PROCEEDINGS OF SCIENCE

Taxonomy of High Mass X-ray binaries from a historical perspective

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High-mass X-ray binaries serve as important laboratories for studying a broad range of fundamental astrophysical questions. These systems host two distinct types of astrophysical objects at different stages of stellar evolution, a massive donor star and a compact object. I will explore how our understanding of these systems has evolved over the past 50 years, from the dawn of the X-ray astronomy era to the present day. Along this historical journey, I will introduce the various classes and sub-classes of high-mass X-ray binaries and highlight their key observational characteristics.

87th Fujihara Seminar: The 50th Anniversary Workshop of the Disk Instability Model in Compact Binary Stars (DIM50TH2025)
22-26 September 2025
Tomakomai, Japan

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[*] Speaker

PoS(DIM50th2025)023

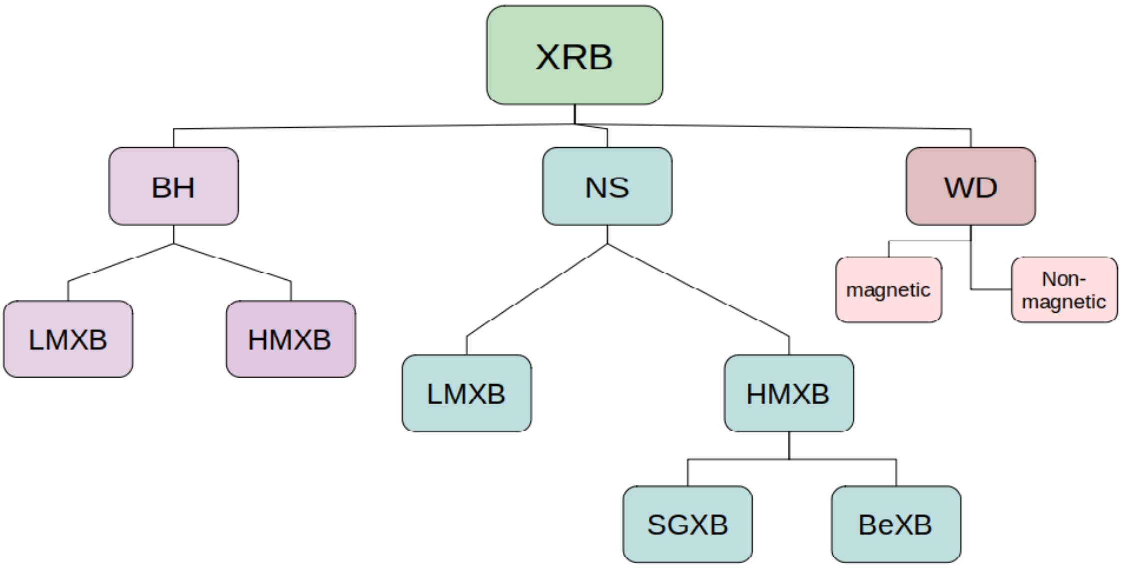

Figure 1: X-ray binaries classification.

1. Introduction

X-ray binaries consist of a compact object orbiting around a “normal” star. They are "close" binary systems because there exists a transfer of mass from the optical component to the compact object. By "normal" star, it is understood that nuclear burning is still taking place in its interior, i.e., it is a star in the process of evolution. The compact object can be a black hole, a neutron star, or a white dwarf; hence, we refer to them as black-hole binaries (BHBs), neutron star binaries (NSBs), or cataclysmic variables (CVs), respectively. The spectral type of the optical star defines whether the system is a low-mass X-ray binary (LMXB) or a high-mass X-ray binary (HMXB). In LMXBs, the spectral type of the optical companion is typically later than A, while in HMXBs is an early-type B or late-type O star. In HMXBs, the mass of the companion is typically larger than ~ 8 $M_\odot$ and the class includes a few BHBs (only one confirmed: Cyg X–1 and two strong candidates: Cyg X–3, and SS 433) and about half of the NSBs. LMXBs, with the mass of the companion below ~ 2 $M_\odot$ include the majority of BHBs and half of the NSBs. CVs contain low-mass companions and are normally considered a different class. The luminosity class of the massive companion divides NS-HMXBs into supergiant X-ray binaries (SGXBs) and Be/X-ray binaries (BeXBs). In SGXBs, the massive star is a luminous evolved supergiant, while in BeXBs, it is a dwarf, subgiant, or giant Be star. Figure 1 depicts a tree diagram illustrating the different types of X-ray binaries. This work is focused on NS-HMXBs.

