Mass distribution of neutron stars and black holes in X-ray binaries

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Abstract

The aim of this thesis is to make a literature review of the mass distribution of neutron stars and black holes in X-ray binaries. X-ray binaries are binary systems which contain a stellar remnant and a main sequence star. The stellar remnant accretes matter from the donor, a main sequence star. This matter forms an accretion disk around the remnant and as the matter spirals in toward the surface of the remnant it becomes so energetic that it radiates its gravitational potential energy away as X-rays. There are next to no objects between the lightest known black holes and heaviest neutron stars making their distribution uneven. The so-called lower mass gap is between $2.5\,\mathrm{M}_\odot$ and $5.0\,\mathrm{M}_\odot$. This was not expected since the stellar masses have a smooth distribution, thus there must be something affecting the formation of neutron stars and black holes. The causes for this mass gap are not yet well known but as more data is gathered from X-ray binary systems we have come up with few explanations for this gap. In general, we either do not understand the situation completely or then there is some bias introduced from the observations as stellar remnants are hard to detect if they are not located inside a binary system. Recent data about the masses of neutron stars and black holes are explored and one can clearly see the mass gap.

Contents

1 Stellar remnants

Neutron stars are one of the densest objects known to mankind. They are extremely compact and have a radius of approximately 10 km but their mass can be from around $1\,\mathrm{M}_\odot$ up until $2.3\,\mathrm{M}_\odot$ thus their average density is around $2.7 \cdot 10^{14}\,\mathrm{g/cm^3}$. Neutron stars are formed when massive giant stars, with the mass of 10-25 $\mathrm{M}_\odot$, have reached the end of their life cycle when the fusion in their cores stop. The fusion in stars with mass over $1.5\,\mathrm{M}_\odot$ is mainly supported via the CNO-cycle, where the carbon, nitrogen and oxygen act as catalysts to create helium out of hydrogen (Karttunen et al., 2016). The amount of helium increases as the fusion goes on and if the star is hot enough the helium may start fusing into carbon and the carbon can start fusing into oxygen and so on all the way until iron. The pressure created from the fusion prevents the star from collapsing under its own gravitational force. When the fusion stops, the outer layers of the giant star get launched outwards in a supernova explosion and the core then collapses under its own weight. The core contains then mostly electrons and protons and it is now supported by electron degeneracy pressure where the electrons and protons get squished so that quantum effects start to take place. According to Pauli exclusion principle the electrons and protons cannot occupy the same quantum state at the same time, creating outwards pushing force, possibly stopping the collapse under its own gravity and making it stable (Casares et al., 2017). At this point the remnant is a white dwarf which is the extremely hot core of a dead star which cannot produce energy via nuclear fusion reactions. It radiates its heat away very slowly and the time required for it to cool down is in the same scale as the age of our universe (Karttunen et al., 2016). If the core's electron degeneracy pressure is not high enough to support the gravitational collapse, the core collapses further and the protons and electrons are pushed together creating neutrons. As well as with electrons and protons, neutrons cannot exist in the same state at the same time thus creating an outward pushing force. This force or pressure is called the neutron degeneracy pressure. This pressure pushes against the collapse of the core and at some point it can become stable creating a neutron star in the process. The maximum mass of neutron stars is thought to be $2.3\,\mathrm{M}_{\odot}$ which is the Tolman-Oppenheimer-Volkoff (TOV) limit given by the TOV-equations. In short TOV-equation is an equation for the hydrostatic equilibrium which takes general relativity into account and is derived from Einstein equations. TOV-equation is

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1 + \frac{P}{\rho c^2}\right)\left(1 + \frac{4\pi r^3 P}{mc^2}\right)\left(1 - \frac{2Gm}{rc^2}\right)^{-1}, \tag{1}$$

where m is mass, ρ is density, P is pressure contained inside the respective radius of r, G is the gravitational constant and c is the speed of light in a vaccuum (Oppenheimer & Volkoff, 1939).

If the core of the dying star is massive enough, the neutron degeneracy pressure is not able to hold against it and the core will collapse into a black hole. Black holes are regions of space that are so dense that their escape velocity is higher than the speed of light thus making even light unable to escape from it. All the matter is thought to be condensed on a single point called the singularity. All black holes have an event horizon which is the border where matter and light can only enter inwards. On paper black holes are pretty simple and are characterized by only three parameters which are mass, spin and charge. On the other hand we really cannot observe them directly since they "eat" all the light away and we have no idea what is inside black holes' event horizon. Even the laws of physics may not work there as we know them.

