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The Missing Population of Be+Black Hole X-Ray Binaries

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At present, 123 Be/neutron star (Be/NS) X-ray binaries (XRBs) are known in the Galaxy and the Magellanic Clouds , but not a single Be/black hole (Be/BH) binary was found so far. We carried out the calculations of stellar population synthesis to investigate the case of the apparently missing population of Be/BH XRBs. According to our calculations, the main reason of this disparity is the fact that within the orbital period range where Be XRBs are found ($\sim$ 10 to $\sim$ 300 days), these systems are formed predominantly with a NS component. The systems with a BH component are formed predominantly with much longer orbital periods and they are not easy to detect.

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1. Introduction

The binary systems composed of a Be star and a neutron star (Be/NS type systems) form the most numerous class of X-ray binaries (XRBs) in our Galaxy.

At present, 123 such systems are known in the Galaxy and the Magellanic Clouds (which is almost a half of the total number of the known NS XRBs). Other classes of XRBs are less numerous: we know 90 X-ray bursters (which are also NS XRBs) and 50 X-ray pulsars not associated with a Be type companion (which form still other classes of NS XRBs: 36 of these NSs are associated with a supergiant type companion and 14 with a low mass companion). In addition, we know 58 black hole candidate (BHC) systems (among them 23 confirmed BH systems). However, not a single BHC binary containing a Be type component (Be/BH binary) was found so far.

This disparity (123 Be/NS type systems out of 262 known NS XRBs vs. not a single Be/BH type system among 58 known BH XRBs) is indeed striking. Let us note, that if we consider XRBs which do not contain a Be component, then the ratio of NSs to BHs is $\sim$ 2:1 (139:58). However, if we consider XRBs with a Be component, then the ratio of NSs to BHs becomes 123:0!

This disparity called the attention of the researchers already for some time. Zhang et al. (2004) noted that, according to the stellar population synthesis (SPS) calculations by Podsiadlowski et al. (2003), BH binaries are formed predominantly with relatively short orbital periods ($P_{\rm orb} <$ 10 days). If this is the case, then, according to Zhang et al., the excretion disc truncation mechanism (Artymowicz & Lubow, 1994) might be so efficient, that the accretion rate is very low and the system remains dormant (and therefore invisible) for almost all the time. One should note, however, that Podsiadlowski et al. considered, essentially, BH systems with Roche lobe filling secondaries, which definitely is not the case of Be XRBs. Therefore, their results are not relevant for the case of Be/BH XRBs.

We carried out the calculations of stellar population synthesis to investigate the case of the apparently missing population of Be/BH XRBs using the Star Track code described by Belczyński, Kalogera & Bulik (2002) and Belczyński et al. (2008).

2. Properties of Be XRBs

Be/NS XRB systems consist of a NS orbiting a Be type star on a rather wide (orbital periods in the range of $\sim$ 10 to $\sim$ 300 days), frequently excentric, orbit. NS has a strong magnetic field and, in vast majority of cases, is observed as an X-ray pulsar (with the spin periods in the range of 34 ms to about 1400 s). The surface of the Be component is located well below its Roche lobe and the mass accretion on a NS is occuring through the interaction of a NS with the excretion disc around Be component. The fact that Be star is much smaller than its Roche lobe is a distinct property of Be XRBs. In almost all other types of XRBs, the optical component always fills or almost fills its Roche lobe (even if the accreted matter is supplied by the winds).

X-Ray emission (with a few exceptions) has distinctly transient nature with rather short active phases separated by much longer quiescent intervals (a flaring behaviour). There are two types of flares, which are classified as Type I outbursts (smaller and regularly repeating) and Type II outbursts (larger and irregular). Type I bursts are observed in systems with highly eccentric orbits. They occur close to periastron passages of NS. They are repeating at intervals $\sim P_{\rm orb}$. Type II bursts may occur at any orbital phase. They are correlated with the disruption of the excretion disc around Be star (as observed in Hα line). They repeat on time scale of the dynamical evolution of the excretion disc ($\sim$ few to few tens of years). This recurrence time scale is generally much longer than the orbital period.

It is well known now that Be/NS systems contain two quasi-Keplerian ($|\, v_{\rm rad} \,| / v_{\rm orb} \lesssim 10^{-2}$) discs: excretion disc around Be star and accretion disc around neutron star. Both discs are temporary: excretion disc disperses and refills on time scales $\sim$ few to few tens of years (dynamical evolution of the disc, formerly known as the "activity of a Be star"), while accretion disc disperses and refills on time scales $\sim$ weeks to months (which is related to the orbital motion on an eccentric orbit and, on some occasions, also to the major instabilities of the other disc). Accretion disc might be absent over a longer period of time ($\sim$ years), if the other disc is very weak or absent. The X-ray emission of Be/X-ray binaries is controlled by the centrifugal gate mechanism, which, in turn, is operated both by the periastron passages (Type I bursts) and by the dynamical evolution of the excretion disc (both types of bursts). This mechanism explains the transient nature of the X-ray emission.