The importance of HMXBs stems from their role as exceptional laboratories for studying a wide range of astrophysical phenomena. Due to their young ages, HMXBs serve as tracers of recent star formation activity [e.g., 20, 27]. As a population, they provide valuable insights into the properties of galaxies [e.g., 17]. The massive companion stars offer critical constraints on stellar mass loss through winds, a key factor in stellar evolution models [e.g., 19]. Furthermore, BeXBs enable detailed investigations of the Be phenomenon, including the formation and variability of circumstellar disks [4, 38]. The compact objects in HMXBs are powerful X-ray emitters, allowing us to probe physical processes under extreme conditions: strong gravitational fields in BHBs and NSBs, and intense magnetic fields in NSBs. These systems facilitate long-term studies of accretion dynamics and accretion disk physics [30, 48]. Additionally, HMXBs allow for precise measurements of neutron star masses, providing crucial constraints on the nuclear equation of state [34, 47]. As close binary systems, HMXBs represent a vital evolutionary stage in massive binary stars, offering insights into the formation channels of neutron stars and black holes [e.g., 46]. Moreover, they are considered likely progenitors of short gamma-ray bursts and sources of gravitational waves [23, 31, 39].

In this work, we present a general overview of the taxonomy, historical development, and observational properties of HMXBs, synthesizing key findings from the literature.

2. The 1960s: the beginning

We start our journey back in the early 1960s when the first X-ray source of extrasolar origin was discovered. This result was reported in a paper published by Giacconi and collaborators in 1962:

- "*It is clear that the observed source does not coincide with any obvious scattering body belonging to our solar system*" [12].

The source was detected relatively close to the galactic center in the Scorpio region. Owing to the poor angular resolution of the detector, an association with the galactic center could not be determined. However, new observations performed soon after ruled out a physical connection with the galactic center and confirmed the origin to be a point source in the Scorpio region:

- "*A strong source was observed centered about the direction R.A. 16 h 10 m and Dec.* $-18°$ *in the general proximity of ν Scorpii. Assuming all the emission to be concentrated at about 5 Å, the computed flux is about* 1.5×10^{-7} *erg cm*$^{-2}$ *s*$^{-1}$" [2].
- "*We have observed two separate and intense sources of cosmic X-rays in the region of the constellations Scorpius and Sagittarius during a rocket experiment launched on August 28, 1964.*" [13].

This source was named Scorpio X-1 (Sco X-1). A few years later, Centaurus X-3 (Cen X-3) was discovered, first as an X-ray source [6] and then as an X-ray pulsar:

- "*In the 150-s exposure several peaks and valleys occur with great regularity, immediately suggesting a periodic phenomenon... The period of the fundamental frequency resulting from this fit is* 4.832 ± 0.004 *s.*" [15].

New sources were quickly discovered and by April 1968, about 30 X-ray sources were known. Most of them were considered to belong to our Galaxy, but a few were found at high galactic latitudes and were suggested to be associated with external galaixies [14]. A new window in the electromagnetic spectrum had opened and the main debate at that time was to find an explanation to the origin of the X rays:

- "*An important question which must be answered about the recently discovered stellar x-ray sources is the nature of the emission spectrum of these sources.*" [7]
- "*No generally accepted model exist for any of the X-ray sources, which is, in part, a reflection of the relative crudeness of the X-ray measurements. The two physical mechanisms that seem to be capable of providing the X-ray emission are the synchrotron radiation from ultrarelativistic electrons gyrating in a magnetic field and the thermal radiation from an extremely hot plasma.*" [14].

One process that was recognized from the very beginning as capable of powering X-ray emission is accretion. As early as 1967, [40] proposed that an accreting neutron star serves as the source of X-rays from Sco X-1:

- "*If the identification of the optical object similar to an old nova with the X-ray source is correct, then the natural and very efficient supply of gas for such a accretion is a stream of gas, which flows from a secondary component of a close binary system toward the primary component which is a neutron star...The flux of gas in the stream is estimated as* $10^{16} - 10^{17}$ *gm/sec* ($\sim 10^{-9}$ $M_\odot$*/year). When this gas falls on the neutron star the production of energy per unit mass may amount to* $\sim 10^{20}$ *ergs/gm. Thus it follows that the suggested modification of the mechanism of the accretion of gas on the neutron star gives the possibility of explaining the power of X-ray emission of the source Sco X-1.*" [40].

