Populating the Galaxy with close Be binaries

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Abstract. Be/X-ray binaries comprise roughly two-thirds of the high-mass X-ray binaries (HMXBs), which is a class of X-ray binaries that results from the high mass of the companion or donor star (\(>10M_\odot\)). Currently the formation and evolution of X-ray producing Be binaries is a matter of great debate. Modelling of these systems requires knowledge of Be star evolution and also consideration of how the evolution changes when the star is in close proximity to a companion. Within this work we complete a full population synthesis study of Be binaries for the Galaxy. The results for the first time match aspects of the observational data, most notably the observed upper limit to the period distribution. We conclude that greater detailed studies on the evolution of Be stars within X-ray binaries needs to be completed, so that rapid binary evolution population synthesis packages may best evolve these systems.

1. Introduction

Detailed X-ray surveys have discovered 130 Be/X-ray candidates within the Galaxy and Large and Small Magellanic Clouds (Raguzova & Popov, 2005). Roughly 50 of these candidates are observed within the Galaxy. Only systems with neutron star primaries have been found, though the presence of helium star accretors has been suggested in some systems (Raguzova, 2001). We evolve populations of binary stars within the Galaxy following both stellar evolution and stellar interactions. We test how certain assumptions affect the final populations of Be binaries by varying a number of parameters within different models.

Up to now population synthesis results have not accurately matched observed trends. One of the most notable trends is that of the orbital period cut off, where no Be/X-ray system has been observed with a period greater than \(\sim 600\) days (see Figure 3 in Raguzova & Popov, 2005 as compared to Figure 7 of Raguzova, 2001). The motivation for this work is, with an up-to-date binary evolution and population synthesis package (Hurley, Tout, & Pols, 2002), to attempt to match theoretical calculations with that of observations. To do this we calculate relative distributions between the differing Be binary types – helium star (He star), white dwarf (WD), neutron star (NS) and black hole (BH) companions – and consider the period distribution of the population.
2. Close Be binary evolution & Population synthesis

The evolution of close Be binaries is not clear. With this in mind we have implemented two different methods for rapidly evolving X-ray producing Be binaries. Firstly we follow Waters et al., (1989) who assumed that the X-ray luminosity of Be binaries is produced by wind-fed accretion onto the primary star (He star, WD, NS or BH) emanating from the circumstellar disk ($\Phi_{\text{Wind}}$ method). We simply model this as a disk wind with a mass loss rate, $\nu_\dot{m}$, this is in addition to any stellar wind from the surface of the Be star. Depending on the orbital parameters some fraction of the material may be accreted by the primary via Bondi-Hoyle accretion (see Hurley, Tout & Pols 2002). We allow our parameter $\nu_\dot{m}$ to vary from $10^{-9}$ to $10^{-12} M_\odot \text{yr}^{-1}$ for different models (Hayasaki & Okazaki 2004) and any interaction between wind material is ignored. Alternatively we model the mass transfer via Roche-lobe overflow (RLOF) from the Be disk ($\Phi_{\text{Roche}}$ method). When a Be star is formed within this method we assume that it has a disk extending to a radius of $\mu_{\text{Be}} \times R$ where $R$ is the radius of the star. If the disk is detected to extend beyond the Roche-lobe radius of the star then mass-transfer from the Be star is initiated. The mass-transfer rate is set by the $\nu_\dot{m}$ parameter and the maximum accretion rate is 10% of this value (Kimitake Hayasaki, private communication). Once a system is evolved, we look for evolutionary phases which fit our criteria for a Be binary: a secondary star spinning at 70% or greater of its break-up speed that is on the MS or first giant branch with mass $\geq 10 M_\odot$, and a He star, WD, NS or BH primary which is accreting matter by either the RLOF or wind method.

The population synthesis simulations were run using a Monte Carlo prescription, a standard initial mass function of Kroupa, Tout, & Gilmore, (1993) is used separately for both primary and secondary masses, with $\alpha = 2.7$. An initial period function flat in log(P) was also used. We evolve primary and secondary masses within a range of 5 to 80 $M_\odot$ and 1 to 80 $M_\odot$ respectively. The initial period for all models is within a range of 10 to 10,000 days. We also assume initially circular binaries with solar metallicities. Models here vary the parameters $\nu_\dot{m}$, $\mu_{\text{Be}}$ and the method of Be binary evolution ($\Phi_{\text{Roche}}$ or $\Phi_{\text{Wind}}$).

