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High-Mass X-ray binary: Classification, Formation, and Evolution

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Abstract. A high mass X-ray binary is a binary system consisting of an accreting neutron star or black hole and an early-type star with more than 10 solar masses. A compact star produces X-ray radiation during the accretion of material from the stellar wind or Roche lobe. High-mass X-ray binaries are ideal places to study dense stars, stellar winds, material exchange between binary stars, and the evolution of massive binary stars. In this review, the observational properties, classification, and evolution of high mass X binaries are described. According to the mass and types of X-ray resources, this review classifies the X-ray binaries and list out their features.

1. Introduction

X-ray astronomy is a branch of astronomy focused on the emission of X-ray of celestial bodies with corresponding wavelength ranging from 0.001 to 100 Å [1]. Because the X-ray emission of these types of objects cannot go through the barrier of the atmosphere, the early research mainly focused on studying the sun. Extrasolar astronomy originated in 1962. Using the X-emission detectors fixed on the rocket, Giacconi and his colleagues found the first X-ray source of the universe [2]. The booming development of X-radiation research benefited from the soaring improvement of space observational technology since the 1970s. The X-ray satellites *Uhuru*, *Einstein*, *Röntgensatellit* (ROSAT), *Advanced Satellite for Cosmology and Astrophysics* (ASCA), *Rossi X-ray Timing Explorer* (RXTE), *BeppoSAX*, *Chandra*, and *X-ray Multi-Mirror-Newton* (XXM-Newton) were successfully emitted, which have greatly promoted the development of X-ray astronomy. The substantial cultivation of data of the astronomy observations largely broadens the horizons and knowledge of the astronomers, which benefits almost every branch of astronomy and directly accelerates the theoretical studies of X-ray astronomy continuously, renewing the investigation on theories that related to X-ray or the radiation mechanism. This review will introduce X-ray binaries, which is an important subject of X-ray astronomy. This paper is organised as follows: Section 2 is about the observation and classification of X-ray binary, the description of high-mass X-ray binary is shown in section3, and the formation and evolution of them are described in Section 4, while the summary is showed in Section 5.

2. The observation and classification of X-ray binaries

In general, an X-ray binary is the brightest source of X-ray emission in the universe, which is composed of a compact star (a white dwarf, neutron star, or black hole) and a component star (a brown dwarf or white dwarf) [1]. Compact stars release the gravitational energy and emit radiation in the X-ray band by absorbing materials transferred from component stars. Utilizing and depending on various X-ray surveys and optical identification, a great number of X-ray binaries within or outside the galaxy have been



discovered. There are more than 400 X-ray binaries found in Milky Way, including Large Magellanic Clouds (LMC), Small Magellanic clouds (SMC) [3-5].

As shown in Figure 1, the tree diagram about the classification of X-ray binary presents different types of X-ray binary sub-systems. When the primary star (or invisible star) is a neutron star or a black hole, the X-ray binary can be divided into low-mass X-ray binaries (LMXBs) and high mass X-ray binaries (HMXBs, with a component star whose mass is lower than one solar mass) according to the mass of their secondary star. When the primary star is a white dwarf, the X-ray system can be classified as many different sub-types based on the difference in observation characteristics. In most situations, they belong to one kind of essential source of X-ray, namely cataclysmic variables (CVs).