The crucial words in the [40] extract are without a doubt *close binary system*. For accretion to occur, an accreting object must be present (in this case a neutron star), but there must be a source of matter. Such a source arises naturally in a binary system.

3. The 1970s: the binary model

In the early 1970s, it was not yet conclusively established that Galactic X-ray sources were binary systems, although the hypothesis was widely spread within the astrophysical community.

- "*At the time of writing (February-March 1972), the bandwagon, associated with the idea that many if not most of the powerful galactic X-ray sources are generated in binary star systems containing at least one exotic object together with gas, is gaining momentum.*" [3].

Three different types of systems were identified:

- "*The primary can either be a white dwarf, neutron star, or black hole.*" [3].

Soon, the binary model consolidated:

- "*...reflects the preponderance of binaries among all of the galactic X-ray sources. In fact, it can be argued that all the X-ray sources are binaries.*" [21]

People realized that that there were binaries with high and low-mass companions:

- "*One group of sources is associated with a very particular kind of stars — a late O or early B supergiant, a star which is very massive and very luminous... Other X-ray sources are clearly not associated with O-B stars, but rather with a much later spectral type stars — stars like the Sun in temperature, luminosity and mass.*" [21]

Among the HMXBs, two different types were identified depending on whether the massive companion is an evolved star (i.e supergiant) or a star still in the main sequence branch (BeXBs). Because of their brightness and persistent X-ray emission, SGXBs were the first to be discovered. They were initially thought to represent the dominating population of HMXBs, whereas BeXBs were considered atypical cases. Hence, the name classical or standard was given to SGXBs. BeXBs, however, were the best candidates for transient X-ray behavior:

- "*We propose that sudden variations in the rate of mass ejection from Be stars in the presence of a compact companion could produce transient X-ray emission, which might recur over a period of years, like the observed optical emission of Be stars. The companion star should be a neutron star, rather than a white dwarf, because the spectrum of the transients is rather hard (a = 1.0 for pulsating sources, and 2-4 for the others) and the luminosity rather high ($\sim 10^{37}$ erg s^{-1}). The total amount of accreted matter required for an outburst is, for a neutron star, $\Delta M \sim 10^{23}$ g, which is only a few per cent of the amount of mass in the envelopes of Be stars required for producing the observed emission lines.*" [28].

A key advance of this decade has been the establishment that the compact objects in HMXBs are strongly magnetized neutron stars, and that these systems host intense magnetic fields. These magnetic fields manifest in two primary ways: through coherent X-ray pulsations and cyclotron resonance scattering features (CRSF or simply cyclotron lines):

- "*An alternative and more likely picture for producing the pulsations requires the funnelling of matter along the magnetic field lines to the surface of the neutron star, where the released gravitational potential energy heats a small area on the surface (~1 km^2) to extremely high temperatures ($\sim 10^8$ K). As the neutron star rotates about its axis (which is presumably not aligned with the magnetic axis), a distant observer will pass over a range of magnetic coordinates and will thereby observe a corresponding X-ray pulse structure.*" [35].

HMXBs also display cyclotron lines. The first cyclotron line was discovered in Hercules X-1 (Her X-1), which although it is not a HMXB, it deserves the credit:

- "*We present further results of our Hercules X-1 balloon observation on 1976 May 3 which confirm the existence of a strong line feature at ~58 keV ... The most likely interpretation of this line is electron cyclotron emission at the basic frequency from the hot polar plasma of the rotating neutron star. The corresponding magnetic field strength is 5.3×10^{12} gauss.*" [45].

We now understand that virtually all HMXBs are X-ray pulsars, exhibiting pulse periods ranging from a few seconds to several thousand seconds. Many of these systems also display cyclotron lines in their X-ray spectra. Lines detected in the energy range of 10–80 keV correspond to magnetic field strengths on the order of $(1 - 10) \times 10^{12}$ G [43].

