X-RAY BINARY STARS

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A binary system is a system that contains two stars which orbit around the center of mass of the system. In an X-ray binary systems one of the two stars is a very small and dense object called a neutron star. A neutron star is a collapsed core of a star which had a mass of more than 8 solar masses. The mass transfer in a high-mass X-ray binary is driven by strong stellar winds and in a low-mass X-ray binary the mass is transferred via Roche lobe overflow.

RENTGENSKE DVOJNE ZVEZDE

Dvojni sistemi zvezd vsebujejo dve zvezdi, ki krožita okrog skupnega masnega središča. V rentgenskih dvojnih sistemih je ena izmed zvezd zelo gost in majhen objekt, nevtronska zvezda. Nevtronska zvezda je ostanek jedra zvezde, ki je imela maso večjo od 8 sončevih mas. Prenos mase v rentgenskih dvojnih sistemih z veliko maso poteka zaradi močnih zvezdnih vetrov. V dvojnih sistemih z majhno maso pa se material prenaša preko Rochovega ovala.

1. Introduction

Massive stars distinguish themselves from low mass stars by their ultimate fate. The stellar evolution is different for low and high mass stars. Low mass star does not reach the temperature that is needed to start fusing heavier elements and it starts slowly collapsing to the point where the core is supported by the degeneracy pressure of electrons, forming a white dwarf. On the contrary, a high mass stars can produce heavier elements until a degenerate iron core is formed. At this point the core is supported by the degeneracy pressure of neutrons. The star then runs out of fuel and starts contracting under its own gravity. This is stopped by the pressure of the neutrons which triggers a shock wave outwards, causing the star to explode in a supernova explosion. Stars with initial masses < 8 solar masses ($M_\odot$), low mass stars, will end up as white dwarfs, whereas stars with masses larger than $8M_\odot$, high mass stars, will form a neutron star or a black hole, depending on the mass of the original star [1]. A neutron star is the residue of the star's collapsed core. Its mass is around $1.5M_\odot$ and its radius is only around 12 km. It is one of the densest objects in the universe. A few neutron stars can be found in isolation, but the majority of discovered objects reside in binary systems. Because of their small size, they are very hard to detect through black body radiation, even if the temperature of the star is very high. These three types of stars can be found in many binary systems.

In the article, first, we will take a look at how we can determine the mass in a binary system. Then we will learn something about mass transfer through Roche lobe overflow. Next, the focus will be on neutron stars and how they behave in binary systems.

2. Binary systems

A binary system is a system of two stars which orbit around the center of mass of the system. We use the approximation of circular orbits and point masses. The approximation of circular orbits is justified in binary stars that will be discussed in this article, where the two stars are very close to each other so that time-dependent tidal stresses eventually bring any elliptical orbit into a circular one. Point masses can be justified as stellar densities are much higher deep inside the star and tidal forces and stellar rotation only act upon a small fraction of the mass of the star. In the next chapters, we will concentrate on semi-detached binaries, where only one star fills its Roche lobe which will be explained later [2].

2.1 Measuring mass

First, we will take a look at how to determine the mass in a binary system. We can do that with Kepler's third law

$$\frac{P^2}{a^3} = \frac{4\pi^2}{G(M_1 + M_2)} , \tag{1}$$

where M_1 and M_2 are masses of the stars, P is the orbital period, a is the distance between the centers of two stars and G is the gravitational constant. If the system we observe is very distant, we have a problem with determining a. By using spectroscopic measurements we are able to determine radial velocity. We can do that by comparing measured wavelengths of known spectral lines with wavelengths from laboratory measurements. In many cases we can only observe one star. That is, if one of two stars is a black hole or, more generally, if one star is much brighter than the other one. The center of mass is defined as $M_1 a_1 = M_2 a_2$, where a_1 is the distance from the center of mass to the first star and a_2 is the distance to the second star. Total distance between stars can be now written as $a = a_1 + a_2$. We assume circular orbits thus we can use $Pv_1 = 2\pi a_1$, $Pv_2 = 2\pi a_2$ and $v_1 M_1 = v_2 M_2$. Another thing to consider is that we observe the system at an angle with respect to the observers. The velocity we need is $v_1 = v_{obs}/\sin i$, where v_{obs} is the observed velocity and i is the inclination, which is defined as the angle between the normal to the orbital plane and the line of sight towards Earth. Now we can write the final formula for determining mass in binary systems

$$\frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{P v_{obs}^3}{2\pi G} . \tag{2}$$

Through a binary system's evolution, mass transfer can occur. One reason is that one of the stars in the binary system can increase in radius and reach a point where the gravitational pull of another star can remove the outer layers of its envelope. This process can happen through Roche lobe overflow. The other reason for matter transfer is that one star can eject mass in the form of stellar wind and the other star can capture the matter using its gravitational pull [3].

