TITLE
ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR**
EDITORS

Origin of the X-ray Activity of Be/X-Ray Binaries

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Abstract. In Be/X-ray binaries, the resonant torque by the neutron star truncates the Be disk at a radius smaller than the periastron distance. In systems with low eccentricity orbits, this truncation is expected to be so efficient that the neutron star cannot capture gas from the Be disk in quiescence. On the other hand, in systems with highly eccentric orbits, the resonant truncation is not efficient, so the Be disk significantly expands during the neutron star orbits far from periastron. These systems will show regular Type I X-ray outbursts. Due to the truncation, the Be disk cannot be steady. Such disks are likely to evolve toward a point at which the outer part becomes unstable to radiation-driven warping. Then, by the strong interaction between the warped disk and the stellar wind and radiation, a large amount of gas in the outer part of the disk will fall onto the neutron star and cause a Type II X-ray outburst.

1. Introduction

The Be/X-ray binaries represent the largest subclass of high mass X-ray binaries. Each system consists of a Be star and a neutron star. The orbit is genrally wide (a couple of ten days $\lesssim P_{\rm orb} \lesssim$ several hundred days) and eccentric ($0.1 \lesssim e \lesssim 0.9$).

Most of the Be/X-ray binaries show only transient X-ray activity due to transient accretion of the circumstellar matter of the Be star. Be/X-ray binaries show the following two types of X-ray outbursts:

- Periodical (Type I) outbursts ($L_{\rm x} \approx 10^{36} - 10^{37}$ erg s^{-1}), which begin close to the time of periastron passage of the neutron star and last several days to a week,
- Giant (Type II) outbursts ($L_{\rm x} \gtrsim 10^{37}$ erg s^{-1}), which show no clear orbital modulation and last several tens of days

(Stella et al. 1986; see also Negueruela et al. 1998).

Since it is the disk around the Be star that supplies the gas to the neutron star, understanding the physics of interaction between the Be disk and the neutron star is essential to understand the X-ray activity of Be/X-ray binaries. In this paper, we construct a model based on the recent development of the study of Be disks and propose some scenarios how resonantly truncated disks around Be stars control the X-ray activity of the Be/X-ray binaries.

2. Viscous Decretion Disk Model for Be Stars

The most promising model for the disks of Be stars is the viscous decretion disk model proposed by Lee et al. (1991) (Porter 1999; Okazaki 2001). In this model, the matter supplied from the equatorial surface of the star drifts outward by viscosity and forms the disk. Basic equations for viscous decretion are the same as those for viscous accretion, except that the sign of the mass flow rate is opposite. Thus, viscous decretion produces a geometrically thin, near Keplerian disk around a Be star. Such a disk is unstable to the $m = 1$ oscillation mode (Negueruela et al. 2001). These features agree well with the observed characteristics of Be disks.

3. Resonant Truncation of Viscous Disks around Be Stars

It is well known that viscous accretion disks in close binaries are truncated by tidal/resonant torques from the companion. This naturally leads us to the idea that Be disks in Be/X-ray binaries are also tidally/resonantly truncated. Observed correlation between the orbital period and the maximum value of the equivalent width of Hα line supports this idea (Reig et al. 1997). On the other hand, the conventional view of the Be/X-ray binaries assumes that the Be disk is so large that it extends beyond the periastron distance. It is, therefore, important to study whether the truncation radius is larger than the periastron distance.

In viscous disks in binary systems, the disk outer radius is the radius inside which the viscous torque $T_{\rm vis}$ is larger than the tidal/resonant torque $T_{\rm res}$. In other words, the criterion of the tidal/resonant truncation is that $T_{\rm vis} + T_{\rm res} < 0$ at a given resonant radius (Artymowicz & Lubow 1994; Negueruela & Okazaki 2001). This criterion is met for α smaller than a critical value, $\alpha_{\rm crit}$.

In order to evaluate the viscous torque in the disk, we adopt Shakura-Sunyaev's viscosity prescription and assume the Be disk to be isothermal of the temperature of $0.5T_{\rm eff}$, where $T_{\rm eff}$ is the effective temperature of the Be star. The tidal/resonant torque is averaged over the binary orbit.

Figure 1 shows $\alpha_{\rm crit}$ for Be disks in eight Be/X-ray binaries of which orbital parameters are known. From figure 1, we find that the Be disk is truncated at a radius smaller than the periastron distance for plausible range of viscosity parameter α. This means that the orbit of the neutron star never intersects in the middle of a disk as has been supposed in the conventional view of the Be/X-ray binaries. As schematically shown in figuer 2, there is a gap between the disk and the neutron star orbit.

Since the gas is continually ejected from the star but the resonant torque prevents gas from going beyond the disk outer radius, the Be disk in Be/X-ray binaries is inevitably time dependent. The gas supplied from the Be star will be accumulated near the disk outer radius. We expect that the accumulation of gas will finally make the disk unstable to radiation-driven warping (see section 5).