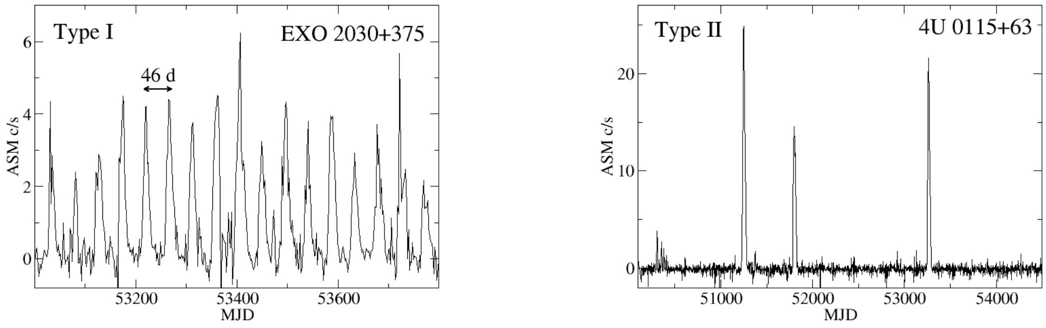

Figure 2: Type I and type II outbursts in BeXBs.

4. The 1980s: mass transfer mechanisms

At the beginning of the 1980s, the prevailing understanding was that that HMXBs comprised two principal classes, namely, SGXBs which are persistent sources and BeXBs which are transient sources:

- "*The BeXB are found to be systematically wider systems, with lower-mass primaries, and with significantly transient behaviour than the standard massive X-ray binaries such as Cen X-3 and SMC X-1.*" [36].

In BeXBs, the optical companion is a Be star. The defining observational characteristics of Be stars include emission lines — most notably in the Balmer series — an infrared excess (i.e., an increase in flux at longer wavelengths), and a small degree of linear polarization (typically $\lesssim$4%). These features are attributed to the presence of a circumstellar disk orbiting the star around its equatorial plane. This disk forms from material ejected from the stellar photosphere and evolves on timescales of years: it can form, grow, and dissipate over time. When the disk is absent, the emission lines revert to absorption, the infrared excess disappears, and no polarization is detected. The long-term X-ray variability of BeXBs is described by two types of transient activity or outbursts:

- "*Class I, periodic transient activity. —- Transient outbursts that recur periodically and have* $L_X(\mathrm{max})/\mathrm{L}_X(\mathrm{min}) \sim 100$*... the neutron star is typically in a moderately eccentric orbit and that the outbursts occur close to the time of periastron passage. This suggests enhanced accretion caused by the closer proximity of the neutron star to the Be star companion.*"
- "*Class II, irregular transient activity. — Transient outbursts that typically last several tens of days and involve an increase in luminosity in excess of a factor of 100–1000. The timing of these outbursts is unrelated to any underlying orbital period.*" [44].

Figure 2 shows two typical examples of these type of outbursts. As more sources were discovered, SGXBs were further divided into low-luminosity (10^{36} erg s^{-1}) and high-luminosity (10^{36} erg s^{-1}) sources.

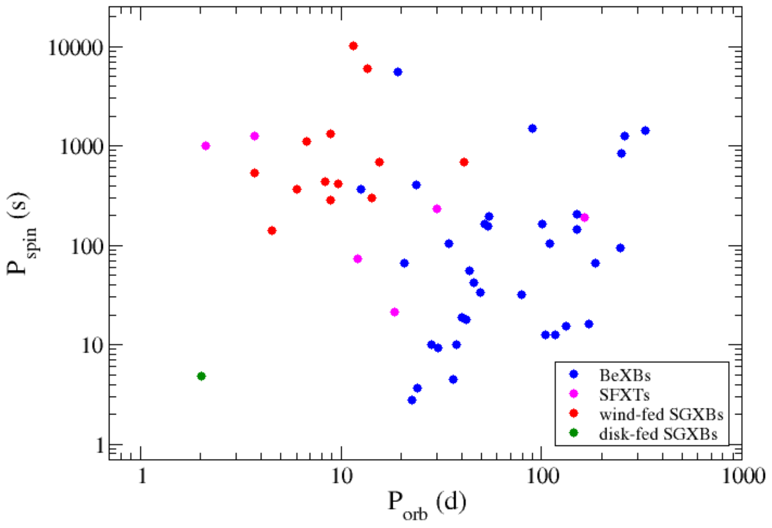

Figure 3: Updated version of the pulse period–orbital period diagram of Galactic HMXBs.

