

## The X-ray outbursts of Be/X-ray transients

Ignacio Negueruela

*SAX Science Data Center, ASI, c/o Nuova Telespazio, via Corcolle 19,  
I00131 Rome, Italy*

Atsuo T. Okazaki

*Faculty of Engineering, Hokkai-Gakuen University, Toyohira-ku, Sapporo  
062-8605, Japan*

**Abstract.** We present a new scenario for the behaviour of Be/X-ray binaries based on long-term multiwavelength monitoring and the decretion disc model. The circumstellar discs of the primaries are truncated because of the tidal and resonant effect of the neutron star. The geometry of the systems and the value of viscosity determine the presence or absence of Type I X-ray outbursts. The interaction of a strongly disturbed disc with the neutron star originates Type II X-ray and optical outbursts.

### 1. Introduction

Be/X-ray binaries are composed of a neutron star orbiting a Be star and accreting from its circumstellar disc. The high-energy radiation is believed to arise due to accretion of material associated with the Be star by the compact object (see Negueruela 1998; see also Bildsten et al. 1997). 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 probably a selection effect) undergo periods in which the X-ray luminosity suddenly increases by a factor  $\gtrsim 10$  and are termed Be/X-ray transients. The distinction between the two groups is difficult to establish solely on terms of the temporal behaviour, since some sources such as A 1118–61 and 4U 1145–619 display relatively weak outbursts, though there is some evidence that the X-ray spectral properties of the two groups could be different.

Be/X-ray transients fall along a relatively narrow area in the  $P_{\text{orb}}/P_{\text{spin}}$  diagramme (see Corbet 1986; Waters & van Kerkwijk 1989), indicating that some mechanism must be responsible for the correlation. Those systems with fast-spinning neutron stars do not show pulsed X-ray emission during quiescence (though non-pulsed radiation could be caused by accretion on to the magnetosphere) because of the centrifugal inhibition of accretion (Stella et al. 1986). Systems with more slowly rotating pulsars show X-ray emission at a level  $L_x \lesssim 10^{35}$  erg s $^{-1}$  when in quiescence. Transients show two different kinds of outbursts:

- Moderate intensity X-ray outbursts ( $L_x \approx 10^{36} - 10^{37} \text{ erg s}^{-1}$ ) occurring in series separated by the orbital period (Type I or normal), generally (but not always) close to the time of periastron passage of the neutron star. The duration of these outbursts seems to be related to the orbital period.
- Giant (or Type II) X-ray outbursts ( $L_x \gtrsim 10^{37} \text{ erg s}^{-1}$ ), lasting several weeks. The parameters of these outbursts do not correlate clearly with orbital parameters, though in A 0535+26 and 4U 0115+63 they seem to start always a few days after periastron passage.

## 2. Radial outflows vs. quasi-Keplerian discs

Waters et al. (1989) tried to model the X-ray luminosities of Be/X-ray transients during outbursts making use of a simple wind accretion model, in which the neutron star accretes from a relatively fast radial outflow. The density in the disc of the Be primary was assumed to follow a power law, as in Waters (1986) model for Be stars. In this scenario, the most relevant parameter is the relative velocity between the outflow and the neutron star, since the X-ray luminosity can then be expressed as

$$L_x = 4\pi G^3 M_x^3 R_x^{-1} v_{\text{rel}}^{-4} F_m \propto \rho v_{\text{rel}}^{-3} \quad (1)$$

where  $M_x$  and  $R_x$  are the mass and radius of the neutron star and  $F_m = \rho v_{\text{rel}}$  is the mass flow. In order to explain the wide range of observed X-ray luminosities, large changes in the value of the radial velocity have to be invoked. For example, Waters et al. (1989) deduced that the relative velocity was  $v_{\text{rel}} \approx 300 \text{ km s}^{-1}$  during a Type I outburst of V 0332+53 in 1983, while it was  $\ll 100 \text{ km s}^{-1}$  during a Type II outburst in 1973.