2 X-ray binaries

X-ray binary is a system that contains a main sequence star and a compact stellar remnant such as black hole or neutron star. Within the system the compact remnant steals matter from its companion and may form an accretion disk. Matter is stolen when the matter on the surface of the star becomes gravitationally bound to the stellar remnant or if the star is big enough to have strong stellar winds which transfer the matter. As the matter falls more close to the remnant the faster and more energetic it becomes and it starts to radiate its gravitational potential energy as X-rays. The observed X-ray activity depends on multiple parameters such as mass transfer rate and magnetic field of the compact remnant (Fryer et al., 2012). The first X-ray source Scorpius X-1, which was discovered in 1962, contains a neutron star and a main sequence star with the mass of $1.4\,\mathrm{M}_\odot$. This ultimately led to the discovery of many other X-ray sources (Giacconi et al., 1962). To date scientists have found numerous X-ray sources and more than 300 X-ray binaries have been found inside Milky Way only (Shao, 2022). X-ray binary systems are classified by the mass of the donor star as Low Mass X-ray Binaries (LMXB) or High Mass X-ray Binaries (HMXB). The full X-ray binary classification can be seen in Figure 1. In LMXB's the donor has mass under 1 $M_\odot$ and it donates matter by overflowing its Roche lobe. Roche lobe is an imaginary boundary within binary systems where the matter can be gravitationally bound to the other star. From Figure 2. one can see an illustration of a typical HMXB and LMXB systems where matter gets pulled towards the remnant from the surface of the main sequence star as it overflows it's Roche lobe. The gravitational forces also bend the otherwise round star to become more like a water droplet.

In HMXB's the donor has a mass above 10 $M_\odot$ which are usually blue

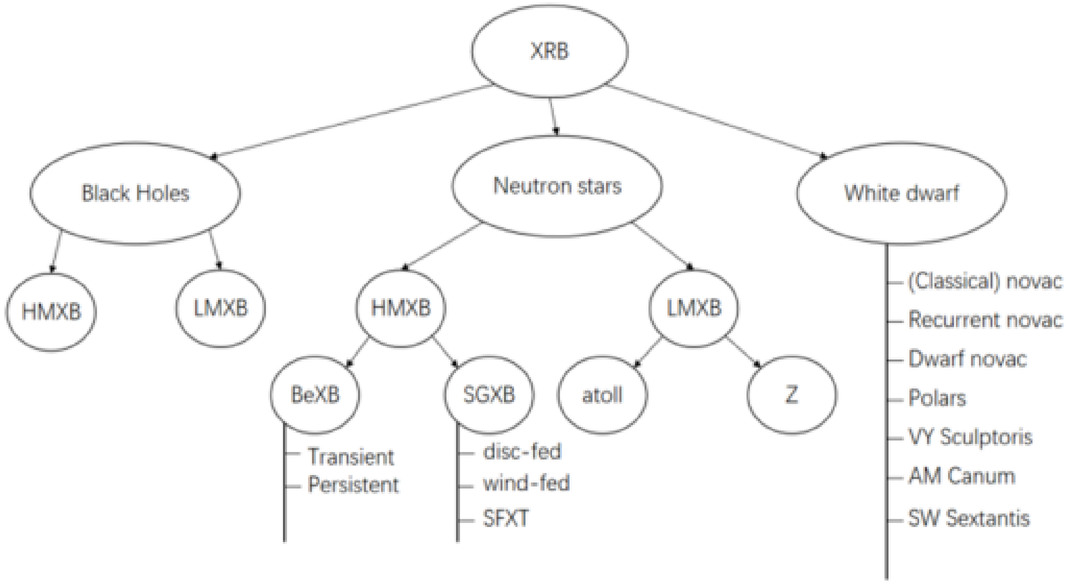

Figure 1: Classification of X-ray binaries, XRB = X-ray binary, BeXB=Be X-ray binary, SGXB = Supergiant X-ray binary, SFXT = Supergiant fast X-ray binaries (Tauris & van den Heuvel, 2006).

giants. In most cases the giant will not overflow its Roche lobe and donates matter some other way. Though some matter can be straight extracted from the blue giant's surface. Blue giants are very active and they have strong stellar winds and with HMXB systems the mass transfer happens mostly via stellar winds, see Figure 2. (Casares et al., 2017). Though the transfer can also happen the same way as in LMXBs where the main sequence star overflows its Roche lobe.