A major breakthrough in the understanding of HMXBs was the recognition that the distinct subclasses correspond to fundamentally different modes of mass transfer.

- "*A natural way of accounting for the separation of high-mass pulsators into three groups is by invoking different mass-transfer processes for the groups. These are, respectively, (i) – accretion from the circumstellar envelope of a Be star, (ii) – accretion from the strong wind of an early-type supergiant, and (iii) – Roche lobe overflow*" [8].

Interestingly, these three subtypes of HMXBs occupy different regions in a diagram where the pulse period is represented as a function of the orbital period.

- "*When segregated this way .... these classes appear to cluster in different regions of the* P_{spin} *versus* P_{orb} *diagram.*" [8].

Figure 3 shows an updated version of this diagram. BeXBs are located in a diagonal branch (blue circles), wind-fed SGXBs populate a horizontal branch in the upper left part of the diagram (pink and red circles), and disk-fed SGXB the lower left part (green circle).

5. The 1990s: the discovery of persistent BeXBs

Our knowledge of HMXBs by the end of the 1980s is summarized in Table 1. In particular, BeXBs appeared to be transient and moderately eccentric systems:

- "*The most notable feature of the Be X-ray binaries is that they are very often bright transient sources... Pulsations are usually detected, many (but not all) with periods around a few*

Table 1: Observational properties of HMXBs as known by the end of the 1980s

Type	Donor star	Compact object	Mass transfer	$P_{\rm orb}$ (days)	$P_{\rm spin}$ (seconds)	L_X erg/s	Variability
BeXBs	Be star III-V	Neutron star	Disk-fed (decretion*)	10–100	10-100	10^{37}	Transient
SGXBs Low L_X	O-B supergiant I-II	Neutron star	wind-fed	4-10	100-1000	10^{36}	Persistent
SGXBs High L_X	O-B supergiant I-II	Neutron star	disk-fed (accretion)	1-4	1-10	10^{38}	Persistent

* The term "decretion disk" in the context of Be stars appears to have been formally introduced in the early 1990s.

seconds. Doppler variations in the pulse period give orbital periods of a few tens of days, with a moderate eccentricity (e ~ 0.3*).*" [49]

Thanks to the improvement of the sensitivity of the X-ray detectors, *ROSAT* and *RXTE* uncovered a new type of BeXBs characterized by persistent X-ray emission:

- "*It therefore seems that we now have a growing subclass of BeXRBs, characterized by persistent, low-luminosity X-ray emission and slowly rotating pulsars. A possible model fo these systems is that of a neutron star orbiting a Be star in a relatively wide orbit, accreting material from only the low-density outer regions of the circumstellar envelope.*" [37].

with the following properties: (i) long pulse periods, (ii) persistent, low-luminosity (10^{34} – 10^{35} erg s^{-1}) X-ray emission; (iii) low cut-off energy, $E_{\rm cut} < 4$–5 keV ; (iv) absent or very weak iron line at 6.4 keV, indicative of only small amounts of material in the vicinity of the neutron star; (v) low X-ray variability: flat light curves with rare and unpredictable increases in flux by a factor of < 10; (vi) no dependence of the X-ray spectrum on intensity. The prototype of persistent BeXBs is X Persei (X Per). Figure 4 shows its long-term X-ray light curve.

6. The 2000s: the discovery of new subtypes of HMXBs

The 2000s represent a golden decade in the study of HMXBs in terms of the number of new sources detected for the first time and the discovery of low eccentricity BeXBs and transient SGXBs. Prior to the launch of the *INTEGRAL* mission in October 2002, the population of BeXBs was increasing rapidly, whereas the number of SGXBs had reached a steady level. Throughout the 1980s and 1990s, the discovery rate of new systems was approximately four to one in favor of BeXBs. This disparity can be attributed to the sensitivity of the detectors and the different nature of the X-ray emission: since SGXBs are persistent emitters, further discoveries primarily resulted from improvements in the sensitivity of X-ray detectors aboard space missions. Although BeXBs also benefited from these technological advancements, their detection additionally depended on the episodic activation of their transient outbursts.

