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The Spectral Distribution of Be/X-ray Transients Implies Supernova Kicks

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Abstract. Be/X-ray binaries are generally assumed to have formed as the result of the evolution of moderately massive binaries in which mass is transferred semi-conservatively from the originally more massive component on to its companion. An alternative model proposes a binary system with a very massive component which loses a large fraction of its mass via very unconservative mass transfer. This scenario allows the formation of Be/X-ray binaries without requiring an asymmetric supernova explosion. We show that the observed properties of most Be/X-ray binaries for which an orbital solution has been found are incompatible with this model.

1. Introduction

Be/X-ray binaries are composed of a neutron star orbiting a Be star and accreting from its circumstellar disc. We still do not understand clearly the reasons that give rise to Be star discs, and it is unclear if any of the many mechanisms proposed (and discussed in these proceedings) can explain the observed phenomenology on its own. The existence of Be stars with compact – or subdwarf (e.g., ϕ Persei; see Gies et al. 1998) – companions indicates that some Be stars started their lives as the less massive component of a binary. However, many Be stars seem to have low-mass companions or no companion at all, suggesting that stars with very different life-stories can become Be stars. It is even possible that the Be phenomenon appears in different stars due to different mechanisms. In spite of that, there does not seem to be any observational difference between the properties of Be stars to the point that no evident subgroup can be defined. Apparently, once a star becomes a Be star, it does no longer matter how it got there (Pols et al. 1991).

2. Formation of Be/X-ray binaries

The generally received model for the formation of Be/X-ray binaries considers the evolution of an intermediate-mass close binary, in which the original primary transfers mass to its companion after the end of the hydrogen core burning phase (case B), resulting in a helium star and a rejuvenated main sequence star. If the helium star is massive enough, it will undergo a supernova explosion and become a neutron star. If the binary is not disrupted, it can then become a

Be/X-ray binary. This model has been developed by Habets (1987), Pols et al. (1991), Portegies Zwart (1995) and van Bever & Vanbeveren (1997), who have calculated the expected population distribution when different assumptions are made. In all cases, the primary must have a mass $\gtrsim 12\,M_\odot$ in order to produce a neutron star, the strong tidal interactions during the mass-transfer phase result in the circularization of the orbit and the Be nature of the original secondary can be caused by the accretion of high-angular-momentum material from the primary. Habets (1987) studied possible evolutionary scenarios and found out that symmetric supernova explosions could only produce low-eccentricity systems. As a consequence, van den Heuvel & van Paradijs (1997) conclude that the presence of Be/X-ray binaries with very eccentric orbits is proof of the existence of intrinsic kicks imparted to the neutron stars during the collapse that leads to their formation.

Iben & Tutukov (1998, hereafter IT98) propose an alternative model in which the Be/X-ray binary is formed as the result of the evolution of a binary containing a massive star ($M_{\rm MS} \gtrsim 20\,M_\odot$ where $M_{\rm MS}$ is the main sequence mass of the primary) and a rather less massive companion (of mass $M_* \sim 10\,M_\odot$), which is originally a Be star. Given the mass ratio $q \lesssim 0.5$, when the primary fills its Roche lobe, mass transfer is highly non-conservative, a common envelope forms and essentially all of the hydrogen-rich envelope of the primary is lost from the system. The resulting system is a relatively massive He star ($M_{\rm He} \sim 5 - 10\,M_\odot$) and an unchanged secondary. In this case, a symmetric supernova explosion can result in a neutron star orbiting a Be star in a very eccentric orbit, since the eccentricity $e = M_{\rm lost}/M_{\rm left}$.

3. The model against the observations

IT98 seem to imply that their scenario can work regardless of the mass of the Be star, though they only show calculations for $M_* = 10\,M_\odot$. However, this is not the case. As a matter of fact, this scenario had already been explored by Habets (1987), who concluded that it could only explain systems in which a neutron star orbits a low-mass Be star in a close, very eccentric orbit. The scenario fails to explain systems with massive Be stars ($M_* \gtrsim 15\,M_\odot$) and systems with wide orbits and large eccentricities. Given that the observed eccentricity of the Be/X-ray binary determines the ratio between the mass lost during the supernova explosion and that the mass of the helium star immediately before the explosion must have been close to that of helium core of the original star, IT98's model has no free parameters and is directly testable.

First, we consider the two systems with moderate eccentricities and close orbits V 0332+53 and 4U 0115+63. We can safely assume masses of 22 and 16 $M_\odot$ for their primaries, given their respective spectral types O8.5Ve and B0.2Ve. We take masses relatively close to those typical for their spectral type (after Vacca et al. 1996), while making some allowance for the fact that rapid rotators could be slightly undermassive for their luminosity (as might be the case in ϕ Per; see Gies et al. 1998). A Be star could also be undermassive for its luminosity if it is the result of semi-conservative mass transfer in a close binary, i.e., if it has been spun up by accreting material from a companion via an accretion disc and this material has mixed efficiently (de Loore & Vanbeveren 1995; van Bever &

Table 1. Observed parameters of the Be/X-ray binaries considered. For references, see Negueruela (1998) and the text.

