponding numbers of associations are larger, than the number of actual X-ray sources. This is simply due to the fact, that multiple counterparts could be assigned to one X-ray source with NWAY (see Sect. 5.1). Moreover, the numbers of MWL associations are also slightly different (for H/LMXBs optics/IR biased cases) due to the difference in adopted priors, which affects final association probabilities estimated by NWAY and thus counterparts selection.

Probability to belong to each of the considered classes for each source is then the final output of a given RF classifier. Note that the estimated probabilities are expected to be different for the two MWL datasets (tailored to H/LMXBs) and are not particularly reliable before additional calibration, which needs to be done for each class. Here we are interested only in XR candidates so we perform such analysis only for HMXBs/LMXBs (using the corresponding output of classifier on MWL dataset tailored for H/LMXBs).

6. Resulting catalogues and finding charts

6.1. Candidate lists construction and quality assurance

In principle, selection of most-likely H/LMXB candidates could be done based on the probability to belong to respective class. However, selection of the P_{HMXB} (P_{LMXB}) probability threshold to consider given object reliable HMXB (LMXB) candidate is not trivial as probability values are actually not calibrated for individual source classes. Common practice here is to rely on purity and completeness metrics which can be calculated for any adopted probability threshold using the labelled set. Purity indicates how frequently other class sources (not H/LMXBs in our case) have corresponding probabilities above the selected cut. Completeness, in turn, denotes the amount of pre-labelled sources of the class of interest (H/LMXBs in our case) with the

probabilities above the selected cut. That is, purity and completeness (for a given *class*) are defined as follows:

$$Purity \equiv \frac{N_{class}(P_{class} > P_{class}^{cut})}{N_{all}(P_{class} > P_{class}^{cut})} \quad (2)$$

$$Completeness \equiv \frac{N_{class}(P_{class} > P_{class}^{cut})}{N_{class}} \quad (3)$$

where N_{class} is the number of pre-labelled sources of the class considered, P_{class} – produced by a ML model probability that source is a member of the corresponding class, P_{class}^{cut} – selected cut on these probability, above which sources are considered as candidates, N_{all} is the number of all class sources (only pre-labelled data). With these 3 numbers (P_{class}^{cut} , purity and completeness) one can estimate the whole amount of the considered class candidates in a given sample.

In Fig. 8 we present histograms of P_{HMXB} (left panel) and P_{LMXB} (right panel) probabilities for our two classes of interest. These probabilities are the output of our RF source classification machine. The results are shown for augmented (SMOTE) verification datasets (top panels), as well as individual real sources (bottom panels). On the bottom panels of the figure, histograms with legend ‘Unknown’ (probabilities for sources with no assigned origin nature) are plotted based on the results of the classifier utilised on tailored towards corresponding source class (H/LMXB optics/IR biased) MWL datasets. We decided to choose the completeness of both XRB candidate samples to be **0.7 (70%)**. This resulted in the probabilistic cuts of **0.472** for HMXBs and **0.476** for LMXBs. Corresponding purity values for resulted XRB candidate lists are **0.83** and **0.76**. Adopting these thresholds results in **94** HMXB and **98** LMXB candidates.

Ultimately, we can also estimate the number of all potential candidates in eRASS1 based on the obtained purity and completeness as summarised in the Table 6. These estimates align well with pre-launch estimates by Doroshenko et al. (2014) who estimate 130-270 and 105-220 LMXBs and HMXBs over entire sky in full eRASS survey. We detect factor of 2-3 less in a single survey (1/8th of exposure considered by Doroshenko et al. 2014), i.e. closer to the upper end of this range. This could, of course, indicate inaccuracies in our estimate of purity/completeness metrics, but could also indicate less strong flattening of the X-ray luminosity function than estimated by Doroshenko et al. 2014 and rather uncertain. The latter would mean that eROSITA will indeed be able to improve XLF constraints.

6.2. Tables content and finding charts

Properties of **94** HMXB and **98** LMXB candidates, including X-ray data from eRASS1M and optical/IR information about the assumed counterpart from *Gaia* DR3, CatWISE2020, 2MASS and VVV surveys are summarised in two catalogue tables respectively to HMXBs and LMXBs. The columns are described in Table A.1 of the Appendix A. We decided to comprise real detection data (the actual values from corresponding surveys) including all those that were used to derive the features (see Table 1), thus, there are empty fields in the candidate catalogues, which for our study were imputed using different methods (see Sect. 4.1). The tables also contain the results of NWAY cross-match (probabilities of the match, separation, etc), P_{HMXB_CTPT} and P_{LMXB_CTPT} likelihoods used for NWAY as priors, as well as the resulting probabilities of the classification P_{HMXB} and P_{LMXB} respectively.

Table 6. Results on HMXB and LMXB candidate selection.

XRB Class	Candidates	Prob. cut	Purity	Completeness	All*
HMXB	94	0.472	0.83	0.7	111
LMXB	98	0.476	0.76	0.7	107

* This is an estimate of all potential candidates that can be found in the data using our methods. The numbers are based on the corresponding amount of candidates selected, as well as purity and completeness values.

To account for possible detections of our candidates by other X/γ-ray facilities, we also cross-matched (3-σ coincidence) both tables with sources from *Chandra* Source Catalog (CSCv2, Evans et al. 2010)⁵⁴, *XMM-Newton* serendipitous survey (4XMM DR11, Webb et al. 2020)⁵⁵, *Swift*/XRT Point Source (2SXPS, Evans et al. 2020)⁵⁶, INTEGRAL Reference Source Catalogue⁵⁷, *Swift*/BAT 157-Month Hard X-ray Survey (Oh et al. 2018; Lien et al. 2023)⁵⁸, Monitor of All-sky X-ray Image Source Catalog (MAXI, Kawamuro et al. 2018)⁵⁹ and *Fermi*/LAT 12-year Source Catalog (4FGL DR3 Abdollahi et al. 2020, 2022)⁶⁰. All corresponding identifications are also included in both of our XRB candidate tables (see Table A.1). It should be noted that we do not claim any solid associations of our candidates with the detections from other X/γ-ray surveys and identifications are shown mostly just for the reference.

In addition to the catalogues themselves, finding charts were also generated in a similar way to the Avakyan et al. 2023; Neumann et al. 2023 (see Sections 3.2 in both of these works) for all candidates in order to facilitate the analysis of each potential XRB. The main difference compared to Avakyan et al. 2023; Neumann et al. 2023 is substitution of ROSAT with eRASS DR1 images. In total, each finding chart can host up to 6 different images. The top row (from left to right) of the chart figure includes an image based on eRASS DR1 RGB maps⁶¹ (left panel), the VVV DR4⁶² or 2MASS⁶³ J-band image (middle panel, in order of preference), and colour image from DECaPS2⁶⁴ (Saydjari et al. 2023) or DSS2⁶⁵ (right panel, in order of preference). The bottom row (from left to right) includes the ‘soft’ X-ray RGB-image of either *Chandra*⁶⁶, *XMM-Newton*⁶⁷, or an image (*Swift*/XRTint in *astroquery*.skyview) from *Swift*/XRT (left panel, in order of preference), and two ‘hard’ X-ray images from *Swift*/BAT⁶⁸ and INTEGRAL⁶⁹ (middle and right panel, respectively). The field of view for eRASS DR1 and *Swift*/XRT image was set to be 5′. In the cases for DECaPS2/DSS and

⁵⁴ cdsarc.cds.unistra.fr/viz-bin/cat/IX/57

⁵⁵ cdsarc.cds.unistra.fr/viz-bin/cat/IX/65

⁵⁶ cdsarc.cds.unistra.fr/viz-bin/cat/IX/58

⁵⁷ www.isdc.unige.ch/integral/science/catalogue

⁵⁸ swift.gsfc.nasa.gov/results/bs157mon/

⁵⁹ cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJS/238/32

⁶⁰ fermi.gsfc.nasa.gov/ssc/data/access/lat/12yr_catalog/

⁶¹ erosita.mpe.mpg.de/dr1/erodat/static/hips/eRASS1_RGB_Rate_c010

⁶² alasky.cds.unistra.fr/VISTA/VVV_DR4/VISTA-VVV-DR4-J

⁶³ alasky.cds.unistra.fr/2MASS/J

⁶⁴ alasky.cds.unistra.fr/DECaPS/DR2/CDS_P_DECaPS_DR2_color

⁶⁵ alasky.cds.unistra.fr/DSS/DSSColor

⁶⁶ cdaftp.cfa.harvard.edu/cxc-hips

⁶⁷ skies.esac.esa.int/XMM-Newton/EPIC-RGB

⁶⁸ cade.irap.omp.eu/documents/Ancillary/4Aladin/BAT_14_20

⁶⁹ cade.irap.omp.eu/documents/Ancillary/4Aladin/INTEGRAL_17_60

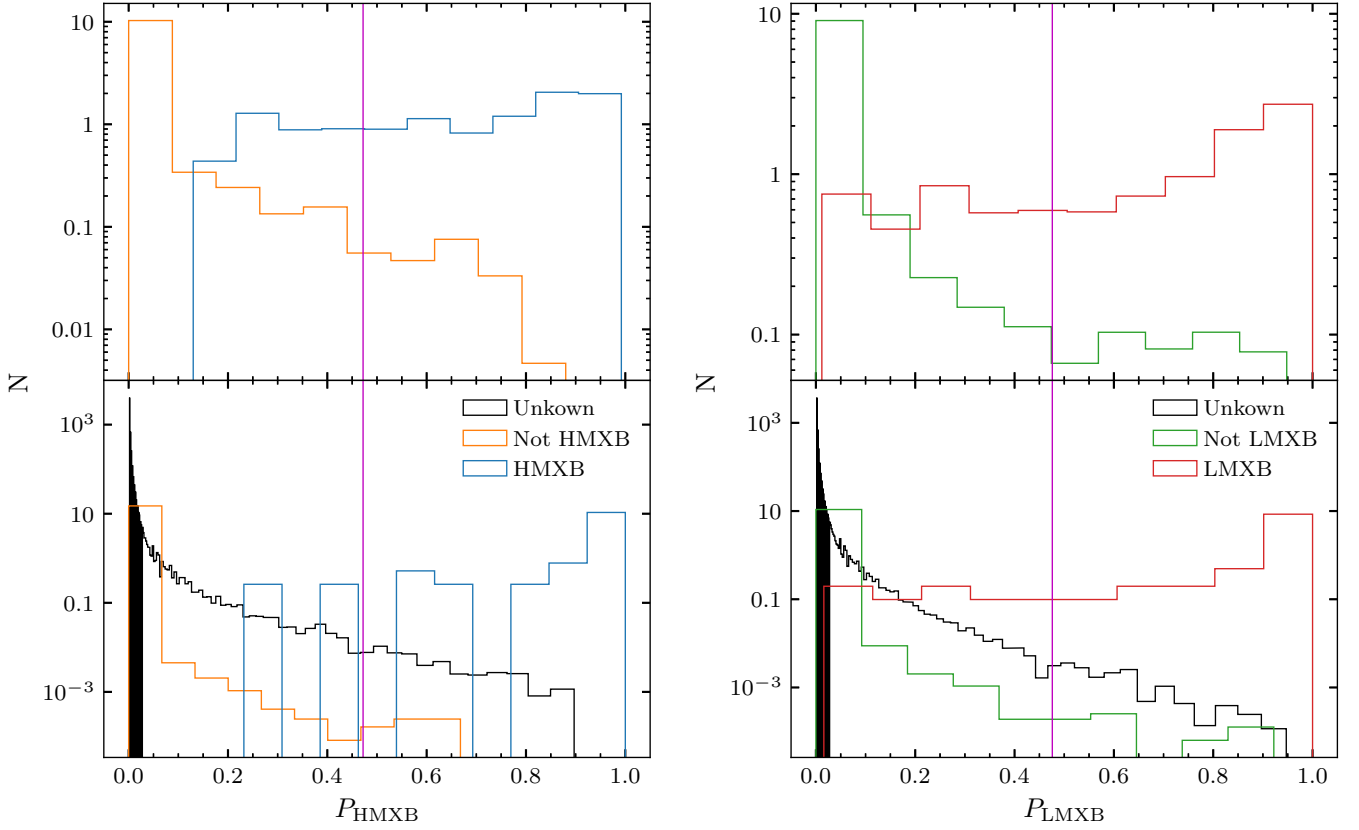


Fig. 8. Probability histograms that the source is HMXB (P_{HMXB} , left figure) and LMXB (P_{LMXB} , right figure) based on MWL RF classification results with optics/IR biased towards HMXBs and LMXBs respectively. *Top panels:* the histograms are presented for augmented (SMOTE) verification sample, separately showing augmented HMXBs (left figure) and LMXBs (right figure) and other class augmented sources. *Bottom panels:* results are shown for the real data sample, including unknown (not labelled) sources. Magenta vertical lines represent $P_{\text{HMXB}}^{\text{cut}}$ and $P_{\text{LMXB}}^{\text{cut}}$ probabilistic cuts respectively, based on the chosen completeness of 70% (see Table 6).

VVV/2MASS images it was set to be $1'$, while for *Chandra*, *XMM-Newton* it is $2.5'$. The field of view for *Swift*/BAT and INTEGRAL was chosen to be 2° . To create images, in most cases we used the Hierarchical Progressive Surveys (HiPS) data from [Fernique et al. 2015](#). SkyView Query was used only for *Swift*/XRT to obtain images. Both services were queried using [astroquery.hips2fits⁷⁰](#), and [astroquery.skyview⁷¹](#) modules.

Each panel of the finding chart shows the position and its uncertainty for corresponding candidate. A red cross ‘X’ and a red circle indicate the eRASS1M X-ray coordinates (corrected) and $3\text{-}\sigma$ positional error. A green plus ‘+’ represents the position of the chosen optical/IR counterpart of the eROSITA source. All images on the finding chart are centred in respect to the suggested counterpart position. In addition, we decided to draw other X-ray positions if there are any around based on the cross-match described above in this subsection. In the case of ‘soft’ X-ray instruments (*Chandra*, *XMM-Newton* and *Swift*/XRT), their positions are shown by error circles to prevent overcrowding. A golden circle indicates the *Chandra* position, a magenta circle indicates the *XMM-Newton* position, and a cyan circle indicates the *Swift*/XRT position. *Swift*/BAT and INTEGRAL detections

are indicated as a deep-pink pentagon and a lime-green triangle, respectively.

As an example, we show the finding chart of one of the HMXB candidates (1eRASS J175528.0–331122) in the Fig. 9. We kindly ask authors who use our catalogues or finding charts to refer to cite this article and Vizier table.

Both XRB candidate catalogues and finding charts are accessible via Vizier database⁷² hosted by the Centre de Données astronomiques de Strasbourg (CDS) system.

7. Summary and conclusions

In this work, we report on a search of new Galactic HMXBs and LMXBs in eROSITA all-sky X-ray survey first data release (eRASS DR1) and present two corresponding candidate catalogues. We relied on a two-step machine learning (ML) approach using Random Forest (RF) supervised technique first to identify likely counterparts to eROSITA sources, and then to classify resulting X-ray source – counterpart pairs based on their MWL properties with the aim to identify XRBs. In the first step RF was specifically trained to optimise identification of likely HMXBs/LMXBs counterparts (depending on regarding which catalogue of the two resulted we are talking about). In the second step properties of identified counterparts were used to classify all eROSITA sources with the aim to identify likely XRB candidates. The accuracy of classification was then assessed in order

⁷⁰ astroquery.readthedocs.io/en/latest/hips2fits/hips2fits.html

⁷¹ astroquery.readthedocs.io/en/latest/skyview/skyview.html

⁷² cdsarc.cds.unistra.fr/cgi-bin/qcat?J/A+A

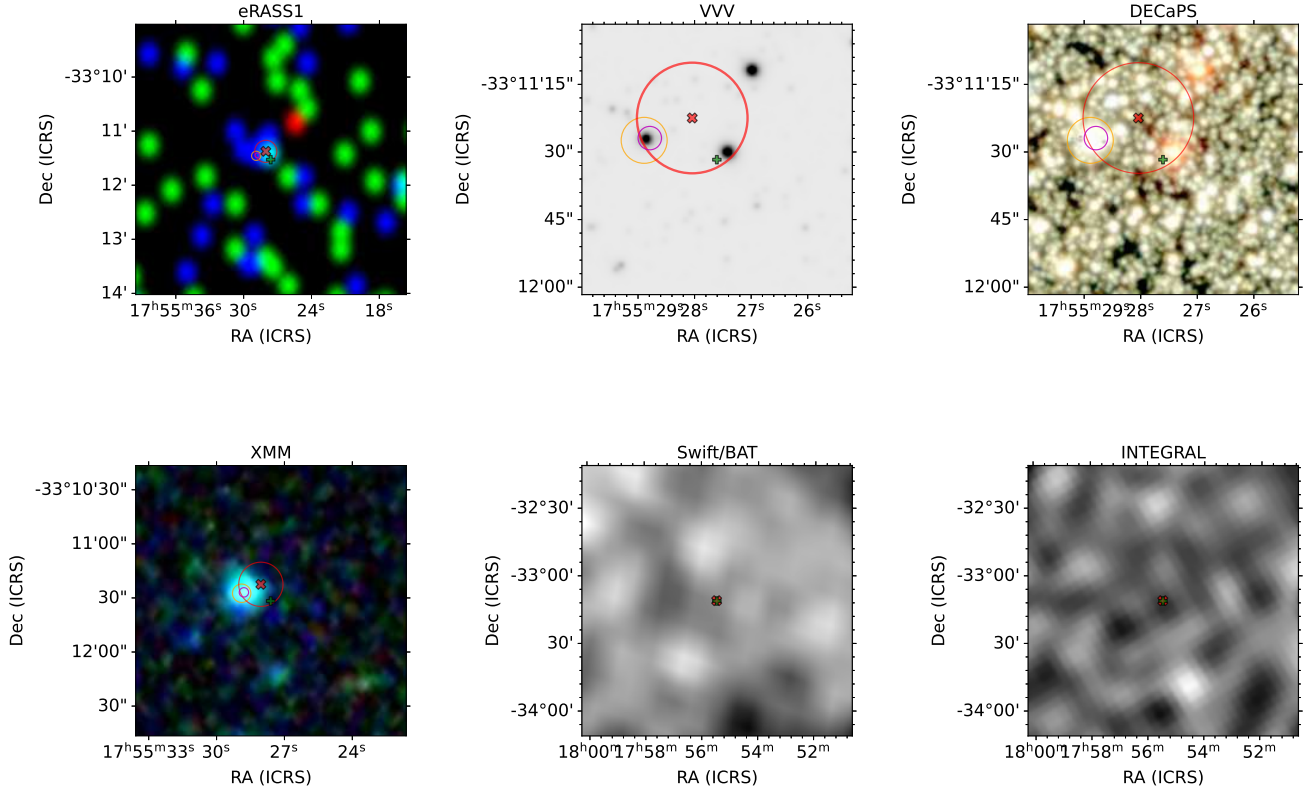


Fig. 9. Finding charts of one of the candidates. The finding charts display markers and error circles representing observations made by different instruments. A red cross ‘X’ and a red circle indicate the eRASS1M X-ray coordinates (corrected) and $3\text{-}\sigma$ positional error. A green plus ‘P’ represents the position of the NWAY selected optical/IR counterpart of the eRASS1M source. The $3\text{-}\sigma$ error circles are used for ‘soft’ X-ray observations to prevent overcrowding, with a golden circle indicating *Chandra*, magenta for *XMM-Newton* and a cyan circle representing *Swift/XRT*. *Swift/BAT* and *INTEGRAL* are indicated as a deep-pink pentagon and a lime-green triangle.

to determine appropriate probabilistic cuts balancing completeness of the eROSITA XRB candidate samples and its purity. In particular, we estimate purity of **76-83%** for the adopted completeness of **70%**, which results in **94** HMXB and **98** LMXB candidates. Properties of these including X-ray properties observed by eROSTIA, MWL properties of identified counterparts, information about possible detection in other X/*gamma*-ray facilities, and assessment of candidate quality are presented as two catalogues with **72** columns each. Description of the columns is presented in Table A.1. In addition we provide finding chart figures for all candidates containing optical/IR and X-ray images with drawn positions. Both catalogue tables with the corresponding finding charts can be obtained through the VizieR database⁷³. We kindly ask authors who use our results to refer to us by citing this article, as well as by referring to the VizieR link.

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⁷³ cdsarc.cds.unistra.fr/cgi-bin/qcat?J/A+A

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Appendix A: Catalogues format

Table A.1. Description of columns in the XRB candidate catalogue tables.

Nº	Column name	Unit	Description
1	'IAUName'		eRASS1M IAU name of the source (1eRASS JHHMMSS.s+DDMMSS)
2	'DetUID'		eRASS1M unique detection ID
3	'eRASS1_RAdeg'	deg	Right ascension of the X-ray source from eRASS1M in degrees (ICRS)
4	'eRASS1_DEdeg'	deg	Declination of the X-ray source from eRASS1M in degrees (ICRS)
5	'eRASS1_posErr'	arcsec	eRASS1M 1- σ positional uncertainty
6	'DetLike0'		eRASS1M detection likelihood in 0.2 – 2.3 keV band
7	'MLFlux1'	erg/s/cm ²	eRASS1M source flux in 0.2 – 2.3 keV band
8	's_MLFlux1'	erg/s/cm ²	1- σ combined error on eRASS1M flux in 0.2 – 2.3 keV band
9	'DetLikeP4'		eRASS1M detection likelihood in 2.0 – 5.0 keV band
10	'MLFluxP4'	erg/s/cm ²	eRASS1M source flux in 2.0 – 5.0 keV band
11	's_MLFluxP4'	erg/s/cm ²	1- σ combined error on eRASS1M flux in 2.0 – 5.0 keV band
12	'DetLikeP5'		eRASS1M detection likelihood in 5.0 – 8.0 keV band
13	'MLFluxP5'	erg/s/cm ²	eRASS1M source flux in 5.0 – 8.0 keV band
14	's_MLFluxP5'	erg/s/cm ²	1- σ combined error on eRASS1M flux in 5.0 – 8.0 keV band
15	'CTPT_RAdeg'	deg	Right ascension of the suggested optical/IR counterpart
16	'CTPT_DEdeg'	deg	Declination of the suggested optical/IR counterpart
17	'CTPT_posErr'	arcsec	1- σ uncertainty on the position of the suggested optical/IR counterpart
18	'Sep_eRASS1_CTPT'	arcsec	Separation between eRASS1M source and suggested optical/IR counterpart positions
19	'P_H(L)MXB_CTPT'		Prior 'H(L)MXB-like' RF pre-Nway probability of the suggested optical/IR counterpart
20	'Nway_p_single'		Distance posterior probability from Nway comparing this association vs. no association
21	'Nway_p_any'		Nway probability that one of the counterpart associations is the correct one
22	'Nway_p_i'		Nway relative association probability
23	'Nway_match_flag'		Nway flag ranking corresponding counterpart association. The most probable match is indicated with 1. Secondary, almost as good solutions are marked with 2
24	'Gaia_Source'		Gaia DR3 unique identifier of the suggested optical/IR counterpart
25	'Plx'		Gaia DR3 parallax
26	'e_Plx'		Standard error of Gaia DR3 parallax
27	'epsi'		Gaia DR3 excess noise
28	'sepsi'		Significance of Gaia DR3 excess noise
29	'Gmag'	mag	Gaia DR3 mean G-band magnitude
30	'e_Gmag'	mag	Error on Gaia DR3 G-band mean magnitude
31	'BPmag'	mag	Gaia DR3 integrated BP mean magnitude
32	'e_BPmag'	mag	Error on Gaia DR3 integrated BP mean magnitude
33	'RPmag'	mag	Gaia DR3 integrated RP mean magnitude
34	'e_RPmag'	mag	Error on Gaia DR3 integrated RP mean magnitude
35	'Dist'	pc	Distance estimate from Gaia DR3
36	'b_Dist'	pc	Lower confidence level (16%) of distance estimate from Gaia DR3

Table A.1. continued

Nº	Column name	Unit	Description
37	'B_Dist'	pc	Upper confidence level (84%) of distance estimate from Gaia DR3
38	'rgeo'	pc	Median of the geometric distance posterior from BJ21
39	'b_rgeo'	pc	16th percentile of the geometric distance posterior from BJ21
40	'B_rgeo'	pc	84th percentile of the geometric distance posterior from BJ21
41	'rpgeo'	pc	Median of the photogeometric distance posterior from BJ21
42	'b_rpgeo'	pc	16th percentile of the photogeometric distance posterior from BJ21
43	'B_rpgeo'	pc	84th percentile of the photogeometric distance posterior from BJ21
44	'CWISE_Name'		CatWISE2020 name (JHHMMSS.ss+DDMMSS.s) of the suggested optical/IR counterpart
45	'W1mproPM'	mag	WPRO magnitude in band-1 (W1: 3.35um) from CatWISE2020
46	'e_W1mproPM'	mag	Uncertainty on WPRO magnitude in band-1 (W1: 3.35um) from CatWISE2020
47	'W2mproPM'	mag	WPRO magnitude in band-1 (W2: 4.6um) from CatWISE2020
48	'e_W2mproPM'	mag	Uncertainty on WPRO magnitude in band-1 (W2: 4.6um) from CatWISE2020
49	'2MASS_ID'		2MASS designation of the suggested optical/IR counterpart
50	'Jmag'	mag	2MASS J-band selected default magnitude
51	'e_Jmag'	mag	2MASS J-band total magnitude uncertainty
52	'Hmag'	mag	2MASS H-band selected default magnitude
53	'e_Hmag'	mag	2MASS H-band total magnitude uncertainty
54	'Kmag'	mag	2MASS K-band selected default magnitude
55	'e_Kmag'	mag	2MASS K-band total magnitude uncertainty
56	'VVV_iauname'		VVV DR2 unique identifier in IAU naming convention (VVV JHH-MMSS.ss+DDMMSS.ss) of the suggested optical/IR counterpart
57	'Jmag3'	mag	Default VVV J-band aperture corrected magnitude
58	'e_Jmag3'	mag	Error in default VVV J-band magnitude
59	'Hmag3'	mag	Default VVV H-band aperture corrected magnitude
60	'e_Hmag3'	mag	Error in default VVV H-band magnitude
61	'Ksmag3'	mag	Default VVV Ks-band aperture corrected magnitude
62	'e_Ksmag3'	mag	Error in default VVV Ks-band magnitude
63	'NH_Gal_22'	10^{22} cm^{-2}	Galactic neutral hydrogen column density from Doroshenko (2024)
64	'e_NH_Gal_22'	10^{22} cm^{-2}	Galactic neutral hydrogen column density error from Doroshenko (2024)
65	'P_H(L)MXB'		Final RF probability that the source is HMXB (LMXB)
66	'2CXO_ID'		2CXO identifier of the <i>Chandra</i> source in $3\text{-}\sigma$ error
67	'4XMM_ID'		4XMM identifier of the XMM- <i>Newton</i> source in $3\text{-}\sigma$ error
68	'XRT_IAUName'		2SXPS IAU-format name of the <i>Swift</i> /XRT source in $3\text{-}\sigma$ error
69	'INTEGRAL_ID'		Identifier of the INTEGRAL source in $3\text{-}\sigma$ error
70	'BAT_NAME'		Name of the <i>Swift</i> /BAT source in $3\text{-}\sigma$ error
71	'3MAXI_ID'		3MAXI identifier of the MAXI source in $3\text{-}\sigma$ error
72	'FERMI_Name'		Name of the Fermi-LAT source in $3\text{-}\sigma$ error

Appendix B: Distance imputation based on *Gaia* sources around

For imputation of missing distances for sources detected by *Gaia* the following code was used:

```
from astroquery.gaia import Gaia
from astroquery.vizier import Vizier
import healpy as hp
import scipy.stats

NSIDE_OUT = 128

Gaia.ROW_LIMIT = -1 # fetch all rows
Vizier.ROW_LIMIT = -1

def get_avg_px(gmin,gmax,NSIDE=32):
    """docstring for get_hpx"""
    order = hp.nside2order(NSIDE)
    job = Gaia.launch_job_async(r"""SELECT source_id/%d as pix, AVG(distance_gspphot)
AS avgd FROM gaiadr3.gaia_source
WHERE (phot_g_mean_mag>%f AND phot_g_mean_mag<%f)
GROUP by pix
"""%(2**(59-2*order),gmin,gmax))
    r = job.get_results()
    davg = ones(hp.nside2npix(NSIDE)) # should be zeros, but zeros scales poorly
    davg[r['pix'].data.data]=r['avgd'].data.data # that's it!
    davg = hp.reorder(davg,inp='NESTED',out='RING') # healpy works
    davg = hp.Rotator(coord=['C','G']).rotate_map_pixel(davg)
    davg = hp.ud_grade(davg,NSIDE_OUT)
    return hp.smoothing(davg,hp.nside2resol(NSIDE)*1.1) # to avoid edge artefacts

# Gaia bright limit is 6 mag, and number of stars brighter
# than that is low, so ignore this range
magrange = [6,9,10,11,12,13,14,15,16,17,18,19,20]
nside = [8,16,16,32,32,64,64,64,128,128,128,128]

# Loop over several NSIDEs chosen depending on magnitude
# such that we always have enough sources
res = []
for i in range(len(nside)):
    print(magrange[i],magrange[i+1],nside[i])
    res.append(get_avg_px(magrange[i],magrange[i+1],nside[i]))
# Save the maps
np.savez_compressed('avg_dist_ag.npz',
mag=0.5*(array(magrange[:-1]+magrange[: -1]))[: -1],
meandist=array(res[: -1]))
```


Paper IV

A. Avakyan, A. Zainab, V. Doroshenko, J. Wilms,
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"XMM-*Newton* follow-up of two eROSITA XRB candidates"

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IV



XMM-Newton follow-up of two eROSITA X-ray binary candidates

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Abstract

We report on the follow-up observations with XMM-Newton of two X-ray binary candidates identified in the first eROSITA all-sky survey data (eRASS1), 1eRASS J061330.8+160440 and 1eRASS J161201.9–464622. Based on the obtained results, in particular, the observed X-ray spectra and lack of pulsations, as well as properties of the identified optical counterparts, we conclude that both candidates are unlikely to be XRBs. Based on LAMOST optical spectroscopy and SED fit results for 1eRASS J061330.8+160440 we classify it as an M0 chromospherically active subgiant star. ZTF and TESS photometry reveal highly significant period for this object of 7.189 days, which likely attributed to starspot(s). On the other hand, SALT follow-up spectroscopy of 1eRASS J161201.9–464622 solidly classifies this source as a bright novalike cataclysmic variable (CV), the second discovered with eROSITA. A persistent 4.802 h signal is found across all three available TESS observations, and is tentatively identified as the orbital period of the binary. Follow-up high-speed photometry and time-resolved spectroscopy are required to confirm the derived orbital modulation.

