# On the nature of Be/X-ray binaries

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**Abstract.** It has been suggested that most Be/X-ray binaries are low X-ray luminosity nearby objects, containing white dwarfs (Chevalier & Ilovaisky 1998). We show that existing evidence indicates that all known Be/X-ray binaries are relatively bright X-ray sources containing neutron stars and that the spectral distribution of this group differs considerably from that of isolated Be stars. We suggest that the different X-ray properties of the systems can be explained by the sizes of the orbits of the neutron stars. Systems with close orbits are bright transients which show no quiescent emission as a consequence of centrifugal inhibition of accretion. Systems with wide orbits are persistent sources and display no large outbursts. Systems with intermediate orbits present a mixture of both behaviours.

## 1. Introduction

Be/X-ray binaries are X-ray sources composed of a Be star and a compact object. The high-energy radiation is believed to arise due to accretion of material associated with the Be star by the compact object.

The name "Be star" is used as a general term describing an early-type non-supergiant star, which at some time has shown emission in the Balmer series lines (Slettebak 1988, for a review). Both the emission lines and the characteristic strong infrared excess when compared to normal stars of the same spectral types are attributed to the presence of circumstellar material in a disc-like geometry. The causes that give rise to the disc are not well understood. Different mechanisms (fast rotation, non-radial pulsation, magnetic loops) have been proposed, but it seems that none of them can explain the observed phenomenology on its own. The discs are rotationally dominated (Hanuschik 1996), but UV spectra of Be stars show evidence of a high-velocity low-density wind, suggesting that mass-loss from Be stars takes the shape of a fast radiative wind in the polar regions and a slow higher-density outflow in the equatorial regions, which generates the disc (Lamers & Waters 1987). It

is generally believed that the material forming the disc accelerates radially at distances larger than those probed by the optical emission lines (see Chen & Marlborough 1994, Okazaki 1997). X-ray activity in Be/X-ray binaries would then be due to the interaction of the neutron star with this radial outflow (Waters et al. 1988)

Be/X-ray binaries can present very different states of X-ray activity (Stella et al. 1986):

– Persistent low-luminosity ($L_{\mathrm{x}} \lesssim 10^{36}$ erg s$^{-1}$) X-ray emission or no detectable emission.
– Short (a few days) X-ray outbursts ($L_{\mathrm{x}} \approx 10^{36} - 10^{37}$ erg s$^{-1}$) separated by the orbital period (Type I outbursts), generally (but not always) occurring close to the time of periastron passage of the neutron star.
– Giant (Type II) X-ray outbursts ($L_{\mathrm{x}} \gtrsim 10^{37}$ erg s$^{-1}$), which do not show clear orbital modulation and last several weeks.

Some systems only display persistent emission, but most of them show outbursts and are termed Be/X-ray transients. Both kinds of systems seem to fall in a relatively narrow region of the $P_{\mathrm{orb}}/P_{\mathrm{spin}}$ diagram, known as Corbet's diagram (Corbet 1986; see also Waters & van Kerkwijk 1989).

Based on distance measurements to several proposed counterparts of Be/X-ray binaries by the *Hipparcos* satellite, Chevalier & Ilovaisky (1998, henceforth CI98) have suggested that the compact object in most Be/X-ray binaries is a white dwarf (WD) and that the class of objects can be characterised as nearby low-luminosity sources. In this paper, we set out to show that the existing evidence does not favour that interpretation, and that Be/X-ray binaries contain mostly neutron stars.

## 2. The sample of Be/X-ray binaries

CI98 use a sample of 13 proposed counterparts to Be/X-ray binaries. Their sample is limited to objects with $V \lesssim 12$ so that they can be observed with *Hipparcos*. Seven of their sources are unconfirmed candidates to faint unidentified hard X-ray sources observed during the $HEAO - 1$ all-sky survey with the Modulation Collimator. Tuohy et al. (1988) proposed their association with Be stars on the basis of positional coincidence. Because of the large error boxes, Tuohy et al. (1988) warned that several of these identifications could be spurious. Since no further