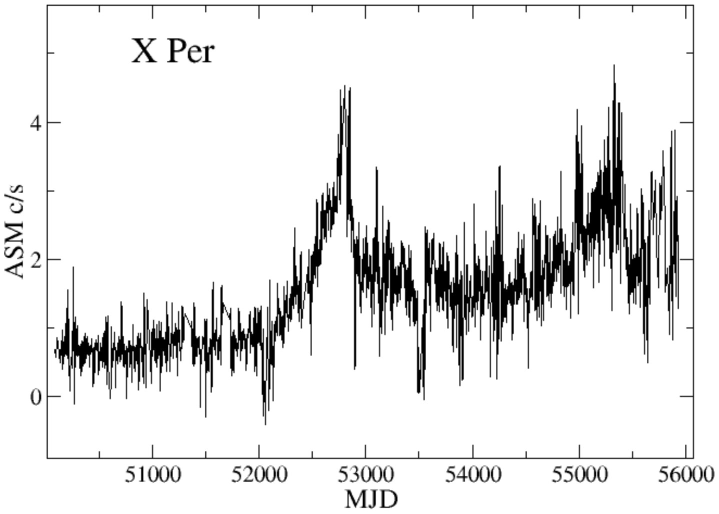

Figure 4: Long-term X-ray variability of X Per.

As pointed out above, the orbit in the vast majority of BeXBs was rather eccentric ($e > 0.3$). This eccentricity results from a large kick during the supernova explosion that leads to the formation of the NS. Thus, it was surprising to discover systems with nearly circular orbits:

- "*...a new observed class of HMXBs with orbits that are distinguished by relatively long periods (*$P_{\rm orb} \sim 30 - 250$ *days) and low eccentricities (*$e < 0.2$*). Members of this new class of HMXBs contain NSs that almost certainly received a fairly small kick (*< 50 *km s*$^{-1}$*) at the time of formation.*" [32].

The explanation for such low orbital eccentricities lies in the dependence of the natal kick imparted to the neutron star on the rotation rate of its progenitor's core following mass transfer. According to [32], rapidly rotating pre-collapse cores produce NSs with small kicks, whereas slowly rotating cores result in larger kicks. If the progenitor's envelope is stripped before deep convection develops, the exposed core retains rapid rotation; conversely, if mass transfer occurs after significant evolution, magnetic torques between the convective envelope and the core can spin down the core to very low rotation rates.

Another relevant result of this decade was the identification of a new subclass of BeXBs was proposed. Although the prototype of this class, γ Cas, had long been well studied, particularly in the ultraviolet and optical bands, it also exhibits X-rays emission. The realization that γ Cas was not an isolated case, but instead representative of an entire new subclass, emerged when several newly discovered X-ray sources were found to share key properties with γ Cas.

- "*It is now clear that the ... γ Cas puzzle is no longer an unique case, ... They constitute a new and well-defined class of X-ray emitters that is characterised by: [1] a hard X-ray emission* *that is very likely thermal and dominated by a component with* $7 < \mathrm{kT(keV)} < 13$*, [2] a variable behaviour, [3] a moderate 0.2–12 keV luminosity* ($32 < \log L_X(\mathrm{ergs}^{-1}) < 33$)*, and from their optical properties, by [4] a large and probably stable circumstellar disc.*" [26].

These systems were designated γ Cas analogues. While their optical properties are consistent with those of BeXBs, their X-ray properties differ significantly. The optical companion in both BeXBs and γ Cas analogues are late-type O or early-type B III-V stars. They both exhibit long-term optical spectral variability, especially in the Hα equivalent width, that can be attributed to the Be star's circumstellar disk.

In contrast, their X-ray emission is predominantly thermal. Indeed, about 90% of the X-ray spectrum of γ Cas in the energy range 1–100 keV can be fitted with a purely thermal plasma component at $\sim$ 15 keV (see Fig. 5 in [41]). The X-ray spectra of BeXBs is clearly non-thermal, characterized by a power law and a high-energy cut off, indicative of Comptonization. Moreover, the X-ray luminosity of γ Cas analogues is significantly lower than BeXBs. Typical luminosities in γ Cas binaries fall in the range $10^{32} - 10^{33}$ erg s^{-1}, compared to $10^{34} - 10^{35}$ erg s^{-1} for persistent BeXBs, $10^{36} - 10^{37}$ erg s^{-1} during type I outbursts, and $10^{37} - 10^{38}$ erg s^{-1} during type II outbursts. Another difference is that among γ Cas binaries, no X-ray pulsars have been found.