2.2 Roche lobe overflow

Roche lobe overflow can occur in the situation where the two stars orbit very closely due to their mutual gravitational attraction, thus acting with tidal forces on each other, causing the matter transfer.

We will continue to use the assumptions made in the chapter above. To describe gas flow between two stars we can use Euler's equation with additional terms which describe centrifugal ($-\boldsymbol{\nabla}\Phi$) and Coriolis force ($-2\boldsymbol{\omega} \times \mathbf{v}$) per unit mass . The new Euler equation is

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \boldsymbol{\nabla})\mathbf{v} = -\boldsymbol{\nabla}\Phi_R - 2\boldsymbol{\omega} \times \mathbf{v} - \frac{1}{\rho}\boldsymbol{\nabla}P , \tag{3}$$

where ω is the angular velocity and Φ_R is the Roche potential

$$\boldsymbol{\omega} = \left(\frac{G(M_1 + M_2)}{a^3}\right)^{\frac{1}{2}} , \tag{4}$$

$$\Phi_R(\mathbf{r}) = -\frac{GM_1}{|\mathbf{r} - \mathbf{r_1}|} - \frac{GM_2}{|\mathbf{r} - \mathbf{r_2}|} - \frac{1}{2}(\boldsymbol{\omega} \times \mathbf{r})^2 , \tag{5}$$

where $\mathbf{r_1}$ and $\mathbf{r_2}$ are the position vectors of the stars' centers. The first two terms in Roche potential represent the gravitational potential of each star and the third term takes into account particles within a rotating reference frame.

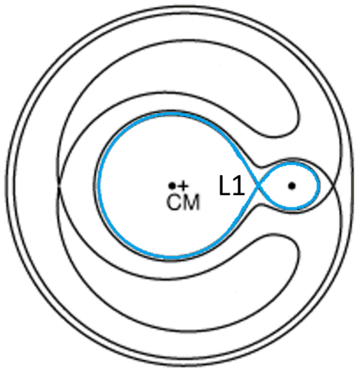

Figure 1. Roche equipotentials ($\Phi_R = const.$) in the orbital plane for a binary system. L1 is the first Lagrangian point, CM is the center of mass and the two dots represent stars. In this case, the mass of the left star is larger than the mass of the right star.

As we mentioned earlier, stars which are close to each other usually move in circular orbits and corotate, which means that the spin period of the star equals the orbital period, as this is an equilibrium state where the forces in corotating coordinate system are constant with time. So all velocities in the corotating system are zero and the system is in hydrostatic equilibrium. This simplifies our problem, as the left-hand side of the Euler equation and the Coriolis term on the right-hand side all vanish. Therefore surfaces of constant pressure coincide with equipotential surfaces. In other words, the surface of a star in an equipotential surface. Equipotential surfaces of Φ_R are shown on figure 1. The shape of equipotentials depends on the mass ratio $q = M_2/M_1$ and the overall scale depends on binary separation a. On figure 1 one of the most important things is the eight shape (blue line) which shows how the two valleys are connected. The surrounding part of each star is called its Roche lobe. The two lobes connect at the inner Lagrangian point L_1, which in three dimensions is a saddle point of Φ_R, where the matter transfer happens. The transfers through the first Lagrangian point occurs when matter from the first star, which is outside of its Roche radius, is lost and then eventually absorbed into the second star. This type of system is called semi-detached system [3].

3. X-ray binaries

Stars in a binary system can be similar or very different. The main differences are in luminosity and size. We will only discuss the extreme case where one of the stars is a neutron star; a very dense and small object.