It is thought that HMXB's evolve from binary which contain two massive stars. The more massive star evolves into a compact stellar remnant more quickly and starts the accretion process. Usually HMXB's are consisted of younger stars due to the higher mass stars dying out quickly compared to lower mass stars. In LMXBs the created X-ray emissions may create a thermal instability inside the disk making it transient. It means that there are cycling periods of high X-ray outbursts and periods of dimmer. If the system is a transient and is having an outburst we can obtain X-ray data and detect it easier since it will get quite luminous. On the other hand when it is having its dimmer period we can straight up observe the system and get radial velocities to obtain more data on the compact object (Brightman et al., 2019a). The mass is calculated via the binary mass function which is

$$f(M) = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_{orb}^2} = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2}, \tag{2}$$

where M_1 and M_2 are masses of the star and its companion, G is gravitational constant, P_{orb} is the orbital period, a is the semi-major axis and i is the inclination angle. This equation is used to study binary systems as the components orbit around their center of mass. This introduces Doppler shift to the spectrum of the star as the objects move away or towards the observer. Doppler shift is the phenomenon of apparent change on the wavelength of a wave due to the movement of the source of the wave. The problem is that the inclination is very hard to obtain and usually it is unknown if the system is not eclipsing. This could mean one of two things: either the measured radial velocity is high and the true orbital velocity is low, which means that there should be low mass objects, or the true velocity is high but inclination is low, which means that there should be high-mass objects. If we can only see the main sequence star then we cannot obtain other than a lower limit on the remnant's mass (Karttunen et al., 2016).

In binary systems the remnants may change form from accretion-induced collapse. The remnant, a white dwarf or neutron star, gains mass from accretion in the process. When it reaches its critical mass, it cannot be supported by its degeneracy pressure and collapses further into a neutron star or a black hole. This happens usually in HMXB systems where the accretion rate is very

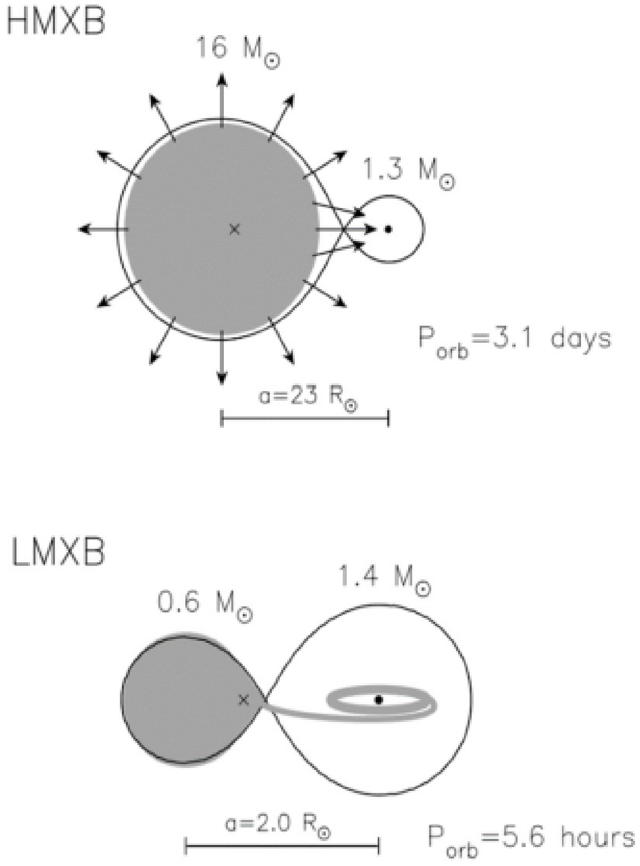

Figure 2: Typical HMXBs and LMXBs with neutron star as the accreting star (Tauris & van den Heuvel, 2006).

high and is limited by Eddington accretion rate. Eddington accretion rate is the rate where the accreting matter radiates at the Eddington luminosity. Eddington luminosity is the maximum luminosity where a star can still keep its balance between radiation pressure and gravitational force.

$$M_{Edd} = \frac{4\pi G M_{BH} m_p}{\eta \sigma_T c}, \tag{3}$$

where where M_{BH} is the black hole mass, m_p is the proton mass, η is the radiative efficiency, σ_T is the Thomson scattering cross section and c is the speed of light. However recent studies and observations suggest that the accretion may in some specific cases, especially in non-spherically symmetric situations, greatly exceed the Eddington limit making the system very luminous. This phenomenon is called super-Eddington accretion (Brightman et al., 2019b). It could also shorten the time needed for neutron stars to reach their critical mass via accretion to make more black holes that lie inside the mass gap (Brightman et al., 2019b).