**Table 1.** Known galactic Be/X-ray binaries with detected X-ray pulsation and their basic parameters. Orbital periods marked with '*' represent the recurrence time of X-ray outbursts and not orbital solutions. Objects for which the orbital period is noted as 'large' are persistent low-luminosity X-ray sources, likely to have periods of a few hundred days. Spectral types marked '*' are estimated from photometry and the distances derived should be treated with caution. Objects for which no quiescence luminosity is given have been detected only during outbursts. The distance to EXO 2030+375 and its luminosity, estimated from the change rates in spin period and X-ray luminosity, are from Parmar et al. (1989).

| Name | $P_{\rm s}$(s) | $P_{\rm orb}$(d) | Optical Counterpart | Spectral Type | Distance | Quiescence $L_{\rm x}$ (erg s$^{-1}$) | Maximum $L_{\rm x}$ (erg s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 4U 0115+634 | 3.6 | 24.3 | V635 Cas | B0.2V[a] | 6 kpc | $\sim 10^{36}$[b] | $\sim 10^{38}$[b] |
| RX J0146.9+6121 | 1412 | large | LS I +61°235 | B1V[c] | 2.3 kpc | $2 - 4 \times 10^{34}$[d] | $\sim 5 \times 10^{35}$[d] |
| V 0332+53 | 4.4 | 34.2 | BQ Cam | O8.5V[a] | 7 kpc | – | $\sim 2 \times 10^{38}$[e] |
| 4U 0352+30 | 837 | large | X Per | B0V[f] | 700 pc | $2 \times 10^{34}$[d] | $\sim 10^{35}$[d] |
| A 0535+262 | 103 | 111 | V725 Tau | B0III[g] | 2.0 kpc | $\sim 2 \times 10^{35}$[h] | $\sim 2 \times 10^{37}$[h] |
| A 0726−26 | 103.2 | 35* | LS 437 | O8.5V[i] | 6 kpc | $\sim 3 \times 10^{35}$[j] | $\sim 10^{36}$[k] |
| GRO J1008−57 | 93.5 | 248* | star | B0*[l] | $\sim 5$kpc | $\sim 5 \times 10^{34}$[m] | $\sim 2 \times 10^{37}$[n] |
| A 1118−616 | 406.5 | large | Wray 977 | O9.5V[o] | 6 kpc | $\sim 3 \times 10^{34}$[o] | $\sim 5 \times 10^{36}$[p] |
| 4U 1145−619 | 292 | 188* | V801 Cen | B0.7V[q] | 3.1 kpc | $\sim 10^{35}$[r] | $\lesssim 10^{37}$[q] |
| 4U 1258−61 | 272 | 132.5* | V850 Cen | B2V[s] | 2.5 kpc | $\sim 10^{35}$[s] | $\sim 10^{36}$[s] |
| 2S 1417−624 | 17.6 | 42.1 | star | B1V[t] | 6 kpc | – | $\gtrsim 10^{37}$[u] |
| EXO 2030+375 | 41.7 | 46 | star | B0*[v] | 5.3 kpc | – | $\sim 10^{38}$[w] |
| Cep X−4 | 66.3 | ? | star | B1*[x,y] | 4 kpc | $\sim 5 \times 10^{33}$[x] | $\sim 10^{37}$[x] |

[a] Negueruela et al., in prep.  [b] Campana (1996)       [c] Reig et al. (1997a)        [d] Haberl et al. (1998)
[e] Whitlock (1989)              [f] Lyubimkov et al. (1997) [g] Steele et al. (1998)       [h] Sembay et al. (1990)
[i] Negueruela et al. (1996)     [j] Corbet & Peele (1997)  [k] Steiner et al. (1984)      [l] Coe et al. (1994)
[m] Macomb et al. (1994)         [n] Wilson et al. (1994)   [o] Janot-Pacheco et al. (1981)[p] Motch et al. (1988)
[q] Stevens et al., in prep.     [r] White et al. (1980)    [s] Parkes et al. (1980)       [t] Grindlay et al. (1984)
[u] Finger et al. (1996)         [v] Coe et al. (1988)      [w] Parmar et al. (1989)       [x] Bonnet-Bidaud & Mouchet (1998)
[y] Roche, priv. comm.