There is a large number of implicit assumptions in this formulation, some of which are difficult to justify, but two obvious problems stand up. The first one is the low-luminosity X-ray emission displayed by many Be/X-ray transients when they are not in outburst (for example, several detections of A 0535+26 at luminosities of  $\approx 2 \times 10^{35} \text{ erg s}^{-1}$  by Motch et al. 1991). The model does not offer any explanation as to why there could be a change from quiescence to outburst, unless very large and sudden changes in the density and velocity of the flow are assumed, while optical and infrared observations do not show any sign of the large variations that would be associated with a change of several orders of magnitude in the density of material.

The major objection to the model is simply the fact that there is no observational evidence whatsoever supporting the existence of such fast outflows. All observations of Be discs imply bulk outflow velocities smaller than a few  $\text{km s}^{-1}$ . The evidence for rotationally dominated quasi-Keplerian discs around Be stars is overwhelming (see Hanuschik et al. 1995; Hummel & Hanuschik 1997), specially due to the success of the one-armed global oscillation model to explain V/R variability in the emission lines of Be stars (see Okazaki 1991, 1997; Papaloizou et al. 1992; Hummel & Hanuschik 1997).

The discovery by Reig et al. (1997) of a correlation between the maximum equivalent width reached by the  $\text{H}\alpha$  emission line in Be/X-ray binaries and their orbital period strongly suggested that the neutron star had some kind of effect

on the disc of the Be primary. Other observational facts, such as circumstantial evidence for the discs in Be/X-ray binaries being optically thicker than those of isolated Be stars, added further support to this idea.

This, together with the increasing evidence for quasi-Keplerian discs around Be stars, has prompted us to investigate whether the properties of Be/X-ray binaries can be better explained if we assume that the disc surrounding the Be primary is a viscous decretion disc. Due to space limitations, we will not try to argue the case here, but refer the interested reader to future publications (Negueruela & Okazaki 2000; Negueruela & Okazaki, in preparation) and concentrate on the derived model. We just note that the choice of the viscous decretion disc model has been prompted by its success at explaining observational characteristics of Be stars (Lee et al. 1991; Porter 1999; Okazaki 2001), but it is not a necessary condition for the majority of the conclusions below. As a matter of fact, the tidal and resonant interaction of the neutron star can effectively truncate the Be star disc for any model in which the outflow velocity in the disc is subsonic.

### 3. Disc truncation

A viscous decretion disc is held by the outwards diffusion of angular momentum due to viscous interaction. This viscous torque communicates angular momentum to the outflowing material, allowing it to follow quasi-Keplerian orbits. A neutron star orbiting the Be star exerts a negative torque on the material which takes away angular momentum. The competing effects of viscosity and resonant torques determine the radial distance at which the disc will be truncated. The effect of the neutron star is most strongly felt at the  $n : 1$  commensurabilities between the orbits of the neutron star and material at that distance, and truncation is likely to take place there. For every resonance  $n : 1$ , there is a critical value of the viscosity parameter,  $\alpha_{\text{crit}}$ , such that if  $\alpha < \alpha_{\text{crit}}$ , the disc is truncated at that resonance. The value of  $\alpha_{\text{crit}}$  depends on the orbital parameters of the system under consideration.

Fig. 1 shows the values of  $\alpha_{\text{crit}}$  that will cause truncation at a given resonance radius for a number of Be/X-ray binaries. The systems have been modelled using as masses for the Be primaries those corresponding to their spectral type, when accurately determined. GRO J1008–57 and EXO 2030+375, were assumed to have spectral type B0V and mass  $M_* = 18 M_{\odot}$ . The orbital parameters are those determined from the analysis of Doppler-shift in the pulse arrival time during X-ray observations. Assuming reasonable values for the viscosity ( $\alpha \sim 0.1$ ), we find that all systems, except GRO J1008–57, will be truncated at either the 4 : 1 or 3 : 1 resonance radius. In all five systems, the likely truncation radii are very close to the size of the effective Roche radius at periastron.

