*High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects*
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# Constraints from luminosity-displacement correlation of high-mass X-ray binaries

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**Abstract.** We have modeled the luminosity-displacement correlation of high-mass X-ray binaries (HMXBs) with an evolutionary population synthesis (EPS) code. Detailed properties including offsets of simulated HMXBs are presented under both common envelope prescriptions usually adopted (i.e., the $\alpha_{\rm CE}$ formalism and the $\gamma$ algorithm), and several theoretical models describing the natal kicks. We suggest that the distinct observational properties may be used as potential evidence to discriminate between models.

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

## 1. Introduction

Using data from *Chandra* and NICMOS on board *Hubble* Space Telescope (HST) of X-ray sources and star clusters, respectively, Kaaret *et al.* (2004) found that: the X-ray sources (number: 66) in three starburst galaxies (M 82, NGC 1569, and NGC 5253) are in general located near the star clusters, and brighter sources are most likely closer to the clusters. Moreover, there is an absence of luminous sources ($L_{\rm X} >\sim 10^{38}{\rm ergs\,s^{-1}}$) at relatively large displacements (>200 pc) from the clusters (i.e., $L_{\rm X}$ versus $R$ correlation). In our work, the spatial offsets of HMXBs are modeled for a range of theoretical models describing the natal kicks and the common envelope (CE) evolution.

## 2. Model

We used the EPS code developed by Hurley, Pols & Tout (2000) and Hurley, Tout & Pols (2002), and updated by Zuo *et al.* (2008) to calculate the number and X-ray luminosity ($L_{\rm X}$) of X-ray binaries (XRBs) and their offsets ($R$) from the clusters where they were born. We calculated the X-ray luminosity for different kinds of HMXBs as in Zuo, Li & Gu (2014). We adopted the same procedure to compute the binary motion in the cluster potential (i.e., the offset $R$) as in Zuo & Li (2010).

We constructed seven models to investigate how the spatial offsets of HMXBs are influenced by the natal kicks we adopted. In our basic model (i.e., model BAC), the dispersion of kick velocity $\sigma_{\rm kick}$ is chosen as $150\,{\rm km\,s^{-1}}$, and we adopted a fallback prescription describing as a modified factor $\eta_{\rm m} = 1 - f_{\rm b}$, where $f_{\rm b}$ the fraction of the stellar envelope that falls back, for BH kicks. We also changed $\sigma_{\rm kick}$ (in units of ${\rm km\,s^{-1}}$) to be 50 (M1), 100 (M2) and 265 (M3) and then fixed the value of $\sigma_{\rm kick}$ at $150\,{\rm km\,s^{-1}}$ and applied three more forms of BH natal kicks (i.e., no natal kicks in model M4, high natal kicks in model M5 and momentum-conserving kicks in model M6, see Table 1), respectively.

We considered several different choices of the CE parameter $\alpha_{\rm CE}$ (see Table 2) in order to constrain its value. They are denoted as A02-A10, respectively, where the last two digits correspond to the value of $\alpha_{\rm CE}$. The maximum value of $\alpha_{\rm CE}$ should be within

**Table 1.** Summary of natal kick models. Here $\sigma_{\rm kick}$ is the dispersion of kick velocity, $\eta_{\rm m}$ is the modified factor, and $f_{\rm b}$ is the fraction of the stellar envelope that falls back.

| Model | $\sigma_{\rm kick}$ [km s$^{-1}$] | $\eta_{\rm m}$ | Description for NS | Description for BH |
|---|---|---|---|---|
| BAC | 150 | $1-f_{\rm b}$ | Basic[a] | Fallback; Basic |
| M1 | 50 | $1-f_{\rm b}$ | Very low kicks | Fallback; Very low kicks |
| M2 | 100 | $1-f_{\rm b}$ | Low kicks | Fallback; Low kicks |
| M3 | 265 | $1-f_{\rm b}$ | High kicks | Fallback; High kicks |
| M4 | 150 | 0 | Basic | No natal kicks |
| M5 | 150 | 1 | Basic | High natal kicks |
| M6 | 150 | $M_{\rm NS}/M_{\rm BH}$ | Basic | Momentum-conserving kicks |

[a] Basic means $\sigma_{\rm kick}=150\,{\rm km\,s^{-1}}$.