A neutron star is born in the aftermath of the gravitational collapse of the star's core at the end of its life, where the mass of the star before the collapse is more than $8M_\odot$. Neutron stars have a mass $M \approx 1.5M_\odot$ and radius R of only around 12 km. They are one of the densest forms of matter that has been found in the observable universe [4]. Neutron stars can be found in both isolation and as members of binary systems. Isolated neutron stars were first detected by their radio emissions and are called pulsars. On the contrary, binary systems that contain neutron stars were initially detected as emitters of X-ray (high-energy) photons [5]. X-ray binaries can also contain a black hole instead of a neutron star, but we will not discuss this types of X-ray binaries in this article.

Scientists discovered X-ray binaries in the 1970s by observing X-ray bursts, which are intense flashes of X-rays that typically last a few seconds [6]. From that point on, more and more bright galactic X-ray sources have been found. X-ray binaries are concentrated close to the galactic center and galactic plane. The bursts typically occur for only a matter of seconds and show typical source luminosity of 10^{27}-10^{31} W. Neutron stars accrete material from their companions. They are one of the strongest galactic X-ray sources and accretion continues to be the only source of power to the binary X-ray neutron star [7].

For a neutron star of mass $M \approx M_\odot$, and of radius $R = 10^4$ m, we can calculate the quantity of energy released by mass m falling into gravitational potential well

$$\Delta E_{acc} = \frac{GMm}{R} \ .$$

The energy released is up to 10^{20} ergs g^{-1}, which makes accretion an ideal source of power. Each unit of accreted mass releases some gravitational potential energy GM/R when it reaches neutron star's surface and the luminosity generated by the accretion process is given by the equation $L_{acc} = GM\dot{m}/R$ where $\dot{m}$ is the accretion rate. It requires an accretion rate of $\approx 10^{17}$ g $\text{s}^{-1} \approx 10^{-9} M_\odot \text{yr}^{-1}$ to generate a typical luminosity of about 10^{30} W. During the process of accretion, radiation passes through accretion flow and begins to influence its dynamics. When there is balance between outward pressure of radiation and the inward gravitational pull, the infalling flow stops, which implies a critical luminosity, which is called Eddington luminosity

$$L_{Edd} = \frac{4\pi GMc}{\kappa} \approx 1.3 \times 10^{31} (\frac{M}{M_\odot}) \text{ W} \ ,$$

where $\kappa = \sigma_T / m_p \approx 3.98$ cm^2 kg^{-1} is the opacity, σ_T is the Thomas scattering cross-section for electron and m_p is the mass of a proton. For spherically symmetric accretion, Eddington luminosity corresponds to a maximum steady accretion rate, the Eddington accretion rate

$$\dot{M}_{Edd} = \frac{L_{Edd}}{\epsilon c^2} \approx 1.4 \times 10^{18} (\frac{M}{M_\odot}) gs^{-1} \approx 2.3 \times 10^{-8} (\frac{M}{M_\odot}) M_\odot yr^{-1} \ ,$$

where $\epsilon \approx 0.1$ is radiative efficiency of the accretion process. Lower accretion rates than the critical value are called the sub-Eddington accretion and the higher accretion rates are called super-Eddington accretion [7].

Over 95% of the neutron star X-ray binaries can be sorted into two distinct categories, high-mass X-ray binaries (HMXB) and low-mass X-ray binaries (LMXB).

3.1 High-mass X-ray binary

A system where the companion star has mass of over $10 M_\odot$ is a high-mass system (figure 2). The companion loses mass in the form of stellar wind. Neutron stars in HMBXs display relatively hard X-ray spectra with a peak energy larger than 15 keV and have a tendency to manifest as regular X-ray pulsars, with spin periods of 1-10^3 s and magnetic fields of 10^7-10^9 T [7]. HMXBs are subdivided into three subclasses.

The first type is supergiant HMXBs with masses from $20 M_\odot$ to $50 M_\odot$. The companion star is an O or early B type supergiant star and it is close to filling its Roche lobe. The orbital period is generally shorter than 15 days. These systems are powered by accreting matter from the companion's stellar wind, which is a permanent X-ray source. SGXBs are rare, only around 30 were observed within the Galaxy, and the compact star in all cases is an X-ray pulsar.

