High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
Proceedings IAU Symposium No. 346, 2019
L. M. Oskinova, E. Bozzo, T. Bulik & D. Gies, eds.

doi:10.1017/S1743921318007457

High-mass X-ray binaries: Evolutionary population synthesis modeling

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Abstract. Using an evolutionary population synthesis code, we modeled the universal, featureless X-ray luminosity function of high-mass X-ray binaries (HMXBs) in star-forming galaxies. We put constraints on the natal kicks, super-Eddington accretion factor, as well as common envelope prescriptions usually adopted (i.e., the $\alpha_{\rm CE}$ formalism and the γ algorithm), and presented the detailed properties of HMXBs under different models, which may be investigated further by future high-resolution X-ray and optical observations.

Keywords. stellar evolution, compact stars, X-ray binaries.

1. Introduction

One of the most striking features of HMXB populations is that the X-ray luminosity function (XLF) takes a universal form of a single, smooth power law (slope ∼1.6) giving an excellent account of X-ray binaries (XRBs) containing NSs, stellar-mass BHs and probably intermediate-mass BHs over the entire X-ray luminosity range $L_{\rm X} \sim 10^{35} - 10^{40}\,{\rm ergs\,s^{-1}}$. This was first discovered by Grimm et al. (2003) and then reconfirmed by Mineo, Gilfanov & Sunyaev (2012). In this work, we applied an updated evolutionary population synthesis (EPS) technique to model the XLF of HMXBs, taking into account both the $\alpha_{\rm CE}$ formalism and the γ algorithm to describe the CE evolution. Several parameters (such as the binary fraction f, the super-Eddington factor $\eta_{\rm Edd}$, the bolometric correction factor $\eta_{\rm bol}$, the mass ratio q [index α], the initial mass function (IMF), the dispersion of the natal kick velocity $\sigma_{\rm kick}$) are also examined. The aim of the work is to constrain the model parameters, and to discriminate between models of the CE.

2. Model

We used the EPS code developed by Hurley, Pols & Tout (2000) and Hurley, Tout & Pols (2002), and modified by Zuo *et al.* (2008) to calculate the X-ray luminosity ($L_{\rm X}$) of XRBs and their numbers. We calculated the X-ray luminosity for supergiant(SG) and main-sequence(MS) HMXBs as in Zuo & Li (2010) and Be-XRBs as in Belczynski & Ziolkowski (2009). Besides the modifications made to the original code by Zuo *et al.* (2008), we also used a more physical estimate of the binding energy parameter λ (Xu & Li 2010; Loveridge *et al.* 2011) in $\alpha_{\rm CE}$ formalism to model the CE evolution.

We first manage to fit the observed XLF in the $\alpha_{\rm CE}$ formalism (Fig. 1). When the best-fit model is achieved, the parameter combination is as follows: $\alpha = 0$, $\eta_{\rm Edd,BH} = 100$, $f = 0.5$, $\sigma_{\rm kick} = 110\,{\rm km\,s^{-1}}$, $\eta_{\rm bol,BH} = 0.6$, $\eta_{\rm bol,NS} = 0.3$, Salpeter IMF **and a constant star formation (i.e., $1\,{\rm M_\odot\,yr^{-1}}$) for 50 Myr**. Then we compare between the two CE mechanisms under the same parameter combination as the above. In this case, only values of γ and $\alpha_{\rm CE}$ are changed to see their effects on the XLF. We consider different CE

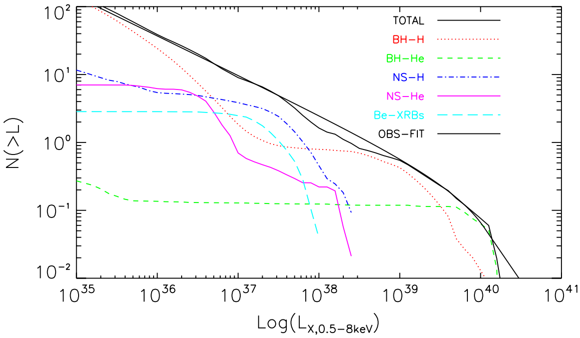

Figure 1. The detailed components of the simulated XLF in the best-fit model of $\alpha_{\rm CE}$ formalism.

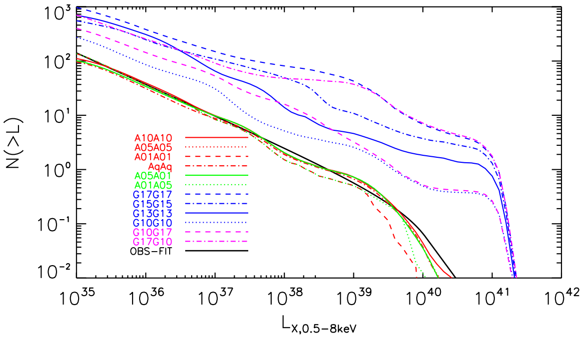

Figure 2. Simulated XLFs of different models on the treatment of the CE phase (Same parameter combination as in the best-fit model of $\alpha_{\rm CE}$ formalism).

efficiencies for the first and second CE episodes. For example, models with different values of $\alpha_{\rm CE}$ are denoted as A01A01, A05A05, A10A10, A01A05, and A05A01, respectively, where the two digits following each letter correspond to the values of $\alpha_{\rm CE}$ during the first and second CE episodes, respectively. It was done similarly for the γ algorithm as well. We also adopt the derived expression of a varied $\alpha_{\rm CE} = 0.05 \times q^{1.2}$ in De Marco *et al.* (2011), denoted as model AqAq (see Fig. 2). At last we manage to determine the best-fit model in the γ algorithm (Fig. 3) by varying all the key parameters and see their effects on the XLF.