Three different scenarios have been put forward to explain the X-ray emission from γ Cas analogues: the magnetic model states that X-rays a produced from the interaction of the small-scale magnetic field of the Be star and the magnetic field in the disk. Rapid stellar rotation drives magnetic reconnection events, accelerating electrons that subsequently produce X-ray emission [42]; the second scenario involves accretion onto a white dwarf or a NS in the propeller regime [16, 33]; the third possibility is that X-rays arise from shocks produced by collision between the disk material and the wind of a hot subdwarf or He-rich companion star [24].

The 2000s also witnessed the discovery of transient SGXBs. Up until the launch of *INTEGRAL*, our understanding was that SGXBs were persistent X-ray sources. However, *INTEGRAL* uncovered a new class of X-ray sources with supergiant companions transient X-ray emission:

- "*These outbursts are very short (lasting from ~3 to ~ 8 hours) and present very sharp rises, reaching the peak of the flare in < 1 h.... We therefore propose that all these objects form a class of HMXBs which we call Supergiant Fast X-ray Transients (SFXTs), because of the fast outbursts and super giant companions. They differ from classical wind-fed SGXBs, whose X-ray luminosity is variable but always detectable around* $L_X \sim 10^{36}$ *erg s*$^{-1}$*.*" [29].

The main observational characteristics of SFXTs are: (i) short outbursts, lasting hours to days compared to weeks or months in transient BeXBs; (ii) often show an asymmetric profile with a fast rise, followed by an exponential decay: the rise time is typically minutes to hours, whereas the decay times is hours to days. Some systems exhibit a multiple peaks profile within a single outburst; (iii) low duty cycle: SFXTs spend less than 5% of their time in high-luminosity flaring states; (iv) high dynamic range: the ratio between maximum and minimum X-ray luminosity is $\gtrsim$100, although some extreme cases display up four orders of magnitude difference in luminosity during flares; low time-averaged luminosity ($L_X \lesssim 10^{34}$ erg s^{-1}), often undetectable in quiescence and only visible during bright flaring events.

SFXTs tend to occupy the same region in the $P_{\rm spin} - P_{\rm orb}$ diagram as the wind-fed SGXBs. However, as can be seen in Fig. 3, some SFXTs lie at intermediate position between BeXBs and wind-fed SGXBs or even fall on top of the BeXBs region (IGR J11215-5952). Moreover, the long-term X-ray variability of IGR J17391–3021 is reminicent of BeXBs type I outbursts [see Fig.2 in 9]. These similarities open the possibility that SFXTs may be the descendants of BeXBs [25].

7. The 2010s: new discoveries

Thanks to the new generation of γ-ray detectors, especially from the mid-2000s onwards, a new class of HMXBs has emerged. They are called Be/γ-ray binaries because most of their radiated power is emitted beyond 1 MeV:

- "*The five binaries detected in VHE gamma rays form a new class of systems, gamma-ray binaries, distinguished by emitting most powerfully beyond 1 MeV and by having a O or Be massive star companion.*" [10].

The main observational properties of Be/γ-ray binaries are: (i) modest X-rays but strong γ-ray emission (> 1 MeV); (ii) massive stellar companion: the optical counterpart is either a luminous O-type star (LS 5039), a Be star (LS I +61 303, PSR B1259-63, HESS J0632+057) or a likely Wolf-Rayet star (Cygnus X-3); (iii) radio emission, in contrast to BeXBs which are radio quiet sources; (iv) orbital modulation at all wavelengths, from radio to γ rays. The NS in these systems is supposed to be recently formed, hence it is rotating very fast and ejecting a strong pulsar wind:

- "*What makes them so bright in gamma rays? The prevailing idea is that gamma-ray non-thermal emission is due to particles accelerated at the shock between the wind of the massive star and the wind of a pulsar. Hence, gamma-ray emission is ultimately powered by the spin-down of a rotating neutron star with a strong magnetic field* $\sim 10^{11} - 10^{13}$ *G. They are pulsar wind nebulae in a binary environment.*" [10].