Keywords XMM-Newton · eROSITA · SALT · X-ray binaries · Corona active stars · Cataclysmic variables

1 Introduction

Searching for faint X-ray binaries (XRBs) in all-sky surveys requires accurate identification of their counterparts in other bands and detailed analysis of their multi-wavelength (MWL) properties. However, since most XRBs in the Galaxy are expected to

Partly based on observations made with the Southern African Large Telescope (SALT).

Extended author information available on the last page of the article

have relatively low X-ray luminosities [1], observations of faint XRBs are essential to understand the properties of the XRB population as a whole, and to study accretion physics at low luminosities. Up to now, however, only a handful of such faint XRBs are known [2–4].¹ ² In particular, the majority of persistently long-term faint XRBs have been discovered in observations of other targets or in deep inspection of the Galactic centre or globular clusters [5–9]. This was due to the low sensitivity of hard X-ray surveys and strong absorption in the Galactic plane (where most XRBs are located).

The situation, however, began to change thanks to the all-sky survey performed by the extended ROentgen Survey Imaging Telescope Array [eROSITA, 10, 11, 12] on board the Spectrum-Roentgen-Gamma (Spektra-RG, SRG) mission. Indeed, eROSITA offers much higher sensitivity compared to previously available all-sky surveys in a similar energy band [by a factor 20–40 compared to Roentgensatellite (ROSAT) All-Sky Survey, 13, 14, 15] or compared to hard X-ray observatories such as the INTErnational Gamma-Ray Astrophysics Laboratory [INTEGRAL, 16]. In addition, it observes in a significantly wider energy band (0.2–10 keV compared to the 0.2–2 keV band covered by ROSAT), which reduces the effects of the absorption in the Galactic plane. eROSITA provides X-ray spectral information, variability on several timescales, and significantly improved point source localisation accuracy compared to all aforementioned wide-field X-ray surveys.

Of the four all-sky surveys completed by eROSITA (eRASS1–4, with a duration of six months each) as part of its deep X-ray all-sky exploration. As part of the German eROSITA Consortium, we have data rights to half the sky (western Galactic hemisphere), of which the first survey has recently been released for public usage [10]. A majority of the X-ray sources detected by eROSITA are active galactic nuclei (AGNs), ordinary stars, and galaxy clusters (GCs) [11, 12]. However, we also expect to discover a large number (up to a few hundreds) of Galactic X-ray binaries, which will help obtain important constraints on their X-ray luminosity function [1, 17]. These constraints mainly concern the low luminosity part of the function, where eROSITA is significantly more sensitive compared to other wide-field instruments.

Identification of faint XRBs among millions of other sources is, however, challenging due to the similarity of their X-ray properties to those of AGNs and stars dominating the survey. Efforts aimed at the classification of all sources detected by eROSITA are ongoing and will follow the first data release (eRASS DR1). In the meantime, several XRB candidates were identified based on the preliminary analysis and classification of X-ray sources detected in the first eROSITA all-sky survey (eRASS1). In particular, the combination of eROSITA X-ray fluxes and near/mid infrared properties from Two Micron All Sky Survey [2MASS, 18, 19, 20] and All-Sky Wide-field Infrared Survey Explorer [AllWISE, WISE, 21, 22, 23] has been used to identify XRB candidates for follow-up observations with the X-ray Multi-Mirror Mission [XMM-Newton, 24] and the Nuclear Spectroscopic Telescope ARray [NuSTAR, 25]. In addition, in order to better identify candidates, three new

¹ <http://astro.uni-tuebingen.de/~xrbcats/>

² <https://binary-revolution.github.io/>

catalogues of high-mass (HMXB) and low-mass (LMXB) X-ray binaries by [3, 4] and [2], respectively, have been used.

Four XRB candidates proposed for X-ray follow-up have been actually observed by this point, the two brighter ones by NuSTAR and the remaining two by XMM-*Newton*. The detailed follow-up results of the first of the two objects followed up by NuSTAR, SRGA J124404.1–632232 has been presented in [26]. The source was classified to be a HMXB consisting of an accreting pulsar with a pulsation period ~ 538 s and a Be-type star as the optical counterpart, making it the first Galactic BeXRB discovered by eROSITA. Analysis of NuSTAR observations of the second candidate, 1eRASS J085039.9–421151, which was found to be a HMXB/Symbiotic XRB with a likely neutron star compact object is presented in [27].

In this work, we report on the analysis of XMM-*Newton* and eROSITA observations of the two XRB candidates (1eRASS J061330.8+160440 and 1eRASS J161201.9–464622, hereinafter J061331 and J161201). The structure of the paper is as follows: in Sect. 2 we first briefly summarise the available eROSITA and XMM-*Newton* data. Then, in the same section, we describe the identification of plausible optical counterparts and their properties. In Sect. 3, we give a detailed spectral and timing analysis of the X-ray properties of the candidates. The same section also presents both spectroscopic and photometric analyses of the two candidates, along with the results of spectral energy distribution fitting for J061331. Finally, we discuss the likely origin of both sources and summarise the results in Sects. 4 and 5, respectively.

2 Observations and MWL counterparts

2.1 X-ray observations and basic data reduction

The initial selection and classification of both sources studied here was based on the preliminary analysis of eRASS1 data using the reduction pipeline available at the time (c946). Since then, three more surveys were carried out (eRASS2, eRASS3, eRASS4) and several updates to the source detection pipeline were implemented. We use the current (c020) eROSITA data analysis software eSASS [28] pipeline configuration (software calibration file version 211214) throughout the paper. Details of the observation times are presented in the Table 1. The details of XMM-*Newton* observations are summarised in Table 2. We use the full data-set for characterising the X-ray

Table 1 Summary of eROSITA observations of both sources

Source	eRASS	T_{start} , MJD	T_{stop} , MJD	Exposure, ks
J061331	1	58943.25	58944.08	0.147
	2	59129.13	59131.00	0.123
	3	59305.46	59306.62	0.203
	4	59489.38	59490.71	0.216
J161201	1	58918.34	58920.01	0.260
	2	59101.45	59103.28	0.274
	3	59272.07	59282.22	0.258
	4	59460.03	59461.86	0.284

Table 2 Summary of XMM-*Newton* observations of both sources

Parameters	J061331	J161201
RA	6 ^h 13 ^m 30 ^s .54	16 ^h 12 ^m 01 ^s .98
DEC	16°04′42″.32	−46°46′21″.88
Pos. error	0″.98	0″.94
OBSID	0883460301	0883460101
T_{start} , MJD	59471.18	59635.10
T_{stop} , MJD	59471.50	59635.41
Exposure, ks	27.219	26.228

properties of the candidates, but emphasise, that candidate selection was based on the first survey data only and used an earlier version of data processing.

The eROSITA source data products (events, light curves and spectra) were extracted using the eSASS commands `evtool` and `srctool`. Source fluxes were then determined based on modelling of the obtained spectra as described in Sect. 3.1). The XMM-*Newton* data reduction was carried out using XMM-*Newton* analysis software XMM SAS 13.5 package, current calibration files and standard filtering criteria.³ Cleaned event list files were produced by commands `evselect` and `tabgtigen` which were then used to select source and background photons from source-centred circular and annular extraction regions using the `xmmselect` task. In particular, we used annuli with radii of $\sim 65''$ and $\sim 132''$ ($\sim 77''$ and $\sim 155''$) for background, and a source circle with radius of $\sim 22''$ ($\sim 19''$) for J061331 (J161201). Radii for source selection region were optimised using the `eregionanalyse` task. Source detection was carried out with `emldetect` routine to derive final X-ray positions for both sources after applying astrometric correction as detailed in Sect. 2.2. The source light curves and spectra were then extracted using the `lcurve` and `especget` tasks. All spectra were grouped using the `specgroup` task to contain at least one count per energy bin to enable use of Cash statistics [29]. Finally, we have also extracted source photons in the energy range 0.5 – 10 keV using the same extraction regions to search for possible pulsations. All timing products were corrected to Solar system barycentre via `barycen` command. Spectral and timing analysis of the extracted high-level products was then finally carried out with the help of the High Energy Astrophysics Software HEASOFT v6.29.⁴

2.2 X-ray positions and optical counterparts

The unambiguous identification of potential optical counterparts in crowded Galactic plane regions requires knowledge of accurate X-ray positions. The accuracy of positions obtained in the eROSITA survey is limited by the counting statistics typical for all-sky surveys. We therefore have used deeper pointed XMM-*Newton* observations to significantly improve the positional accuracy. As a first step we determined the positions of all X-ray sources in the field of view using the `emldetect` task which jointly models data from all three XMM-*Newton* cameras and fully uses the available counting statistics. In order to assess and reduce all remain-

³<https://www.cosmos.esa.int/web/xmm-newton/sas-threads/>

⁴<https://heasarc.gsfc.nasa.gov/docs/software/heasoft/>

ing systematic uncertainties associated with pointing accuracy, we cross-correlated positions of optical sources detected by XMM-Newton optical monitor (OM) with *Gaia* DR3 catalogue [30, 31].⁵ The positions of optical sources were determined using the `omichain` task. We find 84 and 455 (for J061331 and J161201 respectively) objects detected by the OM to have unique *Gaia* counterpart and use those to compute the final astrometrically-corrected positions for both optical and X-ray sources detected by XMM-Newton using the `eposcorr` task. As a result we find $\alpha_{J2000.0} = 6^h13^m30^s.54$, $\delta_{J2000.0} = 16^\circ04'42''.32$ and $\alpha_{J2000.0} = 16^h12^m01^s.98$, $\delta_{J2000.0} = -46^\circ46'21''.88$, with an uncertainty of about $0''.98$, $0''.94$ at $1-\sigma$ confidence level for J061331 and J161201 respectively (see Table 2).

Once accurate X-ray positions are determined, one can search for plausible counterparts using optical, near-infrared (NIR) and infrared (IR) catalogues. The NIR 2MASS-J [19] finding charts (obtained through `astroquery.skyview` package⁶) for J061331 and J161201 are presented in the Fig. 1 (right and left panel respectively). Figures show both the astrometrically-corrected XMM-Newton positions and the original positions from the eROSITA analysis, which appear to be in good agreement with each other, although the accuracy of the XMM-Newton position is of course better. The final corrected X-ray positions of both objects appear to have an unique optical/NIR counterparts, and coincide with *Gaia* sources Gaia DR3 3345882675816728960 and Gaia DR3 5990098842316868352 for J061331 and J161201 respectively. These are, therefore, the likely optical counterparts we discuss in detail below.

2.2.1 Optical counterpart of J061331

The *Gaia* counterpart (Gaia DR3 ID: 3345882675816728960) at an angular separation of $0''.924$ with the corrected XMM-Newton coordinates of J061331, allows us to esti-

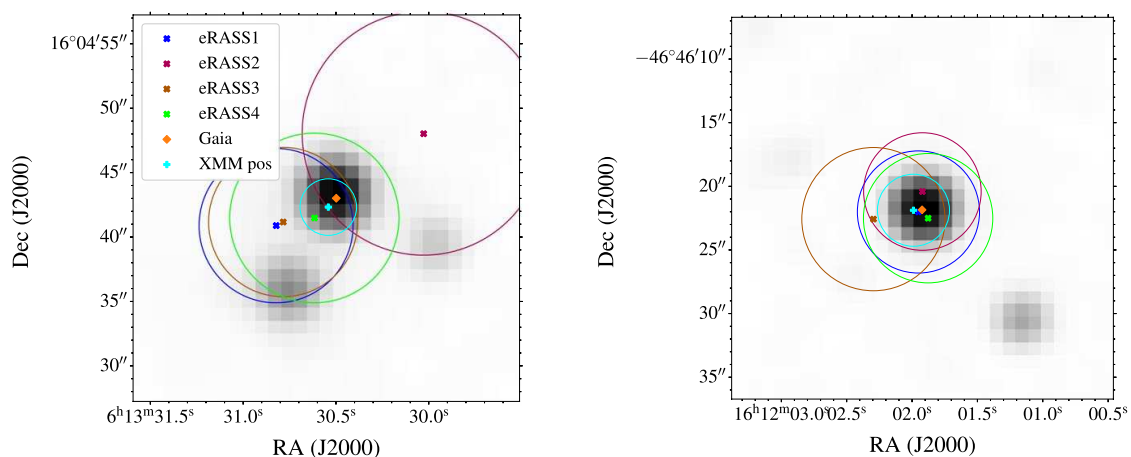


Fig. 1 NIR (2MASS-J) field view around J061331 (left image) and J161201 (right image) candidates with eRASS, *Gaia* DR3 and corrected XMM-Newton's positions. Colour circles show corresponding 3σ positional errors

⁵ <https://cdsarc.cds.unistra.fr/viz-bin/cat/I/355>

⁶ <https://astroquery.readthedocs.io/en/latest/skyview/skyview.html>

mate the distance to the source at 657^{+58}_{-41} pc [32, hereafter BJ21].^{33, 34}⁷ Further, the star is associated with the known variable star ATO J093.3770+16.0786, which has an average V band magnitude of 15.46 mag⁸ according to the All-Sky Automated Survey for Supernovae [ASAS-SN,] catalogue. The source is also monitored by the Zwicky Transient Facility [ZTF, we use DR8, 35]. Inspection of the ZTF data using the SNAD ZTF viewer⁹ [36, 37] reveals periodic variability with period of 7.189 days detected with signal-to-noise ratio $S/N = 22.891$. The Asteroid Terrestrial-impact Last Alert System (ATLAS) catalogue [38, 39],¹⁰ on the other hand, also indicates the variable nature of the star but provides several different values for the possible period, namely: 1.157, 2.315, and 7.211 days. The first two periods seem to be multiplicities of one another caused by aliasing. Furthermore, the ATLAS variable stars catalogue puts ATO J093.3770+16.0786 into the NSINE (noisy sine wave) category, which indicates the presence of sinusoidal variables with strong residual noise or with evidence of additional variability not captured in the fit.

2.2.2 Optical counterpart of J161201

For the second object, we identify the only plausible counterpart $0''.679$ away from the corrected XMM-Newton position of J161201, Gaia DR3 5990098842316868352. The distance to this source is estimated to be 392^{+2}_{-2} pc (see *Gaia* DR3). The substantially more precise distance estimate of J161201 compared to J161331 is due to its closer proximity to us, resulting in a larger parallax (2.53 mas vs. 1.52 mas) and consequently smaller uncertainty. Moreover, J161201 is significantly brighter in the optics than J061331 (12.32 mag vs. 15.31 mag in the *G*-band), so *Gaia* DR3 does not provide a distance estimate with their BP/RP spectra Aeneas algorithm for J061331's counterpart. Consequently, for J061331 we used values from BJ21, despite higher uncertainties arising from their method, which incorporates parallax, photometric measurements, and fitting the distribution of stars in the Milky Way.

The optical counterpart of J161201 is also a known variable star in the ASAS-SN catalogue with an average V band magnitude of 12.42 and a tentatively identified period of about 177.8 days. Additionally, we looked for Transiting Exoplanet Survey Satellite [TESS, 40] catalogue data, and found that the star is flagged as a binary candidate with the suggested periodicity of 7.0753 days [41].¹¹ The object is also present in the AllWISE catalogue, where it is identified as J161201.92–464621.8. The catalogue indicates variability in three out of four of WISE's mid-infrared bands.

A summary of the optical and distance information regarding the suggested counterparts to J161201 and J061331 from *Gaia* DR3 and BJ21, along with NIR JHK information from 2MASS is presented in Table 3.

⁷ <https://cdsarc.cds.unistra.fr/viz-bin/cat/I/352>

⁸ <https://asas-sn.osu.edu/variables/>

⁹ <https://ztf.snad.space/>

¹⁰ <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/AJ/156/241>

¹¹ <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS/522/29>

Table 3 Summary of optical/IR and distance information about the suggested counterparts

Parameters	Description	J061331	J161201
G, mag	Mean apparent G-band magnitude	15.3089 ^{+0.0051} _{-0.0051}	12.3203 ^{+0.0067} _{-0.0067}
BP-RP, mag	BP-RP colour	2.3561 ^{+0.0178} _{-0.0178}	0.9392 ^{+0.0395} _{-0.0395}
A _V , mag	Extinction in V band	—	0.4429 ^{+0.0098} _{-0.0096}
A _G , mag	Extinction in G band	—	0.3717 ^{+0.0084} _{-0.0081}
J, mag	Apparent J-band magnitude	11.555 ^{+0.022} _{-0.022}	10.825 ^{+0.023} _{-0.023}
H, mag	Apparent H-band magnitude	10.598 ^{+0.021} _{-0.021}	10.539 ^{+0.023} _{-0.023}
K, mag	Apparent K-band magnitude	10.169 ^{+0.018} _{-0.018}	10.330 ^{+0.019} _{-0.019}
D, pc	Distance	656.9 ^{+57.5} _{-40.5}	391.7 ^{+2.2} _{-2.1}

3 Data analysis results

3.1 X-ray spectral analysis

Considering the low statistics in eROSITA spectra, we combined the data from all four individual surveys. For *XMM-Newton*, the spectra from each of the EPIC cameras (MOS1, MOS2, PN) were extracted separately and analysed together with the combined eROSITA spectrum using the same model. A cross-normalisation constant was introduced for each of the spectra to account for differences in the absolute flux calibration of individual instruments and possible flux differences arising from asynchronous *XMM-Newton* and eROSITA observations. All spectra were grouped to contain at least one count per energy bin and were modelled using XSPEC v12.11.1¹² [42].

To model the spectra we used the phenomenological models commonly used to describe the spectra of XRBs and active stars. First, we attempted to model the spectra using absorbed cutoff power law (`constant*tbabs*cutoffpl`) and absorbed black body models. To take into account interstellar absorption we use the `TBabs` component [43]. We found that both models fail to provide a statistically acceptable approximation for the spectra of either source. On the other hand, we found that an acceptable fit can be obtained using a two-temperature optically thin thermal plasma emission model [44, 45], i.e. `constant*tbabs*(apec+apec)` commonly used to approximate the spectra of hot [46] and cool [47, 48] stars, as well as some accreting white dwarfs (WDs) a.k.a. cataclysmic variables (CVs) [49, 50]. The best-fit results and residuals are presented in Fig. 2 and Table 4.

The X-ray spectrum of J161201 (see Fig. 2 and Table 4) appears to be harder than that of J061331. More importantly, a closer look at PN data for J161201 in the Fig. 2 (right panel), indicates the presence of an iron emission line around 6–7 keV, which is missed in MOS1–2 data likely due to lower statistics. A zoomed view of the region around the emission line is shown in Fig. 3. The results of a Gaussian fit to the line are presented in the Table 5.

In general, for X-ray sources, iron line emission in the 6–7 keV energy range constitutes a set of distinct lines, consisting primarily of three components: a fluorescent Fe K_α line at 6.4 keV, and two Ly_α lines from Fe XXV (He-like iron) near

¹²<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

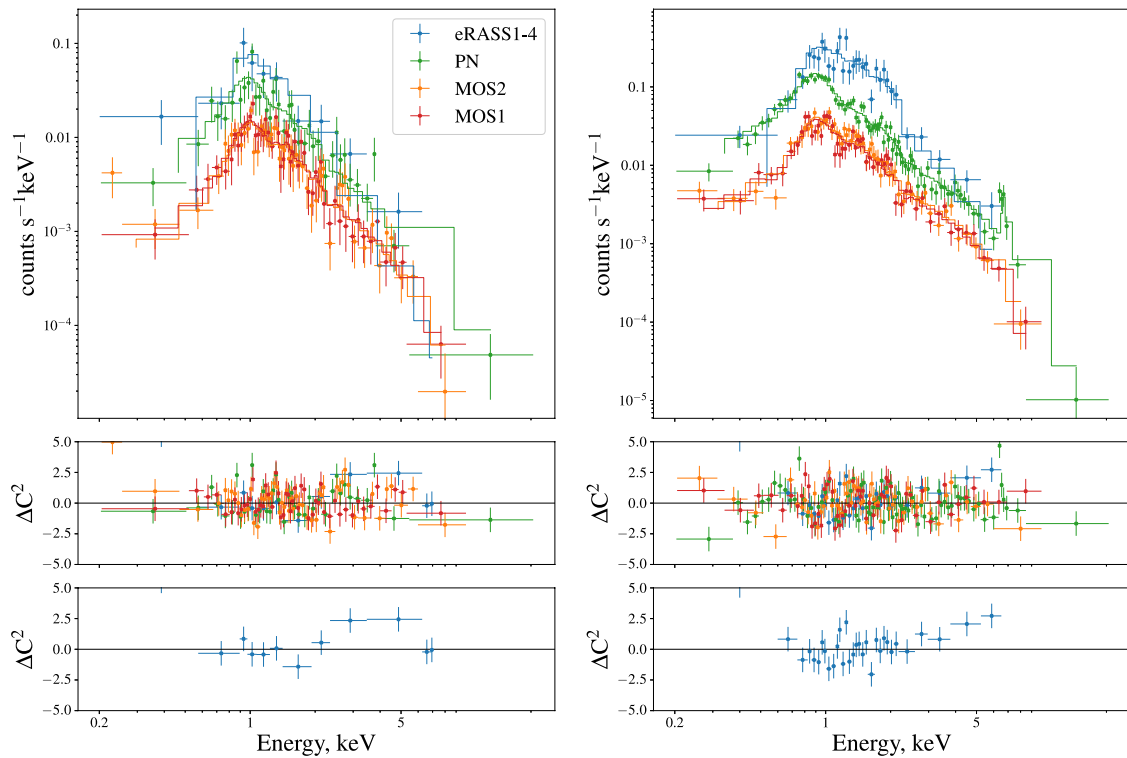


Fig. 2 XMM-Newton and eROSITA spectra of J061331 (left image) and J161201 (right image) fitted with double apec ($\text{const} \times \text{tbabs} \times (\text{apec} + \text{apec})$) model. *Top panels:* spectra themselves and the fit; *Middle panels:* all corresponding residuals; *Bottom panels:* eROSITA residuals only

Table 4 J061331 and J161201 parameters of double apec spectral model $\text{const} \times \text{tbabs} \times (\text{apec} + \text{apec})$ used to fit the XMM-Newton and eROSITA spectra

Components	Parameters	J061331	J161201
constant	C_{MOS1}	1.0	1.0
	C_{MOS2}	$0.93^{+0.13}_{-0.11}$	$1.02^{+0.09}_{-0.08}$
	C_{PN}	$0.80^{+0.12}_{-0.11}$	$0.99^{+0.07}_{-0.07}$
	C_{eROSITA}	$2.07^{+1.34}_{-0.93}$	$6.62^{+1.32}_{-1.10}$
tbabs	$N_{\text{H1,XMM}}, 10^{22} \text{ cm}^{-2}$	$0.33^{+0.10}_{-0.07}$	$0.22^{+0.03}_{-0.03}$
	$N_{\text{H1,eROSITA}}, 10^{22} \text{ cm}^{-2}$	$0.55^{+0.37}_{-0.34}$	$0.71^{+0.13}_{-0.11}$
apec ₁	$kT_1, \text{ keV}$	$0.87^{+0.11}_{-0.09}$	$0.94^{+0.04}_{-0.04}$
	$\text{norm}_1, 10^{-5} \text{ cm}^{-5}$	$3.21^{+1.33}_{-1.00}$	$6.69^{+0.94}_{-0.82}$
apec ₂	$kT_2, \text{ keV}$	$3.46^{+0.87}_{-0.73}$	$5.84^{+1.48}_{-0.81}$
	$\text{norm}_2, 10^{-5} \text{ cm}^{-5}$	$12.86^{+1.97}_{-1.86}$	$22.91^{+1.77}_{-1.70}$

Abundances are fixed to solar

6.7 keV and Fe XXVI (H-like iron) around 6.9 keV. These lines are essential markers of hard X-ray emission acting in sources such as XRBs [51–54], CVs [49, 55–58], AGNs [59–62] and some RS Canum Venaticorum (RS CVn) variables [63–65]. As fluorescent lines, these lines are a measure for the X-ray flux above the K-edge of Fe. In turn, Ly_α lines come from photoionization or collisional excitation in hot plasma with a temperature of $10^{7...8} \text{ K}$.

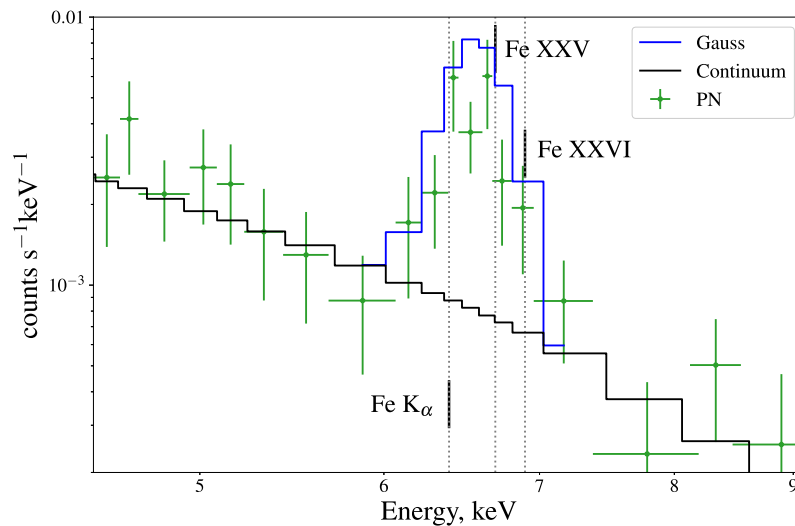


Fig. 3 Zoom-in region of XMM-Newton spectra for J161201 (PN camera only) with shown continuum level and Gaussian fit. Vertical lines show the positions of corresponding main iron emission lines (6.4, 6.7 and 6.9 keV respectively)

Table 5 Gaussian fit parameters for the iron emission line of J161201 spectra

Parameters	Values
Line energy, keV	6.55 ± 0.03
Line normalisation, 10^{-5} photons $\text{cm}^{-2} \text{s}^{-1}$	3.08 ± 0.15
Full width at half maximum (FWHM), eV	435 ± 23

However, poor statistics do not allow us to resolve each iron line separately. Nevertheless, the fact that we do see iron line emission around 6–7 keV indicates the presence of hard X-ray radiation, which is not typical for regular active stars.

3.2 X-ray timing analysis

To assess the long-term X-ray variability of the source we estimated the source flux by modelling source spectra extracted for each of the individual observations and approximated using the same model where all parameters except the normalisation were fixed to their best fit values. To estimate observed flux and its uncertainty the additional `cflux` (as `cflux*tbabs*(apec+apec)`) model component (with an energy range 0.2–2.3 keV for eROSITA and XMM-Newton) was introduced. The energy range was chosen to match that of eRASS1 catalogue.¹³ The flux value was considered to be independent for each observation. The resulting long-term X-ray light curve of the source is presented in Fig. 4.