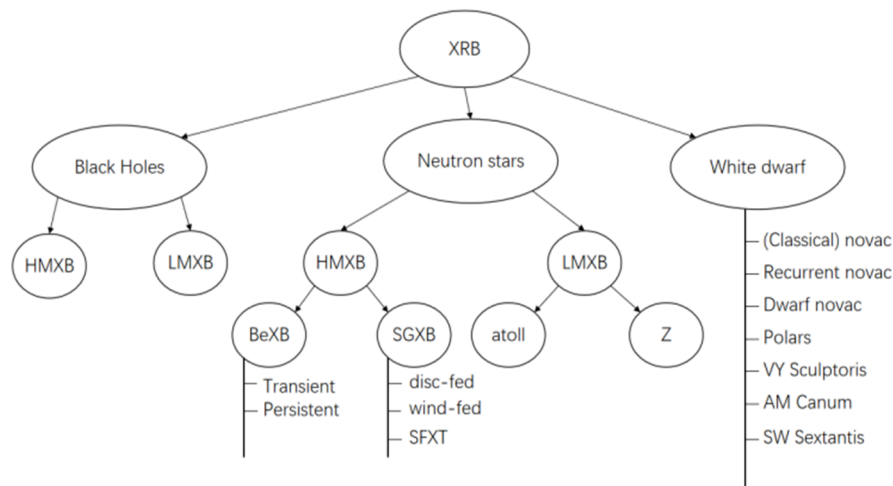


Figure 1. The classification of the X-ray binaries [6].

Meanwhile, there exists another kind of X-ray binaries whose mass of component ranges from 1 to 10 solar mass, and they are named intermediate-mass X-ray binaries (MXBs) [1]. In MXBs, on the one hand, the mass of a secondary star is not big enough to create stellar wind, offering neutron stars with accretion materials. On the other hand, because of the big difference between the mass of the neutron star and that of the secondary star, if the evolution of MXBs is in the phase of Roche Lobe overflow, the unstable material transporting process will happen. In addition, its transmission period lasts only thousands of years which means it's hard to detect. Therefore, we only discuss the observational characteristics of HMXBs and LMXBs, which are illustrated in Figure 2. In the Milky Way, approximately 90% of X-ray sources with strong emission can be classified as LMXBs and HMXBs, which distribute in the space, as shown in Figure 3. The huge difference in the mass of LMXBs and HMXBs results in the diversity of their physical characteristics. Table 1 lists the comparison of the physical and observation characteristics of these two kinds of X-ray binary.

Table 1. The classification of the strong X-ray sources in Galaxy [7].

	HMXBs	LMXBs
X-ray spectra	hard spectrum, $kT \geq 15 \text{ keV}$	Soft spectrum, $kT \leq 10 \text{ keV}$
Type of time variability	X-ray pulses, no X-ray bursts	X-ray bursts but rarely pulses
Accretion process	Stellar winds (or Roche Lobe overflow)	Roche Lobe overflow
The time scale of accretion	10^5 yr	$10^7 \sim 10^9 \text{ yr}$
Accreting compact star	Neutron stars (or black holes) with the strong magnetic field	Neutron stars (or black holes) with the weak magnetic field
Spatial distribution	Galactic plate	Near galactic plate and center
Stellar generation	Young stars, age $\leq 10^7 \text{ yr}$	Old stars, age $\geq 10^9 \text{ yr}$
Optical component star	O(B) stars in the early phase, mass $> 10 M_{\odot}$ ○ brighter, $L_{\text{opt}}/L_X > 1$	Objects in the blue band, mass $< 10 M_{\odot}$ Darker, $L_{\text{opt}}/L_X < 0.1$

3. HMXBs

The component stars of HMXBs are OB stars which are huge and bright, whose life span is determined by the evolutionary time scale of the massive component stars, which usually lasts $10^5 \sim 10^7$ yr [1]. Their distribution is the same as that of newly forming stellar populations, located star-forming regions in the spiral arms and the galactic plane. So far, more than one hundred HMXBs have been observed in Milky Way [4], and such systems are discovered in external galaxies. The companion star's mass is relatively large, with low density around the star, and can produce strong stellar wind. After its material is filled with Roche lobe, it is continuously accreted by the host star, emitting bright X-ray emission (as shown in Figure 2). The companion stars of this kind of source have strong radiation in the optical band. The radiation intensity in the optical band is usually higher than that in the X-ray band. The change of the X-ray luminosity is related to the intensity and change of the stellar wind velocity and the distance between the component star of binaries.

Because the neutron star in a high-mass X-ray binary has not evolved over a long period and only accreted less matter, the neutron star's magnetic field remains in the high-magnetic (10^{12} G) environment at birth [1]. In a strong magnetic field, the accreted material moves along the direction of the magnetic field lines at the star's poles and is ejected as a narrow beam of radiation. The neutron star picks up matter and energy through accretion, which is observed as a pulsar.