3. Results & Analysis

Results are given in Table 1. The two evolutionary methods do not reflect observations in that both produce He, WD, NS and BH companions. However, the two methods do produce a greater relative number of Be/NS systems. If we calculate an accretion luminosity, $L_x$, and only count systems with $L_x > 0.0001 L_\odot$ (as opposed to $L_x > 0$, i.e. all systems) we find that for the $\Phi_{\text{Wind}}$ method the relative number of He to NS systems sharply decreases. We note that 0.0001 $L_\odot$, or about $10^{29}$ ergs/s, corresponds to the observational lower limit suggested by Waters et al., (1989). Decreasing $\nu_\dot{m}$ below $10^{-9} M_\odot \text{yr}^{-1}$ for the $\Phi_{\text{Wind}}$ method does not affect the results because the mass-loss rate from the wind of the Be star itself will be equal to or greater than this. We also see that the choice of $\nu_\dot{m}$ has no effect on the $\Phi_{\text{Roche}}$ numbers however, lowering $\mu_{\text{Be}}$ does decrease the average X-ray phase lifetime. The $\Phi_{\text{Roche}}$ method fails to account for the observed period upper limit, where we find that the average...
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period cut off for Models A, B and C is only $\sim 70$ days. Whereas $\Phi_{\text{Wind}}$ can roughly simulate this upper limit, with all models producing a period limit of $\sim 450$ days. Therefore, we suggest that the $\Phi_{\text{Roche}}$ method is flawed and some manner of wind accretion is required.

Table 1. Models varying different evolutionary parameters. Results given show the relative number of systems at a given age of the Galaxy (13 000 Myr) for two lower limit accretion luminosity values.

| Model | Method  | $\nu_m$ | $\mu_{\text{Be}}$ | Relative numbers; He: WD: NS: BH |
|-------|---------|---------|-------------------|---------------------------------|
| A     | $\Phi_{\text{Roche}}$ | $10^{-9}$ | 8 |
| B     | $\Phi_{\text{Roche}}$ | $10^{-12}$ | 8 |
| C     | $\Phi_{\text{Roche}}$ | $10^{-9}$ | 4 |
| D     | $\Phi_{\text{Wind}}$ | $10^{-9}$ | 1 |

$L_x > 0.0L_\odot$ $L_x > 0.0001L_\odot$

0.25 : 0.07 : 1.00 : 0.06 0.25 : 0.07 : 1.00 : 0.06
0.25 : 0.07 : 1.00 : 0.06 0.25 : 0.07 : 1.00 : 0.06
0.38 : 0.05 : 1.00 : 0.25 0.38 : 0.05 : 1.00 : 0.25
0.98 : 0.61 : 1.00 : 0.04 0.37 : 0.61 : 1.00 : 0.04

4. Conclusion

With the latest rapid binary evolution code we produce a distribution of binary systems with the intent on finding the relative numbers of Be binaries with differing companions in the Galaxy and to match these against observations. We have produced two different methods for evolving close Be binaries rapidly, one involves wind accretion while the other checks for Roche-lobe overflow from a Be disk. We also investigate the effects of varying assumptions within Be binary evolution, such as the wind mass loss rate from the Be star and the size of the Be disk. Although not all of the observational suggestions are simulated we do –for the first time– produce a similar period distribution cut off to that of observations. When considering observations many selection effects must be taken into account, especially when suggestions are made that only Be/NS X-ray systems exits. In consideration of this and the results found here we feel that future work must be towards placing greater constraints upon the description and evolution of Be binaries; modeling of Be disks, the details involved in the accretion onto the Be companion and what the estimated observed relative and total numbers of close Be binary systems are within the Galaxy.

Acknowledgments. PDK thanks the organizers of the Active OB star conference for financial travel support.

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