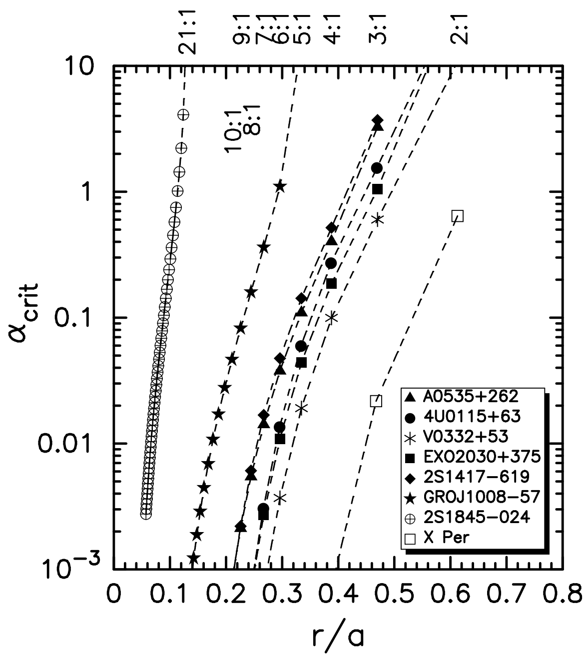

Figure 1. $\alpha_{\rm crit}$ at the $n:1$ resonance radii for eight Be/X-ray binaries of which orbital parameters are known. Numbers on top indicate the locations of the $n:1$ commensurabilities of disk and binary orbital periods.

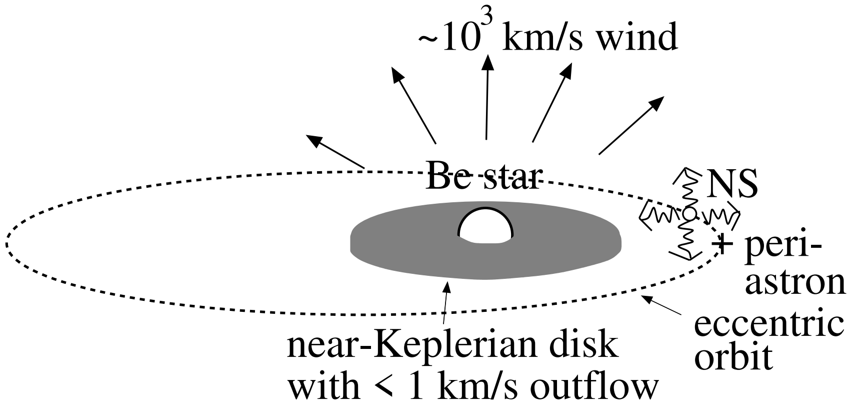

Figure 2. Schematic view of a Be/X-ray binary

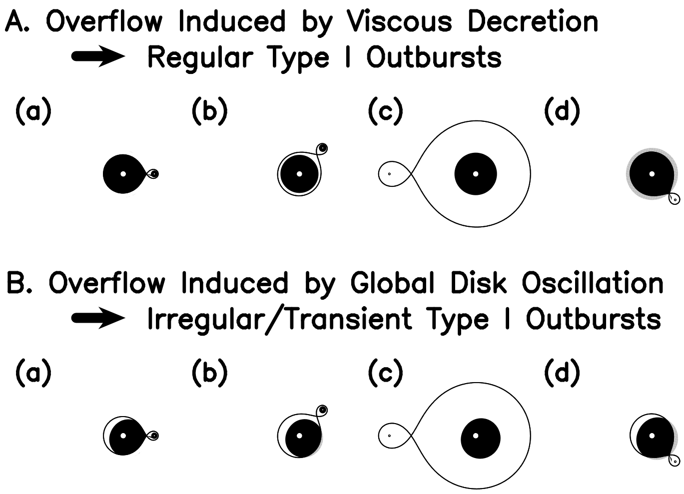

Figure 3. Two scenarios for Type I outbursts. The upper and lower panels show how mass overflow from the disk is induced by viscous decretion and by an $m = 1$ density wave, respectively. (a) Around periastron, gas overflows through the L1 point and forms the accretion disk around the neutron star. (b) At the phase at which the critical Roche radius becomes larger than the disk radius, the overflow stops and the accretion disk begins to fade. (c) During the neutron star orbits far from periastron, the disk material continues to drift outward by viscous decretion. (d) At the phase at which the critical Roche radius becomes smaller than the disk radius (elongated disk size in the lower panel), the gas in the outermost part of the disk begins to overflow. The accretion disk is formed around the neutron star.

4. Two Types of Type I Outbursts

The truncated disk radius is smaller than the periastron distance, but it is stil close to the critical Roche radius. Therefore, if some mechanism works to expand or elongate the disk, the gas in the outermost part of the disk will overflow toward the neutron star at periastron.

In systems with highly eccentric orbits, the period during which strong torque is exterted on the disk is rather limited, and the disk outer radius can expand significantly during the neutron star orbits far from periastron. Such systems will exhibit regular periodic (Type I) X-ray outbursts around periastron passage of the neutron star (panel A of figure 3).