According to the difference of observational properties, especially the type of companion, HMXBs can be divided into supergiant X-ray binaries whose secondary star is an OB supergiant (SGXBs) and Be X-ray binaries whose component star is a Be star. The former one accounts for about one third of all the HMXBs which have been discovered in the Milky Way, and the latter constitutes three fifths approximately.

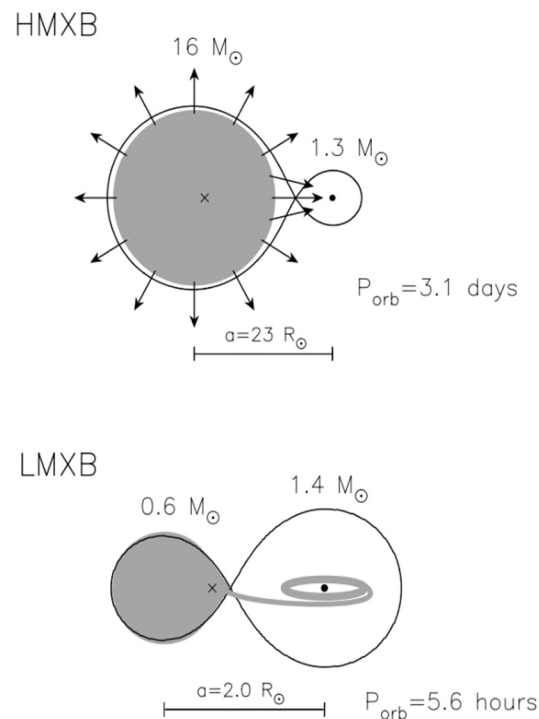


Figure 2. Typical HMXBs and LMXBs with neutron star as the accretion star [7]. As shown is this cartoon, in HMXBs, the accretion matters of neutron stars are offered by strong stellar winds or Roche Lobe overflow that passes through Lagrangian point L_1 , while in LMXBs, neutron stars absorb matters via accretion plate formed by accretion currents of Roche Lobe overflow which passes through Lagrangian point L_1 , too.

"Standard" high-mass X-ray binary star systems, known as SGXB systems, typically have shorter orbital periods of less than 10 days and smaller orbital eccentricity $e < 0.1$, such as Cyg X-1. The OB-type supergiant companion star is in the stage of filling or already filling the Roche lobe, and the material flowing from the companion star orbits outside the dense star in the form of a supersonic stellar wind. The X-ray radiation of a compact star is powered by the material outflow of the companion star's Roche lobe or the stellar wind. These two modes of energy supply show observational differences in X-ray luminosity. Via accrediting stellar winds, SGXBs have constant X-ray radiation, with luminosity ranging $10^{35} \sim 10^{37} \text{ erg s}^{-1}$, while by Roche Lobe overflow, they will present as persistent sources with high luminosity $L_X > 10^{38} \text{ erg s}^{-1}$.

The orbital period of BeXB system whose component stars are Be stars with optical spectral type III-V tends to be longer, varying from dozens of days to several years, and the eccentricity is higher. The amount of BeXB is the biggest among the HMXBs discovered so far [1]. Be stars are namely the B-type emission line stars, which are stars in an early stage with extended gaseous shells. The absorption lines of BE stars are usually very wide, and the broadening mechanism of this kind of absorption line is rotation broadening. The observed spectra of some sources have emission lines, mainly for hydrogen, but also for helium and iron.

Compared with B stars with the same optical spectral type, the infrared radiations of Be stars are stronger, so it is called infrared excess. The formation mechanism of such a disk is an open question and is generally believed to Be caused by the rapid rotation of Be star [8]. Due to the long semi-major axis of the orbit of such sources, the volume of the companion star is much smaller than that of the Roche lobe. Under the influence of the eccentric orbit, the compact star is far away from the peripheral disk of Be star in most cases, so it will stay in a quiet state for a long time [6].