One should add that the excretion discs are not a mystery any more. In recent years, the outflowing viscous discs were used to describe the circumstellar matter around Be stars known earlier as "an envelope of a Be star" (Okazaki, 1997; Porter, 1999; Negueruela and Okazaki, 2001). The modeling with the help of the viscous excretion discs appeared to be by far more succesful in describing the circumstellar matter, than earlier descriptions in terms of "equatorial winds", "expanding envelopes" or "ejected shells". In particular, the viscous disc models were able to explain the very low outflow velocities (the observed upper limits are, at most, few km/sec) and, also, to explain the (so called) V/R variability, observed in Be stars. The viscous excretion discs are very similar to the, well known, viscous accretion discs, except for the changed sign of the rate of the mass flow. Some aspects of these modelings (supply of the matter with the sufficient angular momentum to the inner edge of the disc, interaction of the stellar radiation with the matter of the disc) are not fully solved yet, but the general picture is quite convincing. The viscosity in the excretion discs is usually assumed (similarly as for accretion discs) in the form of α-viscosity. The discs are almost Keplerian (rotationally supported) which explains the very low values of the radial component of velocity. Nearly Keplerian discs (both inflowing and outflowing) were, since a long time, known to undergo a global one-armed oscillation instability (Kato, 1983). This instability (progressing density waves) provide a very successful explanation of V/R variability, observed both in isolated Be stars and in members of Be/X-ray systems. This phenomenon manifests itself in the form of quasi-cyclical changes of the ratio of the strengths of the V(iolet) peak to the R(ed) peak in the double profile emission lines. This variability (best seen for the Hα line) includes phases, when only one peak is visible. The time scales of the quasi-cycles range from months to years or decades. The theoretical line profiles calculated for the discs with the asymmetric matter distribution (due to progressing density waves) were found to be in a good agreement with the observed profiles (Okazaki, 1996; Hummel and Hanuschik, 1997). Also the theoretical time scales calculated for the one-armed oscillation instability agreed with the observed time scales of V/R variability (Negueruela et al., 2001). The one-armed instability leads, finally, to the disruption of the disc and ejection of the matter from its outer rim. This phenomenon is responsible for Type II bursts. Therefore, these time scales describe also the recurrence of Type II bursts.

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3. Definition of a Be XRB for the purpose of SPS calculations

The most characteristic observational property of Be stars distinguishing them from other B stars is the presence of excretion discs producing the characteristic emission lines. The underlying cause of the presence of this disc is, in turn, rapid rotation. In the context of XRBs, the presence of an excretion disc is crucial, because it permits the relatively efficient accretion on the compact companion, even in the case of large orbital separation. It is not clear how Be stars achieved their fast rotation (although different hypothesis like rapid rotation at birth or spin-up due to binary mass transfer are advanced; see e.g. McSwain & Gies, 2005). The fraction of Be stars among all B stars is similar for single stars and for those in binary systems (one quarter to one third).

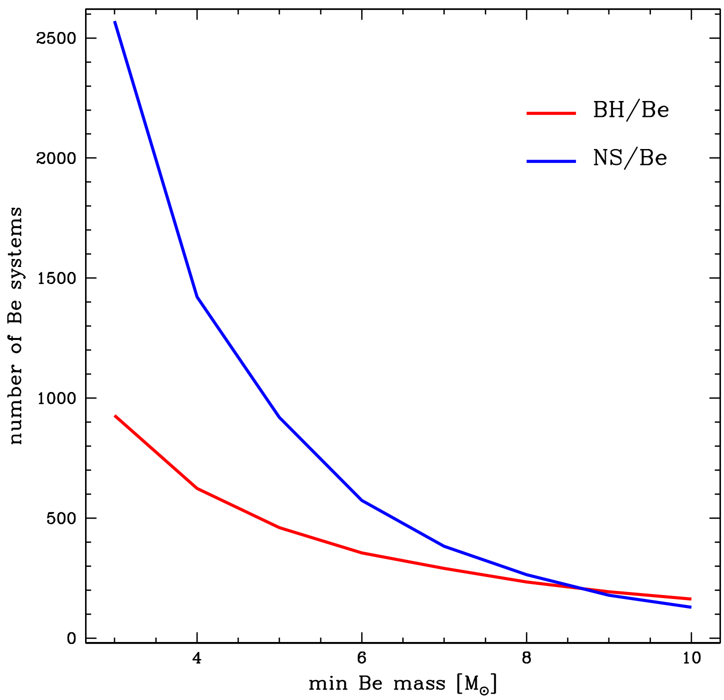

Figure 1: The expected numbers of Be/NS (blue line) and Be/BH (red line) binaries as functions of the assumed minimal mass of a Be component.