**Table 2.** Different models on the treatment of the CE parameter $\alpha_{\rm CE}$.

| Model | A02 | A03 | A04 | A05 | A06 | A07 | A08 | A09 | A10 |
|---|---|---|---|---|---|---|---|---|---|
| $\alpha_{\rm CE}$ | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |

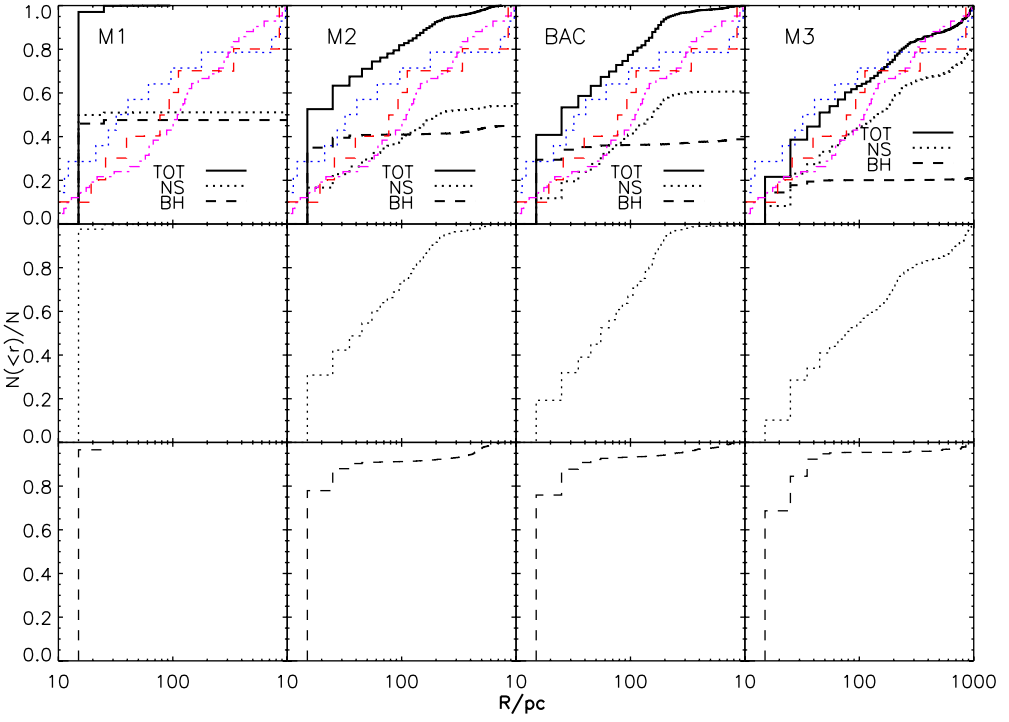


**Figure 1.** The normalized cumulative distribution for the numbers of ALL-XRBs (top), NS-XRBs (middle), and BH-XRBs (bottom), respectively. From left to right are models M1, M2, BAC, and M3.

unity as the potential internal energies have been considered in the quantity of the binding energy of the envelope (see Xu & Li 2010 and Loveridge *et al.* 2011 for the details).

## 3. Results

Fig. 1 shows the normalized cumulative distribution of HMXB offsets (top: Total, along with the relative contributions of NS- and BH- HMXBs; middle: NS-HMXBs; bottom: BH-HMXBs) in the luminosity range $10^{36}<L_{\rm X}<10^{38}$ erg s$^{-1}$ under different choices of $\sigma_{\rm kick}$ (see Table 1). Only sources with offsets $10\,{\rm pc}<{\rm R}<1\,{\rm kpc}$ are selected according to

