Be/X-ray binaries: An observational approach

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Abstract. Be/X-ray binaries are the most numerous class of X-ray binaries. They constitute an excellent tracer of star formation and can be used to study several aspects of astrophysics, from mass loss in massive stars to binary evolution. This short review, intended for the non-specialist, presents a summary of their basic observational properties and outlines the physical mechanisms giving rise to these characteristics.

1. What are we calling a Be/X-ray binary?

A Be/X-ray binary can be trivially defined as a binary system containing a Be star, which, for some reason, produces X-ray emission. Modern reviews of the properties of Be/X-ray binaries can be found in Nagase (2001, concentrating on X-ray properties) and Coe (2000, mainly optical observations). A Be star is trivially defined as “a non-supergiant B-type star whose spectrum has, or had at some time, one or more Balmer lines in emission” (Collins 1987). However, such trivial definitions are necessarily too broad. If we want to define a class of objects with common physical characteristics, these definitions need some qualification.

For a start, we concentrate on “classical Be stars”, early-type (mostly B-type, but also late O-type) stars which show emission lines because they are surrounded by a disk of material lost from their equator (see Porter & Rivinius 2003 for a recent review; see also Balona 2000; Slettebak 1988). The mass loss in a classical Be star is due to causes intrinsic to the star itself (though binary companions, when present, may have some triggering effect; cf. Miroshnichenko et al. 2003). In a Be/X-ray binary, emission lines should be associated with a classical Be star and come from such a decretion disk (Okazaki 2001). A system like the black hole candidate LMC X-3 (Cowley et al. 1983) is not a Be/X-ray binary, as the emission lines most likely come from an accretion disk around the black hole. The case of the bright transient A 0538−66 is less clear, as it looks like a Be star during quiescence states, but has a spectrum completely different from a Be star when in outburst (Charles et al. 1983) and displays optical variability unprecedented in a Be star (McGowen & Charles 2003).

At present, we know the optical counterparts of > 20 Be/X-ray binaries in the Galaxy and > 10 in the Large Magellanic Cloud (LMC). A relatively up-to-date list of massive X-ray binaries, with their properties, is given by Liu et al. (2000) and a recent list of Be/X-ray binaries and candidate is provided by Popov & Raguzova (2004). All the counterparts have spectral type earlier than B2 (Negueruela 1998). As a matter of fact, the spectral distrib-
tion of the counterparts is very strongly peaked around spectral types B0-B0.5 (Negueruela & Coe 2002), suggesting that they all have similar masses.

It is important to note that isolated Be stars do also display X-ray emission. Early-type (<B2) stars in general show X-ray emission with \( L_X \sim 10^{-7} L_{bol} \) (see Berghöfer et al. 1997; see also Harnden et al. 1979; Pallavicini et al. 1981) and Be stars may be marginally brighter (Cohen 2000). In order to have an X-ray binary, the main X-ray source must not be the Be star, but a binary companion, specifically a compact companion: a white dwarf, neutron star or black hole (a general review of the properties of X-ray binaries can be found in White et al. 1995).

The compact companion has no immediate observational signatures apart from the X-ray emission. The optical/infrared flux is completely dominated by the Be star (van Paradijs & McClintock 1995). This results in a fundamental observational bias: an object is recognised as a Be/X-ray binary because it shows an X-ray flux higher than expected for an isolated Be star of its spectral type. Considering the uncertainties in the X-ray flux expected, and more importantly, in the distance and reddening derived to a single star, it is relatively difficult to establish whether a given star fulfills this criterion. Objects displaying an \( L_X \) much higher than an isolated Be star are readily identified as Be/X-ray binaries, while objects only one or two orders of magnitude brighter than an isolated Be star fall into a “grey zone”, where their binary nature is difficult to ascertain. Because of this, the population of objects well studied – and even the population of objects known – is strongly biased toward high \( L_X \) sources, even if they show up as such only sporadically.

If we can accumulate enough photons, we can always look for signatures of the compact companion in the X-rays, such as a characteristic X-ray spectrum, or X-ray pulsations. With sufficient monitoring, tell-tale variability may be detected. A determination of \( P_{\text{spin}} \) (which, of course requires observations over a few years) may allow the differentiation between a neutron star and a white dwarf. So with unlimited observing time on very sensitive X-ray telescopes, the observational bias toward high \( L_X \) systems could perhaps be removed, but, as we stand, it is very obviously present and, for many weak X-ray sources, we simply do not know if they are Be/X-ray binaries or not.