For the systems with close orbits (4U 0115+63, V 0332+53 and EXO 2030+375), the first Lagrangian point  $L_1$  is always further away than the 3 : 1 resonance (see Figure 2). In A 0535+26, on the other hand,  $r(L_1) < r(3 : 1)$  close to periastron, while  $r(L_1) > r(4 : 1)$  always. Similarly, for GRO J1008–57  $r(L_1) < r(6 : 1)$  close to periastron, while  $r(L_1) > r(7 : 1)$  always.

The scenario suggested by these results is as follows. For close systems, the truncation of the disc prevents the accretion of significant amounts of material

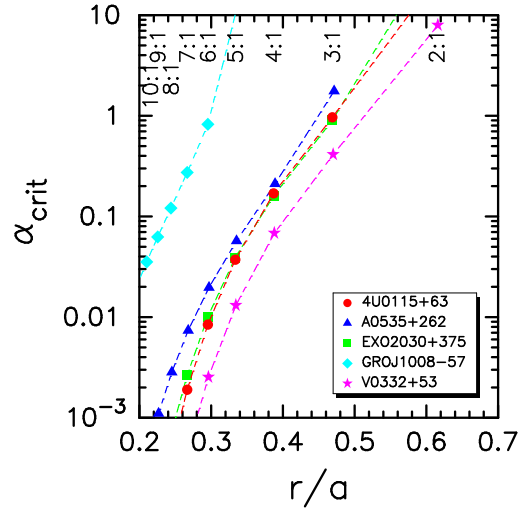


Figure 1. Values of  $\alpha_{\text{crit}}$  for several Be/X-ray binaries. The lower axis shows the distance from the central star (normalised to the mean orbital separation  $a$ ) at which truncation will occur for a given viscosity. The position of the  $n : 1$  commensurabilities is indicated under the upper axis.

by the neutron star. Even though the truncation is not expected to be 100% effective, centrifugal inhibition of accretion for very low accretion rates (Stella et al. 1986) leads to the absence of quiescence X-ray luminosity. However, these systems can still present series of Type I outbursts if the discs surrounding the central Be stars are very disturbed. If some sort of perturbation, such as a global density wave (Okazaki 1997) or radiation-induced warping (Porter 1998), produces an eccentric disc, then material can be accreted through  $L_1$  close to periastron. This situation will lead to short and irregular series of X-ray outbursts, very likely showing decreasing intensity as in the 1996 series of outbursts of 4U 0115+63 (Negueruela et al. 1998).

Systems with wider orbits, such as A 0535+26 and GRO J1008–57 can show series of Type I outbursts if the viscosity is high enough to allow the disc to extend beyond  $r(L_1)$ . Small changes in the viscosity can result in the system switching on or off for relatively long periods. The outbursts in one series will be of approximately the same strength, unless some other effects are involved (it is not clear, for example, how a mediating accretion disc could affect the mass transfer).

The scenario seems to reproduce well the observed properties of most of the systems. Both 4U 0115+63 and V 0332+53 show extended periods of quiescence during which no X-ray emission at all is detected. V 0332+53 seems to have kept a very small disc for the last  $\sim 7$  years (Negueruela et al. 1999). The outer rim of the  $H\alpha$  emitting region, as determined from the peak separation, is at a distance similar to our calculation for the 4 : 1 resonance. 4U 0115+63 has only once displayed a series of Type I outbursts in  $\sim 30$  years of observations and this was when the disc of the Be star was very disturbed (Negueruela et al. 1998). V 0332+53 has only displayed a series of three Type I outbursts since its