Another intrguing unresolved observational puzzle of this decade is the lack of Be star binaries with BHs. By 2009, not a single BeXB with a black hole as the compact object had been discovered. However, there seemed to be no apparent mechanism that would prevent the formation or detection of Be stars with BHs. According to evolutionary scenarios, the ratio of binaries with NSs to the ones with BHs was estimated to be as high as ~ 50. In this case, the non detection of Be-BH systems would be simply a question of small number statistics:

- "*...we know 64 BeXRBs in the Galaxy, but only 42 of these systems are known to host an NS. None of the observed BeXRBs hosts a BH....We predict that both populations of BeXRBs should exist in the Galaxy...If we use the preferred evolutionary models (*$F_{\rm NStoBH} \sim 30{-}50$*...we predict that in the observed sample of BeXRBs of 42 systems with NSs, one should expect only* $\sim 0-2$ *systems with BHs. It is quite possible that none are yet observed (small statistics).*" [1].

However, the number of BeXBs was increasing (~ 80 by mid 2010s) and yet no Be-BH binaries was being found. Finally the discovery of a Be-BH binary was reported:

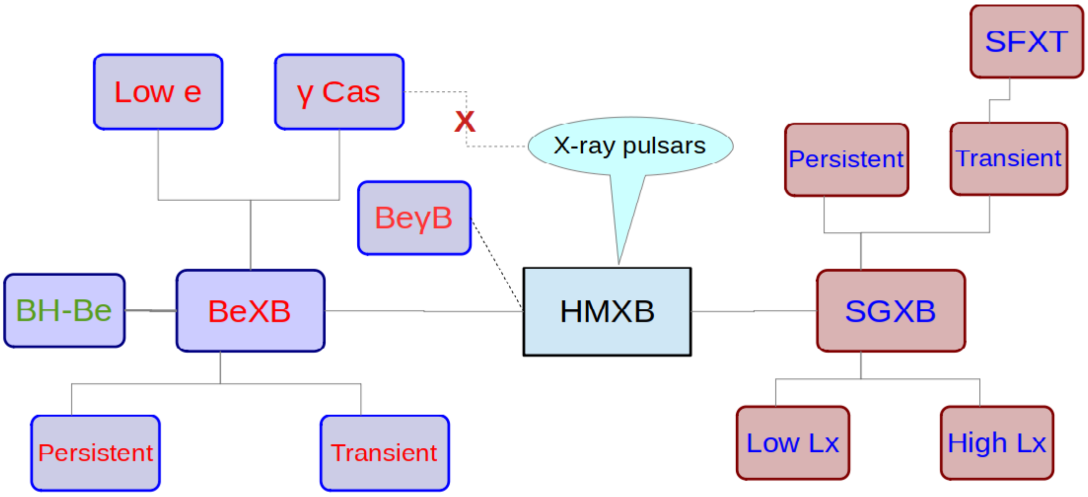

Figure 5: The "zoo" of HMXBs.

- "*MWC 656 (=HD 215227)... Our adopted B1.5–B2 III classification implies a mass of 10–16 solar masses for the Be star, and hence a companion star of 3.8–6.9 solar masses*" [5].

Another BH-HMXB is HD96670, an O8 main-sequence star with a massive secondary component.

- "*HD96670: we model the optical light curve and radial velocity curve simultaneously ... and find a best-fit mass of* $M_1 = 22.7^{+5.2}_{-3.6}$ *solar masses for the primary, and* $M_2 = 6.2^{+0.9}_{-0.7}$ *solar masses for the secondary. An object of this mass is consistent with either a B-type star, or a black hole. Given that we see no absorption lines from the secondary, in combination with an observed hard power-law X-ray spectrum ... that may have been produced by wind accretion onto the secondary, we conclude that the secondary is most likely a black hole.*" [18].

At present, these two systems MWC 656 and HD96670 remain as BH-HMXBs candidates and more observations are needed to better sample the radial velocity curve and to understand the nature of the secondary component. We note that HD96670 is not a OBe star: there is no evidence for a decretion disk. On the contrary, there is some evidence of the presence of a third star in this system. The case of MWC 656 result has been questioned [22].

Figure 5 summarizes the various classes of HMXBs, as they are known today.

8. Conclusions

HMXBs are diverse and fascinating systems offering insight into numerous astrophysical problems, including accretion physics, compact object properties, binary evolution, stellar winds and magnetic interactions to mention just a few. Current estimates set the number of HMXBs in more than 150 systems: about half of them are BeXBs, 34% of SGXBs, and 16% of uncertain classification. Although the most numerous subgroup are BeXBs, the growth in the number of confirmed SGXBs during the last 15 years has been extraordinary, going from 16 systems in 2006 to 52 in 2023 [11].

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