So far, all Be/X-ray binaries that have been observed with sufficient sensitivity have revealed the signatures of a neutron star. Indeed, X-ray pulsations have always been found, the only exception being the microquasar 1E 0236.6+6100 (see below).

A final question to consider is the origin of the X-ray emission. Traditionally, one talks of X-ray binaries when the physical mechanism producing the X-rays is accretion on to a compact object. There are cases, however, when other sources of energy are available. One clear example is the radio pulsar PSR B1259–63, which orbits the Be star LS 2883 (Johnston et al. 1992). The neutron star is young and powered by dissipation of rotational energy. X-rays are believed to originate in shocks at the interface between the pulsar wind and the disk of the Be star (Murata et al. 2003, and references therein). Another system that could be powered by rotational energy is the 34-ms pulsar SAX J0635+0533 (Cusumano et al. 2000). The microquasar 1E 0236.6+6100 could be similar to PSR B1259–63 (Maraschi & Treves 1981), though an accretion-powered source
is currently favoured [Massi 2004]. All these objects have properties widely differ-
thing from those of the majority of Be/X-ray binaries and will thus be excluded
from the following, where we concentrate on systems containing an X-ray pulsar
accreting from the disk of a classical Be star.

2. X-ray properties

As mentioned, all Be/X-ray binaries, when observed with sufficient sensitivity,
display X-ray pulsations, a signature of the strong magnetic field ($B \sim 10^{12}$ G)
of a neutron star. The presence of X-ray pulsations allows the determination of
the orbital parameters of the system, such as the orbital period, $P_{\text{orb}}$, and ec-
centricity, $e$ (e.g., Rappaport et al. 1978; Finger et al. 1999). The X-ray spectra
of Be/X-ray binaries are very similar to those of other accreting X-ray pulsars,
as they depend mostly on the physical conditions close to the neutron star (cf.
Bildsten et al. 1997). They can generally be characterised by broken power laws,
with a high-energy cutoff and absorption at low energies due to interstellar ma-
terial (White et al. 1995; Nagase 2001). In a few systems with low interstellar
absorption, there is evidence for a soft blackbody component at low energies
(Nagase 2001).

The first Be/X-ray binaries were identified as bright X-ray transient sources
(Maraschi et al. 1976), but, as new systems were discovered, very different be-
haviours were observed. Some Be/X-ray binaries are persistent X-ray sources
(see Reig & Roche 1999), displaying low luminosity ($L_x \sim 10^{34}$ erg s$^{-1}$) at a
relatively constant level (varying by up to a factor of $\sim 10$). On the other
hand, most known Be/X-ray binaries (though this is likely a selection effect)
undergo outbursts in which the X-ray luminosity suddenly increases by a factor
$\gtrsim 10$. A given transient can show one or both of the two kinds of outbursts (cf.
Stella et al. 1986):

- X-ray outbursts of moderate intensity ($L_x \sim 10^{36}$ erg s$^{-1}$) occurring in
  series separated by the orbital period (Type I or normal), generally close
to the time of periastron passage of the neutron star. In most systems,
the duration of normal outbursts seems related to the orbital period.

- Giant (or Type II) X-ray outbursts ($L_x \gtrsim 10^{37}$ erg s$^{-1}$) lasting for several
  weeks or even months. Generally, Type II outbursts start shortly after
  periastron passage, but do not show any other correlation with orbital
  parameters (Finger & Prince 1997). In some systems, the duration of the
  Type II outbursts seems to be correlated with their peak intensity, but
  this is not always the case (cf. Finger et al. 1996; Motch et al. 1991).

During giant outbursts, and sometimes during normal outbursts, the spin
period of the neutron star is observed to increase (neutron star spin-up), indicat-
ing that angular momentum is efficiently transfered from the material accreted
to the neutron star, most likely through an accretion disk (e.g., Finger et al.
1999; Wilson et al. 2003).