3 The lower mass gap

The mass distribution of black holes and neutron stars was expected to be continuous just like the stellar masses which have a smooth distribution (Salpeter, 1955). However the observational data contradicts this expectation and shows a clear gap between the $2.5 - 5\,\mathrm{M}_{\odot}$. The lower mass gap (later just mass gap) contains almost no objects. The origin of the mass gap is not very well known but is generally explained by two different very much generalized outcomes. Either there is a bias on the observation of high-mass neutron stars and low-mass black holes or they just do not form in the first place. In Figure 3. one can see the observed neutron stars and black hole masses where one can clearly observe a gap between the most massive neutron stars and lowest mass black holes though some of the objects may fall inside the mass gap (Jonker et al., 2021). Many of the studies suggest that the mass gap might be formed due to complex mechanisms in the supernovae of giant stars. In the study made by (Fryer et al., 2012) the rapid and delayed supernova models differ by a lot, see Figure 5. The delayed supernova model fills the mass gap up but the rapid model does not, suggesting that the real world supernovae would more or less follow the rapid model. This would mean that supernovae are not able to produce objects in the mass gap and they must form some other way.

The mass of the remnant is highly dependent on the conditions just before the supernova explosion. For example the strength of the explosion, the mass of the core and its metallicity, how much mass is lost and the gravitational environment (Fryer et al., 2012). In Figure 4 one can see more how the initial mass and overall status of the core affects the mass loss in stars going supernova.

However the more recent study made by M. Zevin et. al. (Zevin et al.,

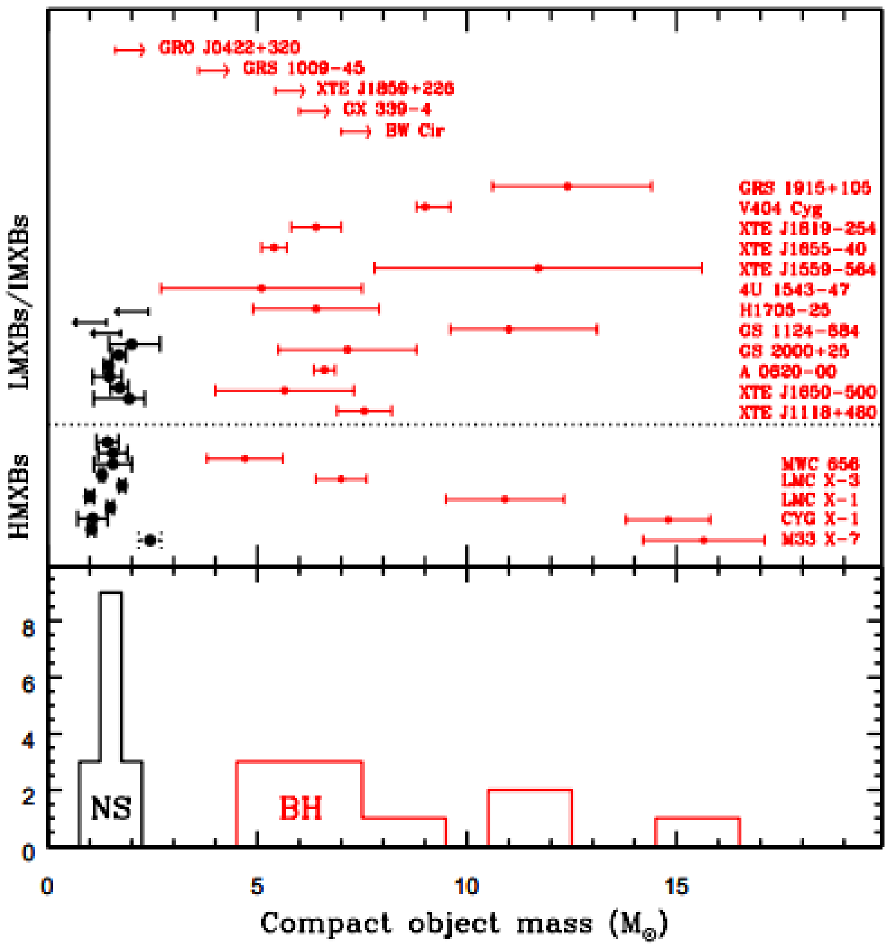

Figure 3: Mass distribution of neutron stars and black holes (Casares et al., 2017).

2020) narrows the theoretical mass gap down even more by introducing corrections to the formula of stellar remnant masses.

The observational bias comes mainly from LMXBs since they are almost always overflowing their Roche lobes resulting in continuous accretion in the compact remnant. This makes the system very luminous and mass measurements almost impossible. This would mean that there is a huge error in the mass measurements in X-ray binaries making the population of the mass gap