detection of any of these sources has been reported, the question of their identification and the real nature of these X-ray sources remains open. This has not been taken into account by CI98. Moreover, their sample is magnitude-limited and necessarily includes only nearby sources (since there is only a limited range of absolute magnitudes for Be stars),

In order to compare these candidates with more secure identifications of Be/X-ray binaries, we set out to select a more appropriate sample. In Table 1, we have listed known galactic Be/X-ray binaries with detected X-ray pulsation and a proposed optical counterpart. Hard X-ray spectra and pulsations are the most typical characteristics of a Massive X-ray Binary. Distances in Table 1 are derived from the spectral type of the counterpart, assuming that they have the average optical luminosity for their spectral type, as given by Vacca et al. (1996) or Schmidt-Kaler (1982) – except for EXO 2030+375 (see caption to Table 1). X-ray luminosities have been calculated using these distances. No attempt has been made to take into account errors due to the uncertainty in the spectral classification or in the luminosity corresponding to a given spectral type, since they are not supposed to be systematic. An important point to be considered here, relevant for the following discussion, is that the optical counterparts to Be/X-ray binaries are supposed to have the same physical characteristics as normal Be stars of the same spectral type.. Detailed simulations by Vanbeveren & de Loore (1994) and de Loore & Vanbeveren (1995), in which Be/X-ray

binaries are formed from moderately massive close binaries that undergo mass transfer, show that the properties of the Be star are those of a normal star of the same mass, at least while it remains in the main sequence. Under certain circumstances, the star can become an overluminous supergiant at a later stage.

Table 2 lists all known Be/X-ray binaries in the Magellanic Clouds (MCs) with detected X-ray pulsation and a proposed optical counterpart. X-ray luminosities in this table, taken from the literature, are calculated assuming standard distances to the MCs.

## 3. Spectral distribution

As can be seen in Tables 1 and 2, all the optical counterparts to galactic and MC sources have spectral types earlier than B2, and there are several Oe stars. Most objects have firm spectroscopic classifications. A few have spectral classifications based on photometric colours or continuum fitting and, due to the intrinsic reddening of Be stars, could be slightly earlier than classified. Also within this spectral range are the optical counterparts to Be/X-ray binaries with no detected pulsations – LS I +61°303 (B0V, Steele et al. 1998), BD +53°2790 (O9.5III, Hiltner & Bautz 1963), RX J0117.6−7330 (∼B1III, Coe et al. 1998) – and all the probable counterparts to likely Be/X-ray binaries in the Magellanic Clouds proposed by Crampton et al.

**Table 2.** Known Be/X-ray binaries in the Magellanic Clouds with detected X-ray pulsation and their basic parameters. The only source for which the orbital period is known is A 0535−668, with a 16.7-d period derived from the recurrence time of X-ray outbursts.

| Name | $P_s$(s) | Spectral Type | Max $L_x$ (erg s$^{-1}$) |
|------|------|------|------|
| 2E 0050.1−7247 | 8.9 | ? | $\sim 10^{36}$[a] |
| 1WGA J0053.8−7226 | 41.6[b] | B1V$^{*}$[c] | ? |
| A 0535−668 | 0.07 | B2IV[d] | $\sim 10^{39}$[d] |
| RX J0502.9−6626 | 4.1 | B0III[e] | $\sim 4 \times 10^{37}$[f] |
| EXO 0531.1−6609 | 13.6 | ? | $\sim 1 \times 10^{37}$[g] |
| RX J0529.8−6556 | 69.5 | $\sim$ B2V[h] | $\sim 10^{36}$[h] |

[a] Israel et al. (1997)   [b] Corbet et al. (1998)
[c] Buckley et al., in prep.   [d] Charles et al. (1983)
[e] Crampton et al. (1985)   [f] Schmidtke et al. (1995)
[g] Burderi et al. (1998)   [h] Haberl et al. (1997)

(1985) and Schmidtke et al. (1994) – e.g., RX J0501.6−7034, RX J0520.5−6932.