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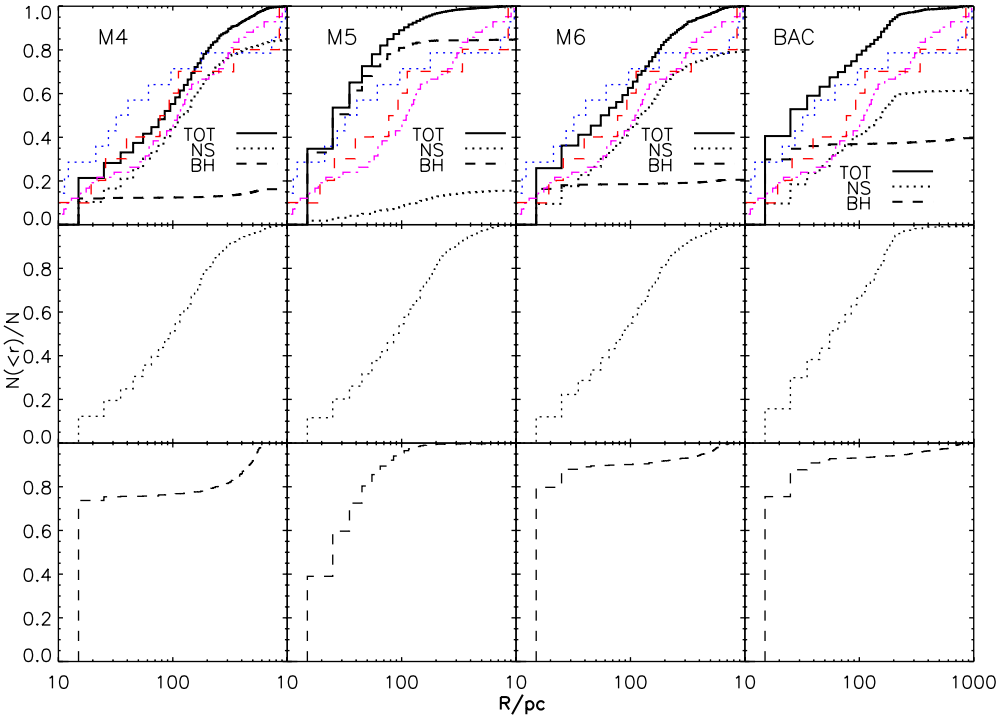


**Figure 2.** Same as in Fig. 1, but for sources in models M4-M6, and BAC from left to right.

the Kaaret *et al.* (2004) sample. The thin-solid, dotted, and dashed lines represent the observed cumulative distributions of source displacements in galaxies M82, NGC 1569, and NGC 5253 (see Fig. 2 in Kaaret *et al.* 2004, similarly hereinafter), respectively. The differences are remarkable. When natal kicks are too weak (i.e., on the order of several tens of km s$^{-1}$, see model M1), no sufficient sources can be kicked to large displacements from star clusters. In order to be compatible with observations, the value of $\sigma_{\rm kick}$ should be greater than $\sim 100\,{\rm km\,s^{-1}}$ (see models BAC, M2, and M3).

Fig. 2 is the same as in Fig. 1, but for different treatments on the BH natal kicks (models M4-M6 versus model BAC). It is clear that when full natal kicks are applied to BHs (i.e., model M5), BH HMXBs dominate the whole population in our interested offset region, greatly different from other models and the observational data. These sources are predicted to be mainly long-period BH sources powered by stellar winds from massive ($\sim 30 - 75 M_\odot$) MS companions (see Fig. 4 in Zuo, Li & Gu 2014 for a typical evolutionary sequence), which may serve as a potential clue to further discriminate between models of BH natal kicks.

Fig. 3 is the same as in Fig. 1, but under different choices of $\alpha_{\rm CE}$ (see Table 2). Clearly models with $\alpha_{\rm CE}$ between $\sim 0.8 - 1.0$ (i.e., models A08-A10) can match the observation quite closely, while models with $\alpha_{\rm CE} <\sim 0.4$ clearly fail. In models A02-A04, very few sources can move to 100 pc away from the star clusters, which is in marked contrast with the observations. We note that this result is also consistent with the one obtained through HMXB X-ray luminosity function (XLF) simulations presented by Zuo & Li (2014).

## 4. Discussion and Conclusions

Our work shows that, using the apparent $L_X$ vs. $R$ distribution of HMXBs, it is possible to investigate the natal kick problem and constrain the value of CE parameter $\alpha_{\rm CE}$.