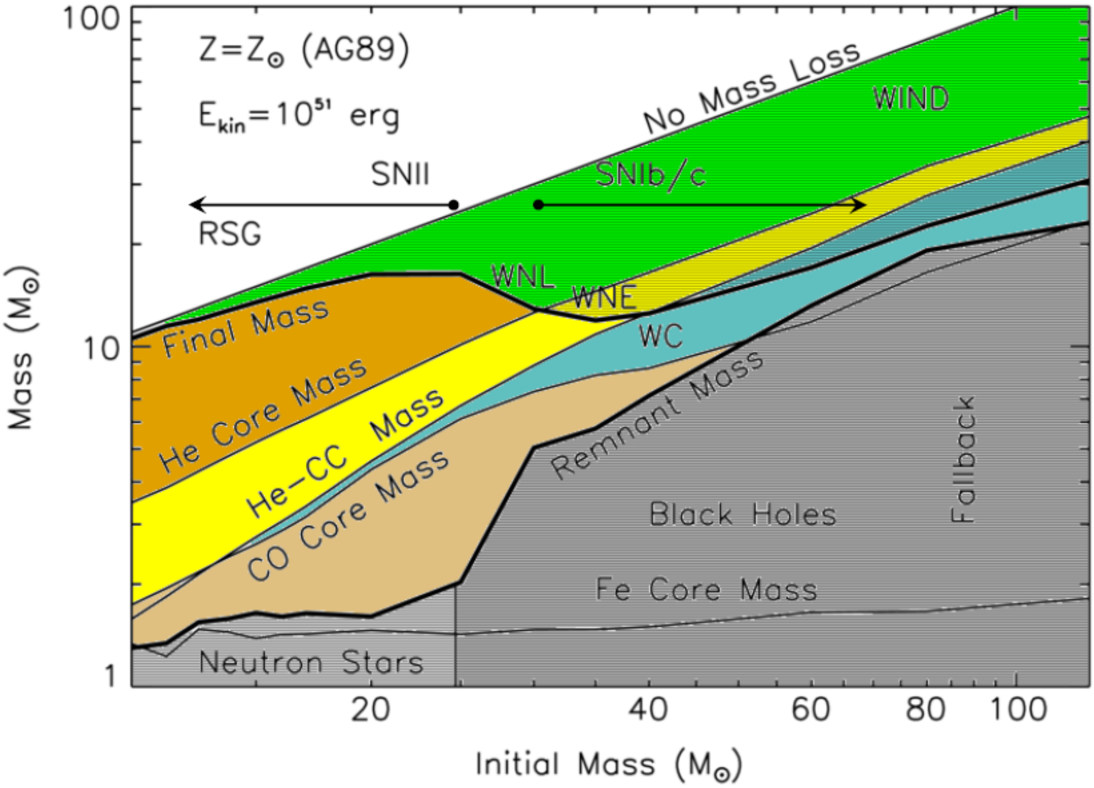

Figure 4: How initial mass affects remnant masses (Limongi & Chieffi, 2010).

possible (Jonker et al., 2021).

Even though according to the observations the mass gap exists there has been few findings of remnants that fit inside the gap. One explanation for this could be that when a neutron star is getting more mass via accretion, it collapses into a black hole. This type of black hole would have a mass of over $2.5\,\mathrm{M}_\odot$. Recent studies however show that the more probable outcome is that black holes with mass of under $5\,\mathrm{M}_\odot$ just will not form, thus making the mass gap naturally occurring and the only possible explanation for stellar remnants in the mass gap is their growth via the accretion. This mechanism is probably very rare since we still are not observing much objects inside the mass gap.

