SF2A 2023
M. N'Diaye, A. Siebert, N. Lagarde, O. Venot, K. Baillié, M. Béthermin, E. Lagadec, J. Malzac, J. Richard (eds)

REWINDING THE HISTORY OF HIGH-MASS X-RAY BINARIES WITH GAIA

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Abstract. High-mass X-ray binaries (HMXBs) are stellar couples that undergo mass exchange between a massive star and a compact object. They represent a peculiar phase in the life of massive stars in binaries, which is preceeded by a supernova event as well as mass transfer episodes. These mechanisms interplay in the evolution of massive stars and need to be constrained to better understand how these binaries may be the progenitors of compact mergers seen by LIGO/Virgo.

Gaia has observed more than 100 HMXBs in the Milky Way. By combining the knowledge we already have on those systems, thanks to the building of a new and up to date catalogue, with the exquisite astrometric measurements from Gaia EDR3, we are able to put constraints to the strength of the natal kick imparted to HMXBs during a supernova event, as well as find out where precisely they were born in the Galaxy. Gaia is thus a precious tool for Galactic archeology and the ecology of massive stars, from their birth to their endpoint as compact binaries.

Keywords: binaries: general; stars: formation; stars: evolution; astrometry; stars: kinematics and dynamics; stars: neutron; stars: black holes;

1 Introduction

High-mass X-ray binaries are stellar couples composed of a compact object –usually a neutron star (NS) and seldom a black hole (BH) – accreting from a massive O-B companion ($M \geq 8\,M_{\odot}$, see a broad review in Chaty (2022)). Mass transfer can occur through a decretion disk around a Be companion in BeHMXBs (Rivinius et al. 2013), or via intense stellar wind from an evolved, supergiant companion in sgHMXBs (Chaty 2013).

X-ray binaries have been observed for more than 60 years now, yet they require multiwavelength observations as well as time series to be properly constrained. Hence, we still unveil new systems today and keep observing known ones to better constrain their properties: orbital periods, spectral type of the companion, nature of the compact object, etc. Not only they are of interest because of the extreme, high-energy physics of accretion-ejection they display, they also are of key importance in the scope of stellar evolution. It is likely that most massive stars spend at least part of their lives in binaries, and by the end of their lives some could be the progenitors of compact mergers now seen by LIGO/Virgo (and later by LISA).

Gaia has been surveying the whole sky to produce a huge astrometrical database that allow us to precisely locate sources within the Milky Way, and may help to understand the role of HMXBs in the Galactic ecology. It is high time we have an updated view of the population of X-ray binaries in our Galaxy in a modern, community-driven database. This HMXB catalogue (Fortin et al. 2023), available online*, is designed to be a starting base for population studies and and tool to help with targeting the right HMXBs to revisit in observing time proposals. I will present the catalogue in Section 2, then review how it has already been used to valorize astrometric data from Gaia by probing the past history of those HMXBs, inferring their natal kick (Section 3) and finding their birthplace in the Milky Way (Section 4).

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*`https://binary-revolution.github.io/HMXBwebcat/`

2 The catalogue of HMXBs in the Galaxy from the INTEGRAL to the Gaia era

The latest catalogue dedicated to Galactic HMXBs was compiled by Liu et al. (2006), a few years after the launch of the *INTEGRAL* satellite. Back then, the census counted 114 HMXBs and candidates in the Milky Way. However, *INTEGRAL* was particularly adapted to the observation of HMXBs and even discovered a new subclass, the obscured sgHMXBs, thanks to its sensitivity in hard X-rays. Hence, in the past 17 years, *INTEGRAL* has triggered many multi-wavelength followup campaigns to identify hard X-ray sources and constrain their nature (Fortin et al. 2018).

All of this observational knowledge, produced by independent teams of researchers over many years, is not easy to collect together in a coherent and updated database because of the many new systems discovered each year and new constraints brought on their nature and intrinsic parameters (orbital period, companion spectral type, presence of pulsations...). It is necessary to have an accurate picture of the current population of X-ray binaries if we want to be able to link them to the growing population of compact binaries, and bring constraints to the evolutionary mechanisms that govern the life of massive stars.

2.1 Building an updated database

For this work, we have extensively used the services of the Centre de Données Astronomiques de Strasbourg (CDS), mainly Simbad and Vizier. First, we retrieved the last HMXB catalogue from Liu et al. (2006), that we supplemented by adding hard X-ray sources detected by INTEGRAL (Bird et al. 2016). We crossmatched the two catalogues, and at this stage kept all INTEGRAL sources labelled either HMXB, LMXB or CV since misidentification is common.

