Be/X-ray Binaries: An Observational Approach

I. Negueruela

*Dpto. de Física, Ingeniería de Sistemas y Teoría de la Señal,
Universidad de Alicante, Apdo. 99, E03080 Alicante, Spain*

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. 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". 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). 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.

At present, we know the optical counterparts of > 20 Be/X-ray binaries in the Galaxy and > 10 in the Large Magellanic Cloud (LMC). All the counterparts have a spectral type earlier than B2. As a matter of fact, the spectral distribution of the counterparts is very strongly peaked around spectral types B0-B0.5, suggesting that they all have similar masses.

It is important to note that isolated Be stars do also display X-ray emission. Early-type stars ($<$B2) in general show X-ray emission with $L_{\rm X} \sim 10^{-7} L_{\rm bol}$ 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.

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. 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 derived to a single star, it is relatively difficult to establish whether a given star fulfils 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. So with unlimited observing time on very sensitive X-ray telescopes, the observational bias toward high L_X systems could be removed, but, as we stand, it is very obviously present. 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. 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, though an accretion-powered source is currently favoured. All these objects have properties widely differing 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 above, 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_{orb}, and eccentricity, e. 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 material. In a few systems with low interstellar absorption, there is evidence for a soft blackbody component at low energies.
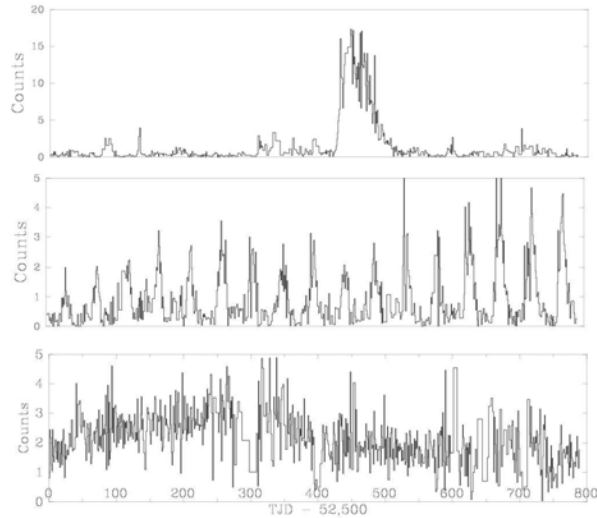
Figure 1.   X-ray light-curves of representative Be/X-ray binaries, from the All Sky Monitor on board *Rossi-XTE*, spanning 800 days. **Bottom panel.** Lightcurve of the prototype persistent source X Persei. The flux is always different from zero and varies smoothly. Sharp peaks are mostly associated 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 ~ 30 years of inactivity. Note the very different scale of the vertical axis.

The first Be/X-ray binaries were identified as bright X-ray transient sources, but, as new systems were discovered, very different behaviours were observed. Some Be/X-ray binaries are persistent X-ray sources (see Reig & Roche 1999), displaying low luminosity ($L_{\rm x} \sim 10^{34}\,{\rm erg\,s^{-1}}$) at a relatively constant level (varying by up to a factor of ~ 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:

- X-ray outbursts of moderate intensity ($L_{\rm x} \sim 10^{36}$ 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 ($L_{\rm x} \gtrsim 10^{37}$ 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 most cases, the spin period of the neutron star is observed to increase during the outbursts (neutron star *spin-up*), indicating 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. Moreover, all persistent sources have relatively long pulse-periods, $> 200\,\mathrm{s}$, while transients have periods ranging from less than one second to several hundred seconds.

Be/X-ray transients fall within a narrow area in the $P_{\mathrm{orb}}/P_{\mathrm{spin}}$ diagram (see Corbet 1986). This correlation between P_{orb} and P_{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.

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).

In Be/X-ray binaries, the maximum strength of Hα ever measured correlates with the size of the orbit, measured through P_{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, Coe & Fabregat 2004). In the well-studied system 4U 0115+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 light-curves and the X-ray light-curves 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.

The size of the truncated disk depends strongly on the orbital parameters of the system, notably the semimajor 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. X Per, the prototypical persistent source, is known to have a wide, low-e orbit. Because of their long P_{spin} and the $P_{\mathrm{orb}}/P_{\mathrm{spin}}$ correlation, all *persistent* Be/X-ray binaries are believed to have similar orbits. The observed distribution of e values in Be/X-ray binaries may 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 onto its companion (see Van Bever & Vanbeveren 1997, and references therein). 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, 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, no such system has been observationally confirmed.

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). However, 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). To date, there are close to 40 X-ray pulsars in the SMC. All of them, except SMC X-1, are Be/X-ray binaries. Such a 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_{orb}/P_{spin} correlation, there is a good statistical correlation between the maximum observed L_X and P_{spin}, which can hence be

used as a measurement of orbital size. Moreover, Laycock et al. (2005) show how $P_{\rm orb}$ can sometimes be derived from observations with non-imaging instruments.