The reason for the X-ray emission bursts of such sources is explained as when the dense star approaches the circumstellar disk of Be star, the compact star accretes the matter with low rotation speed and high density. This process can also be accomplished through Roche lobe overflow. At this point, the brightness of the X-ray radiation near the hot point of the circumstellar disk increases dramatically, producing bursts that last for weeks to months, as shown in Figure 3.

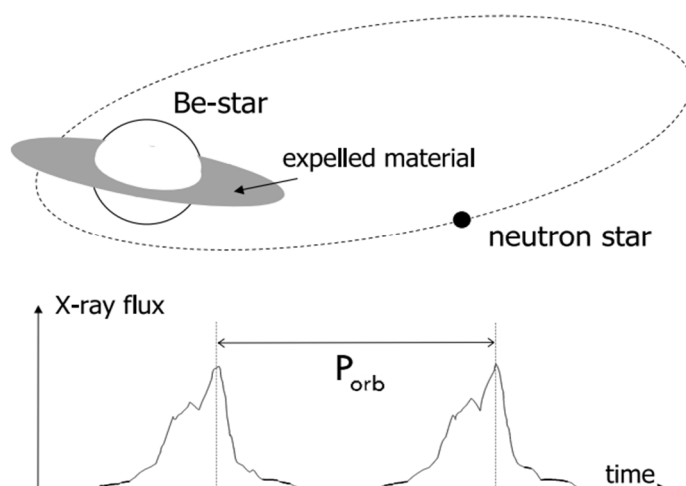


Figure 3. The diagram of orbital movements and optical variation of Be X-ray binaries [7].

4. The formation and evolution of HMXBs

It is generally believed that X-ray binaries in galactic fields evolve from binaries containing massive stars, in which the massive host star evolves into a compact star. The formation and evolution of X-ray binary stars are often accompanied by the physical mechanism and process of the interaction of binary stars, such as mass transfer, mass, and orbital angular momentum loss [1]. In the compact star environment, due to the high number density of stars, the formation of X-ray binary stars also includes

dynamic evolution. For example, compact stars will capture an isolated star through tidal effect or collision to form a binary star system and continue to evolve on this basis. The compact star may also collide with the binary star system. The less massive star is ejected from the original binary star system to form a new binary system with the remaining more massive component. In addition, multi-star systems can also undergo collision and combine to form new multi-star systems. The formation and evolution of the binary system in this situation are restrained by the theory of evolution of binary and constrained by the dynamic process of gravitation.

Suppose the binary stars are far enough apart that no material exchange exists between the two sub-stars. The interactions between the two independent stars do not affect each other. In that case, their evolution will follow the evolution of a single star [1]. However, there are quite a few binaries where the two stars are close together, not far beyond their radius. They influence each other in the gravitational field and radiation field. With the expansion of the stellar volume, the two sub-stars exchange materials and lose angular momentum, making their evolution process more complex than a single star. Such a binary star system is called a close binary star.

The Roche lobe model is an important tool to discuss the evolution of close binary stars. In a binary system, the effective gravitational potential of two-component stars will generate an equipotential surface around the stars (as shown in Figure 4). There is a closed surface that can envelop two component stars and whose area is smallest, as shown in Figure 5, with the shape of “peanut”. This critical equipotential surface is Roche Lobe with the connection point inner Lagrange point L1. The volume of the Roche lobe is the maximum allowable expansion of the two sub-stars, as shown in Figure 4 in the range of the thick black lines. If either component star is filled with its Roche lobe firstly, material from the star's outer layers will flow through L1 to its companion star, causing material exchange that will further affect the evolution of both stars. In practical model calculation, the volume surrounded by Roche lobe is usually equivalent to the volume of a sphere, and its radius is called the Roche lobe radius. The relative inner volume radii of Roche Lobe of a star whose mass is raised by Eggleton [9] is:

$$\frac{R_1}{a} = \frac{0.49(\frac{1}{q})^{2/3}}{0.6(\frac{1}{q})^{2/3} + \ln\left(1 + (\frac{1}{q})^{1/3}\right)}, \quad (1)$$

where a is the binary separation between two components, and $q = M_2/M_1$. When it comes to the radius of Roche Lobe of the companion star, this equation can be described as following,

$$\frac{R_2}{a} = \frac{0.49(\frac{1}{q})^{2/3}}{0.6(\frac{1}{q})^{2/3} + \ln\left(1 + (\frac{1}{q})^{1/3}\right)}, \quad (2)$$