We have also carried out a search for possible coherent pulsations for both objects using the XMM-Newton data. The periodicity search was carried out using the observed event arrival times (corrected to Solar system barycentre) and Z^2 statistics [66] as implemented in the `Stingray`¹⁴ package [67]. We used the energy range (0.5–10 keV) and separately considered two ranges of possible periods for the full data

¹³ <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/682/A34>

¹⁴ <https://docs.stingray.science/>

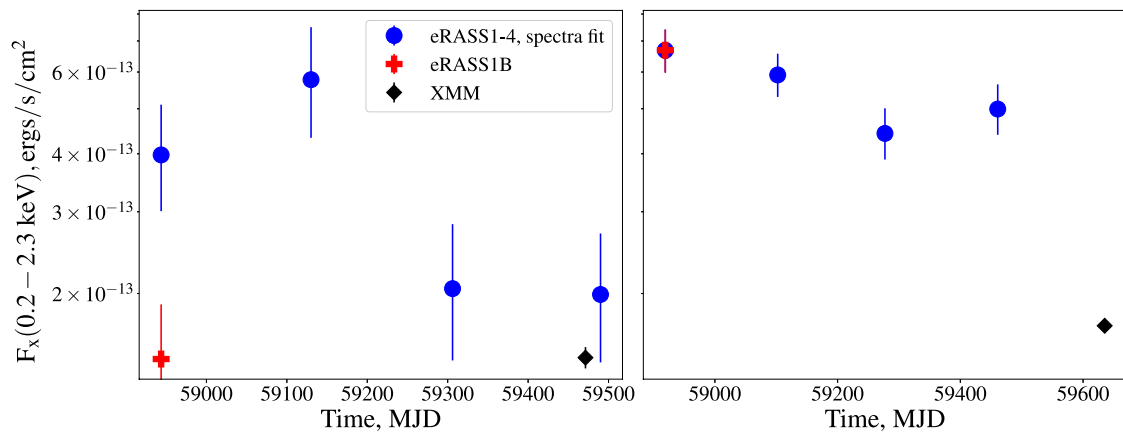


Fig. 4 Intrinsic X-ray fluxes of J061331 (left panel) and J161201 (right panel) based on XMM-Newton and eROSITA data (both from spectra fitting and from eRASS's data)

Table 6 Parameters of pulsation search for J061331 and J161201

Parameters	Camera	J061331	J161201
Counts	all EPIC	1828	5041
	PN only	379	2945
Periods range, s	all EPIC	5.2-27219	5.2-26228
	PN only	0.1468-22055	0.1468-21370
f_{puls} limit, %	all EPIC	23.37	19.01
	PN only	36.23	25.66

set (all three cameras combined and PN camera only) to exploit finer time resolution of the latter instrument. We did not search for pulsations in the eROSITA data due to the low number of counts there. The range of periods searched is, therefore, defined by the duration of the observations and Nyquist frequency ν_{Nyquist} corresponding to time resolution t_{res} of a given detector (in particular $\nu_{\text{Nyquist}} = 0.5 \times t_{\text{res}}$). The resolution of the periodograms was chosen to oversample the latter by a factor of 8 to avoid missing any peaks. In each case, periodograms were averaged over segments with a length exceeding the longest period searched by a factor of 200 to reduce noise and further improve sensitivity. The ranges of periods searched and number of photons used in each search are listed in Table 6.

Unfortunately, no evidence of significant coherent X-ray periodicity was found for either candidate. Considering the relatively low flux of both sources, this could be, however, simply a result of insufficient counting statistics, so we also estimated the upper limits on the amplitude of a possible coherent signal which could be missed by our search. In particular, we used the methods suggested by [68] as implemented and described in detail in [69] and by [70] as implemented in `amplitude_upper_limit` and `pf_from_a_stingray` functions in `Stingray` package.

The resulting upper limits for 3- σ confidence level are also listed in Table 6. The lack of a clearly detected pulse signal is not surprising, given the available statistics for this observation, so no conclusions regarding the nature of either source shall be drawn based on the non-detection of the pulsations.

Table 7 The parameters of J061331's optical counterpart based on LAMOST spectrum

Parameter	T_{eff} , K	$\log(g)$, cm/s ²	M/H, dex	$\text{FWHM}_{\text{H}\alpha}$, Å	[TiO] ₁	[TiO] ₂
Value	3817 ± 101	4.41 ± 0.22	-0.91 ± 0.28	7.4 ± 0.3	0.022	0.012

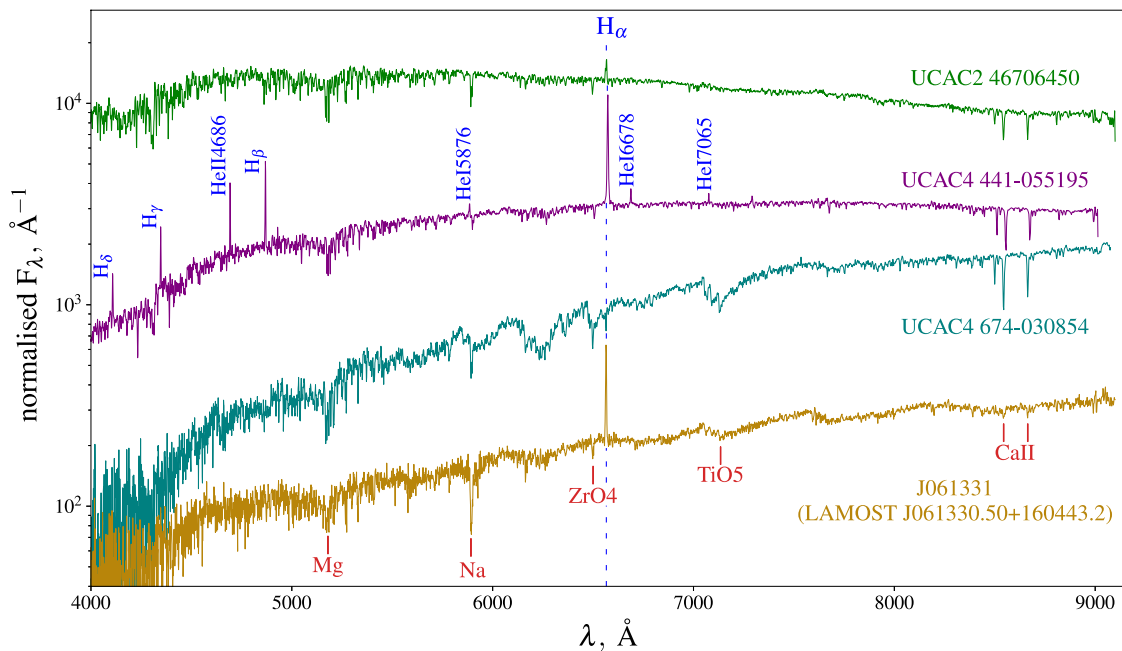


Fig. 5 From the bottom to the top: LAMOST DR9 low-resolution ($\lambda/\Delta\lambda = 1800$) optical spectra of the counterpart to J061331, UCAC4 674–030854 (S-type giant), UCAC4 441–055195 (Symbiotic CV with K-type giant) and UCAC2 46706450 (K-type subgiant with non-accreting WD). Spectra of UCAC4 674–030854 and UCAC4 441–055195 were rescaled for ease of plotting. Strong emission and absorption lines are marked with blue and red coloured text, respectively

3.3 Optical spectroscopy

To complement X-ray observations, we attempted to obtain archival spectral data in optical/IR bands. While there is no archival optical/IR spectral information available for J161201, data from J061331 can be found in the Large sky Area Multi-Object fiber Spectroscopic Telescope [LAMOST, 71] archive. This source has been classified as a late-type star with a spectral type between K7 [72]¹⁵ and M0 [73].¹⁶ In Table 7 we also give other derived quantities for the star as obtained from LAMOST.

3.3.1 LAMOST optical spectrum of J061331

The corresponding LAMOST optical spectra¹⁷ are presented in Fig. 5. Along with the counterpart of J061331, we show spectra of several other sources of different origins which appear in LAMOST low-resolution data, namely UCAC4 674–030854 [S-type

¹⁵ <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJS/244/8>

¹⁶ <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJS/253/19>

¹⁷ <https://www.lamost.org/dr9/>

giant, 74, 75],¹⁸ ¹⁹ UCAC4 441–055195 [Symbiotic CV with K-type giant, 76], and UCAC2 46706450 [K-type subgiant with non-accreting WD, 77].

As is evident from Fig. 5, the LAMOST spectrum of J061331’s optical counterpart shows a very strong H_α emission line (6564.6 Å). The H_α emission line is an essential indicator of rotation and chromospheric/coronal activity for late-type stars [78–81], accreting processes for young stellar objects (YSO) [82–84], Be-type [85, 86] or symbiotic [87] XRBs, as well as CVs [88]. We calculate the corresponding FWHM of H_α line for J061331’s optical counterpart to be 7.4 ± 0.3 Å (also presented in Table 7). However, we do not see other emission signatures, for example, H_β , H_γ , He lines typical for accreting binaries with compact companions [88–91]. On the other hand, even though LAMOST detects TiO and other absorption lines (such as Mg, Na, etc.), which come from the star’s photosphere, those are relatively weak making it less likely for J061331 to be a giant star and rather be still on subgiant stage (see the comparison with UCAC4 674–030854 and UCAC2 46706450 in the Fig. 5).

In order to find the spectral type of J061331’s optical counterpart, we use methods presented in [92]. Based on a large dataset of late-type stars authors found that the depth of TiO bands could be utilised as an indicator for star’s spectral type, namely [see equations 5 and 6 in 92]:

$$ST_1 = 1.75 + 9.31 [\text{TiO}]_1, \quad (1)$$

$$ST_2 = 1.83 + 10.37 [\text{TiO}]_2 - 3.28 [\text{TiO}]_2^2, \quad (2)$$

where the $ST_{1(2)}$ is a spectral type, while $[\text{TiO}]_1$ and $[\text{TiO}]_2$ are corresponding TiO indices [see equations 1 and 2 in 92]. $ST_{1(2)}$ lies around 0 for M0 stars, –6 for K0 stars, and +6 for M6 stars. Following equations 1 and 2 from [92], we calculate TiO indices based on the LAMOST spectra for J061331’s optical counterpart (see Table 7). Therefore, we determine ST_1 and ST_2 for J061331’s optical counterpart to be both around 1.9, resulting in the spectral type of the star close to M2. This is a bit later than what LAMOST archival data suggest (but does not contradict it).

3.3.2 Follow-up spectroscopy of J161201 with SALT

Since no archival spectral data were available for the optical counterpart of J161201, the source was selected for the follow-up with the 10 m class Southern African Large Telescope [SALT, 93]. A 1600 s observation was taken with SALT’s High Resolution Spectrograph [HRS, 94, 95, 96, 97] on February 5.1026, 2025 in low-resolution (LR; $R \sim 15000$) mode. HRS is a dual-beam, fibre-fed échelle spectrograph that spans a wavelength range of 3800 to 8900 Å. The initial processing of the HRS spectra was carried out with the PySALT software package [98]²⁰ which performs tasks such as overscan removal, bias correction, and gain calibration. Spectral extraction was con-

¹⁸ <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJ/931/133>

¹⁹ <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJS/267/5>

²⁰ <http://pysalt.salt.ac.za/>

ducted using the HRS pipeline, which utilizes MIDAS routines [99]. The resulting spectrum is shown in Fig. 6.

The SALT spectrum obtained for J161201 displays a very blue continuum, which continues to rise toward the short-wavelength cut-off near 3800 Å. This suggests a strong ultraviolet component and hints at high temperatures in the emitting region. The spectrum is rich in emission features, prominently showing Balmer series lines such as H_α , H_β , and H_γ (see Fig. 6). In addition to H-Balmer emission lines the source displays He-emission lines (neutral He I 6678 and ionised He II 4686) as well as fluorescent C III/N III Bowen blend [fluorescent for N III, see 100, 101] around 4640 Å, which is often observed in accreting X-ray binaries [102], such as LMXBs [103] and CVs [104, 105]. EWs and FWHMs of emission and absorption line profiles are shown in Table 8. The nature of the optical spectrum robustly points toward a CV classification for J161201. The resulting spectrum shows no evidence of the donor star. The humps and the overall rise in intensity towards higher wavelengths seen in red arm of the SALT HRS data (Fig. 6, bottom panel) are due to the échelle design of the spectrograph²¹ and the lack of flux calibration — not the photosphere of the secondary star.

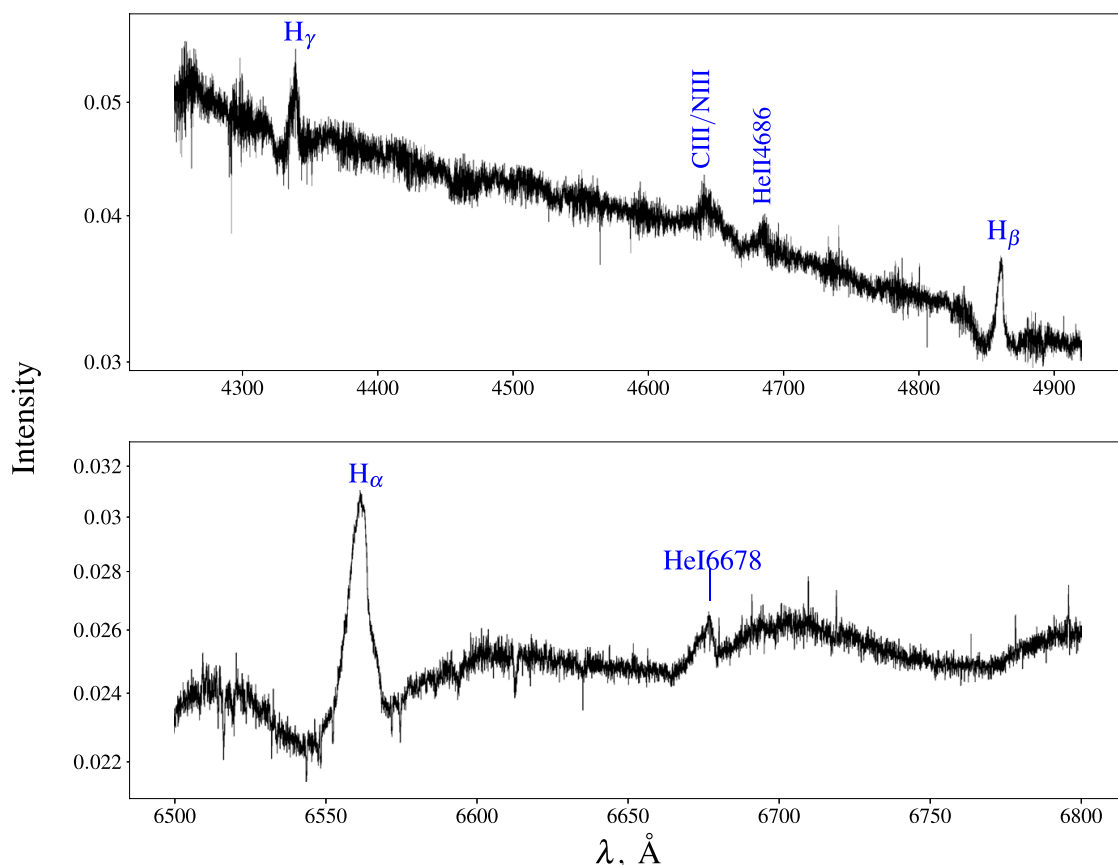


Fig. 6 Blue (top panel) and red (bottom panel) arms of J161201's SALT HRS spectrum. SALT HRS provides data in arbitrary, uncalibrated intensity units. Wavelength regions are selected to showcase identified emission lines

²¹ https://astronomers.salt.ac.za/wp-content/uploads/sites/71/2014/08/3200-AE-0017_SALT_HRS_Instrument_Description_v4.0.pdf

Table 8 Spectral line measurements for J161201 SALT spectrum

Line / Parameter	EW, Å	FWHM, km/s	Abs. EW, Å	Abs. FWHM, km/s
H-alpha	-2.81 ± 0.03	380 ± 30	4.21 ± 0.16	2150 ± 120
H-beta	-1.08 ± 0.02	370 ± 20	2.36 ± 0.07	2350 ± 150
H-gamma	-1.06 ± 0.06	450 ± 70	1.66 ± 0.11	1780 ± 270
He I 6678	-0.22 ± 0.01	330 ± 20	N/A	N/A
C III/N III	-1.48 ± 0.08	1500 ± 70	N/A	N/A
He II 4686	-0.19 ± 0.01	360 ± 30	N/A	N/A

EW and FWHM values are shown for emission and absorption (in case of H-Balmer) line profiles

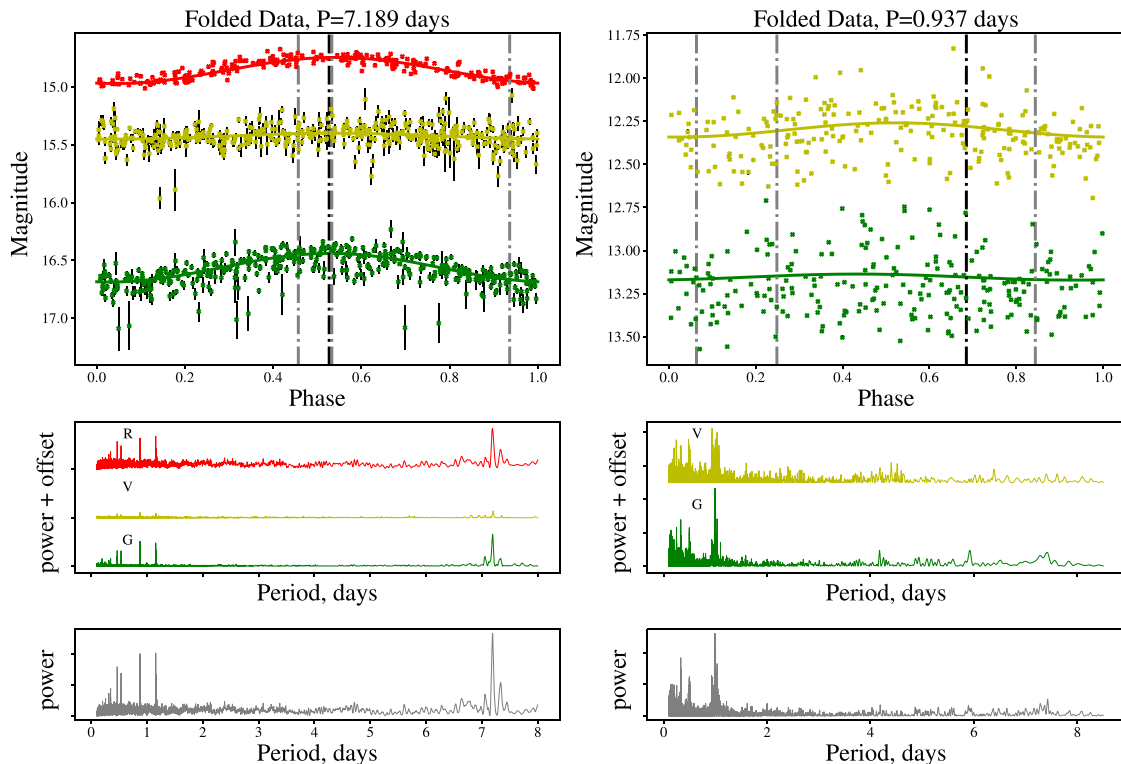


Fig. 7 Phase folded optical light curves of J061331 (left image) J161201 (right image) from ZTF and ASAS-SN (top panels) with standard periodogram in each band (middle panels) and multiband periodogram (bottom panels)

3.4 Optical variability

In order to examine the sources studied here for periodic behaviour in optical bands, we accessed archival data from the databases of ZTF, ASAS-SN and TESS. The corresponding light curves (*R*, *G* and *V* bands from ZTF and ASAS-SN data) are shown in Fig. 7 for J061331 (left panel) and J161201 (right panel). We conducted epoch folding on the light curves and produced periodograms using the python package *gatspy*,²² which is based on the classical Lomb-Scargle algorithm [106, 107], see [108] for more details. For both candidates, black and grey vertical lines indicate the observation times of the corresponding eRASS surveys (eRASS1 and eRASS2–4

²²<https://github.com/astroML/gatspy>

respectively). We searched for periodic behaviour up to 300 days for both sources, but show only a part of the periodogram in Fig. 7 for clarity.

In the case of J061331, the ZTF data allowed detection of some significant modes in the periodogram (see lower and middle panels on the left image of Fig. 7). The two highest peaks on the periodogram with high precision are the same as those reported by ATLAS and ZTF (see Sect. 2.2), at 1.158 and 7.189 days. However, all the peaks in the periodogram below ~ 7 days with high accuracy are simply just beat tones (carrier and envelope frequencies with corresponding aliasing multiplicities) caused by the periodicity of 7.189 days attributed to J061331 and the Earth's rotation harmonic.

The right panel of Fig. 7 shows the optical light curves (V and G band) of J161201's counterpart provided by ASAS-SN telescope (this source is out of sight of ZTF observatory). The peak signal detected by us differs from the one given in ASAS-SN (see Sect. 2.2), but the periodogram overall does not look very promising (see lower and middle panels on the right panel of Fig. 7).

Additionally, we looked for archival TESS lightcurves of the two sources, using the Mikulski Archive for Space Telescopes (MAST).²³ The candidates only appear in Quick-Look Pipeline (QLP) TESS data, which means that we only have access to Simple Aperture Photometry (SAP) flux instead of also having Pre-search Data Conditioning SAP (PDCSAP) flux. PDCSAP flux is generally cleaner than the SAP flux and has fewer systematic trends. Nevertheless, the corresponding light curves are presented in the Figs. 8 and 9 for J061331 and J161201 respectively.

The light curve of J061331's optical counterpart clearly shows a sinusoidal periodic signal, which is really close to the one found in ZTF data, namely 7.189 days (Fig. 8, green line). However, around 58475–80 days, the observed light curve

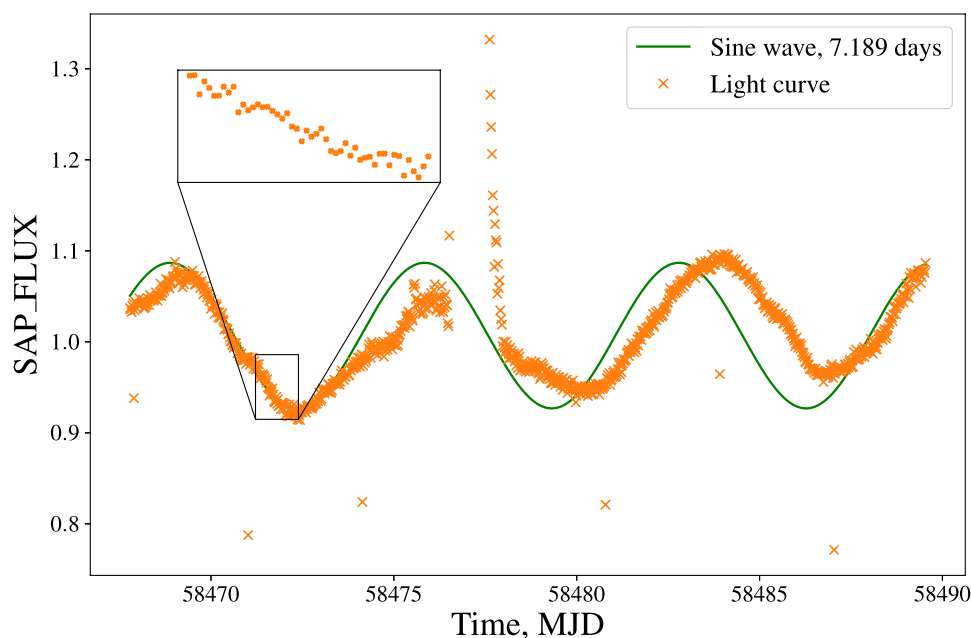


Fig. 8 TESS's optical light curve (~ 21.7 days duration) of the J061331 counterpart along with the sine wave having a period of 7.189 days obtained from ZTF Lomb-Scargle periodogram. Observation is taken in 2018

²³ <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

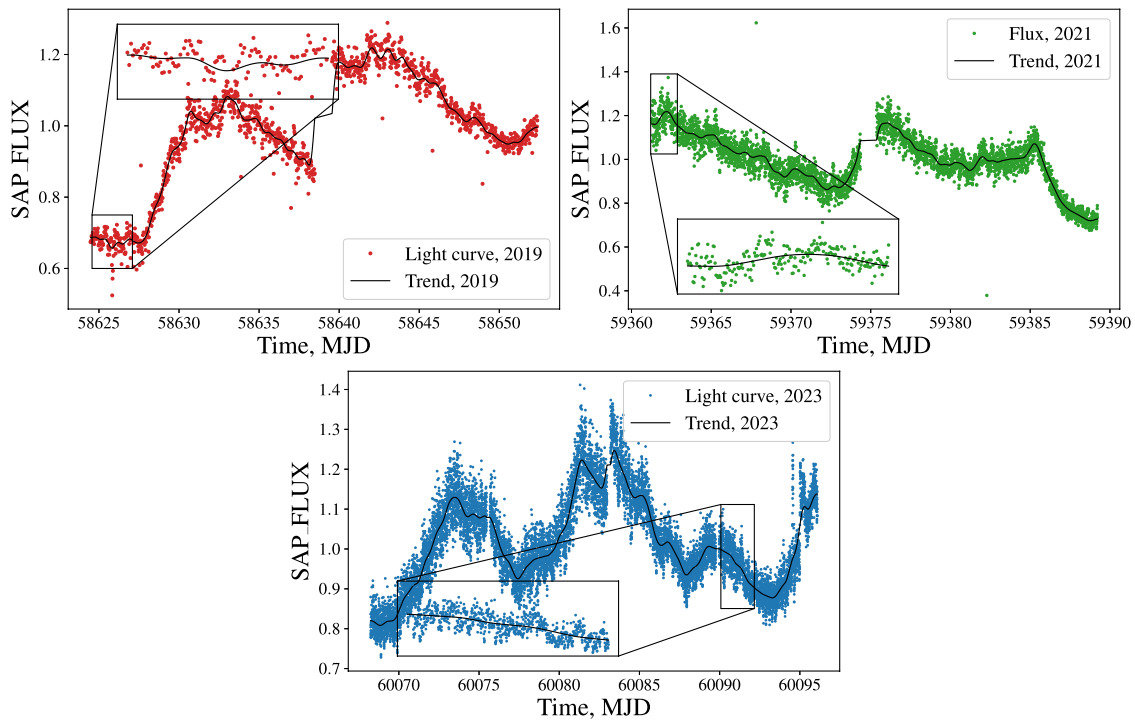


Fig. 9 TESS's optical light curves (~ 27.9 days duration each) of the J161201 counterpart. Black lines represent a trend catapaulted by S-G smoothing filter. Left, right and bottom panels of the figure show observations taken in 2019, 2021 and 2023

diverges from the sine wave, presumably due to a flare seen in that interval, after which, it resumes normal sinusoidal behaviour. Such short-term flares are common for late-type (usually M-type and later) chromospherically/magnetically active stars (especially for rich coronal X-ray emitters), and they are generally associated with stellar coronal mass ejection (CME) events [see 109, 110, 111, 112, and references therein]. Furthermore, we don't detect any light curve variations on a day/sub-day level (Fig. 8, see zoomed-in random section), which appear on the periodogram (see Fig. 7, left image). This supports the idea that any periodic signals found below ~ 7 days are indeed just beat tones and their aliased versions. We can also see in the Fig. 7 that the shape of the TESS light curve changes slightly (≈ 0.1 mag amplitude) and is strongly affected by the flare. Thus, it seems that the 7.189 day signal could be caused by starspots [113–115], rather than come from the modulation of the orbital period.

The case of J161201 stands out in several respects. Figure 9 presents TESS observations of the source from 2019, 2021, and 2023. The 2023 epoch benefits from a significantly higher cadence — ~ 3 min compared to ~ 10 min and ~ 30 min in 2021 and 2019 datasets, respectively, allowing for much finer time resolution. Each light curve displays distinct quasi/a-periodic variability on timescales of several days, with brightness fluctuations reaching nearly 1 mag, consistent with trends seen in the ASAS-SN data.

Given the complex and high variable nature of J161201's photometric behaviour, we applied a de-trending procedure to the TESS light curves before searching for a periodic signal. As SALT spectroscopy identifies J161201 as a CV (see Sect. 3.3), an orbital period on the order of a few hours is expected. To extract variations on this shorter timescale, we used a Savitzky-Golay filter [S-G, 116, 117] to subtract

long-term trends and variability exceeding 1 day (see removed trends in Fig. 9, black lines).