The X-ray spectra of persistent sources show some differences with respect
to those of transients in outburst (Reig & Roche 1999). Moreover, all persistent
Figure 1. X-ray lightcurves of representative Be/X-ray binaries, from the All Sky Monitor on board *RossiXTE*, spanning 800 days. **Bottom panel.** Lightcurve of the prototype persistent source X Persei. The flux is always different from zero and varies smoothly. Sharp peaks are mostly associated with low signal-to-noise points or solar contamination. **Mid panel.** Lightcurve of EXO 2030+375, showing a long series of Type I outbursts, close to the time of periastron. **Top panel.** The Be/X-ray transient X0656−072 displays a single Type II outburst after \( \sim 30 \) years of inactivity. The scale of the vertical axis in the different panels is very different, allowing an estimation of the level of variability. X Persei is the Be/X-ray binary closest to the Sun known and its flux varies between \( \sim 10^{34} - 10^{35} \) erg s\(^{-1}\). The Type I outbursts in EXO 2030+375 generally reach \( \sim 10^{37} \) erg s\(^{-1}\). The distance to X0656−072 has not been determined yet, but generally Type II outbursts reach close to \( \sim 10^{38} \) erg s\(^{-1}\).
sources have relatively long pulse periods, > 200 s, while transients have periods ranging from less than one second to several hundred seconds.

Be/X-ray binaries fall within a narrow area in the $P_{\text{orb}}/P_{\text{spin}}$ diagram (see Corbet 1986). This correlation between $P_{\text{orb}}$ and $P_{\text{spin}}$ is generally interpreted as meaning that the neutron stars in Be/X-ray binaries rotate at the equilibrium velocity between the spin-up caused by accreted matter and the spin down caused by the centrifugal effect of their strong magnetic fields (Waters & van Kerkwijk 1989). The correlation is loose, and there are some clear exceptions (for instance, X0726−260; Corbet & Peele 1997).

3. Optical/infrared properties

As mentioned above, the optical/infrared properties of Be/X-ray binaries are those of the Be star, and so very similar to those of isolated Be stars: emission in the Balmer lines and some singly-ionised metallic lines, infilling or emission in the He I lines and an infrared excess with respect to B-type stars of the same spectral type, resulting in photometric variability (cf. Porter & Rivinius 2003; Slettebak 1988).

In Be/X-ray binaries, the maximum strength of Hα ever measured correlates with the size of the orbit, measured through $P_{\text{orb}}$ (Reig et al. 1997). This is understood as a consequence of the interaction between the neutron star and the disk of the Be star. In the truncated viscous disk model (Okazaki & Negueruela 2001), the tidal torque of the neutron star truncates the disk at the resonances between the orbital periods of disk particles and the neutron star. As a consequence, material accumulates in the disk, explaining why the disks of Be/X-ray binaries appear denser than those of isolated Be stars (Zamanov et al. 2001). This situation is necessarily unstable and will eventually lead to major perturbations in the disk structure. Such perturbations will result in the onset of the giant outbursts (Negueruela et al. 2001).

In several systems, we observe relatively quick (a few years) quasi-periodic cycles, during which the disk forms, grows, gives rise to X-ray activity and then disappears (e.g., Reig et al. 2001; Haigh et al. 2004). In the well-studied system 4U0115+63, these quasi-cycles are highly repeatable (Negueruela et al. 2001). As the mechanisms involved are rather complex, the correlation between the optical and infrared lightcurves and the X-ray lightcurves are rather loose (e.g., Clark et al. 1999). Similar quasicycles are observed in isolated Be stars, though they tend to last longer than in Be/X-ray binaries (e.g., Clark et al. 2003).

The size of the truncated disk depends strongly on the orbital parameters of the system, notably the semi-major axis and $e$. If $e$ is large, truncation is not very effective and the Be/X-ray binary is expected to display Type I outbursts at every periastron passage (similarly to EXO 2030+375 in Fig. 1). If $e$ is low, truncation is very effective and activity should be rare. In intermediate cases, more complex behaviour is expected (Okazaki & Negueruela 2001; Okazaki et al. 2002).