Name	P_s(s)	P_{orb}(d)	e	Optical Counterpart	Spectral Type
4U 0115+63	3.6	24.3	0.34	V635 Cas	B0.2V
V 0332+53	4.4	34.2	0.31	BQ Cam	O8.5V
2S 1845−024	94.8	242.2	0.88	?	?
EXO 2030+375	41.7	46.0	0.36	star	B0III?

Vanbeveren 1997). However, this possibility must be excluded if IT98's model is applied, because the Be stars are left unaffected by the common-envelope phase. Assuming $M_X = 1.4\,M_\odot$, we find that the masses of the He cores just before the supernova explosions are $M_{He} = 8.7\,M_\odot$ and $M_{He} = 7.3\,M_\odot$ respectively, meaning that the original mass ratio cannot have been $\lesssim 0.5$ in any of the systems. In order for IT98's scenario to work, the Be stars must be undermassive by factors of ~ 3 and 2 respectively.

In the case of EXO 2030+375, the mass function $f(M) = 8.9\,M_\odot$ (Stollberg et al. 1999) implies a minimum mass for the primary $M_* \geq 11.2\,M_\odot$. Even unrealistically assuming that the mass of the companion is equal to its lower limit (which would mean an inclination angle $i = 90°$, while $i \sim 40° - 60°$ seems much more likely from the shape of the emission lines), results in $M_{He} = 6.0\,M_\odot$, implying a main sequence progenitor $M_{MS} = 18.6\,M_\odot$. The system would have had $q = 0.6$ and the mass lost during the common envelope would have been $\sim M_*$, which makes the scenario unlikely even for the lower observational limit on the mass.

4. Discussion

The model proposed by IT98 for the formation of Be/X-ray binaries is incompatible with the observed properties of V0332+53, EXO 2030+375 and 4U 0115+63. The recent orbital solution for 2S 1845−024 (Finger et al. 1999), indicating a very high eccentricity ($e = 0.88$) and wide orbit ($P_{orb} = 242$ d) presents another system which cannot be explained by this scenario. Habets (1987) concludes that the model defended by IT98 is very unlikely to form systems with wide eccentric orbits even if the Be stars have low masses. Therefore, in the absence of any other mechanism that could justify the wide eccentric orbits, we must accept that the observational data implies supernova kicks. The model proposed by IT98 can explain the formation of systems such as PSR J0045−7319, in which the primary has a relatively low mass, but this does not exclude that asymmetric supernova explosions take place in such cases as well.

On the other hand, IT98 argue that it is not logical to assume that the mass transfer is completely conservative, since this would imply, for instance, that the $10M_\odot$ B star in PSR J0045−7319 started its life as a $1M_\odot$ star. We must conclude then that the most likely mechanism for the formation of Be/X-ray binaries is partially non-conservative mass transfer in a binary formed by two moderately

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massive stars. Such models have been explored by Habets (1987), Portegies Zwart (1995), Van Bever & Vanbeveren (1997) and Raguzova & Lipunov (1998) and they can be compatible with both normal-mass and undermassive Be components. Moreover, Portegies Zwart (1995) and Van Bever & Vanbeveren (1997) have shown that scenarios in which evolution is mass-transfer dominated, but some mass and angular momentum is lost from the system, can reproduce the observed spectral distribution of Be/X-ray binaries (Negueruela 1998).

It must be pointed out that the kicks needed to produce the observed Be/X-ray binaries seem to be in all cases very small ($v_{\rm kick} \sim 50$ km s^{-1}; see Raguzova & Lipunov 1998), while the observed distribution of radio-pulsar radial velocities seems to favour a modal distribution of kick velocities centred at ~ 250 km s^{-1} or even higher. We note that the probable masses of the actual Be/X-ray binary systems are slightly larger than those considered by Raguzova & Lipunov (1998), which could lead to their underestimating the kicks needed, but will certainly not result in kick velocities close to ~ 250 km s^{-1}. However, it must be pointed out that there must exist a strong observational bias towards systems with close orbits because these are the orbits that can be solved from the X-ray data, and these systems are likely to be brighter X-ray sources because they accrete from inner denser regions of the Be star circumstellar outflow. Recent results (Reig & Roche 1999; Smith & Roche 1999) indicate that there might be a substantial population of Be/X-ray binaries with very eccentric and wide orbits. It is likely that these low X-ray luminosity objects represent the majority of the Be/X-ray binary population.

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