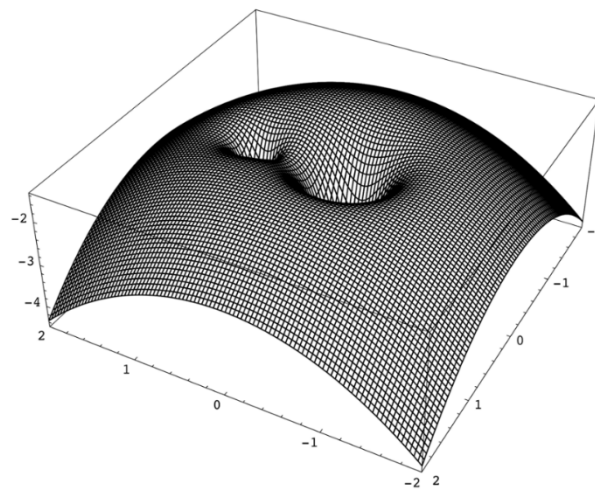


Figure 4. A part of surface Roche potential for a same binary with $q=M_2/M_1=0.25$ in Figure 5 [10].

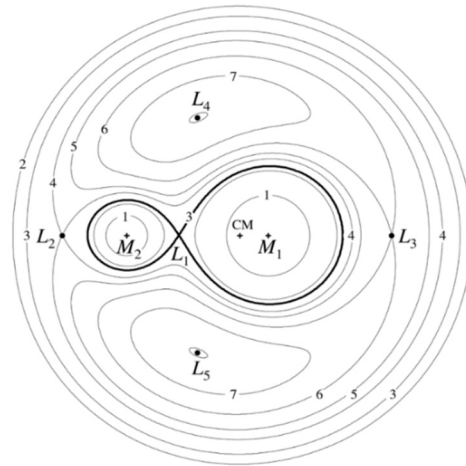


Figure 5. The profile of equipotential surface of a binary system made up by two stars whose mass are M_1 and M_2 respectively in track plane. ($M_1 > M_2$). In this figure, CM and $L_1 - L_5$ illustrate barycenter of the binary and the location of different Lagrange points. The number from 1 to 7 present the potential is growing [10].

The primary formation process of an HMXB requires two stars with a higher initial mass. To describe the complete evolution process of a binary star, an example of the formation and evolution of a high quality X-ray binary star is given in Figure 6. At the beginning of the evolution, the two sub-stars S_1 and S_2 are main-sequence stars with a mass of $M_1 = 14.4 M_\odot$ and $M_2 = 8.0 M_\odot$, respectively, and the initial orbital period is 100.0 d. The evolution includes the following processes:

(a) The stage of zero-age main sequence (ZAMS). At this point, both sub-stars are main-sequence stars.