3. Results

Fig. 1 shows the simulated XLF and its detailed components contributed by accreting NS/BH with hydrogen-rich (NS/BH-H) and helium-rich (NS/BH-He) donors, and Be-XRBs, respectively. The thick triple-dot-dashed line represents the observed average XLF (labeled as "OBS-FIT") derived by Mineo *et al.* (2012) using the data of 29 nearby star-forming galaxies (Similarly hereinafter). The high luminosity ($L_{\rm X} >\sim 10^{39} {\rm ergs\,s^{-1}}$) sources are mainly BH systems, including both wind-fed BH-XRBs with massive ($\sim 10-30 M_{\odot}$) SG donors (i.e., BH-SG HMXBs), orbital period several thousand days to even hundreds of years, and RLOF-fed BH-XRBs, with less massive (typically $< 10 M_{\odot}$) MS donors, and orbital period typically on the order of days. While the low luminosity sources ($L_{\rm X} <\sim 10^{37} {\rm ergs\,s^{-1}}$) are dominated by wind-fed BH systems powered by higher mass ($\sim 30-75 M_{\odot}$) MS stars (i.e., BH-MS HMXBs), with orbital period from about months

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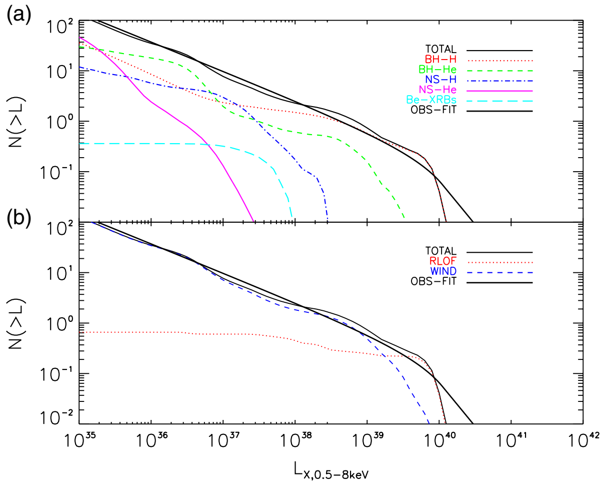

Figure 3. The detailed components of the simulated XLF in the best-fit model of γ algorithm.

to $\sim 10^3$ days. In between are dominated by wind-fed NS systems. In addition, the Be-XRBs are predicted to be very rare. We note that, quantitatively, our calculation is in general consistent with current HMXB population statistics.

Fig. 2 compares the simulated XLFs with different treatments of the CE phase. Clearly, under the same parameter combination the γ algorithm (models with initial letter "G") can produce more (up to one order of magnitude) HMXBs than in the $\alpha_{\rm CE}$ formalism (models with initial letter "A"). In the framework of $\alpha_{\rm CE}$ formalism, the XLF is not very sensitive to $\alpha_{\rm CE}$ and a high value of $\alpha_{\rm CE}$ ($\sim 0.5-1$) seems more preferable. While in the case of the γ algorithm, the number of HMXBs is rather sensitive to the value of γ, especially in the first CE phase (compare models G10G17 with G17G17 or models G10G10 with G17G10).

Shown in Fig. 3 are the detailed components of the simulated XLF (left) and the accretion modes in XRBs (right) in the best-fit model of γ algorithm. It is clear that under the γ algorithm BH-He XRBs dominate in the low luminosity range (i.e., $L_{\rm X} <\sim 10^{37}{\rm ergs\,s^{-1}}$) of the XLF while this is not the case in the $\alpha_{\rm CE}$ formalism, where BH-MS XRBs dominate instead (Zuo, Li & Gu 2014). The orbital period distribution is also distinct from that in the $\alpha_{\rm CE}$ formalism. There are much more sources with period relatively short, i.e, less than several tens of days in this case, which may provide further clues to discriminate between this two models.

4. Discussion and Conclusions

Our work suggests that in the case of HMXBs, both the $\alpha_{\rm CE}$ formalism and the γ algorithm are possible to reproduce the observed XLF. In the framework of the $\alpha_{\rm CE}$ formalism, a high value of $\alpha_{\rm CE}$ (i.e., $\sim$ 0.5-1.0) is more preferred. In addition, we also make constraints on several other parameters, such as the super-Eddington factor $\sim$ 80-100 and the dispersion of kick velocity $\sigma_{\rm kick}$ $\sim$100-150 km/s.

We also give predictions to discriminate both CE mechanisms. For low luminosity sources ($L_{\rm X} < 10^{36}{\rm ergs\,s^{-1}}$), The α-formalism gives: wind-fed BHs with massive MS companion, $M_{\rm opt} \sim 30-75 M_{\odot}$, $P_{\rm orb} \sim$ months-10^3 days, while the γ-algorithm predicts: wind-fed BHs with less massive HeMS companion, $M_{\rm opt} \sim$ several-10 $M_{\odot}$, $P_{\rm orb} \sim$ tens of days.

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We concluded that the simulated HMXBs under the γ algorithm have a much larger population of short-period (less than about several tens of days) BH-He systems than in the $\alpha_{\rm CE}$ formalism, which may serve as clues to discriminate between the two kinds of models. Our work motivates further high-resolution X-ray and optical observations of HMXB populations in nearby star-forming galaxies.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant 11573021), the Natural Science Basic Research Program of Shaanxi Province – Youth Talent Project (No. 2016JQ1016) and the Fundamental Research Funds for the Central Universities.

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