Understanding the X-ray Luminosity Function of High Mass X-ray Binaries

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Abstract. High mass X-ray binary luminosity function (XLF) is an important tool for studying binary evolution processes and also the mass loss and consequent evolution in massive stars. We calculate the XLF for neutron star binaries using standard scenario for formation and evolution of these systems. A one to one relation between primordial binary parameters and the HMXB parameters is established. The probability density function is then transformed using the standard Jacobian formalism. It is shown that the model successfully explains some basic properties of the observed XLF.

Keywords: High Mass X-ray Binary, X-ray Luminosity Function, IMF, Wind Mass Loss

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1. PRIMORDIAL BINARY DISTRIBUTION

According to the standard formation and evolution scenario, the progenitor system of a high mass X-ray binary (HMXB) starts as a binary with two massive main sequence stars. The primary is massive enough to form a neutron star at the end of its life. Such a binary can be characterized by the masses of primary ($M_p$) and secondary ($M_s$) and the initial orbital separation ($a_0$). The orbit is assumed to be circular. These three parameters are considered independent of each other. Hence the net probability density function (PDF) of the primordial binary system is the product of individual PDFs. The stellar masses are assumed to follow the power-law IMF given by Salpeter ([9]). The same power-law index of IMF is taken for both masses with appropriate limits. The orbital separation is assumed to follow a loguniform distribution. Hence the net PDF for primordial binaries is,

$$f_{\text{primo}} = \frac{1}{N} \frac{(M_p M_s)^{-\alpha}}{a_0}$$  \hspace{1cm} (1)

where $\alpha$ is the power-law index of IMF and $N$ is the normalization factor.

At the end of the main sequence life of the primary, it expands and fills its Roche lobe. We assume that mass transfer in this phase is conservative and the entire envelope of the primary is transferred to the secondary ([5]). This assumption, along with the relation between the core mass and the total mass of the star (obtained from stellar evolution codes), is used to write transformation relations between pre and post mass transfer parameters of the system. These relations are then used for transformation of the PDF using Jacobian formalism. The core of the primary evolves further and explodes as a supernova. We assume that the mass of the neutron star is 1.4 $M_\odot$ and rest of the core mass is lost. The post-SN system is characterized by the eccentricity ($e$), along with the companion mass ($M_c$) and the semimajor axis ($a$). The eccentricity is found to be insignificant for HMXBs with a mean value $\sim 0.08$. Distribution of $M_c$ is interesting being a broken power-law, as shown in fig. 1 (a). The break occurs at 30 $M_\odot$ which is the upper limit for $M_p$. The power-law index of PDF is close to IMF index below 30 $M_\odot$. The PDF falls sharply (with index $\sim 8$) above this value.

HMXBs are typically wind-fed systems, the companion being near the end of its main sequence life. We use models given by various authors for wind mass loss from massive stars and a simplified prescription for the capture fraction to calculate the accretion rate ([2], [7], [8]). The second parameter for the transformation can be $M_c$ or the orbital period $P_b$. The two choices lead to different insights about the HMXB distribution. To obtain the XLF we integrate over this second parameter and apply a simple linear transformation from accretion rate to luminosity. We refer to our paper for the detailed mathematical treatment. ([1])
2. PROPERTIES OF THE X-RAY LUMINOSITY FUNCTION

The model XLF has been calculated numerically over a wide luminosity range. It shows a broken power-law with a crossover luminosity $L_{cr} \approx 5 \times 10^{34}$ erg/s. The power-law index in bright regime ($L > L_{cr}$) is $\sim 1.6$, which is in good agreement with observations. For $L < L_{cr}$ the XLF shows a loguniform behaviour. A strong cutoff is seen above $10^{37}$ erg/s, which is well within Eddington luminosity for a neutron star. Fig. 1(b) shows the XLF obtained numerically, the broken power-law so obtained being,

$$\frac{dP}{dL} \propto L^\eta$$

with $\eta = \begin{cases} -1.56 & L_{cr} < L_{36} < 10 \\ -0.979 & 10^{-3} < L_{36} < L_{cr} \end{cases}$ (2)

The parameters affecting this model XLF are (a) the IMF power-law index, (b) the model chosen for wind mass loss rate, (c) the wind velocity and (d) the metallicity of the companion. We discuss here the effect of only the wind mass loss model on the XLF as shown in fig. 1(c). We can see that all models overlap for $L < L_{cr}$. This is explained by the contribution from the entire range of $M_c$ and hence implies a loguniform nature for the XLF. The Castor et. al. model shows a very rapid fall at high $L$, and hence is inapplicable. The other two models have similar power-law indices. Thus measurements of $L_{cr}$ can be used to distinguish between various models.

3. CONCLUSION

We studied the XLF of neutron star HMXBs, obtained by considering the standard model for the formation and evolution of HMXBs using PDF transformation formalism. The numerically obtained XLF matches well with the observed XLF in bright regime ($L > L_{cr}$) which has been extensively studied in last decade for nearby galaxies ([6], [3], [4]). The XLF flattens into loguniform shape in faint regime ($L < L_{cr}$). This change has been observed in some recent studies of SMC ([10]). The dependence of XLF power-law index on wind mass loss models was also studied. We have excluded from our studies extremely close binaries in which atmospheric Roche lobe overflow (ARLOF) is possible. This may extend the cutoff line close to the Eddington limit. We emphasize that, in spite of these simplifying assumptions, the calculated XLF matches the observed one over most of the luminosity range.

We plan to include ARLOF systems and black hole binaries into our scheme in future. The observed XLF does not appear to show any break or change at the Eddington luminosity for neutron stars. This may indicate that the XLF is roughly the same for neutron star and black hole binaries, in spite of the differences in detailed accretion mechanism.

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