The distribution of isolated Be stars is completely different. The number of Oe stars is very low, but the distribution rises sharply at B0, peaking around B2 and then falls down gradually extending up to at least spectral type A0 (Slettebak 1988). In Fig. 1, the spectral distribution of optical components of Be/X-ray binaries is compared with a sample of 150 bright Be stars taken from the catalogue of Slettebak (1982), after Porter (1996). A Kolmogorov-Smirnov test of the probability that both samples are extracted from the same population gives a K-S statistic $D = 0.84$ with a significance of $5.3 \times 10^{-12}$, clearly indicating that the two samples are extracted from different populations (a $\chi^2$-test gives a reduced $\chi^2$ of 7.1).

In order to assess the statistical significance of this result, we must considerer the possible biases in the selection of the two samples compared. The Be star list contains the majority of Be stars in the Bright Star Catalogue (BSC) and it is therefore limited by their optical magnitude. The BSC contains stars brighter than $V \lesssim 6.5$ and it is therefore biased towards earlier spectral types. As a consequence, in a volume-limited sample, the peak of the distribution would be towards later spectral types. Abt (1987) found the maximum of the distribution to be at B3-B4 for a volume-limited sample of field Be stars. In the BSC sample, the higher proportion of Be stars in comparison with normal B stars (27%) occurs at B4 (Jaschek & Jaschek 1983).

The sample of Be/X-ray binaries, on the other hand, is limited by their X-ray luminosity. The spectral distribution of this sample could be biased if there exists a direct correlation between spectral type of the optical component and the X-ray luminosity, i.e., if there are Be/X-ray binaries containing late-type Be stars, but all of them are very weak X-ray sources. However, there are two strong arguments against this hypothesis. First, there is no evidence of any dependence of the X-ray luminosity with spectral type among the known Be/X-ray binaries –
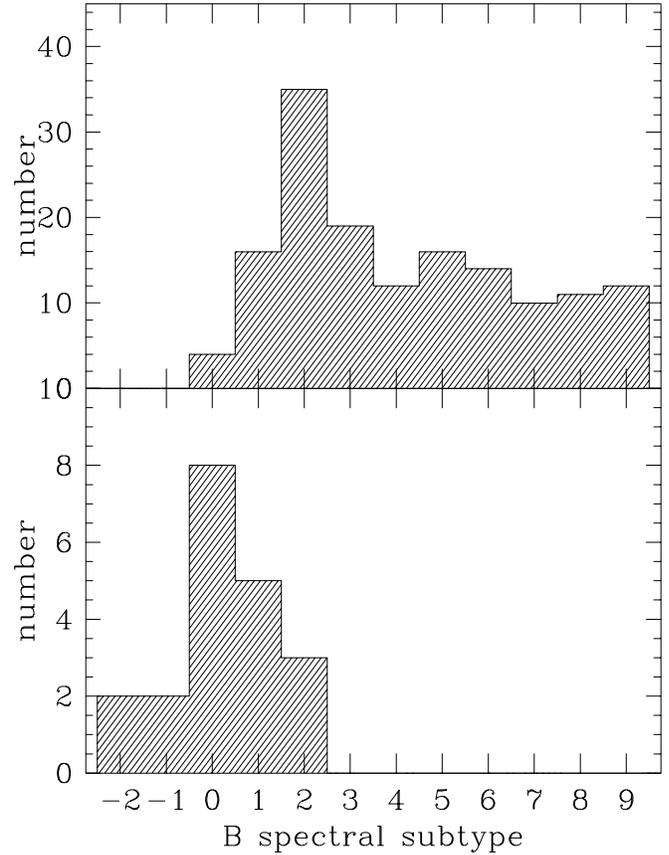


**Fig. 1.** The spectral distribution of isolated Be stars is compared to that of Be/X-ray binary optical components. Negative spectral subtypes are used to represent O-type stars. **Top panel:** The spectral distribution of 150 Be stars present in the BSC, after Porter (1996). **Bottom panel:** The spectral distribution of 20 Be/X-ray binary components, comprising 13 pulsars with spectroscopic spectral-type determinations, 4 pulsars with photometric spectral-type estimation and 3 sources without detected pulsations with spectroscopic determinations.

including those in the Large Magellanic Cloud, which are all at approximately the same distance. The bright transients approaching Eddington luminosity extend over the whole spectral range with the brightest transient known (A 0535−668) having the latest spectral type (B2IV). This is in clear contrast with the sharp cut-off at B3. Second, there is no known correlation between the observable properties of Be stars and their spectral type. The sizes of their envelopes (as reflected in the emission lines) do not seem to depend at all on spectral type. However, if a correlation was to exist between spectral type and X-ray luminosity, it would imply that there is a fundamental difference in the mass-loss processes taking place in early-type and late-type Be stars.