After de-trending, a Lomb-Scargle periodogram was computed for each TESS dataset (see Fig. 10). All three light curves, despite being collected over a span of four years, consistently show a strong, stable peak at around 4.802 hours. While other peaks (seen in 2019 and 2021) are occasionally present, they seem to be transient and disappear in the better-cadence 2023 data. When combining all three epochs to bridge gaps between sectors without cycle count alias, the 4.802-hour peak remains to be one and only prominent feature. To determine the statistical significance of periodic signals, we employed a bootstrap resampling technique. This method generates synthetic datasets that preserve the original observational cadence, allowing to approximate the true distribution of peak maxima in the absence of true periodic variability. Through this computational approach, we established a detection threshold corresponding to a 1% false-alarm probability for peak maxima, as illustrated in Fig. 10.

To ensure that the choice of de-trending method did not artificially introduce or suppress any periodic signals, we tested several alternative smoothing techniques. These included moving average, modified sinc kernel, Whittaker–Henderson smoothing [118, 119] and S-G filter with fitting weights [see 120, for the review]. In all cases, the same dominant periodic signal at ~ 4.8 hours was recovered, confirming the robustness of the result. We also scanned periodogram space up to several days by increasing the long-term cut-off in the de-trending process; however, no other significant peaks were found. Ultimately, the presence of such stable signal in all 3

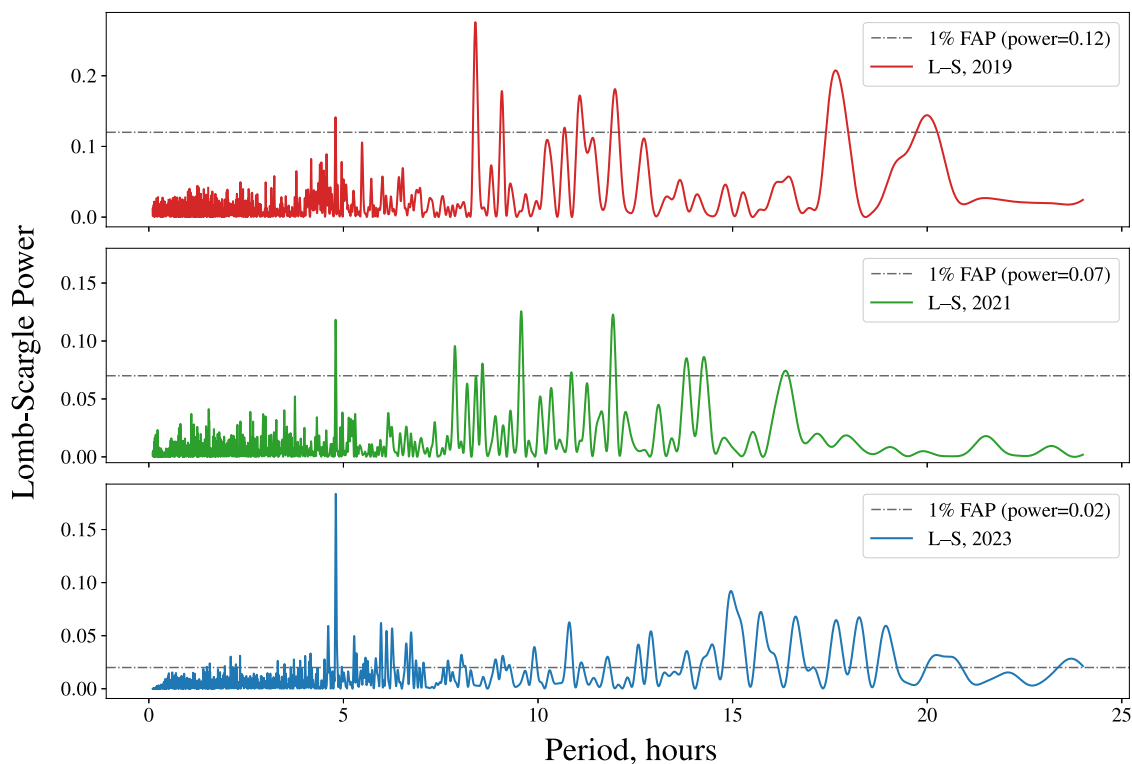


Fig. 10 Lomb-Scargle periodograms for J161201 based on de-trended TESS data from 2019, 2021 and 2023 observations (top, middle and bottom panels, respectively). All three periodograms show a peak around 4.802 h, which becomes more dominant with better cadence. Grey dash-dotted lines show the periodogram levels corresponding to a maximum peak false-alarm probability of 1%

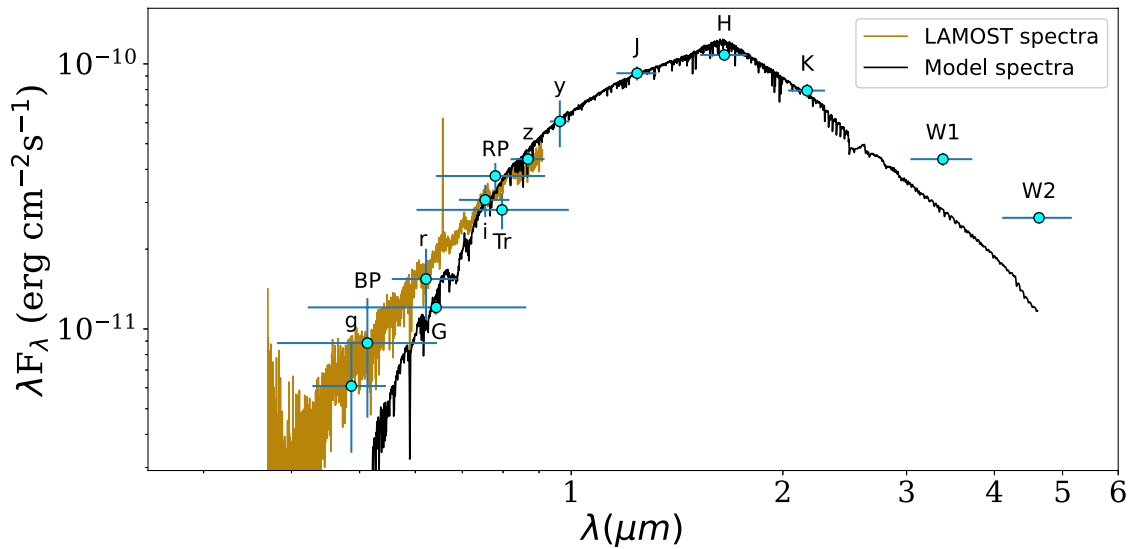


Fig. 11 Fit to the SED of J061331. LAMOST spectra (same as in the Fig. 5), normalized to *i*-band magnitude, is shown in dark goldenrod colour. Model Phoenix flux is drawn with black, while blue errorbar dots represent corresponding photometry

Table 9 Parameters of ARIADNE's SED fit results for J061331 optical counterpart

T_{eff} , K	$\log(g)$, cm/s ²	Fe/H, dex	D , pc	R , $R_{\odot}$	A_V , mag	L , $L_{\odot}$	Age, Gyr
3885.54^{+388}_{-355}	$4.47^{+0.73}_{-0.58}$	$-0.54^{+0.33}_{-0.43}$	787^{+101}_{-71}	$5.07^{+0.94}_{-0.61}$	$3.32^{+0.62}_{-1.48}$	$5.88^{+3.81}_{-1.04}$	$11.9^{+2.4}_{-3.9}$

observations spanned across 4 years strongly supports the identification of J161201's orbital period as 4.8 hours.

3.5 Stellar parameters of J061331 from SED

In order to determine the radii, effective temperatures, luminosities, and other stellar parameters of J061331, we performed a fit of the spectral energy distribution (SED) using spectrAl eneRgy dIstribution bAyesian moDeL averagiNg fittEr [ARIADNE, 121].²⁴ This code is meant to fit MWL photometry to a different stellar atmosphere models based on nested sampling algorithms [122, 123] within Bayesian inference framework, similar to the classic Markov Chain Monte Carlo (MCMC) methods.

Corresponding best fit is shown in Fig. 11. The resulting best fit parameters are presented in Table 9. SED fits were made using *dynesty* engine [124] and Phoenix models [125],²⁵ since they provided more accurate results based on the given photometry. The blue dots in Fig. 11 indicate corresponding filter fluxes converted from the observed magnitudes. ARIADNE uses specific set of allowed photometry filters,²⁶ therefore, we obtained every archival magnitude possible. Specifically, *g*, *r*, *i*, *z*, *y* data for J061331 were taken from the Panoramic Survey Telescope and Rapid Response

²⁴ <https://github.com/jvines/astroARIADNE>

²⁵ <https://phoenix.astro.physik.uni-goettingen.de/data/HiResFITS/PHOENIX-ACES-AGSS-COND-2011>

²⁶ <https://github.com/jvines/astroARIADNE/blob/master/filters.md>

System (Pan-STARRS) catalogue [126, 127].²⁷ In turn, G , BP , RP information, J , H , K data, as well as $W1$, $W2$ magnitudes/fluxes were taken from *Gaia* DR3, 2MASS and WISE catalogues, respectively. TESS mean magnitude is presented as Tr .

As can be seen in Fig. 11, the model predicts observations very well for J061331 from the mid-optical to NIR range, but we have some excess in the blue optical and WISE IR bands. However, there is another bright IR source nearby J061331 (*Gaia* DR3 3345882607097252480, at an angular separation $\sim 7''$), therefore, the observed excess in $W1$ and $W2$ WISE bands could be just the result of a blend. Another possibility is that the IR excess seen is due to gas surrounding the subgiant star, which is caused by its high surface mass-loss rate. Such behaviour is known among subgiant and AGB stars [128, 129]. In turn, we believe that blue optical excess is small to be caused by the other binary component, and is likely just a result of insufficient absorption constraints (see Table 9) and an active chromosphere. Additionally, the resulting SED fit parameters on temperature, surface gravity and metallicity for J061331 seem to be in line with LAMOST archival data (see Tables 7 and 9).

We note that SED modelling of J161201, classified as a CV (see Sect. 3.3 and upcoming discussion Sect. 4), requires an accurate treatment of the individual components of the system — primarily the accretion disc, the boundary layer, and the white dwarf. The contribution from the donor star is expected to be minimal. Proper modelling therefore involves computing synthetic atmosphere spectra under specific physical conditions for each component, which lies beyond the scope and volume of the present study. A dedicated analysis focusing on J161201's SED will be presented in a forthcoming paper.

4 Discussion

Both candidates, in general, have similar initial X-ray observational appearance. Namely, despite relatively high brightness in the X-rays they appear to exhibit X-ray spectra different from those of accretion-dominated XRBs. Indeed, based on the results of spectral analysis, we conclude that spectra of both objects are well approximated with absorbed two-temperature *apec* model. This allows the accurate determination of the intrinsic X-ray fluxes in 0.2–2.3 keV energy range as shown in Fig. 4. Unfortunately, we do not find X-ray pulsations for either candidate, which would help better constrain the nature of the sources based on X-ray data.

Spectral analysis and SED fitting results of J061331 indicate the presence of a late M0–M2 type star ($T_{\text{eff}} \lesssim 4000$ K). Given the resulting radius and bolometric luminosity of this star ($R \sim 5R_{\odot}$ and $L \sim 6L_{\odot}$, see Table 9) we identify J061331's optical counterpart as a subgiant. The source also shows a really strong H_{α} emission signature in its optical LAMOST spectra. However, the absence of other emission line features (such as H_{β} , H_{γ} , and He lines) typical for accreting binaries makes it unlikely for J061331 to be an XRB or a CV. Therefore, H_{α} emission could be just a result of an active chromosphere. SED fit results also show that the source exhibits high reddening ($A_V \sim 3.3$) which is typical for stars at the suggested for J061331's counterpart evolutionary stage and would be in line with high coronal activity [130–132].

²⁷ <https://cdsarc.cds.unistra.fr/viz-bin/cat/II/349>

The optical counterpart of J061331 is found to be periodically variable (the modulation is 7.189 days). Additionally, we see a flare in its light curve (see Fig. 9), which is characteristic for late-type chromospherically active stars. The shape of its light curve suggests that the periodicity could be caused by starspot(s) rather than orbital modulation. Therefore, we can conclude that this candidate is most probably a M-type H_α emitting coronal active subgiant, which has surface starspot(s) causing 7.189 days period found in its optical light curve.

Given the assumption that the 7.189 days optical modulation of J061331's counterpart is caused by starspot(s), with the stellar radius of $5.07^{+0.94}_{-0.61} R_\odot$ (Table 9), we can calculate rotational velocity of the star to be $v_{\text{rot}} = 35.7^{+6.6}_{-4.3} \text{ km s}^{-1}$. However, the observed H_α emission profile ($\text{FWHM}_{H_\alpha} \approx 7.4 \text{ \AA}$) corresponds to a broad width of $\sim 330 \text{ km s}^{-1}$, exceeding the expected rotational width by a factor of nine. Thus, assuming that H_α is bound with the star, FWHM suggests that some part of the emission may come from a region extending outward within a corotating circumstellar environment reaching up to 8–10 stellar radii. This has actually been seen and studied in other active stars [133–136], where it has been suggested that the overall H_α emission is composed of two parts: chromospheric and a circumstellar component.

In turn, J161201 has harder X-ray spectra compared to J061331, and more importantly, shows Fe line emission signatures around 6–7 keV. However, in absence of accretion-dominance spectral features and the overall spectra resembling two temperature hot plasma, one can say that J161201 appears more as a CV or RS CVn candidate rather than an XRB.

The SALT spectrum of J161201 reveals a blue continuum and prominent emission lines, including the H-Balmer series, He I, He II, and the C III/N III Bowen blend — features characteristic of an accreting binary with the optically thin layer of hot plasma which goes in line with X-ray double apec spectrum (see Fig. 2 and Table 4). The absence of donor star signatures in the SALT's spectrum and the overall spectral profile strongly support the classification of J161201 as a CV. Moreover, each Balmer emission line in J161201's optical spectrum is accompanied by the broad absorption wings, which are likely due to the linear Stark effect originating in an optically thick, high-gravity accretion disc viewed at a low inclination angle. The emission lines typically exhibit FWHM around $330\text{--}450 \text{ km s}^{-1}$ (see Table 8), indicating the presence of rapidly moving material in an optically thin region, possibly situated above the disc.

All emission lines have EWs greater than $-10 \text{ \AA}$ ($\text{EW} > -10 \text{ \AA}$, or $|\text{EW}| < 10 \text{ \AA}$) with the He II 4686 to the H_β ratio below 0.2. These spectral characteristics argue against J161201 being a magnetic CV, such as a polar or intermediate polar [137]. Ultimately, considering optical and X-ray spectral features of J161201, its high optical brightness, constant detection in eRASS1-4 (Fig. 4), relatively low X-ray to optical flux ratio ($\log(F_x/F_{\text{opt}}) \approx -2.5$), J161201 is most likely a weakly magnetised, novalike CV. No dwarf nova outbursts were found in archival data, supporting this classification. In such novalike systems the accretion disc's radiation dominates the majority of the optical and near IR SED [138, 139]. Therefore, it is not surprising that we don't see donor star's features in SALT spectrum of J161201, since the accretion disc remains in a persistently hot, accreting state. Ultimately, resulting classification

establishes J161201 as the second bright novalike CV found with eROSITA that is new to the literature [SRGt 062340.2–265751 is the first, see 140].

TESS light curves of J161201 from 2019, 2021, and 2023 exhibit strong quasi/a-periodic variability on multi-day timescales, with brightness changes up to 1 mag. Such high optical variability is not so typical for novalike CVs [even though similar behaviour has been observed in other novalikes, see 141, 142] and may be the result of instabilities in the accretion flow within the disc around a WD [so called “stunted” outbursts, see 143, 144, 145]. However, their exact origin is still puzzling, as well as X-ray to optical correlation during such events, and necessitates simultaneous deep X-ray and optical observations. Nevertheless, a consistent, signal at 4.802 hours was recovered using Lomb-Scargle methods on each TESS observation, which were detrended from the quasi/a-periodic variability. The persistence of such signal over four years of TESS observations firmly establishes it as a tentative orbital period of J161201 binary. Nevertheless, we need time-resolved follow-up spectroscopy and high-speed photometry to unambiguously confirm the derived period, which will be done in the future.

It is interesting, therefore, to also discuss the reasons why both objects (J161201 and J061331) were identified as XRB candidates. First of all, we note that the fluxes initially estimated in the preliminary analysis with the standard eROSITA pipeline, based exclusively on estimated count-rate, were significantly higher ($\sim 1 \times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$ for J061331 and $\sim 1.9 \times 10^{-12}$ erg cm $^{-2}$ s $^{-1}$ for J161201). This discrepancy is due the problems with earlier versions of the eROSITA analysis pipeline [28, 146, 147] and to an assumed spectral shape (which was not known prior to XMM-Newton observations). This can be seen in Fig. 4 where it is apparent that for both sources the fluxes are by factor of 2–3 lower than what obtained in the early processing, and for J061331 there is also a discrepancy by factor of two between the ‘standard flux’ estimate (assuming count rate to flux conversion factor tailored to AGNs), and flux determined directly from the spectrum. On the other hand, the agreement between eROSITA and XMM-Newton derived fluxes for J061331 for which the observations occurred close in time is excellent. It can be also noted that both sources appear to be variable, which is clearly also part of the rather different fluxes measured by eROSITA and XMM-Newton. The observed flux variability is also accompanied by spectral variability, which can be illustrated by comparing the eROSITA and XMM-Newton spectra (see Fig. 2). Indeed, as it can be seen in the lower panels of the figures, eROSITA residuals appear to deviate from the best-fit model mostly defined by XMM-Newton data, even though, along with `const` we untied the `tbabs` column density parameter N_{H} in the fit (see Table 4).

This fact that both spectral shape and flux appear to be variable is quite relevant as the main parameters based on which the observed XRB candidates were selected were the broadband flux and hardness of the spectrum. The fact that the true flux was overestimated has also direct impact on the possible origin of the observed emission, as we discuss below. It should be also noted, that the observed flux of J161201 during the XMM-Newton observation was by factor of five lower than that detected by eROSITA in each of the four surveys, and the observed spectrum during this time was harder than the one of J061331 (see Table 4), which could be also be relevant for the final classification. We conclude, therefore, that the reason for

mis-classification of both candidates was mainly the over-estimated X-ray flux and hardness in our preliminary analysis of eRASS1 data, which were amplified by the intrinsic variability of both objects.

5 Conclusion

In this paper, we reported on follow-up of the two candidates for potential XRB systems, J061331 and J161201, both selected based on the preliminary analysis of X-ray properties of sources in the first eROSITA X-ray survey (eRASS1) with *XMM-Newton*. With *XMM-Newton* observations we were able to refine X-ray positions and unambiguously identify the optical counterparts for both X-ray sources. We have carried out a detailed X-ray spectral and timing analysis for both candidates. In both cases it was found that the X-ray spectrum is more representative of an optically thin thermal plasma rather than of an XRB.

Based on the LAMOST optical spectrum of J061331 and the ARIADNE SED fit results we were able to identify this candidate as a coronal active M-type subgiant. We also reported the detection of a strong H_α emission line and absorption features in the optical spectrum, which favour chromospherically active subgiant origin for this source. Furthermore, it was found that J061331 is photometrically variable with a period of 7.189 days. Based on the optical data analysis, we concluded that this periodicity is likely to come from starspot(s) on the subgiant's surface. TESS light curve also shows that this source has undergone a flare typical for coronal active X-ray emitting late-type stars. With the stellar radius obtained based on the ARIADNE SED fit results, we report that the star is rotating at the velocity $v_{\text{rot}} = 35.7^{+6.6}_{-4.3} \text{ km s}^{-1}$ (assuming that optical period is due to starspots).

J161201 exhibits harder X-ray spectra than J061331, with iron line emission around 6–7 keV, but lacks accretion-dominated features. Its SALT optical spectrum shows a blue continuum, H-Balmer, He I,II and Bowen emission lines, as well as broad H-Balmer absorption wing profiles coming from an optically thick accretion disc around a WD. Emission line features disfavour magnetic CV origin scenario. Coupled with high optical brightness, persistent eRASS1-4 detection, colours, and absence of detected dwarf nova outbursts, J161201 is classified as a weakly magnetised nova-like CV. We also tentatively identify the orbital period for J161201 as 4.802 hours based on TESS observations, pending time-resolved spectroscopic confirmation. The identification of J161201 as a novalike CV marks only the second instance of such a system uncovered by eROSITA, following SRGt 062340.2–265751 [140]. This milestone underscores eROSITA's expanding role in revealing more accreting binaries of different subclasses. In particular, pairing eROSITA's X-ray surveys with large-scale spectroscopic follow-up programs — such as eROSITA/SDSS [148] — will continue to advance the Galactic census of XRBs and CVs.

The main reason for the selection of J061331 and J161201 as XRB candidates was their relatively high X-ray flux in eRASS1 estimated at the time of selection using the preliminary eROSITA processing pipeline (c946) available at the time. Both the analysis of XMM-*Newton* data and the re-processing of eROSITA data with the current pipeline (eRASS1, c020) results in a significantly lower flux, and both objects would now not be selected as plausible XRB candidates even when using eRASS1 data only. Further refinement of classification pipeline is also now possible when considering data from eRASS1-4. We emphasise, however, that variability implies also that candidate selection shall still be done based on detections in individual surveys as most of the XRBs are intrinsically variable and thus non-detection or low observed X-ray flux in one survey does necessarily imply that an object is not a plausible XRB candidate.

Nevertheless, considering the fact that the two other XRB candidates selected for follow-up with NuSTAR based on eROSITA data were in the end classified as XRBs [see 26, 27], we conclude that the success rate for XRB candidates selection based on eRASS1 data only and simplified selection criteria already is significant. In other words, we have already demonstrated the ability of eROSITA to identify new XRBs even if there is room for improving the accuracy. We are working on an improved candidate identification pipeline taking into account these conclusions, and plan to release the final catalogue of eROSITA XRB candidates in a separate publication accompanying the first public data release.²⁸

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²⁸ Under program 2024-2-LSP-001 (PI: David Buckley)

Author Contributions All authors contributed to the study conception and design. A. A. conducted majority of the analysis and wrote most of the initial manuscript text. A. Z. conducted part of the eROSITA analysis, contributed to the manuscript text. V. D. is a PI of the XMM-Newton observations which were analysed in the paper, supervised the project and contributed to the manuscript text. A. Sch. and V. S. contributed to the analysis, manuscript's text and conclusions made. D. B. is a PI of the SALT observations analysed in the manuscript, obtained an identification spectrum. J. B. did the reduction the obtained SALT spectroscopy. J. W. and A. San. both supervised the project, and contributed to the manuscript text.

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Data Availability XMM-Newton (Obs. Ids: 0883460301 and 0883460101) and eRASS1 data used in the study are publicly available. SALT spectral data are available upon request.

Declarations

Competing Interests The authors declare no competing interests.

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Paper V

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V

The effect of thermal winds on the outbursts evolution of LMXB systems

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ABSTRACT

Theoretical models of accretion discs and observational data indicate that the X-ray emission from the inner parts of an accretion disc can irradiate its outer regions and induce a thermal wind, which carries away the mass and angular momentum from the disc. Our aim is to investigate the influence of the thermal wind on the outburst light curves of black hole X-ray binary systems. We carry out numerical simulations of a non-stationary disc accretion with wind using upgraded open code FREDDI. We assume that the wind launches only from the ionized part of the disc and may turn off if the latter shrinks fast enough. Our estimates of the viscosity parameter α are shifted downward compared to a scenario without a wind. Generally, correction of α depends on the spectral hardness of central X-rays and the disc outer radius, but unlikely to exceed a factor of 10 in the case of a black hole low-mass X-ray binary (BH LMXB). We fit 2002 outburst of BH LMXB 4U 1543 – 47 taking into account the thermal wind. The mass-loss in the thermal wind is of order of the accretion rate on the central object at the peak of the outburst. New estimate of the viscosity parameter α for the accretion disc in this system is about two times lower than the previous one. Additionally, we calculate evolution of the number of hydrogen atoms towards 4U 1543 – 47 due to the thermal wind from the hot disc.

Key words: accretion, accretion discs – radiation mechanisms: thermal – X-rays: binaries – X-rays: bursts – X-rays: individual: 4U 1543 – 47.

1 INTRODUCTION

X-ray Binary (XRB) is a binary system featuring an accreting compact object, which can be either a neutron star or a black hole (BH). Up to now, about several hundreds of XRBs are known in our Galaxy (Avakyan et al. 2023; Fortin et al. 2023; Neumann et al. 2023).^{1,2} XRB population is typically categorized into two groups: low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs), based on the properties of the counterpart. In contrast to the HMXB case, the donor companion in an LMXB is a low-mass star, typically a main-sequence star or a white dwarf. In an LMXB, the matter coming from the donor star usually forms an accretion disc around the compact object. As the material falls on to the compact object through the disc, it releases a large amount of energy in the form of X-rays. The majority of LMXBs are X-ray transient sources, which occasionally show outburst behaviour.

During an outburst of an LMXB, almost all the energy is radiated as X-rays, so the ‘X-ray Novae’ are some of the brightest objects in the X-ray sky. X-ray outbursts last much longer and repeat less frequently than outbursts in systems with accreting white dwarfs. Apparently,

this can be related to central X-rays illuminating the outer disc during outbursts (Meyer & Meyer-Hofmeister 1984; King & Ritter 1998; Lasota 2016). Currently, few dozens of LMXB systems with BHs are known in our Galaxy (see e.g. Cherepaschuk 2013; Tetarenko et al. 2016; Avakyan et al. 2023), from which bright X-ray outbursts were detected, implying episodes of high accretion rate in these systems.

In this work we presume that during an outburst an outflow from an accretion disc takes place. The presence of such a wind in the LMXBs is supported by modern observations indicating the expansion of ionized matter. Outflows from accretion discs are observed as blue-shifted X-ray absorption lines (e.g. Ueda, Yamaoka & Remillard 2009; Díaz Trigo & Boirin 2016), as emission lines broadening in the optical range (e.g. Casares et al. 2019; Charles et al. 2019; Muñoz-Darias et al. 2019), and P-Cygni profiles (Miller et al. 2016; Miškovičová et al. 2016; Muñoz-Darias et al. 2016; Fijma et al. 2023). In most cases, X-ray absorption lines of highly ionized Fe are observed in systems with an inclination of more than $\sim 50^\circ$. Therefore, the absorbing plasma should have a higher density closer to the equatorial plane, which suggests that it is a substance flowing out of the disc (Higginbottom & Proga 2015).

The nature of such winds and their physical characteristics are an open question. Namely, in addition to the model of thermal heating of matter by central radiation in optically thin regions of the disc (Begelman, McKee & Shields 1983; Shields et al. 1986; Woods et al. 1996, hereinafter B83, S86, and W96, respectively), other mechanisms are considered: hydromagnetic winds (Blandford &

¹<http://astro.uni-tuebingen.de/~xrbcat/>

²<https://binary-revolution.github.io/>

Payne 1982; Pelletier & Pudritz 1992; Fukumura et al. 2010, 2017; Scepi, Begelman & Dexter 2023), local radiation pressure at super-Eddington accretion rates (Shakura & Sunyaev 1973; Proga & Kallman 2002), and radiation pressure in spectral lines (‘line driven’ winds) (Shlosman, Vitello & Shaviv 1985; Murray et al. 1995; Suleimanov 1995; Feldmeier & Shlosman 1999; Proga & Kallman 2004).

The observational rates of mass-loss in the wind for the intermediate-mass X-ray binary Her X-1 are obtained by Kosec et al. (2020). They find that the estimates strongly depend on the assumed wind geometry. According to them, if the wind moves along the disc, then the rate of mass-loss in the wind in Her X-1 is approximately equal to the accretion rate on to the compact object. However, if the wind is spherically symmetric, then the estimated mass-loss rate increases by an order of magnitude. Ponti et al. (2012) provide observational estimates of the outflow rate in several X-ray transients; it follows that the ratios of the mass-loss rate in the wind to the accretion rate on to compact objects are in the range from 1 to 10. In hydrodynamical numerical simulations of thermally driven disc winds (Luketic et al. 2010; Higginbottom et al. 2017, 2019), this ratio is obtained to lie in the range from 2 to 15. Apart from observational spectral signatures of outflowing matter, an outflow takes away angular momentum and mass and thus affects the long-term dynamical disc evolution.

In the standard model of disc accretion (Shakura 1972; Shakura & Sunyaev 1973), the dimensionless parameter of the turbulent viscosity $\alpha \lesssim 1$ is introduced, which characterizes the angular momentum transfer rate in the disc. Parameter α determines the viscous time of the accretion disc and can be estimated for cataclysmic variables and X-ray novae (Smak 1984; Dubus, Hameury & Lasota 2001; Kotko & Lasota 2012). It was found that two values of α are needed to explain observed long-term evolution: α_{hot} , which determines outburst evolution, and α_{cold} , quiescent times. For particular X-ray novae outbursts parameter α_{hot} was estimated by Lipunova & Shakura (2000), using analytical time-dependent solution for α -disc (see Lipunova & Shakura 2000; Suleimanov 2008, Lipunova & Shakura; Tetarenko et al. 2018b).