Then, we queried Simbad for all sources labelled "HXB", and performed a spatial selection on the plane of the sky to discard extragalactic sources (which are densely clustered in their host galaxies, contrary to Galactic HMXBs which are mainly spread whithin the Galactic plane). After crossmatching the Simbad HMXBs with the sample from Liu et al. (2006) and Bird et al. (2016), we added 66 new candidates to review.

At this point, we performed an individual, minute search in the literature for each source to retrieve the original references for already published data on their parameters, find out if anything new was publised since the last catalogues and confirm they are indeed HMXBs. For this, we queried NASA's ADS using a combination of a variety of keywords. This process is quite lengthy but necessary to ensure the quality of the data presented in the catalogue and have a proper track of references for each listed parameter.

Finally, we performed a semi-automatic search for counterparts of each HMXB at various wavelengths, including the detections from Gaia EDR3 in order to also retrieve a distance estimation whevever possible. This allows us to precisely locate HMXBs whithin the Galaxy, as shown in Figure 1 (left panel).

2.2 Contents of the catalogue and availability

At the time of publication, the finished catalogue counted 153 HMXBs in the Milky Way (Fortin et al. 2023). That was a 33% increase compared to the sample in Liu et al. (2006), or a 100% increase if we limit to the confirmed systems (hard X-ray detection and early spectral type confirmed for the optical counterpart). 111 HMXBs had a Gaia counterpart, which offer an unprecendented opportunity to precisely locate them whithin the Milky Way. We compiled astrometric information, orbital data, spectral types and spin periods, which allows us to draw the most up to date picture of the Galactic HMXB population.

The catalogue is hosted at the CDS in a fixed version; but in order to take into account new discoveries (or correct the few mistakes that are unavoidable on such a large, manually built database), we host the catalogue on an independent website, HMXBwebcat[†]. The database itself is hosted on our GitHub collaboration, and is able to receive updates from the community as new observations are performed. This is why, at the time of writing, the catalogue now counts 159 HMXBs and the numbers keep steadily growing. New versions of the catalogue are published regularly, with a track reccord of each modifications to ensure continuity. The database can be browsed directly in a navigator, or downloaded in various formats to be explored (we recommend Topcat).

[†] `https://binary-revolution.github.io/HMXBwebcat/index.html`

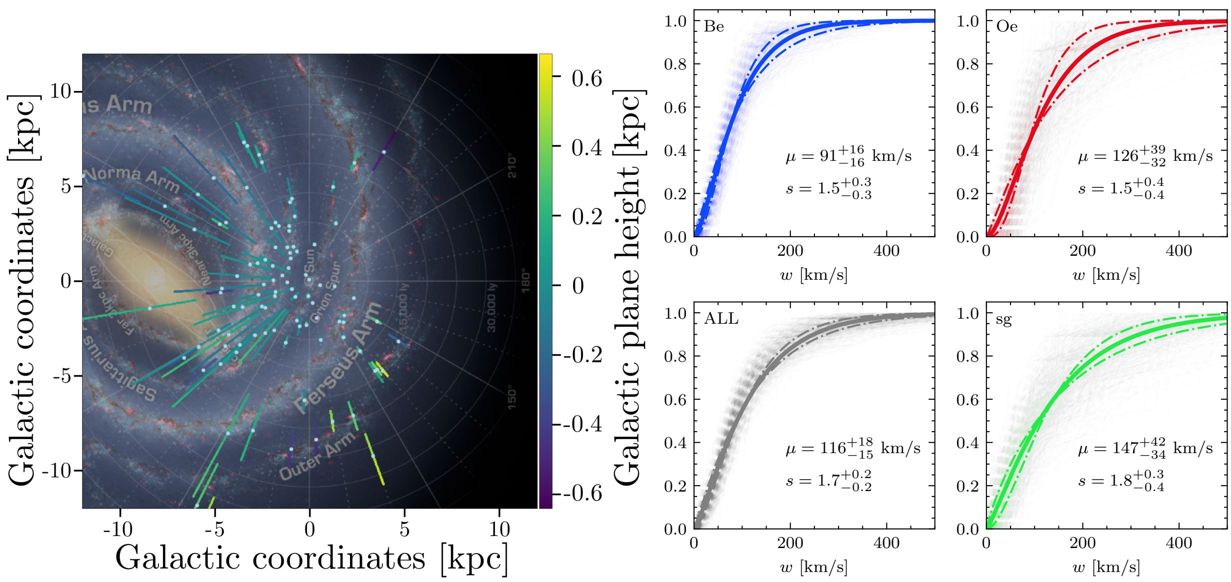

Fig. 1. Left: Face-on view of the Galactic HMXBs seen by Gaia Right: Cumulative distribution of neutron star kicks in Galactic HMXBs.