The second type of high-mass X-ray binaries includes a Be star as the companion star (non-supergiant B stars that are very close to the main sequence) whose masses ranges from $8 M_\odot$ to $20 M_\odot$. These systems are recurrent transients. This means that they can suddenly become a strong pulsating X-ray source for weeks to months, even if they were quiet for a few 100 years. As the Be star is a rapid rotator, this causes the gas on the equatorial disk to be ejected. The accretion would start and for a short period of time become a strong X-ray source. Their orbital periods can last

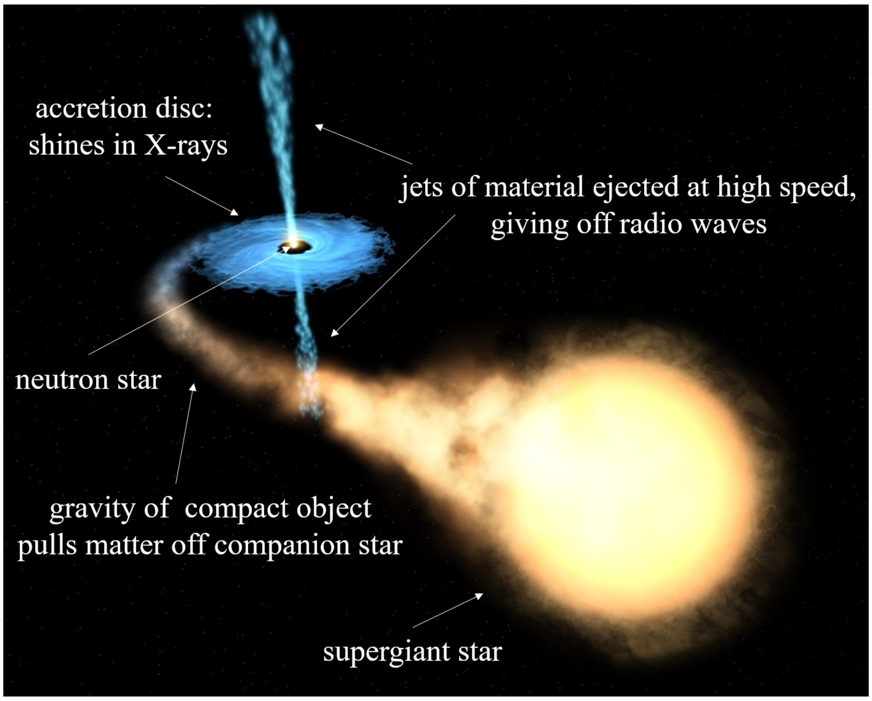

Figure 2. Example of high-mass X-ray binary. The neutron star accreting material with strong stellar wind from the supergiant stars. Adapted from [9].

from 15 days to 4 years. This type of HMXBs is the most common of all three types (220 found in the Galaxy).

The last class is the Wolf-Rayet X-ray binaries. They are all located in external galaxies and only 7 were found. Wolf-Rayet stars are helium stars with masses $> 8M_\odot$. Most likely the compact star, in this case, is a black hole [8].

3.2 Low-mass X-ray binary

In low-mass X-ray binaries, the mass transfer between the companion and the neutron star occurs through Roche-lobe overflow (figure 3). First we will show, how small the mass of the companion star should be. In the case of low-mass X-ray binaries we can transform equation 5 to the approximate analytic formula

$$\frac{R_2}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + ln(1+q^{1/3})} \, , \tag{6}$$

where q is the mass ratio. For q between $0.1 \le q \le 0.8$ we can simplify equation 6 even more

$$\frac{R_2}{a} \approx \frac{2}{3^{3/4}}\left(\frac{q}{q+1}\right)^{1/3} = 0.462\left(\frac{M_2}{M_1+M_2}\right)^{1/3} \, . \tag{7}$$

The radius of the Roche lobe can be characterized with some average radius b_1, which is the distance from the inner Lagrange point L_1 to the center of the star, which would be the same as if we had a sphere with the same volume as the Roche lobe. This radius can be fitted with great accuracy with the formula

$$\frac{b_1}{a} = 0.500 - 0.227 \, log(q) \, . \tag{8}$$

The consequence of equation 7 for R_2/a for $q \le 0.8$ is that the mean density $\bar{\rho}$ of the companion star can be determined only by the period P. To do this, we will use equation 1 to eliminate a.