During an outburst, inner parts of the accretion disc irradiate its outer parts. This self-irradiation plays a crucial role in the evolution of the disc, as pointed out by King & Ritter (1998) and Dubus, Hameury & Lasota (2001). Consequently, if a disc is irradiated, α_{hot} cannot be determined uniquely from the X-ray outburst decay alone without analysing the optical light curves (Lipunova & Malanchev 2017; Lipunova et al. 2022).

Using a disc instability code, Dubus et al. (2019) have analysed the effects of thermal wind on light curves of X-ray novae. The authors used the analytical model of the thermal wind from W96 and assumed that self-irradiation of the disc is enhanced due to scattering in the optically thin wind. They argue that thermal wind (by affecting self-irradiation) plays an important role in the outburst dynamics. However, there is still inconsistency between analytic estimates of X-ray illumination from scattering in the wind and the observed data, even in combination with direct illumination (Tetarenko et al. 2020). Tetarenko et al. (2018b) suggest that winds influence estimates of α obtained from the light curves.

Our open code FREDDI calculates X-ray and optical light curves of soft X-ray transients outbursts, solving the evolution equation for a viscous α -disc of variable size (Malanchev & Lipunova 2016;

Avakyan, Malanchev & Lipunova 2019; Avakyan et al. 2021).³ Main input parameters of FREDDI are the turbulent parameter α , BH mass $m_x \equiv M_x/M_{\text{odot}}$, and Kerr parameter a_{Kerr} . Self-irradiation of the disc is taken into account and the degree of irradiation can vary with time. Calculated light curves or $\dot{M}(t)$ can be used to fit the observed ones to deliver an estimate of α -parameter (see Lipunova & Malanchev 2017; Lipunova et al. 2022). For this, it is essential to perform a spectral analysis of data to try to obtain as accurately as possible the evolution of bolometric luminosity or accretion rate.

In this work, we report the results of implementing the Compton-heated wind to our code. For X-ray transients, the wind model is taken into account following W96. We analyse how the action of the wind imitates large parameter α and show that a high value of α parameter, potentially obtained from observed light curves, corresponds to a smaller α if the wind is acting.

We also apply the model to 2002 outburst of X-ray transient 4U 1543 – 47 (V* IL Lup). The system is a BH LMXB that demonstrates outbursts about every decade (Kitamoto et al. 1984; Harmon et al. 1992; Miller & Remillard 2002; Negoro et al. 2021). Lipunova & Malanchev (2017, hereafter LM17) have obtained the evolution of the central accretion rate $\dot{M}(t)$, using archival X-ray spectral observations by Proportional Counter Array aboard the Rossi X-ray Timing Explorer observatory (RXTE/PCA; Jahoda et al. 1996). In particular, it was demonstrated that a reflare around the 12th day after the maximum is an artefact of spectral evolution and underlying dependence of $\dot{M}(t)$ is monotonic during almost 30 d after the maximum, when the source was in the ‘high/soft’ state (McClintock & Remillard 2006) according to Park et al. (2004).

For 4U 1543 – 47, we compare the central accretion rate $\dot{M}_{\text{acc}}(t)$ with the model taking the thermal wind into account. As a result, we obtain new estimate of the α -parameter, comparing to LM17. Value of the self-irradiation parameter in 4U 1543 – 47 is determined from the V optical light curve obtained by Buxton & Bailyn (2004).

The structure of the paper is as follows. In Section 2, the physical model of a thermal wind is briefly described. A viscous disc evolution model, which takes into account the wind, is reviewed in the same Section 2. In Section 3, we explain how we take into account the disc self-irradiation and irradiation of the companion star. Thermal wind model from W96 and S86 and numerical method of solving disc evolution equation are described in Section 4. In Section 5, we present the results of disc modelling, as well as the fitting of the BH LMXB 4U 1543 – 47 outburst in 2002. The discussion and conclusions are given Sections 6 and 7, respectively. In Appendix A, we study the numerical-solution stability of the non-linear diffusion-type equation of the disc evolution. Appendix C describes how we tested the work of our code FREDDI by reproducing S86 results on luminosity oscillations. Appendix D overviews analytical solutions to some of the wind models that are used in the code to test it. Comparison of the two different self-irradiation models is given in Appendix E.

2 THERMAL WIND AND THE VISCOUS DISC DYNAMICS

2.1 Compton-heated wind

Theoretical models of accretion discs and observational data supply evidence that the radiation flux from the centre of the disc can irra-

³FREDDI can be freely downloaded from the web page <https://github.com/hombit/freddi/>.

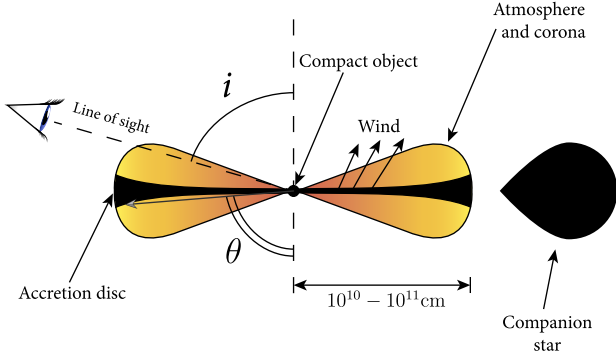


Figure 1. Schematic representation of an LMXB system with accretion disc wind. Angles i and θ are the disc inclination and polar angle, respectively.

diate its outer surface. In the standard accretion model by Shakura & Sunyaev (1973) the disc is concave, and becomes geometrically thicker with radius. As a result, the accretion disc's surface (mostly its outer parts) is exposed to the central radiation, which heats the disc material. Schematic picture of a disc in a binary system is presented in Fig. 1.

In the atmosphere of the outer disc, the energy of the incident photons transfers to the energy of particles through different processes: photoabsorption, photoionization, scattering, and bremsstrahlung. The heating rate per particle is proportional to the radiation intensity. The cooling rate per particle depends on the two-particle processes and, therefore, it decreases with density, that is, with the distance from the equatorial plane of the disc. When the density drops to a critical value, the heating exceeds cooling, and the gas heats up to a high temperature determined by a balance between the principal processes at such conditions: the Compton and inverse Compton scatterings. In particular, for X-ray binaries and quasars hosting compact objects, the central radiation is sufficiently hard and the gas can be heated to temperatures exceeding 10^7 K.

Let us briefly recall the model proposed by B83 and introduce basic parameters to describe winds from a disc irradiated by an X-ray or ultraviolet continuum. The thermal state of the irradiated gas is determined by the shape of the X-ray spectrum along with the pressure ionization parameter (B83):

$$\Xi \equiv P_{\text{rad}} / P_{\text{gas}} = \mathcal{F} / (c P_{\text{gas}}), \quad (1)$$

where P_{rad} and P_{gas} are the radiation and gas pressure, respectively, $\mathcal{F}$ is the radiative flux and c is the speed of light. Thermal equilibrium of a stellar atmosphere gas exposed to ionizing X-ray radiation was calculated by Basko & Sunyaev (1973) and London, McCray & Auer (1981). Fig. 2 shows the schematic dependence of the equilibrium temperature on a value, which is proportional to the pressure ionization parameter Ξ (the picture is adopted from Higginbottom et al. 2017). It follows that there are two stable phases of gas depending on the value of Ξ : 'cool' and 'hot', when $\Xi < \Xi_{\text{c,max}}$ and $\Xi > \Xi_{\text{h,min}}$. In the cool phase, close to the disc photosphere, the photoionization is balanced by the recombination, so the gas is maintained at the temperature $T \approx 10^4$ K. Away from the disc surface, the pressure and density drop, consequently the pressure ionization parameter grows, eventually exceeding the critical $\Xi_{\text{c,max}}$, which leads to the heating of gas. This heating is quenched when the Compton heating by energetic photons is balanced by the inverse Compton cooling by softer photons.

The equilibrium temperature in this state is generally close to the 'inverse Compton temperature' (hereinafter the term 'Compton

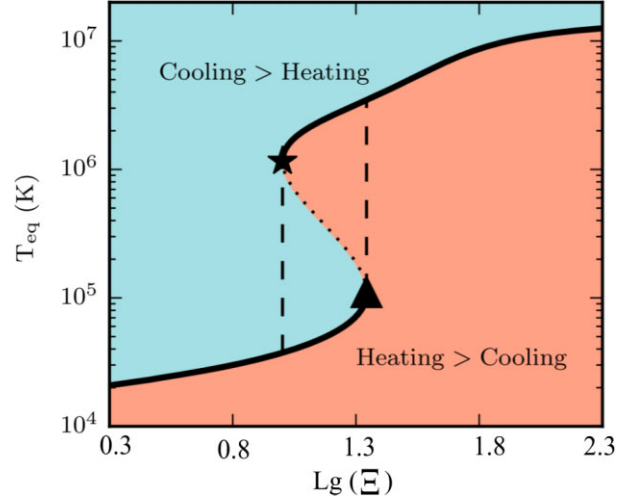


Figure 2. Schematic disc thermal equilibrium curve (basing on a figure from Higginbottom et al. 2017). The triangle denotes the position of the maximum value of the pressure ionization parameter $\Xi_{\text{c,max}}$, at which the gas is in a cold state. The asterisk corresponds to the minimum value $\Xi_{\text{h,min}}$ in the hot state. The dotted part of the thermal equilibrium curve shows the instability zone.

temperature' will be used), which is defined as

$$T_{\text{IC}} \equiv \frac{1}{4k} \langle \epsilon \rangle = \frac{1}{4k} L^{-1} \int_0^{+\infty} h\nu L_\nu d\nu, \quad (2)$$

where $\langle \epsilon \rangle$ is the mean photon energy, h is the Planck constant, k is the Boltzmann constant, ν is the radiation frequency, L_ν is the luminosity per frequency interval, and L is the bolometric luminosity.

B83 also introduce the 'escape temperature': $T_{\text{e}} \equiv GM_x \mu m_p / (kr)$, which follows from the equality of the thermal and escape velocities of a particle. Here, M_x is the mass of the compact object, r is the axial distance from the centre of the disc, m_p is the proton mass, and μ is the mean mass of ions, and electrons per particle (we use value of 0.61 as for the solar abundances). If the medium temperature is higher than T_{e} , it expands. Thus, the characteristic 'Compton radius' can be defined as follows (B83):

$$R_{\text{IC}} \equiv \frac{GM_x \mu m_p}{k T_{\text{IC}}} = \frac{1.0 \times 10^{10}}{T_{\text{IC8}}} \left(\frac{M_x}{M_\odot} \right) \text{ cm}, \quad (3)$$

where $T_{\text{IC8}} = T_{\text{IC}}/10^8$ K. B83 suggest that the matter begins to flow out of the disc in the form of a wind at radii greater than $0.1 \times R_{\text{IC}}$, where the height of the corona is already significant. The upper layer, which is heated up to the Compton temperature T_{IC} , expands with the sound speed $c_{\text{IC}} = \sqrt{k T_{\text{IC}} / (\mu m_p)}$.

B83 also define some critical luminosity:

$$L_{\text{cr}} \equiv \frac{1}{8} \left(\frac{m_e}{\mu m_p} \right)^{1/2} \left(\frac{m_e c^2}{k T_{\text{IC}}} \right)^{1/2} L_{\text{Edd}} = 0.030 \times T_{\text{IC8}}^{-1/2} L_{\text{Edd}}, \quad (4)$$

where m_e is the mass of an electron, L_{Edd} is the Eddington luminosity limit, which characterizes the efficiency of overcoming the gravity directly by the radiation pressure:

$$L_{\text{Edd}} \equiv \frac{4\pi G M_x \mu_e m_p c}{\sigma_T} \approx 1.5 \times 10^{38} \left(\frac{M}{M_\odot} \right) \text{ erg s}^{-1}, \quad (5)$$

where σ_T is the Thomson cross-section and μ_e is the mean molecular weight per electron (which we set to be equal 2μ). Thus, if the ratio L/L_{Edd} specifies the effectiveness of the radiation pressure in overcoming gravity, the ratio L/L_{cr} characterizes the efficiency of

overcoming the gravity by electromagnetic radiation via the heating of the matter by the Compton processes.

On the other hand, at smaller radii and/or lower luminosity, most of the material of the disc remains gravitationally bound, forming a hydrostatic corona (Jimenez-Garate, Raymond & Liedahl 2002; B83; S86; W96).

2.2 Viscous disc evolution

The evolution of the accretion disc with the wind is described by a modified equation of the diffusion type (for example, S86):

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{4\pi} \frac{(GM_x)^2}{h^3} \frac{\partial^2 F}{\partial h^2} - \dot{\Sigma}_w(F, h), \quad (6)$$

where $h = \sqrt{GM_x r}$ is the specific angular momentum of the accretion disc's material, Σ is the surface density, F is the torque of the viscous forces acting on a given disc ring, which is expressed as $F = 2\pi W_{r\varphi} r^2$ using the height-integrated viscous stress tensor $W_{r\varphi}$ (assumed to be positive, see e.g. Lyubarskij & Shakura 1987). Function $\dot{\Sigma}_w$ is a local wind mass-loss rate, the outflow of mass per unit disc surface area per unit time, and $\dot{\Sigma}_w > 0$ if the wind is present. In the upcoming Section 4, we will discuss the form of this function in more detail.

The surface density Σ and viscous torque F are related in the Keplerian disc as follows (e.g. Shakura et al. 2018, chapter 1):

$$F = 3\pi h \nu_t \Sigma, \quad (7)$$

where ν_t is the kinematic coefficient of turbulent viscosity, whose dependence on the radius r and surface density Σ is determined by physical processes underlying the viscosity. It follows from conservation of angular momentum:

$$\dot{M} = \frac{\partial F}{\partial h}. \quad (8)$$

To effectively describe a complex phenomenon of the turbulent viscosity, Shakura (1972) introduced the dimensionless turbulent parameter α (see also Shakura & Sunyaev 1973). It relates the total pressure in the disc and the viscous stress tensor component:

$$w_{r\varphi}^t = \alpha P_{\text{tot}}, \quad (9)$$

where P_{tot} is the sum of the gas pressure P_{gas} and radiation pressure P_{rad} . The height-integrated viscous stress tensor $W_{r\varphi}$ is as follows:

$$W_{r\varphi}(t, r) = \int_{-z_0}^{+z_0} w_{r\varphi}^t(t, r, z) dz, \quad (10)$$

where z_0 is the disc half-thickness at the radius r .

The condition at the inner boundary of the disc (corresponding to the last stable orbit) is the zero viscous torque F (Shakura & Sunyaev 1973):

$$F(h_{\text{in}}, t) = 0, \quad (11)$$

where h_{in} is the specific angular momentum at the inner edge of the disc. We set outer boundary conditions in two different ways. First, when we assume that the outer radius of a viscously evolving disc is fixed, we set the external boundary condition of the second type:

$$\left. \frac{\partial F}{\partial h} \right|_{h=h_{\text{out}}} = \dot{M}_{\text{out}}, \quad (12)$$

where $\dot{M}_{\text{out}}$ is the mass rate of matter entering the disc, and h_{out} is the specific angular momentum at its outer edge. This approach is used for the oscillations test (see Appendix C), which we use to verify our code.

Alternatively, we assume that a disc consists of two zones: an ionized ‘hot’ inner part and a ‘cold’ one with recombined hydrogen. Presumably, they have different values of the viscosity parameter α , α_{hot} , and α_{cold} for the ‘hot’ and ‘cold’ zones, respectively. The viscous evolution in the colder part has a much longer time-scale, since $\alpha_{\text{cold}} \ll \alpha_{\text{hot}}$. This means that the viscous evolution in the colder part has almost no effect on the central accretion rate during an outburst. Near the outer boundary of the hot zone r_{hot} , the viscous torque F reaches an extremum. For all simulated outbursts, we thus assume that the mass flow rate vanishes at the boundary: $\partial F / \partial h (h = h_{\text{hot}}) = 0$, where h_{hot} corresponds to r_{hot} .

Finally, the initial distribution of the viscous torque must satisfy the boundary conditions:

$$F(h, 0) = F_0(h). \quad (13)$$

The numerical technique of solving the system of equations (6), (11), (12), and (13) is described in detail in Appendix A.

3 SELF-IRRADIATION AND OPTICAL FLUX

3.1 Self-irradiation of the disc and the radius of the hot zone

We assume that during an outburst there are generally two zones in the disc, with ionized and neutral material, separated at R_{hot} – the ‘radius of the hot zone’. If the accretion rate is very high, the hot zone can reach its outer radius, close to the Roche lobe radius. In the binaries with large P_{orb} , however, the hot zone is often smaller than the whole disc, and it shrinks during an outburst decay.

We find radius of the hot zone following Lipunova et al. (2022), considering irradiating and viscous heating rate:

$$Q_{\text{irr}} = C_{\text{irr}} \frac{L_x}{4\pi r^2}, \quad (14)$$

$$Q_{\text{vis}} = \frac{3}{8} \frac{\sqrt{GM_x}}{\pi r^{7/2}} F, \quad F \approx \dot{M}_{\text{acc}} h, \quad (15)$$

where $L_x = \eta (a_{\text{Kerr}}) \dot{M}_{\text{acc}} c^2$ is the X-ray luminosity, $\dot{M}_{\text{acc}}$ is the central mass accretion rate, $\eta (a_{\text{Kerr}})$ is the accretion efficiency, which depends on the dimensionless Kerr parameter a_{Kerr} , and C_{irr} is the irradiation parameter. Note that for the ‘hot’ and ‘cold’ parts of the accretion disc, the value of irradiation parameter can be different. Below, C_{irr} denotes the value of the irradiation parameter for the ‘hot’ part of the disc, while $C_{\text{irr}}^{\text{cold}}$ corresponds to the ‘cold’ one. Let us define the ‘viscous temperature’ T_{vis} from $Q_{\text{vis}} \equiv \sigma_{\text{SB}} T_{\text{vis}}^4$, where σ_{SB} is the Stephan–Boltzmann constant. By analogy, the ‘irradiation temperature’ T_{irr} is defined from $Q_{\text{irr}} = \sigma_{\text{SB}} T_{\text{irr}}^4$.

We assume that disc at radius r is in the hot state if irradiation temperature is higher than $T_{\text{hot}} = 10^4$ K (Tuchman, Mineshige & Wheeler 1990; Dubus et al. 1999; Tavleev, Lipunova & Malanchev 2023). Thus, radius of the hot zone $R_{\text{hot}}(t)$ can be calculated from the central accretion rate:

$$\sigma_{\text{SB}} T_{\text{hot}}^4 = C_{\text{irr}} \frac{\eta (a_{\text{Kerr}}) \dot{M}_{\text{acc}} c^2}{4\pi R_{\text{hot}}^2}. \quad (16)$$

when $Q_{\text{irr}} > Q_{\text{vis}}$.

Due to gradual cooling of the disc, shrinking of the hot zone, and higher radial dependence of the viscous flux, eventually irradiation ceases to be important. If the irradiation parameter was constant, condition $Q_{\text{irr}} > Q_{\text{vis}}$ would break down at some radius, independent of the accretion rate, since one can write the ratio $Q_{\text{irr}}/Q_{\text{vis}}$ as (Suleimanov, Lipunova & Shakura 2007):

$$\frac{Q_{\text{irr}}}{Q_{\text{vis}}} = \frac{4}{3} \eta (a_{\text{Kerr}}) C_{\text{irr}} \frac{r}{R_{\text{grav}}}, \quad (17)$$

where the gravitational radius $R_{\text{grav}} = 2GM_{\text{x}}/c^2$.

Later, the irradiation-controlled evolution is superseded by an evolution determined by the cooling-front propagation, in accordance with the disc instability model (DIM; Dubus, Hameury & Lasota 2001; Lasota 2001, LM17). To find a position of R_{hot} one can take into account results of a cooling-front parameter study in the framework of DIM (Ludwig, Meyer-Hofmeister & Ritter 1994). To determine if a radius belongs to the hot zone, we check if any of the following conditions is met: (1) $T_{\text{irr}} > T_{\text{hot}}$; (2) $\Sigma > \Sigma_{\text{crit}}^-$ (Lasota, Dubus & Kruk 2008); (3) $r < R_{\text{hot}}(t - \Delta t) - v_{\text{front}}\Delta t$, where the cooling front velocity is calculated following Ludwig, Meyer-Hofmeister & Ritter (1994).

Regarding the irradiation parameter C_{irr} in (14), one can estimate its value by the following analytic expression (e.g. Suleimanov, Lipunova & Shakura 2007):

$$C_{\text{irr}} = \Psi(\theta)(1 - A) \frac{z_0}{r} q, \quad \text{where } q \equiv \left(\frac{d \ln z_0}{d \ln r} - 1 \right), \quad (18)$$

where z_0 is the semi-thickness of the disc, $q(z_0/r)$ is the angle of incident rays, $(1 - A)$ is the portion of absorbed and thermally reprocessed incident flux, and $\Psi(\theta) = 2\cos(\theta) \approx 2z_0/r$ is the angular distribution of the irradiating flux from the central plane disc, where θ is the polar angle (see Fig. 1).

To take into account the radial dependencies of the irradiation parameter (see also discussion in Appendix E) we use auxiliary constant parameters $\widetilde{C}_{\text{irr}}$ and $\widetilde{C}_{\text{irr}}^{\text{cold}}$, for the hot and cold parts of the disc, respectively. Using them, the genuine parameters C_{irr} and $C_{\text{irr}}^{\text{cold}}$ are expressed as follows:

$$C_{\text{irr}} = \widetilde{C}_{\text{irr}} \left(\frac{z_0/r}{0.05} \right)^k \Psi(\theta(r)), \quad k = 1; \\ C_{\text{irr}}^{\text{cold}} = \widetilde{C}_{\text{irr}}^{\text{cold}} \Psi(\theta^{\text{cold}}). \quad (19)$$

3.2 Observed flux from the disc

Both parts of the accretion disc (hot and cold) contribute to the total optical flux of the system. Observed flux from the outer disc, which falls in the optical range, is determined by the contributions from the viscous heat Q_{vis} and self-irradiation Q_{irr} . Thus, the local effective temperature can be expressed as

$$T_{\text{eff}}^4 = T_{\text{irr}}^4 + T_{\text{vis}}^4. \quad (20)$$

Accordingly, the observed flux from the disc in a band is calculated by the formula:

$$\mathcal{F}_{\text{disc}} = \frac{2\pi \cos i}{d^2} \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} d\nu \int_{R_{\text{in}}}^{R_{\text{hot}}} B_{\nu}(T_{\text{eff}}(r)) r dr, \quad (21)$$

where d is the distance to the source, i is the disc inclination, ν_{min} and ν_{max} are the limits of the observational spectral band, and B_{ν} is the Planck intensity. The viscous temperature is found from the viscous torque:

$$\sigma T_{\text{vis}}^4 = \frac{3(GM)^4 F}{8\pi h^7}. \quad (22)$$

where F is a solution to the viscous evolution equation (6).

Due to the fact that we do not find a solution for the vertical structure of the cold disc, its relative semi-thickness assumed as $z_0/r = 0.05$ ($\theta^{\text{cold}} = \text{const}$) and its viscous temperature T_{visc} is set to zero. Value of $\widetilde{C}_{\text{irr}}^{\text{cold}}$ parametrizes all associated uncertainty.

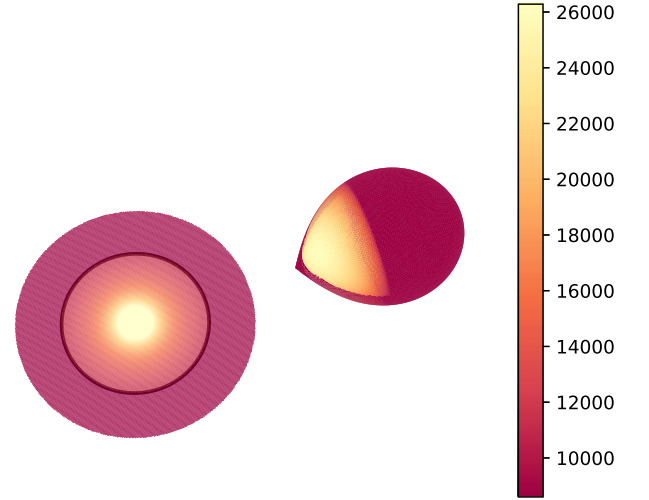


Figure 3. Visualization of the binary system 4U 1543 – 47 at the peak of the 2002 outburst. Effective temperature is colour coded. The circle on the disc shows the border between the hot and cold zones.

Table 1. Parameters used in fitting of the 2002 outburst of 4U 1543 – 47.

Parameter	Value	Ref.
Mass of the BH, M_{x}	$9.4 M_{\odot}$	[1], [2]
Orbital period, P	1.116 d	[3]
Inclination, i	20.7°	[3]
Mass of the companion, M_{opt}	$2.5 M_{\odot}$	[1], [2]
Distance to the system, d	8.6 kpc	[4], [5]
Kerr parameter, a_{Kerr}	0.4	[6]
Pressure ionization parameter, Ξ	7.53	[7]
Compton temperature, T_{IC}	1.5×10^7 K	Fig. 10
Wind efficiency, η_{wind}	1.0	—
Effective temperature of the star surface	8600 K	[8]
Bolometric albedo of the star surface	0.5	[9]
Roche-lobe filling factor of the star	1.0	—

Note. [1] Orosz et al. (1998), [2] Orosz et al. (2002), [3] Orosz (2003), [4] Gandhi et al. (2019), [5] LM17, [6] Morningstar & Miller (2014), [7] Higginbottom et al. (2017), [8] Chevalier & Ilovaisky (1992), [9] Basko, Sunyaev & Titarchuk (1974).

3.3 Flux from the companion star

The central X-ray source impacts not only the disc but also the optical component of the binary system, if the latter is not completely shadowed. Code FREDDI is capable of calculating orbit-modulated light curves (Lipunova et al. 2022) of a companion star irradiated with an X-ray flux when there is no self-occultation in the system. The effective temperature distribution in a close binary system (namely, BH LMXB 4U 1543 – 47) is shown in Fig. 3. Model parameters are listed in Table 1 for the outburst in Fig. 11.

4 WIND MODELS AND METHODS

In order to take into account the effect of the wind, it is required to specify a physically substantiated form of the inhomogeneity function $\dot{\Sigma}_{\text{w}}$ in equation (6). The modified version of the FREDDI code can take into account any user-specified wind model. In the subsection below we only describe the main thermal wind model adopted from S86 and W96 used to fit X-ray Novae light curves. All other available wind model options are listed and described in Appendix D. We also verify the work of our code with the ‘toy’

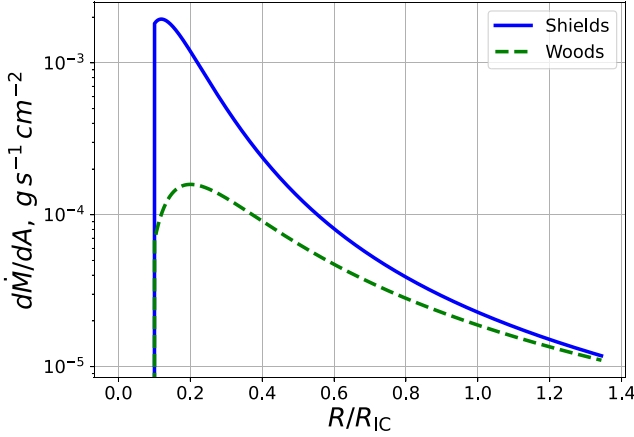


Figure 4. Distribution of the surface flow rate due to wind along the radius for S86 (B8) and W96 (23). The Compton temperature $T_{IC} = 1.5 \times 10^7$ K, $M_X = 10 M_\odot$, and bolometric luminosity $L = L_{Edd}$.

wind model adopted from S86. In this ‘toy’ model, wind’s impact creates oscillations in luminosity if the constant inflow of matter into the disc occurs in the system ($\dot{M}_{out} = \text{const}$, see equation 12). In Appendix C, we describe this model in detail and compare FREDDI and S86 results, reproducing $\dot{M}_{acc}$ oscillations.

4.1 Thermal wind model

The dynamics of the Compton-heated wind and corona have been analytically studied in B83 (see basic definitions in Section 2). The authors have estimated the mass-loss rate as a function of distance along the disc’s radius. They consider the flow carried away by the wind as a set of streamlines and solve equations of momentum and energy conservation along them. S86 have proposed analytical approximation for the results obtained in B83 (see equations B1–B8 in Appendix B).

In a later work, W96, two-dimensional magnetohydrodynamic calculations have been performed and the results of B83 and S86, generalized. W96 take into account the various processes contributing to X-ray heating and radiation cooling, while B83 consider heating and cooling only through the Compton processes. Secondly, while B83 suggest a disc is geometrically thin, W96 take into account the structure of the upper layers of the disc in an optically transparent approximation. The wind model elaborated by W96, applicable for winds in AGNs, is also added to the FREDDI’s list of choices.