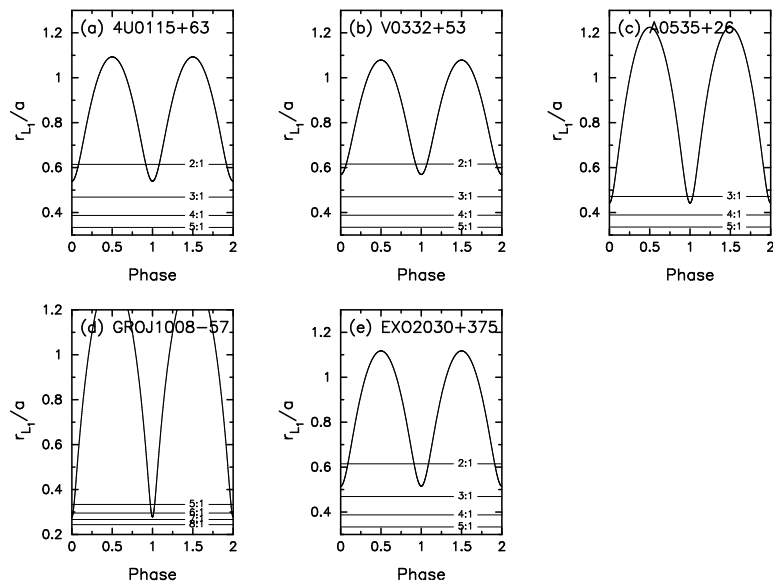


Figure 2. Some orbital parameters for the Be/X-ray binaries considered in the text. The distance of the first Lagrangian point  $L_1$  (normalised to the mean orbital separation  $a$ ) is plotted against orbital phase. The position of the  $n : 1$  commensurabilities is indicated by the horizontal lines.

discovery. Another source with comparable behaviour is 2S 1417–62, which has similar orbital parameters.

On the other hand, A 0535+26 shows longer series of Type I outbursts as well as long periods of quiescence (during which it displays low-luminosity X-ray emission). The change between these two states can be explained as a consequence of small variations in the physical conditions in the disc which result in the outer edge moving between the 3 : 1 and 4 : 1 resonances.

It must be pointed out that the behaviour of EXO 2030+375 is very different from that predicted, since it displays very long series of Type I outbursts, similar to those predicted for systems with larger eccentricities. In principle, it could be argued that this is an indication of very high viscosity ( $\alpha \sim 1$ ), but we note that there is no observational knowledge about the stellar parameters of the central star, which is too heavily obscured to allow even an approximate spectral classification. The actual values for the mass and radius of the Be star could be very different from those used here.

#### 4. Disc dynamics and Type II outbursts

An interesting consequence of the model presented above is the fact that the discs surrounding the Be primaries cannot reach a steady state. Material, hav-

Table 1. Orbital and stellar parameters used in the modelling of the Be/X-ray binaries considered. For references, see Negueruela (1998). The orbital parameters for GRO J1008–57 are based on the best fit to the BATSE data (M. Scott, priv. comm.). Data marked with a ‘\*’ are assumed values.

Name	$P_s$ (s)	$P_{orb}$ (d)	$e$	Optical Counterpart	Spectral Type	Mass ( $M_\odot$ )
4U 0115+63	3.6	24.3	0.34	V635 Cas	B0.2V	18
V 0332+53	4.4	34.2	0.31	BQ Cam	O8.5V	20
A 0535+26	103.5	110.3	0.47	V725 Tau	O9.7III	23
GRO J1008–57	93.5	247.5	0.66	star	B0V*	18*
EXO 2030+375	41.7	46.0	0.36	star	B0V*	18*

ing lost the angular momentum needed to outflow, will fall back and form a dense torus close to the truncation resonance. This situation will lead to the dynamical instability of the disc, which will produce large-scale perturbations, such as warping or global density waves. Such perturbations will either lead to the dispersion of the disc or settle down after some time. Therefore we expect the discs to undergo cycles of reformation and dissipation and/or major perturbations and resettling.

In the case of V635 Cas, the optical counterpart to 4U 0115+63, spectroscopic monitoring has shown that the Be star undergoes cycles of disc reformation, warping and dissipation with time-scales of 3–5 years (see Figure 3). These cycles are reflected in the X-ray behaviour of the source, which has shown quasi-periodicities of  $\sim 3$  years, associated with the main cycle, and  $\sim 6 - 8$  months, when the perturbed disc is precessing. BQ Cam, the optical counterpart to V 0332+53, on the other hand, suffered some major perturbation around the time of its last Type II outburst in 1989, but then settled down to a semi-steady state (Negueruela et al. 1999). Unfortunately, monitoring of the optical counterparts to other sources has been very sparse.