Among the first results of the work on the large SMC sample of Be/X-ray binaries, Laycock et al. (2005) 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. (2005) 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.

References

Bildsten, L., et al. 1997, ApJS, 113, 367
Clark, J.S., et al. 1999, MNRAS, 302, 167
Coe, M.J., et al. 2005, MNRAS, 356, 502
Cohen, D.H. 2000, In: Smith, M., Henrichs, H.F., & Fabregat, J. (eds.) IAU Colloq.
        175, The Be Phenomenon in Early-Type Stars. ASP, San Francisco, p. 156
Corbet, R.H.D. 1986, MNRAS, 220, 1047
Cowley, A.P., et al. 1983, ApJ, 272, 118
Cusumano, G., et al. 2000, ApJ, 528, L25
Finger, M. H., & Prince, T. A. 1997, In Proceedings of the Fourth Compton Symposium,
        AIP, Woodbury, NY, part 1, p. 57
Finger, M.H., et al. 1999, ApJ, 517, 449
Haigh, N.J., Coe, M.J., & Fabregat, J. 2004, MNRAS, 350, 1457
Laycock, S., et al. 2005, ApJS, 161, 96
Majid, W.A., Lamb, R.C., & Macomb, D.J. 2004, ApJ, 609, 133
Meurs, E.J.A., & van den Heuvel,E.P.J. 1989, A&A, 226, 88
Meurs, E.J.A., et al. 1992, A&A, 265, L41
Miroshnichenko, A.S., et al. 2003, A&A, 408, 305
Murata, K., et al. 2003, PASJ, 55, 473
Negueruela, I., et al. 2001, A&A, 369, 117
Okazaki, A.T. 2001, PASJ, 53, 119
Okazaki, A.T.,& Negueruela, I. 2001, A&A, 377, 161
Podsiadlowski, Ph., et al. 2004, ApJ, 612, 1044
Porter, J.M.,& Rivinius, T. 2003, PASP, 115, 1153
Raguzova, N.V. 2001,A&A, 367, 848
Reig, P., & Roche, P. 1999, MNRAS, 306, 100
Reig, P., Fabregat, J., & Coe, M.J. 1997, A&A, 322, 183
Reig, P., et al. 2001, A&A, 367, 266
Van Bever, J., & Vanbeveren, D. 1997, A&A, 322, 116
Waters, L.B.F.M., & van Kerkwijk, M.H. 1989, A&A, 223, 196
Wilson, C.A., et al. 2003, ApJ, 584, 996
Zamanov, R.K., et al. 2001, A&A, 367, 884

Discussion

Stan Owocki: Thank-you very much - I learned a tremendous amount from this talk and it's really very fascinating. One of the things that is really great about this is that these X-ray binaries are giving you the ability to really probe the conditions of the disk. Since you believe that a Be X-ray binary is most likely a case where you had mass exchange and the Be star was spun up, as opposed to some internal evolution of an isolated star, I would ask: Did you ever see the star when it was a Be star and then it went through one of these quiescent phases? In other words, has there ever been a case that was known to be a Be X-ray binary, then became an ordinary B star?

Ignacio Negueruela: Yes, it happens all the time. Basically, as I showed, the evolution of Hα is basically telling you that they undergo cycles of disk formation.

Stan Owocki: So they do just like the single stars.

Ignacio Negueruela: Yes, and even quicker, actually.

Stan Owocki: And during these times when it doesn't have the Be emission, then the X-ray pulsation shuts off?

Ignacio Negueruela: Yes.

Ken Gayley: I wonder if that relates to the issue that you say you don't see a white dwarf plus a Be star in this situation. Is it possible that's because you're imagining conservative mass-transfer, whereas if it's highly non-conservative, it would have to start from a very massive star as the companion?

Ignacio Negueruela: I don't know. I'm not the one who makes the models! They predict that for every Be X-ray binary, there's going to be about 10 white-dwarf systems. And as I've said, we don't have any convincing candidate. Well, we have some candidates that could be a neutron star and a white dwarf in a close orbit. But there's nothing in the spectral type of the companion, X-ray properties or whatever, that really pushes you to think this is a white dwarf system. So there *may* be some around, but from the observational point of view we are not really sure. In the same sense we are completely sure there are lots with neutron stars and we are completely sure there are *none* with black holes (BH).

Dany Vanbeveren: Yes, but isn't that more an observational problem? It's very difficult to detect the white dwarf when it has a Be companion.

Philipp Podsiadlowski: I have a comment and a question. First the comment. You know of these very faint Chandra X-ray sources in the Galactic centre. I think many of them could actually be these low-luminosity Be X-ray binaries you were talking about. The other thing is, in your truncation model you get a

very low eccentricity. Can you give us an estimate of the error bar or is that for the next talk?

Ignacio Negueruela: It's probably better to ask Atsuo.

Ignacio Negueruela

Atsuo Okazaki