To model a viscous evolution of a disc with a wind in the current study, we take the function $\dot{\Sigma}_w(h)$ as the approximation to the results of S86 in a form provided by W96:

$$c\dot{\Sigma}_w = 2\eta_{wind}\dot{m}_{ch} \times \left(\frac{1 + ((0.125l + 0.00382)/\xi)^2}{1 + (l^4(1 + 262\xi^2))^{-2}} \right)^{1/6} \times \exp\left[-\left(1 - (1 + 0.25\xi^{-2})^{-1/2}\right)^2 / (2\xi)\right], \quad (23)$$

where $\xi = r/R_{IC}$ and $l = L/L_{cr}$, see equations (3) and (4), and the characteristic mass-loss rate per unit area $\dot{m}_{ch}(\Xi)$ can be found in Appendix B. Value of the pressure ionization parameter Ξ at the wind–disc interface is assumed to be equal to $\Xi_{c,max}$ on definition (W96, see Fig. 2). We also introduce parameter η_{wind} – a dimensionless factor allowing easy wind-power adjustment. Corresponding distribution, as well as the function (B8) from S86, is shown in Fig. 4.

Thus, parameters of the wind and its rate are controlled by parameters T_{IC} , L , and Ξ (see Appendix B). The mass-loss rate

per unit area above is to be used in equation (6) whose method of solution is described in the next subsection.

4.2 Methods

Using an implicit difference scheme, we reduce the solution of the differential equation (6) with boundary conditions to sequential solution of a system of algebraic equations at each time-step, which is carried out using the tridiagonal matrix algorithm described in Appendix A. The new scheme supersedes the original one in the code FREDDI (Malanchev & Lipunova 2016; LM17), described also in Shakura et al. (2018).

The thermal wind model described above is applicable for an outburst of the accretion disc in the case of X-ray nova, triggered by a critical accumulation of mass during a quiescent state or by a short-term mass transfer. As the initial condition, we take the distribution found by Lipunova & Shakura (2002) for a disc without wind. It implies a zero inflow of matter ($\dot{M}_{out} = 0$) at the external boundary and, thus, the zero first derivative of $F(h)$ there (see equation 12). This quasi-stationary distribution describe hot parts of α -discs without winds after the peak of a fast-rise exponential-decay outburst, as pointed out by Lipunova (2015). Recall that the inner boundary condition is the same for all models, namely: the zero value of the viscous torque F (Shakura & Sunyaev 1973).

5 RESULTS

5.1 The impact of wind on the course of the outburst

To analyse the wind effect during an outburst in an LMXB, we use the wind model (23). Outbursts are simulated for two values of the peak accretion rates: $\dot{M}_{acc,0} = \dot{M}_{Edd}$ and $\dot{M}_{acc,0} = 0.1 \times \dot{M}_{Edd}$, where $\dot{M}_{Edd} = 1.4 \times 10^{18} (M_X/M_\odot) \text{ g s}^{-1}$ for a compact object of mass $M_X = 10 M_\odot$. We also vary the turbulent viscosity parameter α and the self-irradiation coefficient of the disc C_{irr} . For the calculations described in this subsection, the temperature T_{IC} is fixed at 10^8 K. Parameter $\Xi = 7.53$ is taken from simulations of the heating and cooling processes (Higginbottom et al. 2017).

Resulting accretion rate evolution is shown for models with and without wind in Fig. 5. Figs 6 and 7 show the evolution of the radius of the hot zone R_{hot} and the ratio of the mass-loss rate due to wind to the accretion rate $C_w \equiv \dot{M}_{wind}/\dot{M}_{acc}$ (where $\dot{M}_{wind} > 0$), respectively.

Fig. 5 shows that the effect of the wind, accelerating the evolution of the central accretion rate, is more pronounced in models with higher values of the initial accretion rate $\dot{M}_{acc,0}$ and self-irradiation parameter of the disc C_{irr} . This is explained as follows. Higher accretion rate means higher luminosity and a more powerful wind, according to its prescription (23). Furthermore, higher accretion rate and irradiation parameter, they both result in a bigger hot disc, enhancing the role of the wind and the mass lost with it (see Fig. 6).

In the presence of a wind the outburst duration decreases: ‘wind models’ demonstrate shorter characteristic times as if the turbulent parameter α was higher. In Fig. 8, we plot an ‘ α -correction’: the value of the turbulent parameter α_{nw} in a disc without wind, divided by the viscosity parameter α_w in a disc with thermal wind and the same decline rate. The wind force is parametrized by the dimensionless quantity η_{wind} (see the formula (23)). For each η_{wind} and α_w , we calculate a model with wind. Afterwards, we fit the resulting $\dot{M}(t)$ curves with models without wind and find best-fitting value of viscosity parameter α_{nw} . Since the wind takes away disc’s mass and its angular momentum, the ratio α_{nw}/α_w is always > 1 (because with the same decline rate the viscosity processes contribute less when

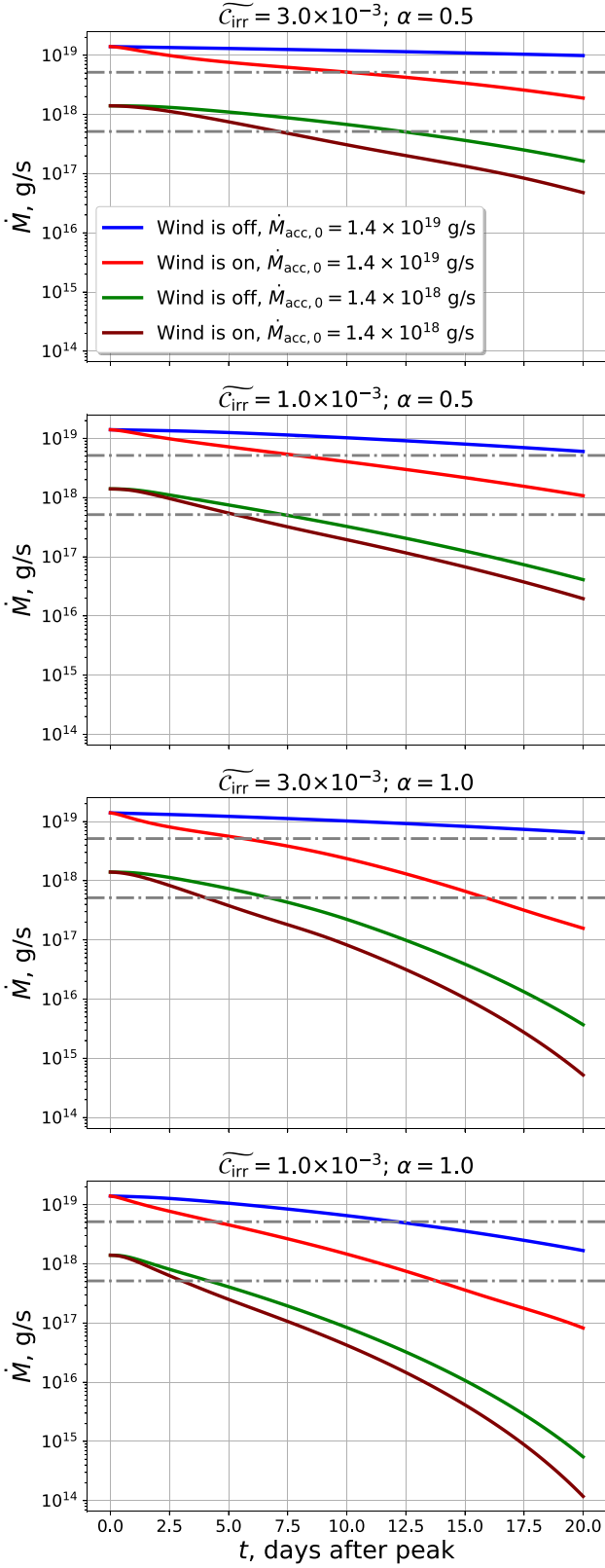


Figure 5. Evolution of an accretion disc central accretion rate in the presence of the thermal wind and without it. Two sets of curves are shown for different initial peak accretion rates, namely: $\dot{M}_{\text{acc},0} = \dot{M}_{\text{Edd}}$ and $\dot{M}_{\text{acc},0} = 0.1 \dot{M}_{\text{Edd}}$, where $\dot{M}_{\text{Edd}} = 1.4 \times 10^{18} (M_x/M_\odot) \text{ g s}^{-1}$. Other parameters are $M_x = 10 M_\odot$, the external radius is the tidal one, $\Xi = 7.53$, and $T_{\text{IC}} = 10^8 \text{ K}$. Two grey dash-dotted line indicate levels, where the accretion rate drops by e times from the initial one.

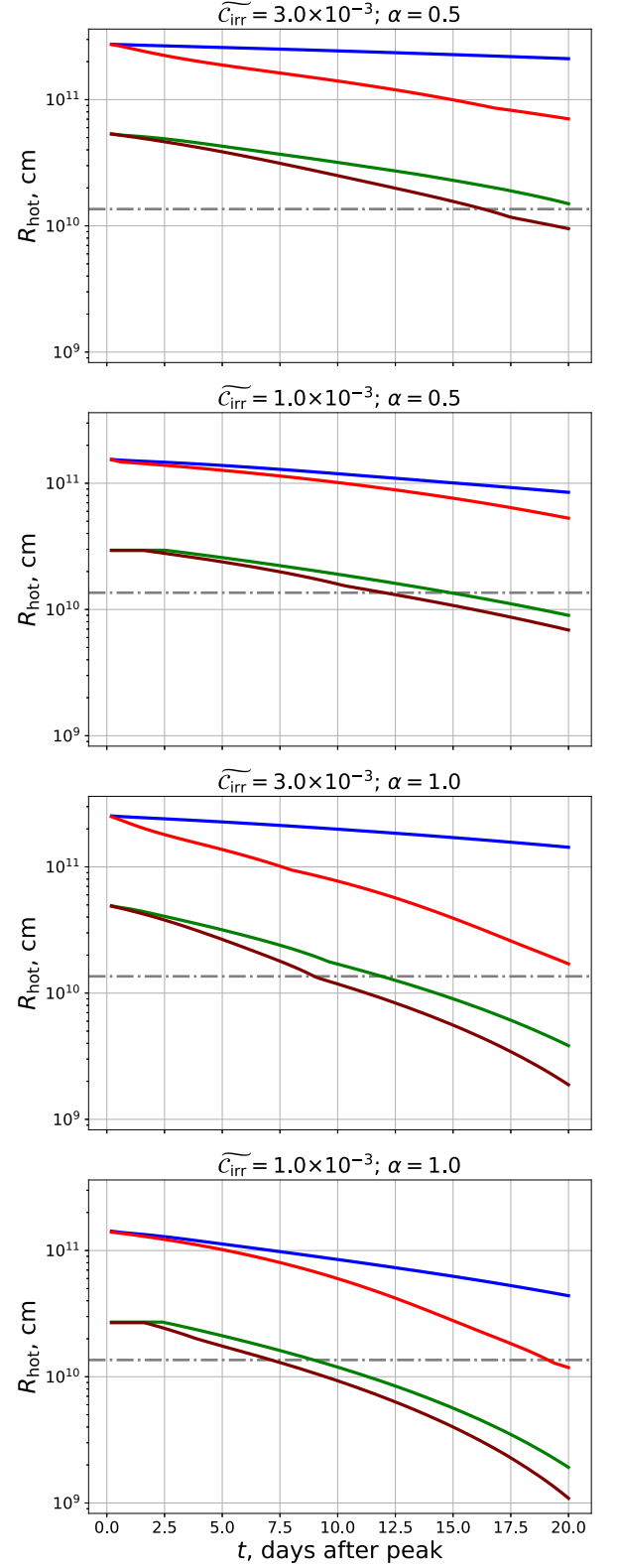


Figure 6. Hot (ionized) zone radius R_{hot} versus the time after the peak of a light curve. The parameters and curves styles (legends) are the same as in Fig. 5. Grey dash-dotted line represents wind launching radius $0.1 R_{\text{IC}}$.

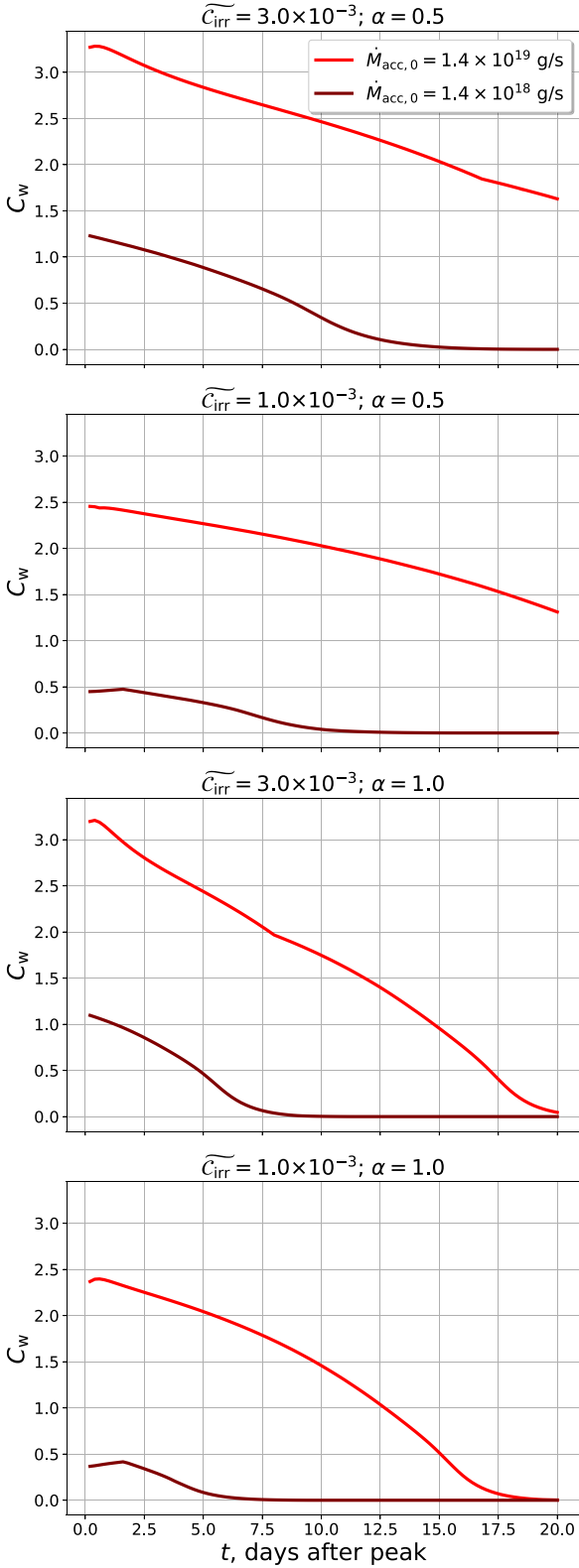


Figure 7. The ratio between the mass-loss rate due to the thermal wind and the central accretion rate ($C_w \equiv \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$) versus the time after the peak of a light curve. Parameters are as in Figs 5 and 6.

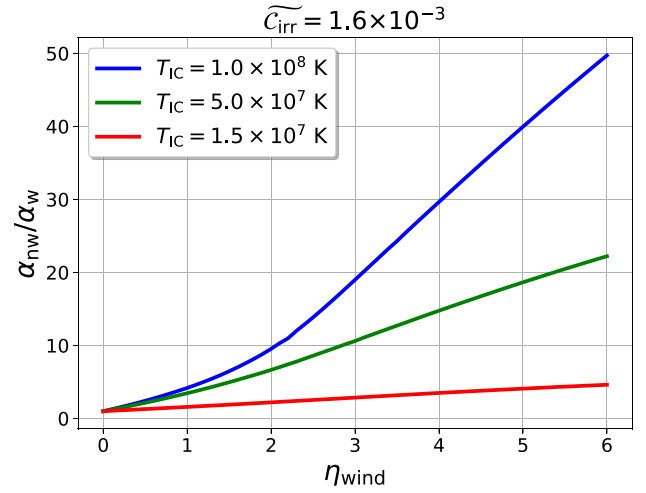


Figure 8. Dependence of the thermal wind α -correction on the wind's power η_{wind} . This correction is the inverse ratio between calculated α parameter value in disc simulations with the wind presence (α_w) and without it (α_{nw}), while the same resulting decline rate of the central accretion rate is considered. All light-curve simulations are made with $\alpha_{\text{nw}} = 1.0$, $M_x = 10 M_\odot$, and $\dot{M}_{\text{acc},0} = 1.4 \times 10^{19} \text{ g s}^{-1}$.

the wind acts). An apparent degeneracy between parameters α and η_{wind} is discussed in the beginning of Section 6.

In the framework of the thermal wind, the spectrum hardness plays a crucial role in changing the rate of an outburst decline (Fig. 8), because increasing the Compton temperature leads to the increase of the area where the wind is launched (see equation 3). For parameters $\eta_{\text{wind}} = 1$ and $T_{\text{IC}} = (0.15-1) \times 10^8 \text{ K}$, the estimate of the turbulent viscosity parameter α can be overestimated due to neglect of the influence of the thermal wind by approximately 1.4–4 times.

It is expected that the wind ' α -correction' depends on the disc size. Thus, we have calculated a number of models for different values of the outer radius. Fig. 9 shows α -correction for outbursts in discs of different sizes and Compton temperatures. It can be seen that until some point α -correction grows with the accretion disc size. This is explained by the fact that the area, where the wind operates, grows as the square of the external (tidal) radius (R_{tid}^2). But it continues until the outer radius is smaller than R_{hot} (16). The α -correction curve levels off for bigger discs because the hot disc area is limited and defined by $\dot{M}_{\text{acc},0}$ and C_{irr} . Thus, the α -correction value never exceeds a few for a moderate Compton temperatures, for any binary periods.

The wind power, which can be set by η_{wind} , affects simultaneously the shape of a light curve and the value of C_w . Thus, it is theoretically possible to impose restrictions on the wind strength relative to the accretion rate, namely, on the value of C_w (see fig. 16 in Section 6) from a light-curve profile.

5.2 Modelling outburst of 4U 1543–47 in 2002

To illustrate the effect of the wind for an outburst of a real transient, we fit the evolution of the central accretion rate and optical flux of the 2002 outburst of the X-ray nova 4U 1543 – 47. The observed central accretion rate $\dot{M}_{\text{acc}}(t)$ is obtained from spectral modelling of the archival data of *RXTE/PCA* (LM17). The optical light curves in the *V* and *J* bands used in the current work are also described there. The system parameters are listed in Table 1.

Fig. 10 shows the evolution change of the T_{IC} during the outburst 4U 1543 – 47 (2002) obtained using results of the spectral modelling

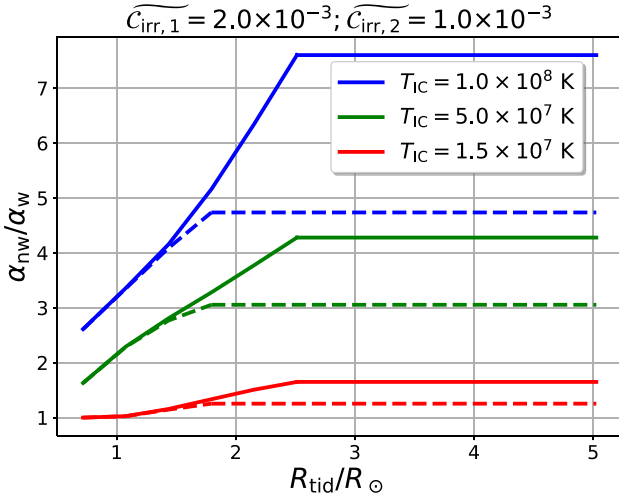


Figure 9. Thermal wind α -correction versus the outer radius of an accretion disc for the different Compton temperatures. This correction is the inverse ratio between calculated α parameter value in disc simulations with the wind presence (α_w) and without it (α_{nw}), while the same resulting decline rate of the central accretion rate is considered. All models are calculated for $\alpha_{nw} = 1.0$, $M_x = 10 M_\odot$, and $\dot{M}_{acc,0} = 1.4 \times 10^{19} \text{ g s}^{-1}$. All solid curves correspond to $\widetilde{C}_{irr,1} = 2.0 \times 10^{-3}$, while dashed ones to $\widetilde{C}_{irr,2} = 1.0 \times 10^{-3}$.

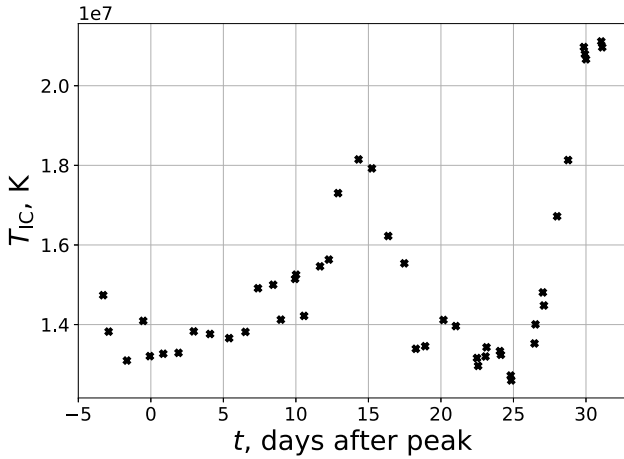


Figure 10. Inverse Compton temperature T_{IC} calculated for the 2002 outburst of 4U 1543 – 47 (see equation 2).

of the *RXTE* data. To simulate the 4U 1543 – 47 light curve in the present work, we take the average value of T_{IC} over the shown time interval: $1.5 \times 10^7 \text{ K}$ or 1.3 keV. The bump in the interval between the 10th and 20th day after the peak happened due to a turn-on of an additional spectral component, possibly, a jet (Buxton & Bailyn 2004; Russell et al. 2020, LM17). To assess impact of the variation in T_{IC} , we make auxiliary fits, adopting maximum and minimum values of T_{IC} during this 30-d period for wind model. The resulting α parameter estimate change within 15 per cent at the very worst.

Fits for models with and without thermal wind along with the observational data are presented in Fig. 11. To fit modelled accretion rate to $\dot{M}_{acc}(t)$ obtained from observational data, we use Levenberg–Marquardt non-linear least-squares minimization curve fitting method from the PYTHON package LMFIT (Newville et al. 2023). We exclude seven middle points from the fit because the spec-

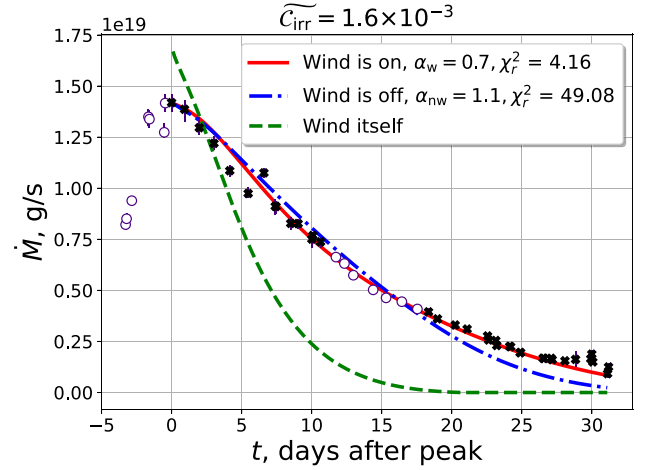


Figure 11. Central accretion rate evolution $\dot{M}_{acc}(t)$ during the 4U 1543 – 47 outburst (2002). The plot shows $\dot{M}_{acc}(t)$ dependence based on the observations (black ‘X’), which is fitted by two models, presented by the curves ‘Wind is on’ and ‘Wind is off’, meaning that the corresponding simulation fit takes or does not take thermal wind presence into account respectively. Empty circles are excluded from the fitting due to them not being a part of the decay. The ‘Wind itself’ curve shows the rate of the mass-loss in the thermal wind ($\dot{M}_{wind}(t)$). All parameters used in simulations are listed in Table 1.

tral modelling for these data was carried out with frozen distance’s value while all other points were modelled with thawed distance parameter (see LM17 for details). Nevertheless, it is remarkable how these seven data points lie neatly on the light curve. Tetarenko et al. (2018a) presented a bolometric light curve for this outburst, but its slope differs from that of our $\dot{M}(t)$, apparently, because the bolometric corrections applied by them cannot correctly reflect the spectral evolution.

As expected, to explain the temporal evolution, lower value of the turbulent parameter is needed in the model with the thermal wind. The fit results are: the initial accretion rate onto the BH is $\dot{M}_{acc,0} = 1.4 \times 10^{19} \text{ g s}^{-1}$, the viscosity parameter α for cases with and without wind is about 0.7 and 1.1, respectively. It should be also noted that in the absence of the wind the best-fitting value of the turbulent parameter α is lower than the value found in LM17 for the same BH parameters. The explanation of this effect is given in Appendix E.

Fig. 12 shows the hot radius evolution corresponding to Fig. 11. It can be seen that the radius $R_{hot}(t)$ in the wind model (the red curve) becomes less than $0.1 \times R_{IC}$ (the grey horizontal line) on the 21st day. This leads to a complete shutdown of the thermal wind from the hot zone (see also Fig. 13). We note that first $\sim 30 \text{ d}$ after the outburst’s maximum, hot radius of the disc is controlled by irradiation. This is true for the both models (with and without wind). Thus, our resulting estimate of the alpha-correction due to wind is mostly free from effects of the later disc evolution when the cooling front advances.

The self-irradiation parameter C_{irr} can be determined from the optical data. Within the framework of our model, three components contribute to the optical flux of the system: a hot disc, a cold disc, and an irradiated donor star (see Sections 3.1–3.3). Figs 14 and 15 show the observed optical data in the V and J bands obtained by Buxton & Bailyn (2004), as well as the model light curves, corrected for the interstellar absorption with $A_V = 1.6 \text{ mag}$ and $A_J = 0.282 A_V$ (see LM17).

It can be seen that the emission from the hot disc alone cannot explain the observed data, in accordance with results of LM17. To

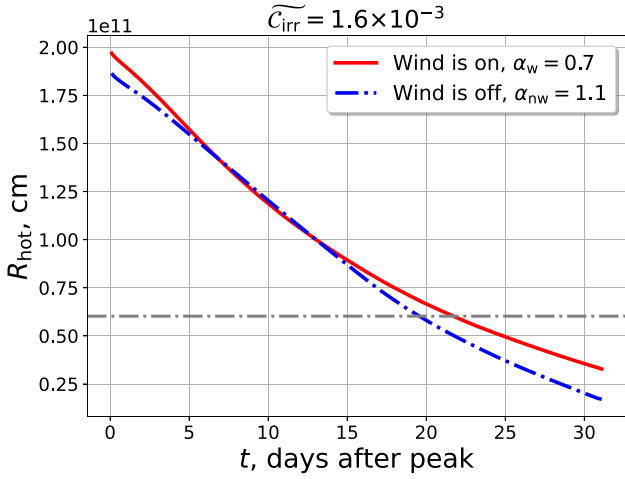


Figure 12. Modelled evolution of hot zone radius during the 2002 outburst of 4U 1543 – 47 (see Fig. 11). Grey dash–dotted line represents wind launching radius $0.1 R_{IC}$.

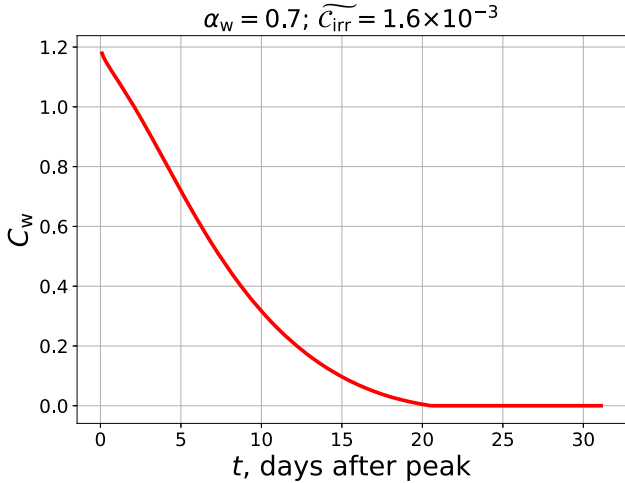


Figure 13. Evolution of the ratio of the mass-loss rate due to wind to the accretion rate on to the BH ($C_w \equiv \dot{M}_{wind}/\dot{M}_{acc}$), corresponding to the ‘Wind is on’ model in Fig. 11.

explain the optical flux in V , it is necessary to take into account either re-emission from a cold disc or from irradiated optical companion (or maybe both). The self-irradiation parameter $\widetilde{C}_{irr}$ for the hot part of the disc is set to 1.6×10^{-3} . In Appendix E, we discuss distinctions between irradiation parameter prescriptions in this work and LM17. At the same time, in the J band, full agreement cannot be reached. Perhaps this happens due to the fact that the contribution of the jet of the system is noticeable in this band (Buxton & Bailyn 2004; Russell et al. 2020; LM17).