3 Constraints to neutron star kicks in HMXBs

All the HMXBs present in the catalogue contain a compact object, and most of them are NSs. Hence, most of HMXBs, prior to their X-ray phase, underwent a supernova event. Not only the explosion induces a sudden mass loss that affects the orbit of the binary, the supernova may happen with a certain degree of asymetry, kicking the center of mass in a random direction and adding to the eccentricity of the system. Because we have compiled intrinsic parameters such as orbital periods, eccentricities and stellar masses in HMXBs, and retrieved astrometric measurements from Gaia, it is possible to observe the effects of this natal kick in HMXBs and thus allow us to estimate the strength of the supernova explosion and its effect on the binaries.

The information on the natal kick is indeed contained within the peculiar velocity of HMXBs, which is the proper motion corrected for the Galactic co-rotation velocity. Hence, we can compute the peculiar velocity of HMXBs on the condition of them having a precise distance determination from Gaia data (Bailer-Jones et al. 2021) as well as having an independent radial velocity measurement. The peculiar velocity is used as an input the the equations that describe the effects of an asymetric supernova explosion on the center of mass of a binary system (Brandt & Podsiadlowski 1995; Kalogera 1996). Using Monte-Carlo Markov-Chain simulations, we can compute the posterior probability of the natal kick strength in each of the neutron stars of our HMXB sample. Because a complete set of orbital parameters, masses and astrometry of high quality are necessary, we were able to perform this on 35 Galactic HMXBs.

On top of deriving the kick strength for each system, we agregated those results to get average kick distributions across sub-types of HMXBs, namely the BeHMXBs, OeHMXBs (slightly more massive than Be) and sgHMXBs (Figure 1, right panel).

4 Finding the birthplace of HMXBs in the Milky Way

For the few HMXBs that have exquisite astrometry and radial velocity measurements, it is possible to look even further back in time to search for their birthplace in the Milky Way. Not only this would provide an estimation of their age, this can also give an estimation of the initial masses of the stars whithin the binaries, which is of prime importance to understand what is the population of star that are the progenitors of HMXBs.

We are looking for birthplaces in the Galactic spiral arms as well as the open clusters in the Galaxy. Recent publications, also using Gaia EDR3 astrometry, bring very good constraints on the shape, pitch angle and rotation velocity of the spiral arms (Castro-Ginard et al. 2021), and the precise location of 2000 open clusters whithin the Milky Way (Cantat-Gaudin et al. 2018). To find birthplace candidates, we integrate the motion of the HMXBs, clusters and spiral arms 100 Myr back in time and look for spatio-temporal coincidences.

When a coincidence is found, the time at which it happened provides an estimation of the time since supernova. In the case of a candidate birthplace in a cluster, since we have access to the age of the cluster via isochrone fitting, we can assume the binary formed at the same time as the cluster and thus have access to the full age of the binary. Combined with the knowledge of the time since supernova, and currently measured mass of the companion star, we can infer the initial masses of the two stars, the mass gained by the companion during the initial mass transfer as well as the pre-supernova mass of the primary star.

5 Conclusion

The building of an up to date catalogue of Galactic HMXBs lead to getting an accurate view of their population, and is a tool that can be used in various ways to explore the history and ecology of X-ray binaries in the Milky Way. Combined with recent astrometric data from Gaia, we can constrain the evolution of massive binaries from their formation (Fortin et al. 2022a) up to the supernova event that preceeds the X-ray phase (Fortin et al. 2022b). Multiple other evolutionary mechanisms punctuate the life of massive stars in binaries, e.g. the common envelope event, and are of prime importance to understand how massive stars reaching the endpoint of their lives coalesce as double compact systems.

Gaia is thus a precious tool for Galactic archeology. HMXBs, that involve massive stars right at their birth as binaries, are contributors to the Galactic ecology as they may impact their environement throughout multiple phases of their lives, either via intense stellar winds, jets, X-rays, supernova explosion as well as kilonova ejecta, that feeds the interstellar medium with heavy elements from the r-process.

The authors were supported by the LabEx UnivEarthS, Interface project I10, "From evolution of binaries to merging of compact objects" and Interface project "Binary rEvolution". The authors would like to thank Thierry Foglizzo, Jérôme Guillet and Thomas Tauris for fruitful discussions. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/Gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/Gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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