X Per, the prototypical persistent source, is known to have a wide, low-$e$ orbit (Delgado-Martí et al. 2001). Because of their long $P_{\text{spin}}$ and the $P_{\text{orb}}/P_{\text{spin}}$ correlation, all persistent Be/X-ray binaries are believed to have similar orbits. The existence of Be/X-ray binaries with both low and high values of $e$ has
a bearing on models for their formation (van den Heuvel & van Paradijs 1997; Pfahl et al. 2002) and may even have implications for our understanding of supernovae (Podsiadlowski et al. 2004).

4. The population of Be/X-ray binaries

Be/X-ray binaries are thought to be the product of the evolution of a binary containing two moderately massive stars, which undergoes mass transfer from the originally more massive star on to its companion (see Pols et al. 1991; Verbunt & van den Heuvel 1995; van Bever & Vanbeveren 1997). As such, they are necessarily young and trace recent star formation.

Be/X-ray binaries are very numerous. Extrapolations from the observed numbers suggest that there are a few thousands of them in the Galaxy (van Paradijs & McClintock 1995), while estimates based on population synthesis models predict that the number of B-type stars with a neutron star companion is $>10,000$ (Meurs & van den Heuvel 1989). Some authors have assumed that the mass transfer phase leading to the formation of the Be/X-ray binary necessarily forces the B-type companion of a neutron star to be a Be star. This is at present not an obvious conclusion (see discussion in van Bever & Vanbeveren 1997) and it may well be that the majority of these systems can never be seen as X-ray sources: if the B-type star is not in a Be phase, the neutron star has nothing to accrete.

A major discrepancy between population synthesis models and observations are the relative numbers of Be/X-ray binaries (Be + neutron star) and their lower $L_X$ relatives, the Be + white dwarf (wd) binaries. All models predict very large numbers of Be+wd systems, in most cases outnumbering Be/X-ray binaries by a factor $>10$ (e.g., van Bever & Vanbeveren 1997; Raguzova 2001). Unfortunately, though there are a few candidates to be Be+wd binaries (Motch et al. 1997; Torrejón & Orr 2001), so far no system has been unambiguously confirmed to be a Be+wd binary by observations.

There are strong selection effects against the detection of Be+wd binaries. For a start, their expected $L_X$ is not much higher than that of an isolated Be star. Their relatively soft X-ray spectra are strongly affected by interstellar absorption, meaning that it becomes difficult to differentiate them from weak Be/X-ray binaries with neutron stars in wide orbits (and hence slow pulsations). In spite of this, because of their large numbers, we should expect to have found some in our immediate neighbourhood, but searches for them have so far failed (Meurs et al. 1992), rendering population synthesis models somewhat suspect.

5. The SMC: laboratory for the Be/X-ray binaries

For the last few years, observations with a new generation of X-ray telescopes offering good spatial resolution have revealed the presence of a huge population of Be/X-ray binaries in the Small Magellanic Cloud (SMC; cf. Haberl & Sasaki 2000; Yokogawa et al. 2003). To date, there are close to 40 X-ray pulsars in the SMC (Haberl & Pietsch 2004). All of them, except SMC X-1, are Be/X-ray binaries. Such large population of objects at a given distance, with similar chemical composition, and very little affected by interstellar absorption renders the SMC the perfect laboratory to study Be/X-ray binaries.
The main limitation of the SMC is its large distance. Dedicated pointings with X-ray telescopes are needed to detect X-ray pulsations and existing and previous all sky monitors do not detect or resolve its sources. For this reason, knowledge of the orbital parameters of SMC Be/X-ray binaries is almost null. However, some promising techniques are being developed. Majid et al. (2004) have shown that, because of the $P_{\text{orb}}/P_{\text{spin}}$ correlation, there is a good statistical correlation between the maximum observed $L_X$ and $P_{\text{spin}}$, which can hence be used as a measurement of orbital size. Moreover, Laycock et al. (2004) show how $P_{\text{orb}}$ can sometimes be derived from observations with non-imaging instruments.

Among the first fruits of work on the large SMC sample of Be/X-ray binaries, Laycock et al. (2004) show an excellent correlation between the distribution of Be/X-ray binaries and star-forming regions in the SMC, a promising result for the study of more distant galaxies. Meanwhile, Coe et al. (2004) find that the spectral distribution of counterparts to SMC Be/X-ray binaries is very different from that of Milky Way systems, seriously challenging many current models.

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