6 DISCUSSION

Analysis of the LMXBs light curves observed during outbursts shows that α lies in the range of ~ 0.2 – 1 (Lipunova & Shakura 2002; Suleimanov, Lipunova & Shakura 2008; Malanchev & Shakura 2015; Lipunova & Malanchev 2017; Tetarenko et al. 2018a; Martin et al. 2019; Lipunova et al. 2022). However, three-dimensional simulations of the magnetorotational instability as a source of momentum transfer

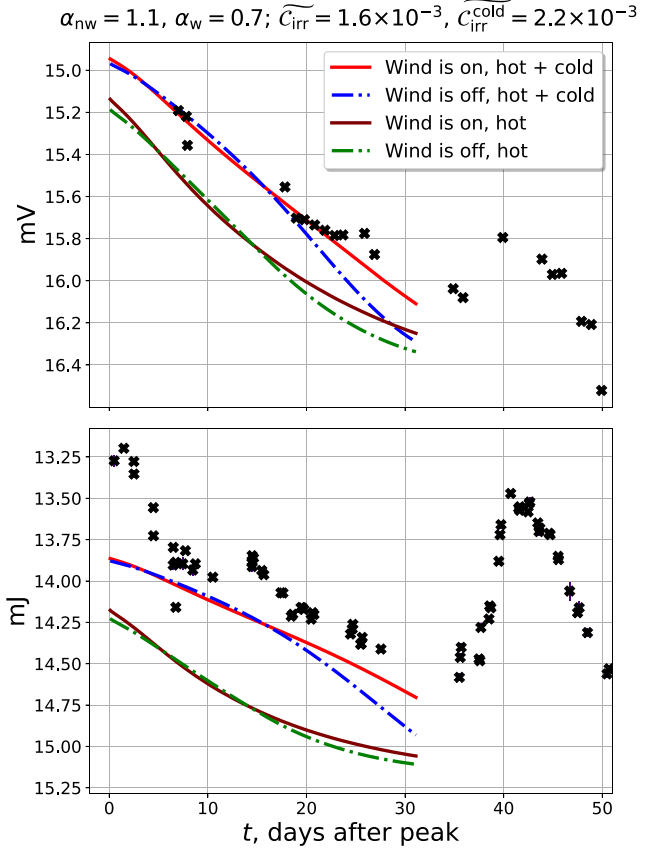


Figure 14. Observed and modelled optical/IR light curves in V (top panel) and J (bottom panel) bands during the 2002 outburst of 4U 1543 – 47. The plots show two types of modelled light curves: ‘hot’ and ‘hot + cold disc’, which means that either the simulation considers that only the hot part of the disc emits optical/IR flux or its cold part does that as well, respectively.

and matter in a disc yield values that are an order of magnitude smaller: $\alpha \lesssim 0.1$ (Balbus & Hawley 1991; Hirose et al. 2014). To a certain degree, this discrepancy could be explained by an overestimate of the value of the parameter α from observations, which, in turn, can be caused by the presence of non-viscous mechanisms of the momentum transport in the accretion discs.

Tetarenko et al. (2018b) pointed to the importance of wind and the issue of overestimating the α parameter when analysing the light curves of the X-ray binaries. According to the authors, outburst’s fast evolution in the considered systems can be interpreted either as a strong intrinsic rate of angular momentum transfer in the disc, which can be achieved if a large-scale magnetic field threads the disc, or as a direct indication of mass outflow in the system.

Both α and η_{wind} influence the decay rate of an outburst (see Fig. 8). To test the degree of degeneracy between them, we fit the same data for 4U 1543 – 47 changing η_{wind} . Fig. 16 shows fits’ results for the same 2002 outburst of 4U 1543 – 47, obtained using different values of η_{wind} , which parametrizes the wind power (see equation 23). On the top panel, reduced chi-square value is presented, while lower panel shows corresponding mean of mass-loss ratio $\langle C_w \rangle = \langle \dot{M}_{wind}/\dot{M}_{acc} \rangle$ during the outburst. From the overall behaviour of fit statistics, one can conclude that there is a dependence of the shape of a modelled light curve on the wind power, which may help to resolve a degeneracy between parameters α and η_{wind} . For particular outburst, Fig. 16 favours the model with the wind comparing to the model of disc evolution without a wind, when $\eta_{wind} = 0$. As one can

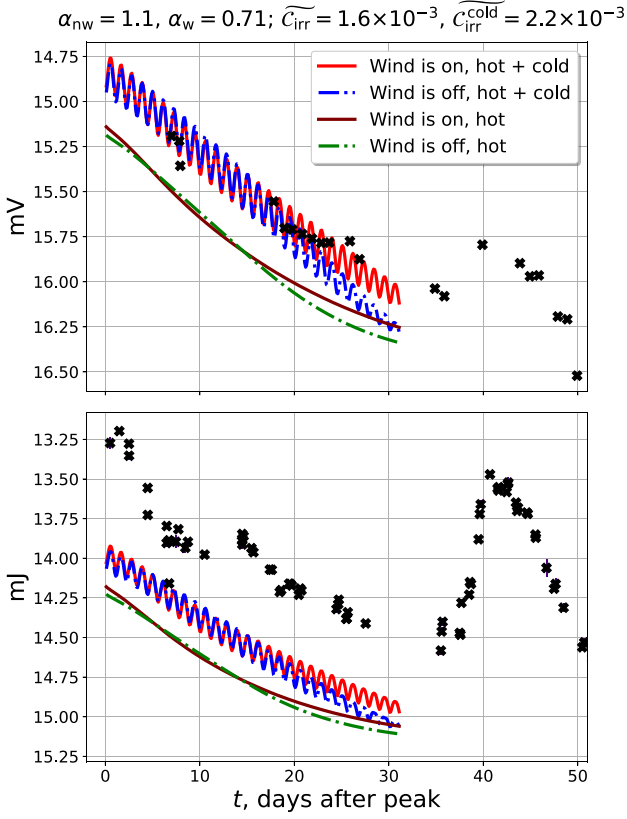


Figure 15. Observed and modelled optical/IR light curves in V (top panel) and J (bottom panel) bands during the 2002 outburst of 4U 1543 – 47. The plots show two types of modelled light curves: ‘hot’ and ‘hot + star’, which means that either the simulation considers that only the hot part of the disc emits optical/IR flux or the irradiated donor star counterpart does it as well, respectively.

see on the top panel, reduced chi-square curves all have a minimum near the value $\eta_{\text{wind}} \sim 1$, i.e. the original wind model. This fact, while could be a coincidence, is quite remarkable.

Observational manifestation of an outflow depends on the inclination of the disc to our line of sight. Let us estimate the number of hydrogen atoms in the wind along the line of sight. In a simplified picture, the wind starts at disc radius $R_w \equiv 0.1 \times R_{\text{IC}}$, but at a greater distance we can consider that it has spherical geometry with density depending solely on the angle i with the disc normal. For the density distribution, we suppose that the number of particles decreases exponentially with the cosine of i . With that in mind, we get the following expression for the number of the hydrogen atoms N_H :

$$N_H(t, i) = \int_{\frac{R_w}{\sin i}}^{R_{\text{max}}(t)} n_H(t, R, i) dR, \quad (24)$$

where the hydrogen number density n_H is given by

$$cn_H(t, R, i) = \frac{k}{1 - \exp(-k)} \times \exp(-k \cos i) \times \frac{1}{4\pi R^2 v_{\text{out}}(R) \mu m_p} \int_{R_w}^{R_{\text{out}}} \dot{\Sigma}_w \left(r, t - t_{\text{fly}} \left(\frac{r}{\sin i}, R \right) \right) 2\pi r dr. \quad (25)$$

The upper limit $R_{\text{max}}(t)$ is the external radius of the envelope, which expands with velocity $v_{\text{out}}(R)$. The mass-loss per unit area $\dot{\Sigma}_w = \dot{\Sigma}_w(r, t)$ is given by equation (23). The time delay t_{fly} is calculated as

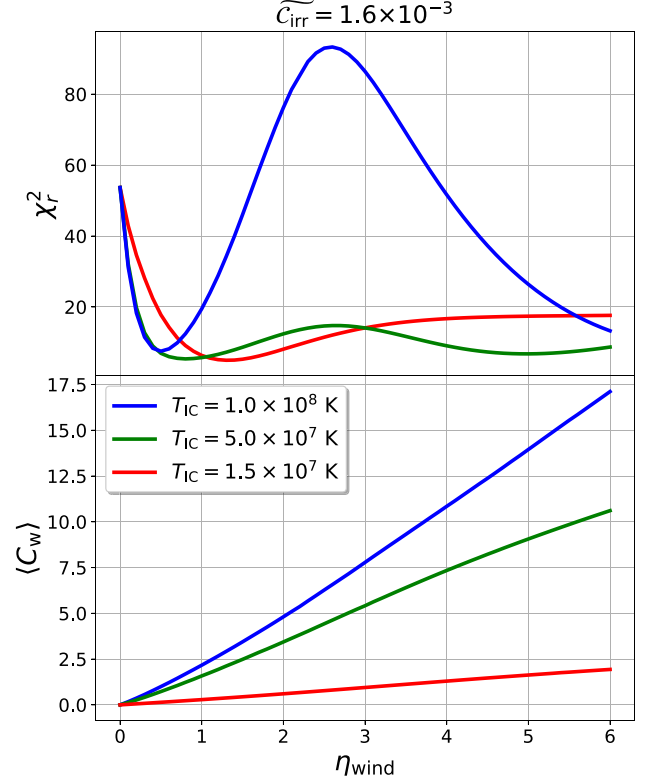


Figure 16. Reduced chi-square for the best-fitting models of 2002 4U 1543 – 47 outburst (top panel) and mean value of wind to accretion ratio $\langle C_w \rangle = \langle \dot{M}_{\text{wind}} / \dot{M}_{\text{acc}} \rangle$ (bottom panel) depending on the wind’s power parameter η_{wind} . Model dependencies are taken with different values of T_{IC} . Value of α parameter without wind $\alpha_{\text{nw}} = 1.1$ and self-irradiation $C_{\text{irr}} = 1.6 \times 10^{-3}$ is constant for all fits.

the time required for the matter to move from ‘a start of expansion’ $r/\sin i$ to R . In our case of constant velocity, $t_{\text{fly}} = (R - r/\sin i)/v_{\text{out}}$. The first two multipliers in equation (25) are the damping factor for the density distribution over polar angles with a dimensionless parameter k and its normalization.

The above estimate leaves out the complexity of density and streamlines’ configuration in the proximity of the disc. Time delay between the moment when matter leaves the disc and the moment that we consider as the ‘start of expansion’ is ignored, so the accuracy of the estimate should deteriorate for very small angles i .

For a typical wind velocity $\sim 500 \text{ km s}^{-1}$ (Higginbottom et al. 2019), a spherical layer expands to $\sim 10^{13} \text{ cm}$ in 3 d, which shows that for not very small inclination angle i the simple spherical geometry should be satisfactory. During first days after the peak of an outburst, the estimate is rough, since we ignore the matter launched before the peak.

Fig. 17 shows the column density versus the system inclination at the 10th day after the 2002 outburst of 4U 1543 – 47 for different damping parameters k . It can be seen that the number of particles corresponding to the uniform angular distribution ($k = 0$) hardly depends on i . Its mild variation is explained by the dependence of the starting radius of the envelope $R_w/\sin i$ on the inclination i . In Fig. 17, the black dash–dotted line shows the dependence calculated following equation (6) from Done, Tomaru & Takahashi (2018), with

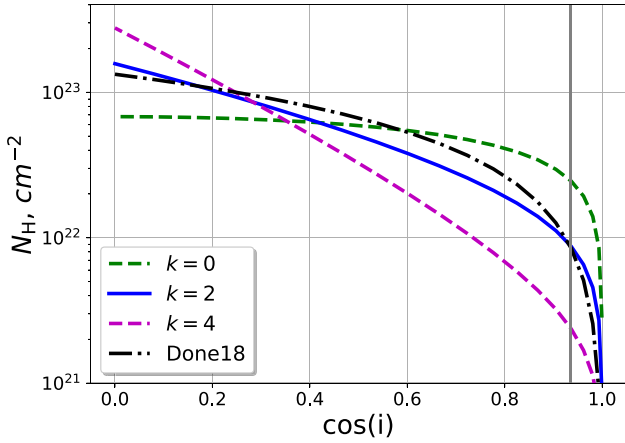


Figure 17. Column density at 10th day of an outburst with parameters as in Fig. 11 versus the inclination of a binary for various values of the damping coefficient k in the angular distribution of wind density (equations 24 and 25). Black dash-dotted line shows the dependence calculated following Done, Tomaru & Takahashi (2018, see equation 26). Grey line indicates the adopted value of inclination for 4U 1543 – 47 (20.7°).

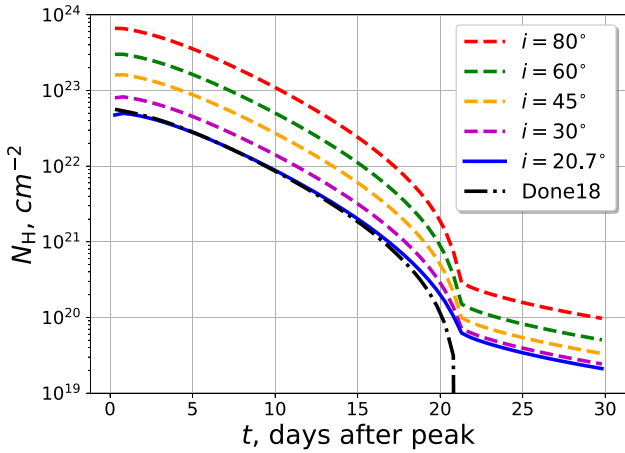


Figure 18. Column density versus the time after the peak of the 2002 outburst of 4U 1543 – 47 for damping coefficient $k = 2$, see equation (24), (25). Black dash-dotted line shows the dependence calculated following Done, Tomaru & Takahashi (2018) with $i = 20.7^\circ$ (see equation 26).

a proper normalization applied:

$$N_H^{\text{Done18}} = \frac{\dot{M}_{\text{wind}} (1 - \cos i)}{2\pi R_w v_{\text{out}} \mu m_p}, \quad (26)$$

with the same $v_{\text{out}} = 500 \text{ km s}^{-1}$ and $R_w = 0.1 \times R_{\text{IC}}^4$.

As the envelope expands, the number of atoms along the line of sight should decrease due to spherical divergence principle. Fig. 18 shows the column density $N_H(t)$ versus time for the same set of the wind parameters as in Fig. 17 and fixed $k = 2$. Different curves correspond to different values of the binary inclination. Approximately on the 21st after the peak, all curves show a break due to the thermal wind shutdown, which happens after the hot

zone radius becomes less than R_w (see Section 5.2 and Fig. 12). This characteristic trend is explained by the fact that the main contribution to the number of N_H comes from the wind matter close to the disc.

Done, Tomaru & Takahashi (2018) have analysed effects of the spectral evolution (with spectrum parametrized using bolometric luminosity) on the wind using the analytical model for the thermal wind by W96. This work neglects the spectral evolution because we assume the constant Compton temperature (based on observational data; see Section 5.2). Thus, we focus on the effects of the thermal wind on the viscous disc evolution. Naturally, to apply our scheme to a source with strong spectral evolution, one should take into account evolution of T_{IC} .

Fig. 18 demonstrates that the column density is not proportional to the mass accretion rate, or the luminosity, as in Done, Tomaru & Takahashi (2018), but drops faster following the mass-loss rate. The difference between our results apparently results from different treatment of the wind-launching zone. We assume that the wind operates only in the hot zone (because it affects disc evolution only there), while Done, Tomaru & Takahashi (2018) assume constant outer radius of the launching zone. Actually, the outer recombined disc can be shadowed by the thicker inner parts of the disc and this could explain no thermal wind there. On the contrary, if scattered but effective irradiation works, the thermal wind is expected from the outer disc part as well (see Dubus et al. 2019).

The dash-dotted line in Fig. 18 shows $N_H(t)$ calculated using (26) from Done, Tomaru & Takahashi (2018) for $i = 20.7^\circ$. It demonstrates that slightly different angular distributions of mass in the wind (our $k = 2$ and formulation of Done, Tomaru & Takahashi 2018) does not affect the evolution of N_H . More crucial is how the wind-launching zone changes.

When the cooling front reaches the innermost wind-launch radius ($6 \times 10^{10} \text{ cm}$), $N_H(t)$ changes remarkably. At late times this evolution has the asymptotics t^{-2} expected for an envelope expanding with the constant speed and mass. As a result, if such deceleration of $N_H(t)$ is observed, that will confirm the concept of the evolving viscous disc and shadowing of the outer disc at the same time. However, if $N_H(t)$ is proportional to luminosity, this will indicate the whole surface of the disc persistently launches the wind. A hardening of X-ray spectrum will result in the increase of N_H (Done, Tomaru & Takahashi 2018).

In spectral modelling of the X-ray data (LM17), the absorption of soft X-rays by ISM was accounted for with Xspec model TBabs assuming column density $N_H = 4 \times 10^{21} \text{ cm}^{-2}$ (absorption by photoionization in gas, molecules and grains of ISM). This number is less than expected in the wind during the first $\sim 15 \text{ d}$ after the peak (see Fig. 18). This fact bears no conflict, since, if the wind material is highly ionized, the absorption is mainly due to electron scattering. The optical depth of the wind by the Thomson scattering is 0.04 near the peak of the outburst.

Approximate evolution of the ionization parameter ξ (cf. pressure ionization parameter Ξ , $\xi = 4\pi \Xi k T c = L_x^{(i)} / (n_H R^2)$, $n_H = n_H(t, R, i)$) in the distant spherical wind along the assumed line of sight of 4U 1543 – 47 is shown in Fig. 19. Here, $L_x^{(i)} = 4\pi d^2 F_x^{\text{obs}}$ is the isotropic luminosity derived from the flux in 0.5–50 keV. A constancy of ξ over radii close to the origin is explained by an assumed constant speed of expansion (see also equation 7 in Done, Tomaru & Takahashi 2018). At first, ξ rises at each radius, since the mass-loss rate drops faster than accretion rate (and L_x). Along the particular line of sight, no lines can be produced in the distant wind for such high values of the ionization parameter. After the 21th day the wind stops: it is seen as an outward shift of the left edge of the curves since the wind material moves away. The black line shows a distribution of ξ parameter just near the disc surface at the base of the

⁴Done, Tomaru & Takahashi (2018) adopt the angular density distribution $\rho(R, \cos i) = \rho_0(R)(1 - \cos i)$. From the mass conservation law, $\dot{M}_{\text{wind}} = R^2 v_{\text{out}} \int_{\Omega} \rho(R, \cos i) d\Omega$, one obtains $\rho_0(R) = \dot{M}_{\text{wind}} / (2\pi R^2 v_{\text{out}})$.

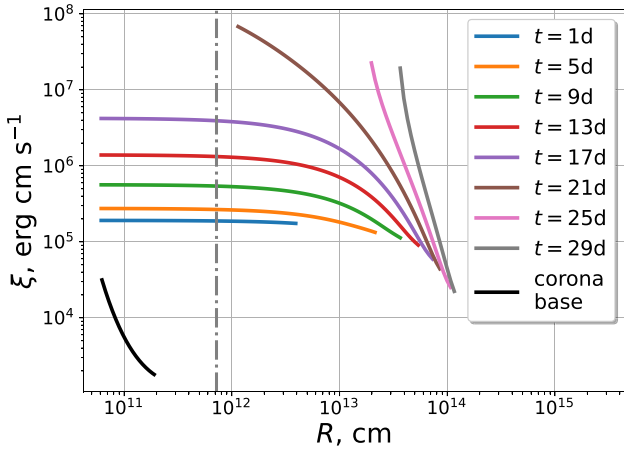


Figure 19. Radial distribution of $\xi = L_x^{(i)}/(n_H R^2)$, where n_H is given by (25). Colour lines show profile of ξ along the line of sight of the observer ($i = 20.7^\circ$) for an indicated number of days after the peak. Line ranges show expansion of the wind. Dash-dotted grey line marks the semimajor axis.

corona, where $n_H = \dot{\Sigma}_w/(2v_{out} \mu m_p)$. The corona base distribution of ξ is plotted for constant i corresponding to $z_0/r = 0.05$ at time $t = 1d$ and covers the radial range from R_w to R_{hot} . This value has a very weak time dependency and evolves as $\sim 1/\log L_X$. Evidently, sources at high inclination would be better candidates to observe spectral lines produced in the wind matter.

It would be reasonable to assume that all the material ejected in the thermal wind, not only increases N_H , but can also influence the process of self-irradiation of the disc through scattering of X-rays. Dubus et al. (2019) have actually shown that including a dependence of C_{irr} on the mass-loss in the wind can lead to a more complicated form of light curves of X-ray novae. For instance, it is theoretically predicted that C_{irr} is proportional to the column density in the wind material. This could affect the α -correction that we obtain and requires a dedicated study. As of now, we can evaluate the irradiation parameter according to equation (10) of Dubus et al. (2019). Resulting C_{irr} is about 6×10^{-2} at the maximum of the outburst which is about 2 orders higher than the irradiation parameter obtained from comparison of observed and model optical flux in V, $C_{irr} \lesssim 3 \times 10^{-4}$ (see Fig. E2 in Appendix E). A similar result was obtained in LM17, where it was shown (for the same BH parameters), that C_{irr} cannot be significantly higher than $(3-6) \times 10^{-4}$. This is also consistent with the results of Tetarenko et al. (2020) for BH LMXB GX 339 – 4 on analytic estimates of self-irradiation from scattering in thermal wind. Namely, in the beginning of an outburst of GX 339 – 4, the value of C_{irr} is highly overestimated even from the scattering in thermal wind alone (fig. 6 in Tetarenko et al. 2020, following Dubus et al. 2019). And this is despite the fact that after transitioning to the intermediate state the situation actually reverses, which is pointed out by the authors.

7 CONCLUSIONS

In this work, we studied how the course of the viscous evolution of an accretion disc changes in the presence of the thermal wind. A numerical method for solving this problem was developed and implemented as a part of the open code FREDDI.

We have incorporated stationary thermal wind models of B83, S86, and W96 into FREDDI.

We have simulated typical light curves during LMXB outbursts with the thermal wind by W96 and compared them with light curves obtained for accretion discs without wind. All simulations are conducted through solving the evolution equation for a viscous α -disc. It was found that in the presence of the thermal wind, the evolution of accretion disc noticeably accelerates, which is especially pronounced for brighter outbursts. This is due to the fact that the power of the wind increases with the accretion rate as well as with the disc size.

Ignorance of the thermal wind can lead to an overestimation of the viscosity parameter α determined from observations. A factor of several is suggested by Fig. 8; it depends on the spectral hardness of central X-rays. This change may not be enough to fully explain the discrepancy between MHD calculations and observations concerning the magnitude of the turbulent parameter; however, the change is significant and must be taken into account when modelling disc bursts evolution.

We have tested our method by comparing its results with those of S86 in the context of the accretion disc luminosity oscillations. Oscillations of luminosity arise and do not decay if the rate of mass-loss in the wind is proportional to the rate of accretion onto a compact object and the ratio $C_w = \dot{M}_{wind}/\dot{M}_{acc}$ is large enough, namely, $C_w \gtrsim 12.8$, which is reasonably consistent with the results of S86.

Using implemented thermal wind model W96, we have fitted $\dot{M}_{acc}(t)$ of the BH LMXB 4U 1543 – 47 outburst of 2002. We find that, when the thermal wind is ignored, the observational value of the turbulent viscosity parameter α for the particular outburst is overestimated by about a factor of 1.6. Moreover, the fits to the $\dot{M}_{acc}(t)$ dependence are in favour of a model-predicted power of the thermal wind.

With an updated version of FREDDI now also capable of reproducing more complex optical/IR light curves, we simulated these as well. We have compared observed optical/IR (V and J) light curves of the 2002 4U 1543 – 47 outburst with our model ones. Ultimately, we conclude that, while V band flux could be explained within our models, the emission from the hot disc, cold disc and irradiated by X-rays optical companion still cannot fully account for J band flux. This may be a sign of the presence of some unaccounted by us source of additional optical/IR radiation, possibly a jet.

We have calculated the wind column density N_H evolution along the line of sight. The model predicts that after the wind stops (when disc hot-zone radius becomes smaller than the wind launch radius), the number of hydrogen atoms along the line of sight undergoes a break of a temporal evolution. At the same time, the residual envelope is hardly observable due a very high ionization parameter.

It should be said that if during an outburst the accretion rate becomes higher than the super-Eddington accretion rate, an outflow starts from the central, radiation-dominated region of the disc (Shakura & Sunyaev 1973), that can partly screen the outer parts of the disc from central X-rays. Such outbursts should be modelled with another wind function $\dot{\Sigma}_w$.

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DATA AVAILABILITY

Spectral parameters evolution obtained by modelling the archival data from *RXTE* observations of 4U 1543 – 47 in 2002 is available at <https://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=J/MNRAS/468/4735>. Optical data from Buxton & Bailyn (2004) is available

from us upon request. The FREDDI code is available at <https://github.com/hombit/freddi/tree/dev>.

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APPENDIX A: NUMERICAL SOLUTION OF THE NONLINEAR DIFFUSION EQUATION

A1 Formulation of the problem

It is necessary to construct a method for the numerical solution of equation (6) and study it for stability, taking into account the influence of the wind. Let us consider the problem in a more general form which is equivalent to the task of solving the equation (6) with boundary (11), (12), and initial (13) conditions. This problem can be presented as the following system of equations:

$$\begin{cases} \frac{\partial Z(U(x, t), x)}{\partial t} = \frac{\partial^2 U(x, t)}{\partial x^2} + V\left(\frac{\partial U}{\partial x}, U, x\right), x \in [a, b], t \in [0, T]; \\ U(a, t) = 0; \\ \frac{\partial U(x, t)}{\partial x} \Big|_{x=b} = 0; \\ U(x, 0) = \Phi(x); \end{cases} \quad (\text{A1})$$

where T is the considered evolution time of the disc, V and Z are known functions of their variables, U is the desired function, $\Phi(x)$ is the initial condition. The functions Z , U , and Φ are strictly positive in the interval $x \in [a, b]$.

We represent the function V in the form:

$$V\left(\frac{\partial U}{\partial x}, U, x\right) = A(x) \frac{\partial U(x, t)}{\partial x} + B(x) U(x, t) + C(x), \quad (\text{A2})$$

where A , B , and C are the expansion coefficients, which in a known manner depend on x . Then, taking into account (A2), the first equation in the system (A1) will look as follows:

$$c \frac{\partial Z(U(x, t), x)}{\partial t} = \frac{\partial^2 U(x, t)}{\partial x^2} + A(x) \frac{\partial U(x, t)}{\partial x} + B(x) U(x, t) + C(x). \quad (\text{A3})$$

Note that the functions Z , U , and V from the first equation of system (A1) correspond to the functions Σ , F , and $-\dot{\Sigma}_w$ from equation (6), respectively.

A2 Constructing a solution to equation (A3)

We introduce a difference scheme by constructing a grid:

$$\begin{aligned} x_0 < x_1 < \dots < x_n < \dots < x_{N-1} < x_N, \\ h_n &= x_n - x_{n-1}, n = 1..N; \\ t_0 < t_1 < \dots < t_m < \dots < t_{M-1} < t_M; \\ \tau_m &= t_{m+1} - t_m, m = 0..M-1. \end{aligned} \quad (\text{A4})$$

Thus, the initial functions Z , U , and Φ are replaced with the corresponding grid ones:

$$\begin{aligned} cZ(U(x_n, t_m), x_n) &\rightarrow z_n^m, \\ U(x_n, t_m) &\rightarrow u_n^m, \\ \Phi(x_n) &\rightarrow \phi_n. \end{aligned} \quad (\text{A5})$$

First, we write the difference equations for the boundary and initial conditions. In our case of a BH, the internal boundary condition of the first type is written as

$$u_0^m = 0, \quad \forall m. \quad (\text{A6})$$

In turn, the initial condition is as follows:

$$u_n^0 = \phi_n, \quad \forall n. \quad (\text{A7})$$

In order to write down an external boundary condition of the second type, we expand u_{N-1}^{m+1} in a Taylor series at the point x_N :

$$u_{N-1}^{m+1} = u_N^{m+1} - h_N \frac{\partial U}{\partial x} \Big|_{x_N} + \frac{h_N^2}{2} \frac{\partial^2 U}{\partial x^2} \Big|_{x_N} + o(h_N^2). \quad (\text{A8})$$

If we substitute the value of the second derivative u_n^{m+1} with respect to x , expressed from the initial equation (A3), into the equation (A8), then, in terms of differences up to the second order h_N inclusively, we can write the outer boundary condition (third equation in A1) as follows:

$$\begin{aligned} c \frac{u_N^{m+1} - u_{N-1}^{m+1}}{h_N} + \frac{h_N}{2} \frac{z_N^{m+1} - z_N^m}{\tau_m} - \frac{A_N}{2} (u_N^{m+1} - u_{N-1}^{m+1}) - \\ - \frac{B_N}{2} u_N^{m+1} h_N - \frac{C_N}{2} h_N + o(h_N^2) + o(\tau_m) = 0. \end{aligned} \quad (\text{A9})$$

Here, the time derivative of the function $Z(x_N, t)$ is written as

$$\frac{\partial Z(x_N, t)}{\partial t} = \frac{z_N^{m+1} - z_N^m}{\tau_m} + o(\tau_m). \quad (\text{A10})$$

Henceforth, in the expression for the external boundary condition, the terms of order of smallness $o(h_N^2) + o(\tau_m)$, $\forall m$ and higher will be omitted.