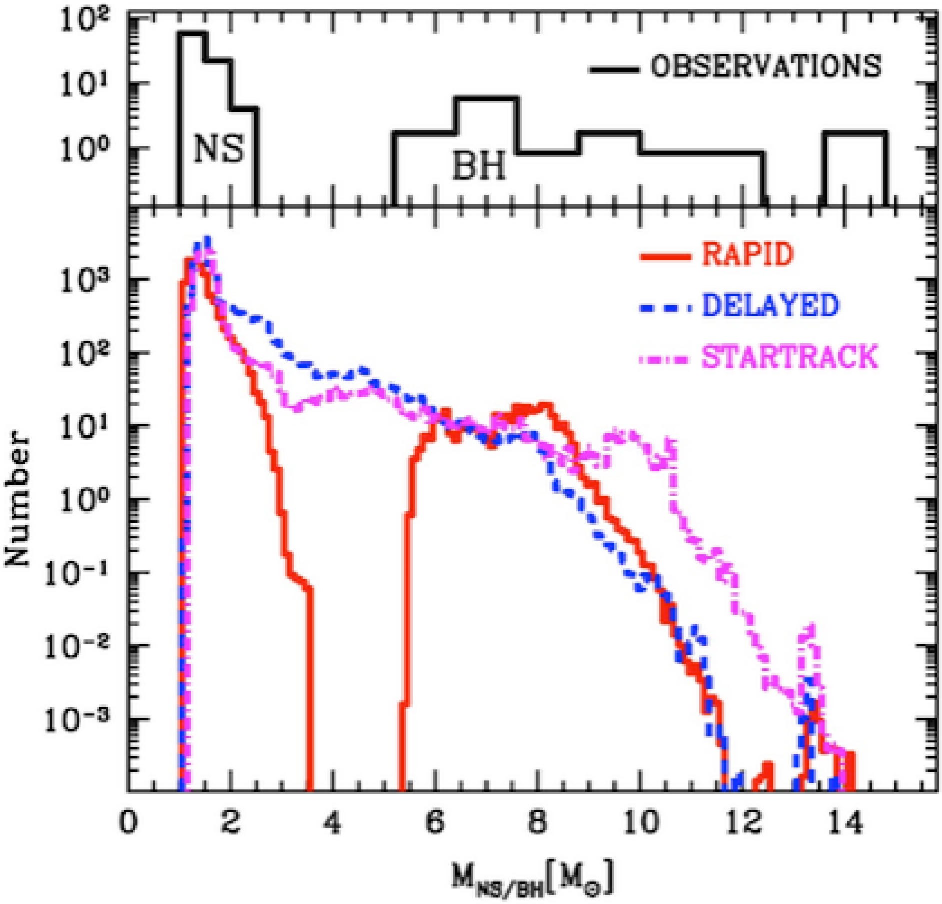

Figure 5: Observed black hole and neutron star masses compared to the simulated supernova models (Casares et al., 2017).

Other thing is that we might not yet understand the situation completely, since most of our black hole and neutron star observations are from binary systems which further complicate the already complicated mechanisms of stellar evolution and supernovae (Jonker et al., 2021).

4 Recent data

There is some of recent observational data on the masses of black holes and neutron stars in binary systems, which all show a clear gap in the mass distribution. However some studies suggest that the mass gap is formed due to some kind of bias in the detection of black holes. The study made by (Brightman et al., 2019a) where they studied LMXB black hole masses via simulations, has gotten some interesting results and they state that mass measurements for black holes are possible only for transient X-ray systems. There is more recent data of the masses of stellar remnants in X-ray binaries and below I have consisted the data I found.

Table 1: Neutron star massses.

References: 1. (Jonker et al., 2021) and references therein, 2. (Özel & Freire, 2016) and references therein.

Ref	Name	Mass ($M_\odot$)	Class	Comments
1	LMC X-4	1.29 ± 0.05	HMXB	
1	Cen X-3	1.49 ± 0.08	HMXB	
1	SMC X-1	1.04 ± 0.09	HMXB	
1	EXO 1722-363	1.55 ± 0.45	HMXB	
1	OAO 1657-415	1.42 ± 0.26	HMXB	
1	4U 1538-522	1.00 ± 0.10	HMXB	
1	SAX 18027-2016	1.2-1.9	HMXB	
1	Her X-1	1.07 ± 0.36	IMXB	
2	SAX J1802.72017	1.57 ± 0.25	HMXB	
2	XTE J1855-026	1.41 ± 0.24	HMXB	
2	Vela X-1	2.12 ± 0.16	HMXB	
1	4U 1700-37	2.44 ± 0.27	HMXB	Remnant type unknown
1	Cyg X-2	1.71 ± 0.21	LMXB	
1	V395 Car	1.44 ± 0.10	LMXB	
1	Sco X-1	< 1.73	LMXB	
1	XTE J2123-058	$1.46^{+0.30}_{-0.39}$	LMXB	
1	Cen X-4	$1.94^{+0.37}_{-0.85}$	LMXB	
1	4U 1822-371	1.52-1.85	LMXB	
1	XTE J1814-338	$2.00^{+0.7}_{-0.5}$	LMXB	
1	SAX J1808.4-3658	< 1.4	LMXB	
1	HETE 1900.1-2455	< 2.4	LMXB	
2	4U 160852	$1.57^{+0.30}_{-0.29}$	LMXB	
2	4U 1724207	$1.81^{+0.25}_{-0.37}$	LMXB	
2	KS 1731260	$1.61^{+0.35}_{-0.37}$	LMXB	
2	EXO 1745248	$1.65^{+0.21}_{-0.31}$	LMXB	
2	SAX J1748.92021	$1.81^{+0.25}_{-0.37}$	LMXB	
2	4U 182030	$1.77^{+0.25}_{-0.28}$	LMXB	

Table 2: Black hole massses.
References: 1. (Casares et al., 2017) and references therein, 2. (Aleksić et al., 2015) and references therein.