The large perturbation in the disc of V725 Tau, the optical counterpart to A 0535+26, which occurred at the time of its last Type II outbursts (Negueruela et al. 1998) has led to the gradual dissipation of the circumstellar envelope (see Haigh et al. in this proceedings). Such behaviour is reminiscent of that observed in V635 Cas and is probably indicating some similarly quasi-cyclical activity on a longer time-scale.

The association of large-scale perturbations and Type II outbursts in Be/X-ray binaries had already been noted by Negueruela et al. (1998). The observations of V635 Cas showing very fast changes in the shape and width of the emission lines indicate that the circumstellar disc of this source can become warped and precess. Observations from 1989 (covering the last three cycles of disc loss and reformation) indicate that X-ray activity occurs only after the disc is warped, showing that it is the perturbation in the disc which leads to the outburst, and not otherwise. This is perfectly consistent with the model outlined above. Estimates of the accretion rates during Type II outbursts show that a

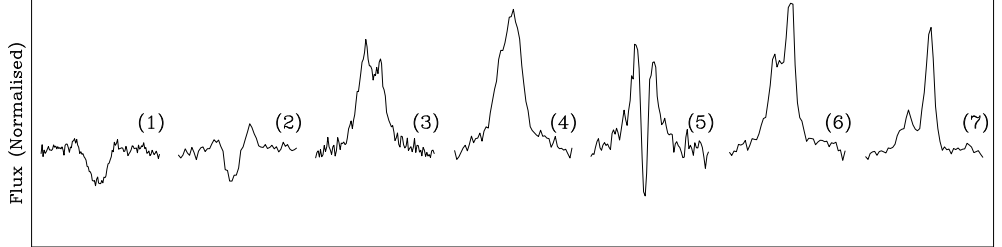


Figure 3. A hypothetical cycle for the  $H\alpha$  line in V635 Cas, the optical counterpart to 4U 0115+63, created by superposing the observations from 1997–1998 (profiles 1–4; present cycle) and those from 1995–1996 (profiles 5–7; end of previous cycle). The cycle starts with the absence of the circumstellar disc (profile 1). When the disc appears (2), it quickly grows into a typical double-peaked profile (3). Gradually, the peaks converge until a single-peak profile is seen (4), indicating the warping of the disc. This is followed by a number of fast transitions between single-peaked and shell profiles (5), as the warped disc precesses. Finally, the disc is very perturbed and the asymmetry grows as the strength of the emission line decreases (6 & 7), leading to a new disc-less phase.

significant fraction of the disc material has to be accreted by the neutron star. Since the disc is truncated, accretion of large amounts of matter will only be possible if the disc has become sufficiently asymmetric and dense to overflow the truncation radius.

## 5. The global view

The main advantage of the model outlined in this paper over previous ones is that it provides a global picture, though still a very sketchy one, in which the whole phenomenology of Be/X-ray binaries is seen as deriving from a small set of simple physical facts. The truncation of the discs surrounding the Be stars by the neutron star companions provides an explanation for the long periods of quiescence, while the dependence of the truncation radius on the physical properties of the disc gives a natural way of understanding the onset of the series of Type I outbursts and their eventual disappearance. Our modelling of different systems shows that in all cases the parameters involved are such that values of the viscosity in the range expected from theoretical considerations and modelling ( $0.01 < \alpha < 1$ ) result in truncation at distances comparable to the size of the effective Roche lobe of the Be star. Moreover, in all cases, small changes of the viscosity result in variations in the distance at which truncation takes place.

As a consequence of disc truncation, the circumstellar discs cannot be steady, which will lead to the development of the perturbations that have been

observed. When the perturbations give rise to large asymmetries in the density distribution, the truncation mechanism will be much less effective and large amounts of material will be able to make their way to the neutron star, producing the giant Type II outbursts.

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