For the purpose of our calculations, we we assumed, for simplicity, that one quarter of all B stars are always Be stars and that these stars are always efficient mass donors, independently of the size of the binary orbit (as is, in fact, observed in Be/NS XRBs). Therefore, according to our definition, a Be XRB is a system composed of a compact object (NS or BH) and a main sequence B star (and we apply a factor 0.25 to the number of such systems, to account for the fact that not every B star is a Be star).

4. Preliminary Results

Fig. 1 shows that, when we count the total expected numbers of Be/NS and Be/BH binaries, these numbers should be, roughly comparable. The estimated masses of observed Be stars cover the range from $\sim$ 2.3 $M_\odot$ (Lejeune & Schaerer, 2001) to $\sim$ 25 $M_\odot$ (McSwain & Gies, 2005). Therefore, if we assume 3$M_\odot$ as a reasonable lower limit for the mass of a Be component, then the Be/NS systems should outnumber Be/BH systems only by a factor of about 2.5.

The reason for the observed large disparity becomes obvious, when we look at Fig. 2. According to our calculations, the distribution of the orbital periods is completely different for Be/NS and Be/BH systems. Within the orbital period range where Be XRBs are found ($\sim$ 10 to $\sim$ 300 days), Be systems are formed predominantly with a NS component. The ratio of the expected number of Be/NS systems to the expected number of Be/BH systems is, for this orbital period range, larger than 50. The systems with a BH component are formed predominantly with much longer orbital periods. Such systems are very difficult to detect, both due to very long orbital periods and due to, probably, very low luminosities (the accretion at such large orbital separations must be very inefficient).

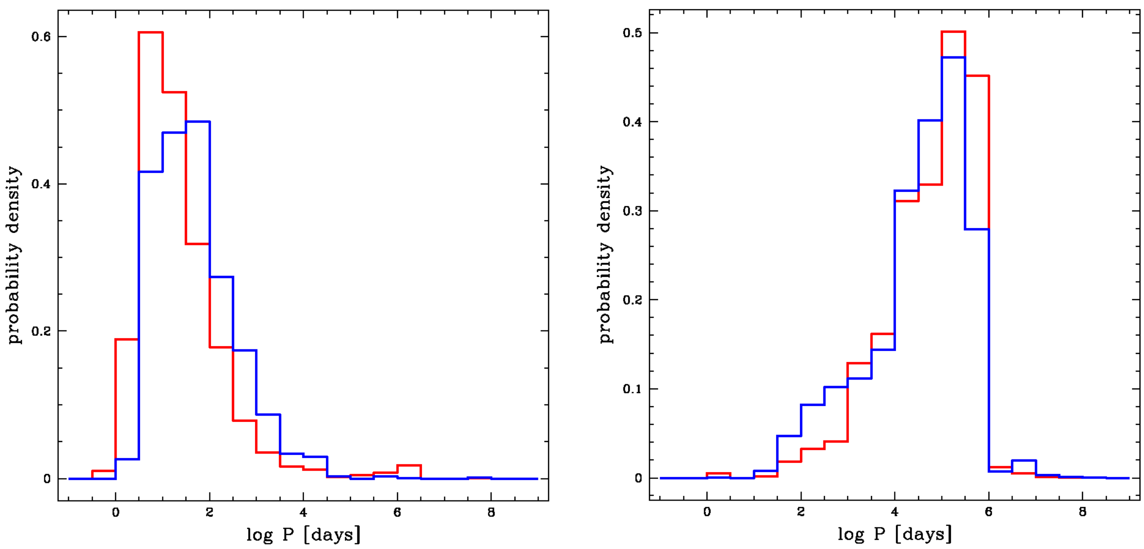

Figure 2: The expected distributions of orbital periods of Be/NS (left panel) and Be/BH (right panel) binary systems. Red lines correspond to the minimum mass of a Be component equal 3 $M_\odot$ and the blue lines to the minimum mass equal 8 $M_\odot$.

We should stress, that the results presented above are only very preliminary results. We plan to carry out further calculations. In particular, we shall try to explain the physical reasons for so different orbital periods distributions for the systems with NSs and with BHs.

We should also stress that, while our results provide a major factor explaining the observed disparity in the numbers of Be/NS and Be/BH systems, this might be not the only factor. Another possible factor may be related to the previous evolution of a Be star. If, indeed, a B star must be a member of a binary system and undergo a mass transfer in order to become a Be star, then one can imagine that the systems composed of a Be star and a relatively less massive companion (which collapses to a NS) remain bound, while those composed of a Be star and a relatively more massive companion (which collapses to a BH) are disrupted in the process of supernova explosion.

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