On the other hand, in systems with low $\sim$ mild eccentricity, the disk cannot expand so much. Therefore, no regular Type I outbursts will be seen in these systems unless the truncation radius happens to be very close to the critical Roche radius. However, if the disk is strongly elongated, e.g., by the $m = 1$ density waves, the overflow of gas can occur near periastron passage of the neu-

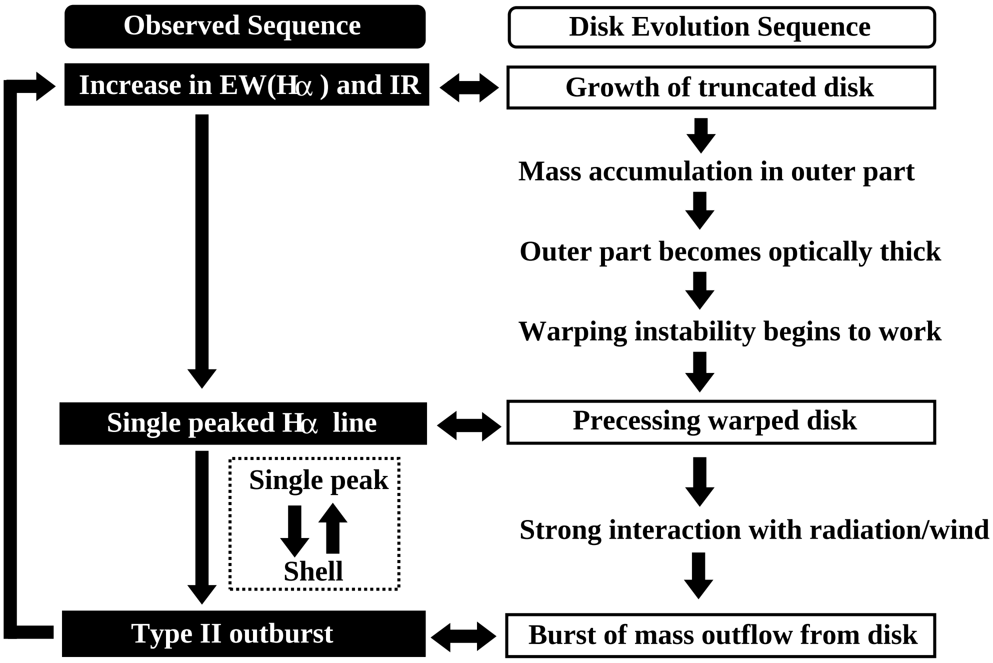

Figure 4. Observed quasi-cyclic activity of 4U 0115+63 (left part) and the corresponding sequence of Be disk evolution (right part).

tron star. Such events will be observed as transient/irregular Type I outbursts (panel B of figure 3).

5. Scenario for Type II Outbursts: Be Disk as the Mass Reservoir

Analysing multi-wavelength, long-term monitoring observations of V635 Cas, the Be star in 4U 0115+63 ($P_{\rm orb} = 24.3$ days and $e = 0.34$), Negueruela et al. (2001) found that the Be star of this system shows quasi-periodical (~ 3 years) disk formation and loss episodes. They also found that the Hα line profile, which is usually double-peaked, becomes single-peaked before a giant (Type II) X-ray outburst occurs. Moreover, this single-peaked profile was sometimes followed by the shell profile. Since the line shape is considered to reflect the inclination of the disk with respect to the line of sight, this drastic change in the line shape indicates that the Be disk was warped and began to precess (Negueruela et al. 2001). After a couple of Type II outbursts, the disk emission becomes faint. The left part of Figure 4 summarizes the observed sequence of the quasi-cyclic activity of 4U 0115+63.

Based on the disk truncation model described above, we propose the following disk evolution sequence, which is summarized in the right part of Figure 4, as the interpretation of the observed quasi-cyclic activity sequence.

After a disk loss episode, the disk is reformed by viscous decretion of material ejected from the Be star. As the disk grows, the emission from the disk increases. While the gas is continually supplied from the star and decretes outward, the outflow of gas is blocked at a truncation radius by the resonant torque. This leads the accumulation of gas in the outermost part of the disk. The disk outer part, which is optically thin in quiescence, finally becomes optically thick. At this point, it begins to be warped and precess, because an optically thick disk is unstable to radiation-driven warping (Pringle 1996; Porter 1998). As the warped disk precesses, the line profile changes its shape. The warped region of the disk is likely to have a strong interaction with the fast stellar wind and the stellar radiation. This will strongly deform and elongate the disk outer part, from which a large amount of gas will fall onto the neutron star to cause a Type II X-ray outburst. Losing a large amount of gas, the Be disk becomes fainter.

It is important to note that the truncated disk around the Be star in Be/X-ray binaries acts as a reservoir of mass. The disk accumulates gas for years to decades and eject it in a much shorter timescale. That is why Be/X-ray binaries can exhibit giant (Type II) outbursts corresponding to the mass accretion rate much higher than the mass loss rate from the Be star. It should be emphasized that it is the dynamical evolution of the resonantly truncated disk around the Be star that controls the X-ray activity of Be/X-ray binaries.

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