Ref	Name	Mass ($M_{\odot}$)	Class	Comments
1	GRS 1915+105	$12.4^{+2.0}_{-1.8}$	LMXB	
1	V404 Cyg	$9.0^{+0.2}_{0.6}$	LMXB	
1	BW Cir	> 7.0	LMXB	
1	GX 339-4	> 6.0	LMXB	
1	XTE J1550-564	$7.8 - 15.6$	LMXB	
1	H1705-250	$4.9 - 7.9$	LMXB	
1	GS 1124-684	$11.0^{+2.1}_{-1.4}$	LMXB	
1	GS 2000+250	$5.5 - 8.8$	LMXB	
1	A0620-00	6.6 ± 0.3	LMXB	
1	XTE J1650-500	$4.0 - 7.3$	LMXB	
1	GRS 1009-45	> 3.6	LMXB	
1	XTE J1859+226	> 5.42	LMXB	
1	GRO J0422+32	> 1.6	LMXB	
1	XTE J1118+480	$6.9 - 8.2$	LMXB	
1	XTE J1819.3-2525	6.4 ± 0.6	IMXB	
1	GRO J1655-40	5.4 ± 0.3	IMXB	
1	Cyg X-1	14.8 ± 1.0	HMXB	
1	LMC X-1	10.9 ± 1.4	HMXB	
1	LMC X-3	7.0 ± 0.6	HMXB	
1	M33 X-7	15.7 ± 1.5	HMXB	
2	MWC 656	$3.8 - 5.6$	HMXB	

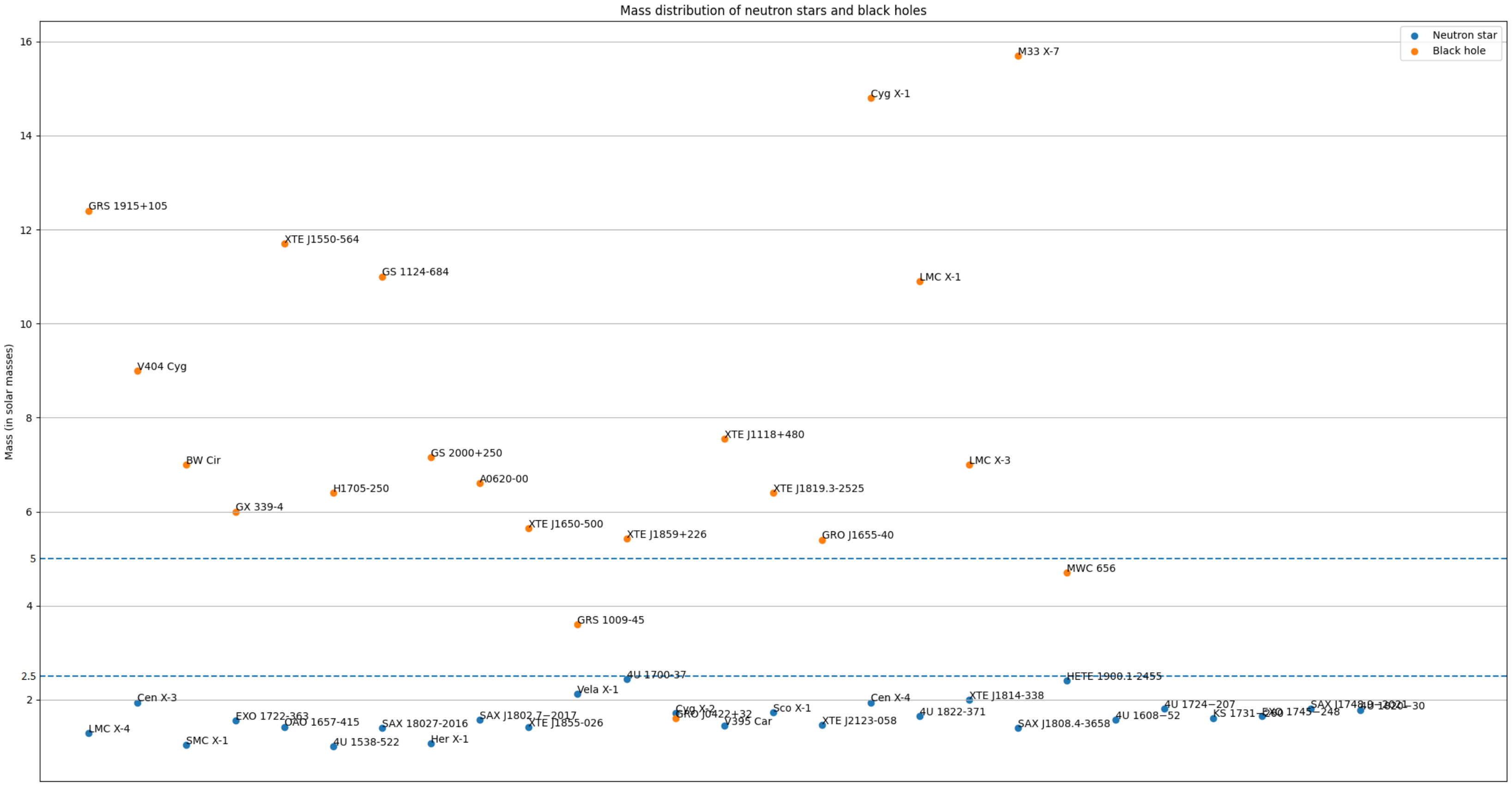

Figure 6: Mass distribution of neutron stars and black holes. This chart contains data I found to be excellent. The dotted lines represent the mass gap. Values are taken from Tables 1 and 2.