From the above arguments, we conclude that the difference seen between the spectral distributions of field Be stars and optical components of Be/X-ray binaries must reflect a real difference in the populations from which they are drawn. With a sample of 20 objects all earlier than B3, it seems unlikely that

any optical member of a Be/X-ray binary is going to have a later spectral type.

The early limit in the spectral range of Be/X-ray binary components could be simply due to the cessation of the Be phenomenon at earlier spectral types. Although a few O7e stars are known (Conti & Leep 1974), they are very rare. The upper limit is in broad agreement with the predictions of the models of close binary evolution by Van Bever & Vanberen (1997). Models in which a large amount of angular momentum per unit mass is lost from the system during non-conservative mass transfer predict no Be + neutron star binaries with late-type Be stars (Portegies Zwart 1995; Van Bever & Vanberen 1997). The distribution shown in Fig. 1 indicates that all the Be stars with neutron star companions have masses $M_* \gtrsim 8 - 9 M_\odot$.

## 4. A phenomenological model

The X-ray characteristics of the confirmed Be/X-ray candidates are sufficiently consistent to derive a phenomenological model for these systems. The low-luminosity persistent X-ray emission seen in many objects is due to accretion of low-density material. This could be the fast polar wind, but it is more likely to be the equatorial outflow beyond the regions in which motion is rotationally dominated (and where the optical emission lines form), since X-ray emission from 4U 1258−61 ceased completely when the disc around the companion star disappeared even though the polar wind should still be present (Corbet et al. 1986). In the sources with short pulsation (and therefore orbital) periods, this quiescent emission is prevented by centrifugal inhibition of accretion (Stella et al. 1986): due to the fast rotation and strong magnetic field of the neutron star, matter approaching the magnetosphere is shocked by supersonic rotation and ejected beyond the accretion radius (propeller mechanism).

Previous authors (e.g., Corbet 1986) have assumed that the long periods without outbursts are due to the shrinkage of the disc and that series of outbursts take place after discrete episodes of mass ejection from the Be star. The results of Reig et al. (1997b) point very strongly to the possibility that the size of the disc is limited by the orbit of the neutron star, presumably due to tidal truncation (Okazaki 1998). The existence of X-ray outbursts, indicating that the neutron star interacts with material from the dense regions of the disc, implies that the density distribution in the disc can differ from this quiescence configuration. Negueruela et al. (1998) have shown how the presence of a density wave in the disc can provide such a perturbed configuration. Systems with small orbits will then accrete from very dense regions and become high-luminosity transients. Systems with wider orbits, in which centrifugal inhibition does not occur, accrete from less dense regions and show smaller outbursts. Like the transients, A 0535+262 and GRO J1008−57 display both Type I and Type II outbursts, but in the case of 4U 1145−619 and A 1118−616 the distinction is not so clear. In systems with relatively wide orbits, outbursts can only occur close to periastron passage (e.g., A 0535+262), but in closer systems they can take place at different orbital phases, depending on the actual density distribution in the disc, e.g., recent outbursts at phase

$\sim 0.3$ from 4U 0115+634 (Negueruela et al. 1998) and at phase $\sim 0.5$ from 2S 1417−624 (Finger et al. 1996).

The two systems with longer spin periods, X Per and LS I +61°235 have never been observed to undergo X-ray outbursts. In both cases, however, long periods of increased X-ray luminosity have been observed (see Haberl et al. 1998). Given the known relationship between the spin and orbital periods of Be/X-ray binaries (Corbet 1986), both systems are expected to have very long orbital periods (many hundred days). The neutron star in a very wide orbit can only accrete from the outer low-density regions of the circumstellar disc, which explains the low X-ray luminosity. The long periods of increased X-ray luminosity seen in both systems could be associated with the dissipation of the discs (Haberl et al. 1998). Type II outbursts are very likely to be the corresponding events in systems with close orbits.