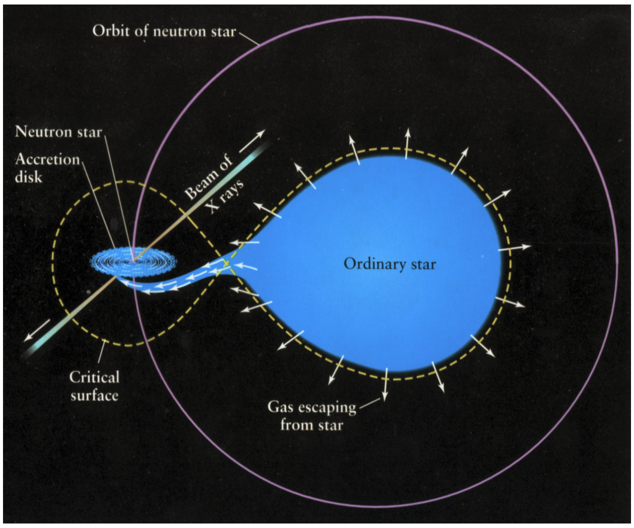

Figure 3. Example of low-mass X-ray binary. Neutron star accreting matter from its companion through the first Lagrangian point. Adapted from [11].

Also we can assume that, by carefully checking the conditions for this to be true, the structure of the companion star, which fills the Roche lobe, is close to the lower main sequence. This means the radius is approximately equal to the mass in solar units. Therefore we can use the relation $M_2 \approx R_2/R_\odot$. We get an equation for mean density and finally the relation between mass and period of the companion star [3]

$$\bar{\rho} = \frac{3M_2 M_\odot}{4\pi R_2^3} = \frac{1.4}{M_2^2} \text{ g cm}^{-3} , \tag{9}$$

$$M_2 \approx 0.11 P_{hr} . \tag{10}$$

Typical orbital periods are ≈ 5 hr ([10]), so we can calculate the mass of the companion star, which is $\approx 0.55 M_\odot$. These masses are typical for stars in the lower main sequence.

When the star's surface exceeds its Roche lobe, the material can transfer to a neutron star through the first Lagrangian point. The transfer is driven either by the expansion of companion star (systems with orbital periods $P_{orb} \geq 2$ days) or by losing angular momentum due to gravitational radiation (systems with very small masses and orbital separations) and magnetic braking (systems with $P_{orb} \leq 2$ days) [7]. The first case occurs when the companion star evolves and leaves the main sequence. In the second case, the gravitational radiation is very efficient in spinning down the companion star which causes it to lose angular momentum, as tides force the companion star to corotate. The nature of the process strongly depends on how the companion star reacts to mass loss. If the mass loss is gentle, the star stays close to the thermal equilibrium, keeping the radius approximately proportional to its mass [3].

In LMXBs, the neutron star possesses relatively weak surface magnetic fields of $10^4 - 10^5$ T and short spin periods of a few 10^{-3} s, while the companions of neutron stars are late-type main-sequence stars, subgiant stars with F and G type spectra or white dwarfs. LMXBs are distributed towards the galactic center and have a wide distribution around the galactic plane. This characterizes a relatively old population, with ages of $(0.5 - 1.5) \times 10^{10}$ yrs [7].

3.3 Intermediate-mass X-ray binary

There is also another class of X-ray binaries called intermediate-mass X-ray binaries. The companions of neutron stars have masses of $1-2M_{\odot}$. This type of systems is rare because mass transfer through the Roche lobe is unstable and would lead to a very quick ($\approx 10^3 - 10^5$ yrs) evolution of the system. In the case of stellar wind accretion, the mass accretion rate is very low causing a system like this to be very dim and hard to detect [7].

4. Conclusion

X-ray binaries are the brightest X-ray sources in our galaxy where the compact object is a neutron star or a black hole. They orbit around each other in a period ranging from minutes to a few days. The two most important categories are high-mass X-ray binaries and low-mass X-ray binaries. The mass transfer in high-mass X-ray binaries happens through stellar wind, while in low-mass X-ray binaries the transfer takes place by Roche lobe overflow. X-ray binaries were one of the first X-ray sources discovered. In the future, observations of isolated neutron stars and binary pulsars hold the promise of effective limitations on neutron star maximum masses, radii, and internal composition.

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