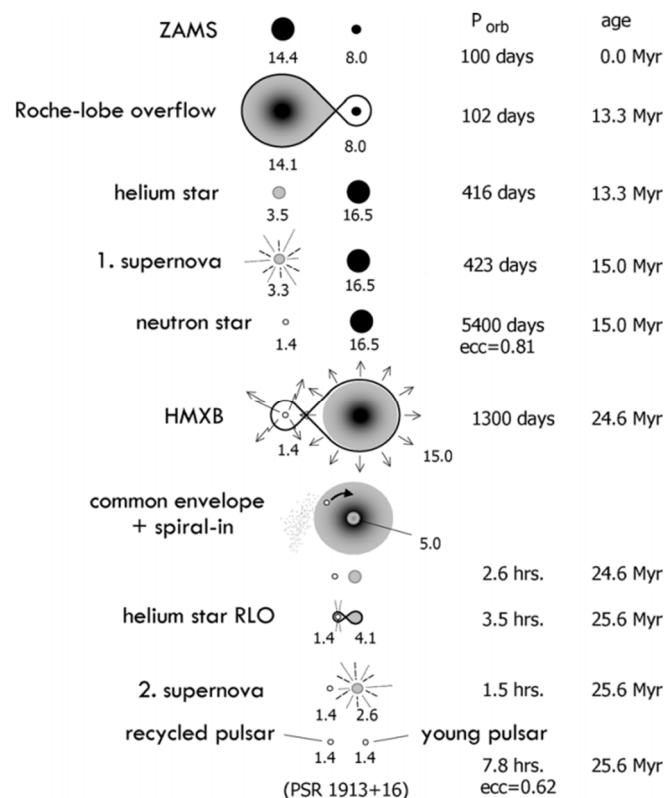


Figure 6. the diagram of the formation and evolution of HMXBs [7].

(b) Roche-lobe overflow (RLOF). After evolution for 13.3 Myr, because the massive primary component S₁ transfer faster than S₂, S₁ firstly fill up Roche-lobe overflow. At this point, the period of this system is 102 days approximately. With the evolution of binary going on, when Roche-lobe overflow occurs, if the difference between the mass of S₁ and S₂ is minor, the process of matter transportation from S₁ to S₂ is stable and not fierce. As the substances are diverted, about 8.5M_⊙ of helium-rich covering on the surface of the S₁ is transferred to S₂, and at this time, the ratio of the mass of S₁ to that of S₂ reaches the critical value, which is 1. After that, the mass of S₁ starts to be lower than that of S₂, and the distance between them is expanding.

(c) A binary system including an ammoniacal star. After the first material exchanging as a process (b), a new binary system is formed, composed of an ammoniacal star whose mass is 3.5 M_⊙ and a star whose mass is 16.5 M_⊙. At this point, the physical exchange ended, and the two stars evolved independently for 1.7 Myr.

(d) The stage of supernova outburst. After evolution for 1.7 Myr, the Supernova explosion happens to ammoniacal stars, with substantial materials ejected. The left substances of S₁ are compressed because of the process of supernova explosions, becoming a neutron star, the mass of which is 1.4 M_⊙. After the supernova outburst, the orbital parameter changes because plenty of matters with velocity vector are ejected. Meanwhile, the orbital eccentricity of binary is altered, and the period of the binary system is lengthened.

(e) The stage of HMXB. Behind a 24.6-Myr-long evolution of the binary system, massive company star makes a further evolution, and materials gradually fill up the Roche lobes, at the period of (d), neuron stars start to absorb the substances blown out by strong stellar winds of companion stars or materials of Roche lobes overflow. The second matter diversion begins, the evolution of binary enters the stage of HMXB. Resulted from the disparity of orbital parameter and transferring the state of partner star, they will turn into SGXBs or BeXBs.

(f) The stage of the evolution of common envelope (CE). All the HMXBs whose compact star is a neutron star will go through the phase of the evolution of the common envelope. Because the transportation process in which massive stars transfer substances to neutron stars with lower mass is dynamically unstable, neutron stars are covered by the envelope of massive companion stars, the track of binary starts to contract gradually. Part of common envelopes is stripped away from the binary system by degrees, finally leaving a close binary system formed by a helium star and a neutron star, with a very short period.

(g) After continuous Roche-lobe overflow of helium star and the second time of supernova explosion, it is possible to generate a binary system finally.

5. Conclusion and Future Plans

High-mass X-ray binary stars are a kind of important celestial body. They evolved from massive binary stars. The study of their evolution process is of great significance to the evolution of binary stars and material exchange and other astrophysical fields and plays an important role in relativity. In this review, we review the observations, classification and evolution of massive binaries. By collecting, observing and analysing more samples of these massive X-ray binaries, our understanding of these objects will be further advanced.

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