## 5. Discussion

The X-ray luminosities of all the objects listed in Tables 1 and 2 are too high for the expected luminosities of Be + WD binaries, estimated to be in the range $10^{29} - 10^{33}$ erg s$^{-1}$ (Waters et al. 1989), indicating that they contain neutron stars. It is worth noting that only three of these sources could be observed by *Hipparcos*. The distances given in Table 1 for A 0535+262 and 4U 1145−619 are those derived from their spectral types, since Steele et al. (1998) have shown that the distances to A 0535+262 and LS I +61°303 calculated by *Hipparcos* (which are based on very poor astrometric solutions) are inconsistent with several other distance indicators (and, at least in the case of A 0535+262, its X-ray spectrum, which can only be explained in terms of accretion on to a neutron star). This could also be true of the distance to 4U 1145−619. Since $\gamma$ Cas seems unlikely to be a binary X-ray source (Smith et al. 1998), the sample of objects with accurate distances in CI98 consists of only one confirmed Be/X-ray binary and eight unconfirmed identifications. Six of these objects have spectral types later than B3 (up to B8) and therefore there is an almost negligible statistical probability that they are extracted from the same population as the optical components of standard Be/X-ray binaries. Moreover, if these identifications are correct, they represent a class of objects with much lower X-ray luminosities than those on our sample of Be/X-ray binaries (and this also applies to the two objects with spectral types in the acceptable range, HD 34921 and BZ Cru). The conclusion is that, if the identifications are correct, they represent a class of objects extracted from a different population to the standard Be/X-ray binaries.

Can they represent a sample of the population of Be + WD binaries? Since we have no previous sample of this population, we do not know its spectral distribution. Indeed, the only known white dwarf orbiting a massive star is the companion of the B5V star HR 2875 (Vennes et al. 1997). However, there is a major drawback to this interpretation: if the X-ray activity of these sources is attributed to accretion on to a white dwarf, centrifugal inhibition is not a possibility and there is no reason why these systems should not be persistent X-ray sources. However,

none of these sources has been detected during the Rosat All-Sky Monitor survey, in spite of thorough searches for possible binaries (Meurs et al. 1992; Motch et al. 1997). Berghöfer et al. (1996) list BZ Cru, $\mu^2$ Cru and HD109857 (the three objects in the sample that appear in the BSC) as non-detections. No detections of any of the objects have been reported since the discovery paper, where it is reported that BZ Cru and HD 34921 (the two B0 counterparts) had been observed by other satellites (Tuohy et al. 1988).

If the identification of these X-ray sources with the proposed Be stars is real, they represent a population of very low luminosity transients. These low-luminosity transients cannot be explained in terms of Be + WD binaries or neutron stars in very wide orbits – since these objects would not be transients. The simplest explanation is that most of these counterparts – if not all – are really field Be stars and not accreting binaries, i.e., they are not optical counterparts to X-ray sources. This is not surprising, given that they were proposed only because of positional coincidence with very large error boxes. The sample used by CI98 is, in consequence, not representative of Be/X-ray binaries and therefore their conclusions do not apply to these systems.

## 6. Conclusions

We have studied the global characteristics of Be/X-ray binaries by comparing the properties of different systems. We find that all the optical counterparts have spectral types in the range O8-B2, which represents a distribution very different from that of isolated Be stars. The very different spectral type distribution of Be/X-ray binaries and isolated Be stars sets strong limits on acceptable models of close binary evolution.

We have developed a coherent model to explain the different X-ray properties of Be/X-ray binaries, in which the main parameter is the size of the orbit of the neutron stars. Systems with close orbits are fast spinners and show no quiescence emission as a consequence of centrifugal inhibition. When the density distribution in the circumstellar disc of the Be star becomes very asymmetric, they become bright transients. Systems with wide orbits are persistent sources accreting from a low-density radial outflow and display no large outbursts. Systems with intermediate orbits present a mixture of both behaviours.

We have shown that the sample recently used to conclude that Be/X-ray binaries are low-luminosity X-ray sources containing white dwarfs consists of objects extracted from a different population and therefore it is not relevant to the study of Be/X-ray binaries.

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