From Figure 6. and from Tables 1. and 2. we can observe more massive neutron stars in LMXBs compared to HMXBs. With black holes this reverses and we can find more massive black holes in HMXBs.

4.1 Interesting objects

There are many objects that could lie inside the mass gap and here are some interesting findings. However these mass measurements may have huge errors and they might be subject to many uncertainties.

4.1.1 GX 339-4

GX 339-4 is a LMXB system and it has been studied extensively. This could be the first black hole that falls into the mass gap as the study made by M. Heida et al states its mass to be between $2.3\,\mathrm{M}_\odot$ and $9.5\,\mathrm{M}_\odot$. (Heida et al., 2017) This is not in line with Table 2. where its minimum mass is stated to be $7.0\,\mathrm{M}_\odot$ (Casares et al., 2017).

4.1.2 GRO J0422+32

GRO J0422+32 is a LMXB system thought to contain a black hole and a red dwarf star. Its mass has been derived to be around $3.97 \pm 0.95\,\mathrm{M}_\odot$ which is inside the mass gap (Gelino & Harrison, 2003). However the later study made by Laura Kreidberg et. al. stated that its mass may be subject to many errors and they estimated that the remnants mass could be as low as $2.1\,\mathrm{M}_\odot$ (Kreidberg et al., 2012).

4.1.3 Cyg X-3

Cyg X-3 is a HMXB system which is thought to contain a Wolf-Rayet star which makes the system extremely luminous in X-rays and thus people have called it a micro-quasar. It is not known if the compact remnant is a black hole or a neutron star because it has unusual mass between $1.3\,\mathrm{M}_\odot$ and $4.5\,\mathrm{M}_\odot$ (Koljonen & Maccarone, 2017).

4.1.4 4U 1700-377

4U 1700-377 is a HMXB system which contains a blue supergiant and either a black hole or a neutron star. Its mass has been determined to be $2.44 \pm 0.27\,\mathrm{M}_\odot$ (Clark et al., 2002). This could be inside the mass gap.

4.1.5 MWC 656

MWC 656 is an interesting system since it was the first system confirmed to contain a black hole with a Be star (Aleksić et al., 2015). Remnant's mass has been estimated to be $3.8 - 5.6\,\mathrm{M}_\odot$.

4.1.6 XTE J1650-500

XTE J1650-500 could have one of the smallest known black holes from X-ray observations. Its mass had been estimated to be $2.7 - 7.3\,\mathrm{M}_\odot$ around 2001 era (Orosz et al., 2004). However the more recent study has measured the black hole mass to be $9.7 \pm 1.6\,\mathrm{M}_\odot$ (Shaposhnikov & Titarchuk, 2009).

5 Summary and discussion

X-ray binaries are binary systems that contain a compact stellar remnant. They differ from regular binary system by being luminous in X-rays where the remnant is stealing matter from its companion star. This matter then falls on the surface of the remnant and it starts to radiate the gravitational potential energy as X-rays. X-ray binary systems are categorized in two main categories by the mass of the remnants companion. The categories are HMXBs and LMXBs.

The masses of the stellar remnants was thought to be continuous as with the stellar masses but the observations showed a lack of objects between of $2.5\,\mathrm{M}_\odot$ and $5\,\mathrm{M}_\odot$ called the lower mass gap. The source of this mass gap is not fully yet understood but we have multiple possible explanations why this mass gap exsists. The first possible solution is that no objects can form inside this mass gap which would be related to the complex mechanisms of supernovae. The other explanation is that there is some kind of bias in the detection of stellar remnants which we have detected relatively little compared to the scale of our galaxy.

In the end current observations are not sufficient enough to prove or disprove that the mass gap exists or not. To really grasp the situation we would need much more observational data on the X-ray binary compact objects and stellar remnants in general. In my opinion the most probable cause of the mass gap is the inability to study remnants that are not accompanied by other stars or objects. This introduces huge bias to the mass distribution. There have been also a few gravitational wave observations which have contained objects inside the mass gap (Casares et al., 2017). I hope we get more data from these gravitational wave observations that could contain the keys for debunking the mass gap.

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