Now, we obtain the difference form of the differential equation (A3) itself. We write the Taylor series expansion of the function u_n^{m+1} for x_{n+1} and x_{n-1} at the point x_n .

$$\begin{aligned} cu_{n+1}^{m+1} &= u_n^{m+1} + h_{n+1} \frac{\partial u^{m+1}}{\partial x} \Big|_{x_n} + \frac{h_{n+1}^2}{2} \frac{\partial^2 u^{m+1}}{\partial x^2} \Big|_{x_n} + o(h_{n+1}^2), \\ u_{n-1}^{m+1} &= u_n^{m+1} - h_n \frac{\partial u^{m+1}}{\partial x} \Big|_{x_n} + \frac{h_n^2}{2} \frac{\partial^2 u^{m+1}}{\partial x^2} \Big|_{x_n} + o(h_n^2), \end{aligned} \quad (\text{A11})$$

where $n = 1..N-1$ and $m = 0..M-1$.

Hence, omitting terms of order $o(h_{n+1}^2)$, $o(h_n^2)$ and higher, we obtain that the first derivative $\partial u^{m+1} / \partial x$ at the point x_n :

$$\frac{\partial u^{m+1}}{\partial x} \Big|_{x_n} = \frac{u_{n+1}^{m+1} \frac{h_n^2}{h_n + h_{n+1}} + u_n^{m+1} (h_{n+1} - h_n) - u_{n-1}^{m+1} \frac{h_{n+1}^2}{h_n + h_{n+1}}}{h_n h_{n+1}} \quad (\text{A12})$$

and the second derivative:

$$\frac{\partial^2 u^{m+1}}{\partial x^2} \Big|_{x_n} = 2 \frac{u_{n+1}^{m+1} \frac{h_n}{h_n + h_{n+1}} - u_n^{m+1} + u_{n-1}^{m+1} \frac{h_{n+1}}{h_n + h_{n+1}}}{h_n h_{n+1}}. \quad (\text{A13})$$

Finally, substituting the values of the derivatives (A10), (A12), and (A13) into the differential equation (A3) and replacing the outer boundary condition from (A1) with its difference analogue (A9), we

get a difference scheme for our problem:

$$\left\{ \begin{aligned} \frac{z_n^{m+1} - z_n^m}{\tau_m} &= 2 \frac{u_{n+1}^{m+1} \frac{h_n}{h_n + h_{n+1}} - u_n^{m+1} + u_{n-1}^{m+1} \frac{h_{n+1}}{h_n + h_{n+1}}}{h_n h_{n+1}} + \\ &+ A_n \frac{u_{n+1}^{m+1} \frac{h_n^2}{h_n + h_{n+1}} + u_n^{m+1} (h_{n+1} - h_n) - u_{n-1}^{m+1} \frac{h_{n+1}^2}{h_n + h_{n+1}}}{h_n h_{n+1}} + \\ &+ B_n u_{n-1}^{m+1} + C_n, \\ \frac{u_N^{m+1} - u_{N-1}^{m+1}}{h_N} + \frac{h_N}{2} \frac{z_N^{m+1} - z_N^m}{\tau_m} - \frac{A_N}{2} (u_N^{m+1} - u_{N-1}^{m+1}) - \\ - \frac{B_N}{2} u_{N-1}^{m+1} h_N - \frac{C_N}{2} h_N &= 0, \end{aligned} \right. \quad (\text{A14})$$

where $n = 1..N-1$ and $m = 0..M-1$, with internal boundary condition (A6) and initial condition (A7).

Note that the accuracy of the resulting system (A14) is of the order of $o(h_{\max}^2) + o(\tau_{\max})$, where $h_{\max} = \max(h_n)$, and $\tau_{\max} = \max(\tau_m)$.

To find the values of function u at the next time step $m+1$, it is necessary to solve system (A14). Consider the transition from the known values of u at $t = t_m$ to the unknown values of u at $t = t_{m+1}$.

For convenience, we denote

$$\begin{aligned} u_n &\equiv u_n^m, & \tilde{u}_n &\equiv u_n^{m+1}; \\ z_n &\equiv z_n^m, & \tilde{z}_n &\equiv z_n^{m+1}; \\ \tau &\equiv \tau_m. \end{aligned} \quad (\text{A15})$$

We also introduce the new grid function $\tilde{\lambda}$:

$$\tilde{\lambda}_n \equiv \frac{\tilde{z}_n}{\tilde{u}_n}. \quad (\text{A16})$$

Note that due to the strict positiveness of the functions Z and U from the system (A1), $\tilde{\lambda}$ is also a positive definite function.

We transform the first equation of system (A14) using the new notation:

$$\begin{aligned} c \left(\frac{2h_{n+1}}{h_n + h_{n+1}} - A_n \frac{h_{n+1}^2}{h_n + h_{n+1}} \right) \tilde{u}_{n-1} - \left(2 + \frac{h_n h_{n+1} \tilde{\lambda}_n}{\tau} \right) \tilde{u}_n - \\ - (-A_n(h_{n+1} - h_n) - B_n h_n h_{n+1}) \tilde{u}_n + \frac{2h_{n+1}}{h_n + h_{n+1}} \tilde{u}_{n+1} + \\ + A_n \frac{h_{n+1}^2}{h_n + h_{n+1}} \tilde{u}_{n+1} = -\frac{h_n h_{n+1}}{\tau} z_n - C_n h_n h_{n+1}, \end{aligned} \quad (\text{A17})$$

where $n = 1..N-1$. We also rewrite the initial and boundary conditions for the grid function u :

$$\left\{ \begin{aligned} u_0 &= 0, \\ \left(1 - \frac{A_N h_N}{2} \right) \tilde{u}_{N-1} - \left(1 + \frac{h_N^2 \tilde{\lambda}_N}{2\tau} - \frac{A_N h_N}{2} - \frac{B_N h_N^2}{2} \right) \tilde{u}_N &= \\ &= -\frac{h_N^2}{2} \left(\frac{z_N}{\tau} + C_N \right), \\ u_N^0 &= \phi_N. \end{aligned} \right. \quad (\text{A18})$$

A3 Solution of a system of nonlinear equations

Equations (A17) and (A18) form a system of nonlinear equations. To find the values $\tilde{u}$ and $\tilde{z}$ at the next step of time, we will use the iteration method. Thus, it is necessary to solve the system of $N-1$

linear equations:

$$\begin{aligned} c \left(\frac{2h_{n+1}}{h_n + h_{n+1}} - A_n \frac{h_{n+1}^2}{h_n + h_{n+1}} \right) \tilde{u}_{n-1}^{(s+1)} - \\ - \left(2 + \frac{h_n h_{n+1} \tilde{\lambda}_n^{(s)}}{\tau} - A_n (h_{n+1} - h_n) - B_n h_n h_{n+1} \right) \tilde{u}_n^{(s+1)} + \\ + \left(\frac{2h_{n+1}}{h_n + h_{n+1}} + A_n \frac{h_{n+1}^2}{h_n + h_{n+1}} \right) \tilde{u}_{n+1}^{(s+1)} = -\frac{h_n h_{n+1}}{\tau} z_n^{(s)} - C_n h_n h_{n+1}, \end{aligned} \quad (\text{A19})$$

where $n = 1..N-1$ and s is the number of iteration step. The initial and boundary conditions for this system of linear equations are defined in (A18).

This system is solved using the tridiagonal matrix algorithm (see Section A4).

Iterations stop when the criterion is met:

$$\max_{n=1..N-1} \frac{|\tilde{\lambda}_n^{(s+1)} - \tilde{\lambda}_n^{(s)}|}{\tilde{\lambda}_n^{(s+1)}} < \epsilon, \quad (\text{A20})$$

where ϵ is the requested relative accuracy.

A4 Tridiagonal matrix algorithm for solving a system of linear equations

Let us consider a system of equations, where the desired variables are y_n :

$$\begin{cases} D_n y_{n-1} - E_n y_n + F_n y_{n+1} = -G_n, & n = 1..(N-1) \\ y_0 = \mu_1 + k_1 y_1, \\ y_N = \mu_2 + k_2 y_{N-1}. \end{cases} \quad (\text{A21})$$

To resolve this system, we use the tridiagonal matrix algorithm (Kalitkin 1978).

The forward sweep allows finding auxiliary coefficients α_n and β_n :

$$\begin{aligned} \alpha_1 &= k_1, \\ \beta_1 &= \mu_1; \\ \alpha_{n+1} &= \frac{F_n}{E_n - \alpha_n D_n}, & n &= 1..N-1; \\ \beta_{n+1} &= \frac{\beta_n D_n + G_n}{E_n - \alpha_n D_n}, & n &= 1..N-1. \end{aligned} \quad (\text{A22})$$

Back substitution gives the desired values y_n :

$$\begin{aligned} c y_n &= \alpha_{n+1} y_{n+1} + \beta_{n+1}, \\ y_N &= \frac{\mu_2 + \beta_N k_2}{1 - \alpha_N k_2}. \end{aligned} \quad (\text{A23})$$

Sufficient stability conditions for the system (A21) are as follows (Kalitkin 1978):

$$\begin{aligned} |E_n| &\geq |D_n| + |F_n|, & n &= 1..N-1; \\ |k_1| &\leq 1, |k_2| \leq 1; \\ |k_1| &+ |k_2| < 2. \end{aligned} \quad (\text{A24})$$

Using this method to solve the system of linear equations (A19), with initial and boundary conditions (A18), we find that the criterion for stability of the system (A19) is the condition:

$$B_n \leq \tilde{\lambda}_n / \tau, \quad n = 1..N-1. \quad (\text{A25})$$

This condition is satisfied automatically for the case $V \left(\frac{\partial U}{\partial x}, U, x \right) = V(U) = B(x)U(x, t)$, because $\tilde{\lambda}$, τ and U are strictly positive, and the coefficient B of the expansion of the function V (A2) in this case should be negative (the function V corresponds to the function $-\tilde{\Sigma}_w$, $\tilde{\Sigma}_w > 0$ from (6), thus $V < 0$).

In the general case, the condition (A25) may not be fulfilled (the function V may be negative for positive B and negative A and/or C). But, for our set of wind patterns (see Section 4 and Appendices B, C, D), the condition is always satisfied, because the functions $\dot{\Sigma}_w$ from those sections do not simultaneously contain more than one term in decomposition (A2). This means that the solution of system (A19) is stable for all models presented in the manuscript.

APPENDIX B: EQUATIONS OF THE THERMAL COMPTON WIND

B83 have proposed the following model. The rate of mass-loss per unit area $\dot{m} = \rho V y^{(\beta)}$ is constant along a streamline, and its value depends on the sonic point position, pressure and temperature there, as well as on a divergence parameter β . Here, V and ρ are the velocity and density of the flow, respectively. An increase in the cross-sectional area of streamlines is described by function $y^{<\beta>}$, $y = r'/r$, and $(r' - r)$ is the distance along the streamline from the base of the corona/wind, where $y = 1$. Spherical flow corresponds to $\beta = 2$.

B83 have established that the mass-loss rates are insensitive to the trajectories of streamlines. At the same time, the complexity of the model follows from the fact that the escape, characteristic, and Compton temperatures relate to each other differently, depending on the disc radius and luminosity. S86 have proposed a formula that approximates the results obtained in B83. It can be written in terms of dimensionless rate as follows:

$$\dot{m}^* \equiv \frac{\dot{m}}{\dot{m}_{\text{ch}}} = \mathbf{M} \frac{c_{\text{ch}}}{c_s(r')} \frac{p(r')}{p_0} y^{(\beta)}, \quad (\text{B1})$$

where the characteristic mass-loss rate per unit area $\dot{m}_{\text{ch}} \equiv p_0/c_{\text{ch}}$ is expressed from the gas pressure at the base of the corona/wind $p_0 \equiv L/(4\pi r^2 \Xi c)$ and a characteristic speed c_{ch} such that a flow, which has been moving at this speed along a streamline to a height equal to the radius of the streamline's base r , is heated to temperature $T_{\text{ch}} \equiv \mu c_{\text{ch}}^2/k$. Since the optically thin heating rate at radius r :

$$\Gamma = \frac{k T_{\text{IC}} \sigma_T L}{m_e c^2 \pi r^2} \quad (\text{B2})$$

determines the characteristic temperature as follows:

$$k T_{\text{ch}} = \Gamma \frac{r}{c_{\text{ch}}}, \quad (\text{B3})$$

it is possible to obtain the exact expression for the characteristic mass-loss rate per unit area (see also Middleton et al. 2022):

$$\dot{m}_{\text{ch}} = \frac{1}{2^{8/3} \Xi} \frac{m_e c}{\sigma_T R_{\text{IC}}} \left(\frac{\mu_e}{\mu} \right)^{2/3} l^{2/3} \xi^{-5/3}, \quad (\text{B4})$$

where $\xi = r/R_{\text{IC}}$ and $l = L/L_{\text{cr}}$, see the definitions (3) and (4). In (B1), the isothermal Mach number $\mathbf{M} \equiv V/c_s(r') = \sqrt{\rho V^2/p}$ and $c_s(r')$ is the speed of sound at location r' along the streamline.

Ultimately, S86 propose the following relations that approximate the result of B83 in different zones of the wind:

$$p/p_0 \approx 0.5 \exp[-(1 - y^{-1})^2/(2\xi)], \quad (\text{B5})$$

$$\frac{\mathbf{M}}{c_s/c_{\text{ch}}} = \left[\frac{1 + (l+1)\xi^{-1}}{1 + l^{-4}(1 + \xi^2)^{-1}} \right]^{1/3}, \quad (\text{B6})$$

$$y^{(\beta)} = y^2 = 1 + \frac{1}{4\xi^2} + \frac{\xi^2}{1 + \xi^2} \left[\frac{1.2\xi}{\xi + l} + \frac{2.2}{(1 + l^2\xi)} \right]^2. \quad (\text{B7})$$

Substituting the above expressions into (B1), one obtains the mass-loss rate from two sides of the disc:

$$\dot{\Sigma}_w = 2 \dot{m} = 2 \dot{m}_{\text{ch}}(\xi, l) \dot{m}^*(\xi, l). \quad (\text{B8})$$

APPENDIX C: VERIFYING THE CODE WITH THE S86'TOY' WIND MODEL

S86 have shown that the instability arising in accretion discs under the influence of a wind can lead to oscillations in the brightness of an object. This phenomenon occurs only if the wind from a disc is quite powerful compared to the accretion rate.

Therefore, in order to test our code and verify the presence of oscillations, we use the following wind term from S86:

$$\dot{\Sigma}_w = \frac{1}{2\pi} \left(\frac{C_w(t) \dot{M}_{\text{acc}}}{\ln(R_{\text{out}}/R_w) r^2} \right), \quad (\text{C1})$$

where R_{out} is the outer radius of the accretion disc, R_w is the inner radius of the wind launching zone, and $C_w \equiv \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$. The wind occurs only in the area outside the radius R_w (i.e. $r \geq R_w$) in other parts of the disc the function $\dot{\Sigma}_w$ is assumed to be zero.

The physical reasoning of the parameter C_w here is the following. Thermal wind is caused by the irradiation of the disc photosphere by a central source of X-ray (or UV) flux. Presumably, the mass-loss rate due to the wind rises with the accretion rate on to a compact object. Hence, parameter C_w formalises an assumption that the rate of wind mass-loss is proportional to the accretion rate on to a compact object.

Note that this 'toy' wind model does not include the notion of the hot and cold zone in the disc (Section 3.1). We rather fix the outer radius of an evolving disc zone, i.e. $R_{\text{hot}} = R_{\text{out}}$. Furthermore, a constant inflow of matter into the disc is required. Thus, we set a non-zero external boundary condition ($\dot{M}_{\text{out}} = 10^{17} \text{ g s}^{-1}$). An initial condition should comply with boundary conditions. Thus, a stationary, linear dependence of F on h is chosen, $F_0(h) = \dot{M}_{\text{acc},0} \times h_{\text{out}}(h - h_{\text{in}})/(h_{\text{out}} - h_{\text{in}})$.

In the end, to test our numerical method, we reproduce oscillations of the accretion rate on a compact object arising in the disc in the presence of a sufficiently strong Compton thermal wind (S86). For this, we use the wind function (C1), which contains a dependence on the luminosity (or the rate of accretion on the central object), the parameter `windtype` in FREDDI is 'ShieldsOscil1986'. The accretion rate evolution is calculated for various values of the parameter C_w (Fig. C1). The launch radius of the wind R_w is set equal to $0.9 \times R_{\text{out}}$.

When the central luminosity L increases, the rate of the wind mass-loss also increases. If the wind dominates, the disc mass decreases, and, after a short delay, L and $\dot{M}_{\text{acc}}$ decline, as well as $\dot{M}_{\text{wind}}$, which allows the disc mass to increase again, starting a new cycle of oscillations. The authors give the critical value C_w^{crit} , above which the oscillations of the central accretion rate grow with time (see their fig. 1). The critical value C_w^{crit} depends on the functional form of the viscosity. For example, $C_w^{\text{crit}} = \cosh \pi \approx 11.6$ for the viscosity law $\nu_1 \propto r$.

The oscillations that we obtain confirm the results of S86 for the OPAL opacity (Iglesias & Rogers 1996), approximated by the power law $\propto \rho T^{-5/2}$ (see the last row in table 1 of S86), when $\nu_1 \propto r \Sigma^{1/2}$. For such viscosity law, S86 give the critical value $C_w^{\text{crit}} = 15.2$. To find C_w^{crit} , we have calculated the relative difference in amplitudes of the central accretion rate deviation at the first and seventh oscillation cycle for different values of the parameter C_w spaced by 0.1. Examples of resulting evolution are shown in Fig. C1. Resulting $C_w^{\text{crit}} \approx 15.5$, which is in a very good agreement with

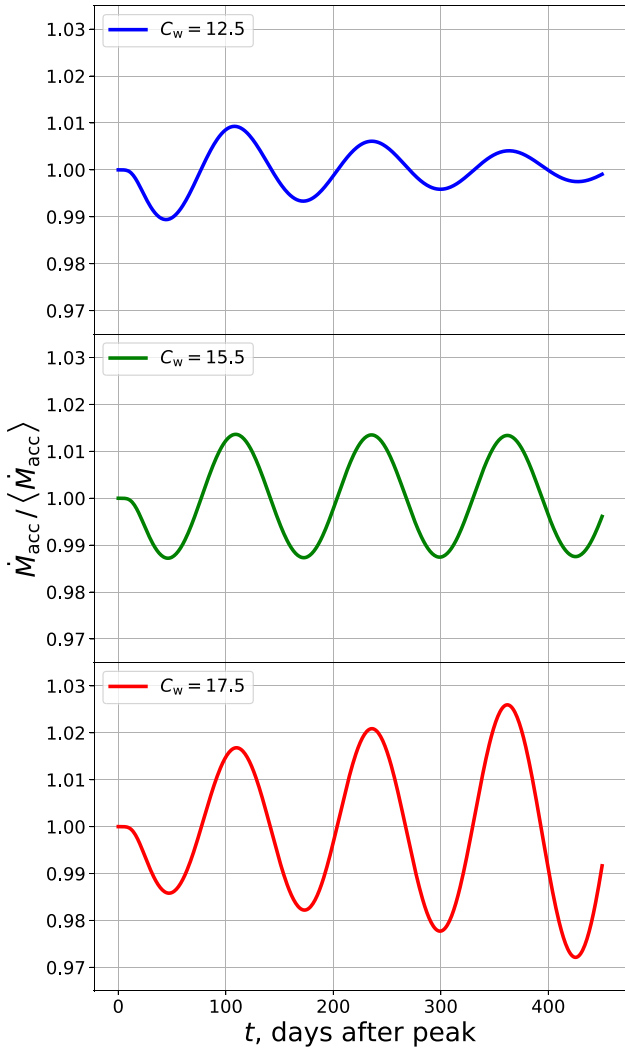


Figure C1. The time dependence of the central accretion rate for a disc with wind (C1). The innermost wind launch radius is $0.9 \times R_{\text{out}}$. The top, middle, and bottom panels show the cases for $C_w \equiv \dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$ ratio: $C_w = 12.8$, $C_w = C_w^{\text{crit}} = 15.5$, and $C_w = 17.8$, respectively.

that found by S86. We note, that this also agrees with possibility of appearance of accretion rate oscillation suggested by Shakura & Sunyaev (1973).

Additional wind models to verify FREDDI work are described in Appendix D. These tests reproduce the radial structure of stationary discs with different types of wind. All solutions for the corresponding $\dot{\Sigma}_w(h)$ functions were found analytically.

APPENDIX D: VALIDATION OF THE NUMERICAL METHOD BY ANALYTICAL SOLUTIONS FOR STATIONARY DISC

To validate the numerical method, we have checked that a numerical solution converges successfully to an analytical one in the case of the constant $\dot{M}_{\text{out}}$.

A solution for a stationary accretion disc can be found from equation (6) with $\partial \Sigma / \partial t = 0$:

$$\frac{1}{4\pi} \frac{(GM_x)^2}{h^3} \frac{\partial^2 F}{\partial h^2} = \dot{\Sigma}_w(F, h). \quad (\text{D1})$$

In every test, we set an initial condition, which did not satisfy (D1), and run a simulation long enough to reach a stationary solution. For all the tests, it takes up to a hundred time iterations to reach relative accuracy of $F(h)$ of 1 percent. Below, we describe different wind types and find corresponding analytical solutions.

D1 S86 ‘toy’ wind model

This type of wind is described by Section C and equation (C1). The solution of equation (D1) for such a wind is

$$F(h) = \begin{cases} \frac{\dot{M}_{\text{out}} h}{1 + C_w} \left(1 - \frac{h_{\text{in}}}{h}\right), & h < h_w; \\ \frac{\dot{M}_{\text{out}} h}{1 + C_w} \left(1 - \frac{h_{\text{in}}}{h} + C_w \frac{\ln(h/h_w) + h_w/h - 1}{\ln(h_{\text{out}}/h_w)}\right), & h \geq h_w, \end{cases} \quad (\text{D2})$$

where $C_w < C_w^{\text{crit}}$. Here, we use the fact that for the asymptotic solution $\dot{M}_{\text{acc}} = \dot{M}_{\text{out}}/(1 + C_w)$.

D2 Wind term is proportional to local accretion rate

In view of Equation (8), we define

$$\dot{\Sigma}_w(F, h) = k \frac{(GM_x)^2}{4\pi h^3} \frac{h - h_{\text{in}}}{(h_{\text{out}} - h_{\text{in}})^2} \frac{\partial F}{\partial h}, \quad (\text{D3})$$

where k is a dimensionless coefficient.

This case corresponds to a non-zero value of A coefficient and zero values of B and C coefficients in equation (A3). In other words, $\dot{\Sigma}_w(h, l) \propto \partial F / \partial h \propto \dot{M}$. The corresponding solution of equation (D1) is

$$F(h) = \dot{M}_{\text{out}}(h_{\text{out}} - h_{\text{in}}) \sqrt{\frac{\pi}{2k}} e^{-k/2} \text{erfi} \left(\sqrt{k/2} \frac{h - h_{\text{in}}}{h_{\text{out}} - h_{\text{in}}} \right), \quad (\text{D4})$$

where erfi is the imaginary error function.

D3 Wind term is proportional to viscous torque

We define

$$\dot{\Sigma}_w(F, h) = \frac{(GM_x)^2}{4\pi h^3} \frac{k}{(h_{\text{out}} - h_{\text{in}})^2} F(h), \quad (\text{D5})$$

where k is a dimensionless coefficient. This case corresponds to a non-zero B coefficient and zero A and C coefficients in equation (A3), that is, $\dot{\Sigma}_w(F, h) \propto F(h)$. The corresponding solution of equation (D1) is

$$F(h) = \dot{M}_{\text{out}}(h_{\text{out}} - h_{\text{in}}) \frac{1}{\sqrt{k} \sinh \sqrt{k}} \sinh \left(\sqrt{k} \frac{h - h_{\text{in}}}{h_{\text{out}} - h_{\text{in}}} \right). \quad (\text{D6})$$

APPENDIX E: RELATION BETWEEN THE SELF-IRRADIATION PRESCRIPTION AND ESTIMATE OF α

The estimate of α , obtained from comparison with observations, depends on the assumed self-irradiation model. In this work, we parametrize the irradiation parameter taking into account its dependence on the thickness of the disc that comes from the changing incident angle and the angular distribution of the central radiation (see equation 19). The relative thickness determines the angle of incident photons and also enters in the angular distribution of the central emission. In LM17, the irradiation parameter was taken constant throughout the modelled time interval.

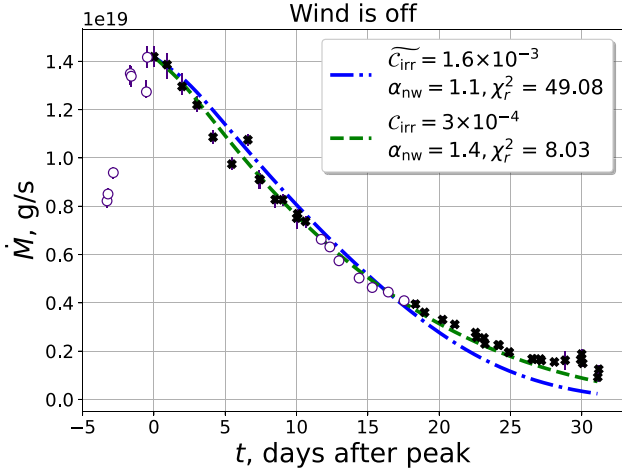


Figure E1. Models and observed $\dot{M}_{acc}(t)$ during the 2002 outburst of 4U 1543 – 47. Models are calculated with different prescription for C_{irr} : $k = 1$ and plane irradiation (the blue line) and $k = 0$ and isotropic irradiation (the green line, as LM17 suggests), see equation (19).

Consequently, this leads to different resulting estimates of α : in LM17 the estimate of the viscosity parameter α was about 1.4 for the 2002 X-ray nova outburst of 4U 1543 – 47 for binary parameters as in Table 1. In this work, $\alpha_{nw} = 1.1$ is obtained, when no wind is present (Fig. 11). Fig. E1 shows two fits of the accretion rate evolution of 4U 1543 – 47 (2002) for such prescriptions of C_{irr} . Fig. E2 shows corresponding parameters C_{irr} : constant, as in the modelling by LM17, and the one changing with z_0/r (see equation 19).

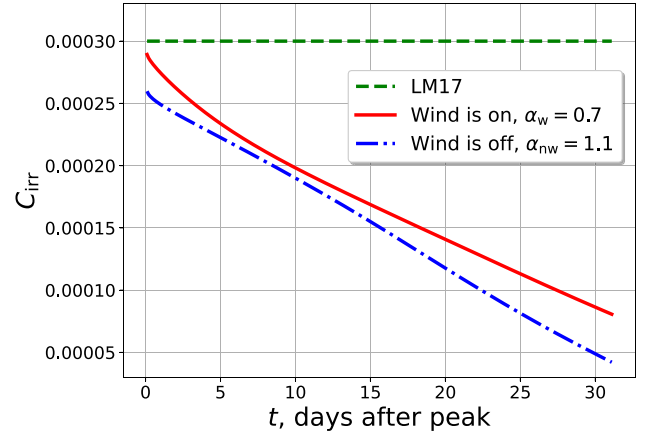


Figure E2. Irradiation parameter of the hot disc versus time (see equation 19) shown for models with and without wind, see Fig. 11). Horizontal line shows constant C_{irr} from LM17 model of the 2002 outburst of 4U 1543 – 47.

However, it is important to keep in mind that processes involving scattering in a media above the disc may infringe a simple geometrical approach like (19). Also, the evolution of the X-ray’s albedo is a non-trivial matter (Tavleev, Lipunova & Malanchev 2023). Thus, a decision cannot be made yet, which description of C_{irr} is more effective for modelling: constant C_{irr} or thickness dependent. In FREDDI, both options are available. Meanwhile, the robust conclusion is that an estimate of α becomes lower if we take into account decreasing of C_{irr} with time.

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