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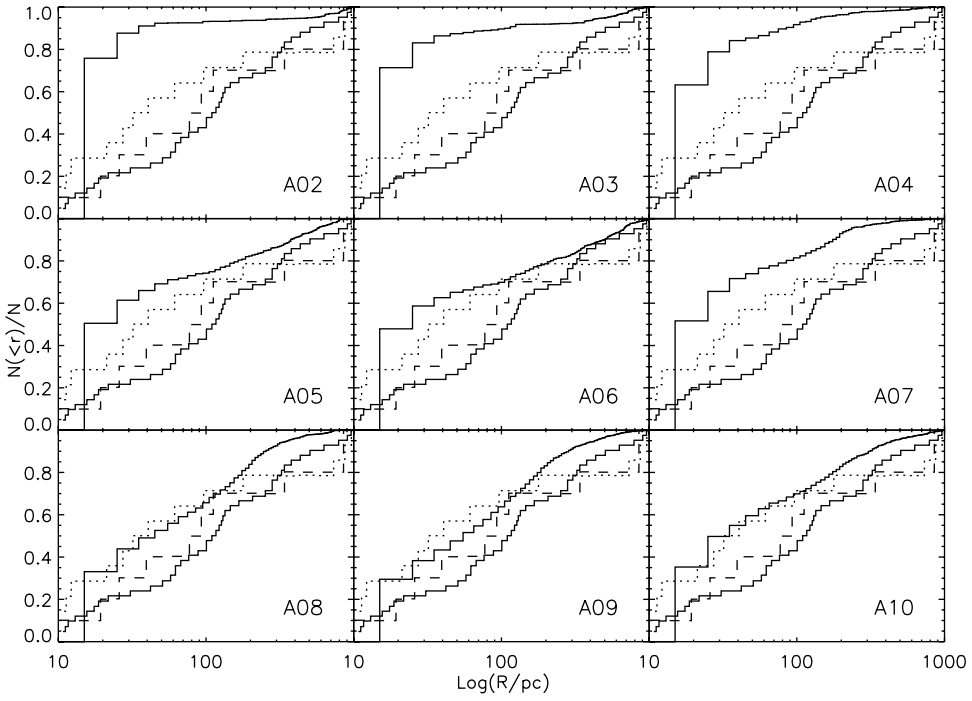


**Figure 3.** The normalized cumulative distribution (thick-solid line) for models A02-A10, respectively (see Table 2).

The magnitude of $\sigma_{\rm kick}$ is constrained to be larger than $\sim 100\,{\rm km\,s^{-1}}$, while $\sigma_{\rm kick}$ on the order of several tens ${\rm km\,s^{-1}}$ may be excluded. More importantly, full BH natal kicks (i.e., similar to those that NSs may receive) are likely to be ruled out though it has just been suggested recently by Repetto, Davies & Sigurdsson (2012) to explain the observed distribution of low-mass X-ray binaries with BHs. We also made constraints on the CE efficiency $\alpha_{\rm CE}$. Within the framework of the standard energy formula for CE and core definition at mass X = 10 per cent, a high value of $\alpha_{\rm CE}$, i.e. around 0.8−1.0, is more preferable, while $\alpha_{\rm CE} <\sim 0.4$ likely can not reconstruct the observed $L_{\rm X}$ vs. $R$ distribution.

The results are also subject to some uncertainties and simplified treatments. For example, we did not consider dynamical interactions in our calculation though it may play a non-negligible role in binary formation and kinematics (Mapelli *et al.* 2013). And when constraining the natal kicks, we only selected one typical value of $\alpha_{\rm CE}$ for simplicity. However CE efficiency is also an important parameter, which may not only affect the system velocity, and hence the spatial offset of the system, but also the whole population of resultant XRBs as well. In addition, the range of $\alpha_{\rm CE}$ we obtained here itself suffers from great uncertainties. It may vary greatly with different assumption describing the CE, such as different core-envelope boundaries, different energy sources used to unbind the envelope, etc.

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