RESONANT TRUNCATION OF BE DISKS AND TYPE I OUTBURSTS IN BE/X-RAY BINARIES

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ABSTRACT We study the resonant interaction of neutron stars with disks around Be stars in Be/X-ray binaries, assuming that Be disks are formed by viscous decretion. Comparing the viscous and resonant torques exerted on the gas, we find that the Be disk is truncated at a radius which depends on the orbital parameters and viscosity. Based on this result, we propose two posssible scenarios for Type I X-ray outbursts in Be/X-ray binaries.

KEYWORDS: binaries: general – circumstellar matter – stars: emission line, Be – stars: neutron – X-rays: bursts

1. INTRODUCTION

Be/X-ray binaries form a major subgroup of high mass X-ray binaries. These are systems consisting of a Be star earlier than B2 and a compact star, presumably a neutron star. The orbit is generally wide and eccentric.

Be/X-ray binaries exhibit three types of X-ray activity:

- persistent low-luminosity X-ray emission ($L_X \lesssim 10^{34}\,\mathrm{erg\,s^{-1}}$),
- periodical (Type I) X-ray outbursts, coinciding with periastron passage ($L_X \approx 10^{36-37}\,\mathrm{erg\,s^{-1}}$),
- giant (Type II) X-ray outbursts ($L_X \gtrsim 10^{37}\,\mathrm{erg\,s^{-1}}$), which show no orbital modulation

(Stella et al. 1986; see also Negueruela et al. 1998), which suggest a complicated interaction between the Be-star envelope and the neutron star.

2. DECRETION DISKS AROUND BE STARS

A Be star has two-component envelope, a polar wind and an equatorial disk. The former consists of a low-density, fast outflow emitting UV radiation, while the latter consists of a high density plasma rotating at near Keplerian speed. Optical emission lines and the infrared excess arise from the equatorial disk.

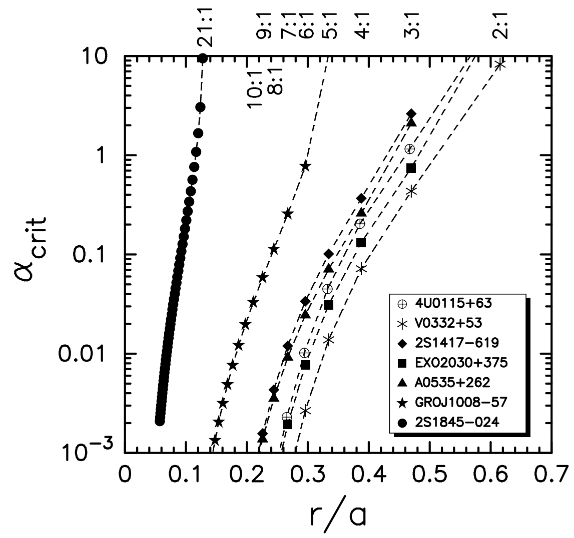

FIGURE 1. $\alpha_{\rm crit}$ at the $n:1$ resonance radii for some Be/X-ray binaries. Numbers on top indicate the locations of the $n:1$ commensurabilities of disk and binary orbital periods. The disk temperature is assumed to be 80% of the effective temperature of the Be star.

Although there is no widely-accepted model for Be disks, the viscous decretion disk model proposed by Lee et al. (1991) seems promising (see Porter 1999). 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. The outflow in the disk is very subsonic at least within several tens of stellar radii (Okazaki 2000). In addition, such a disk is unstable to the very-low frequency, $m = 1$ oscillation mode (Negueruela and Okazaki 2000). These features agree well with the observed characteristics of Be disks.

3. RESONANT TRUNCATION OF BE DISKS

From the direct comparison of the viscous torque (which is providing angular momentum to the material) and the tidal torque (which is taking angular momentum from the material) at a given resonance radius, we have the criterion for resonant truncation as

$$\alpha \le \alpha_{\rm crit} \equiv \frac{|T_{\rm reson}|}{3\pi\Sigma\Omega^2 r^2 H^2} \tag{1}$$

(Artymowicz & Lubow 1994), where α is Shakura-Sunyaev's viscosity parameter, H the scale-height of the disk, Σ the disk surface density, Ω the angular frequency of

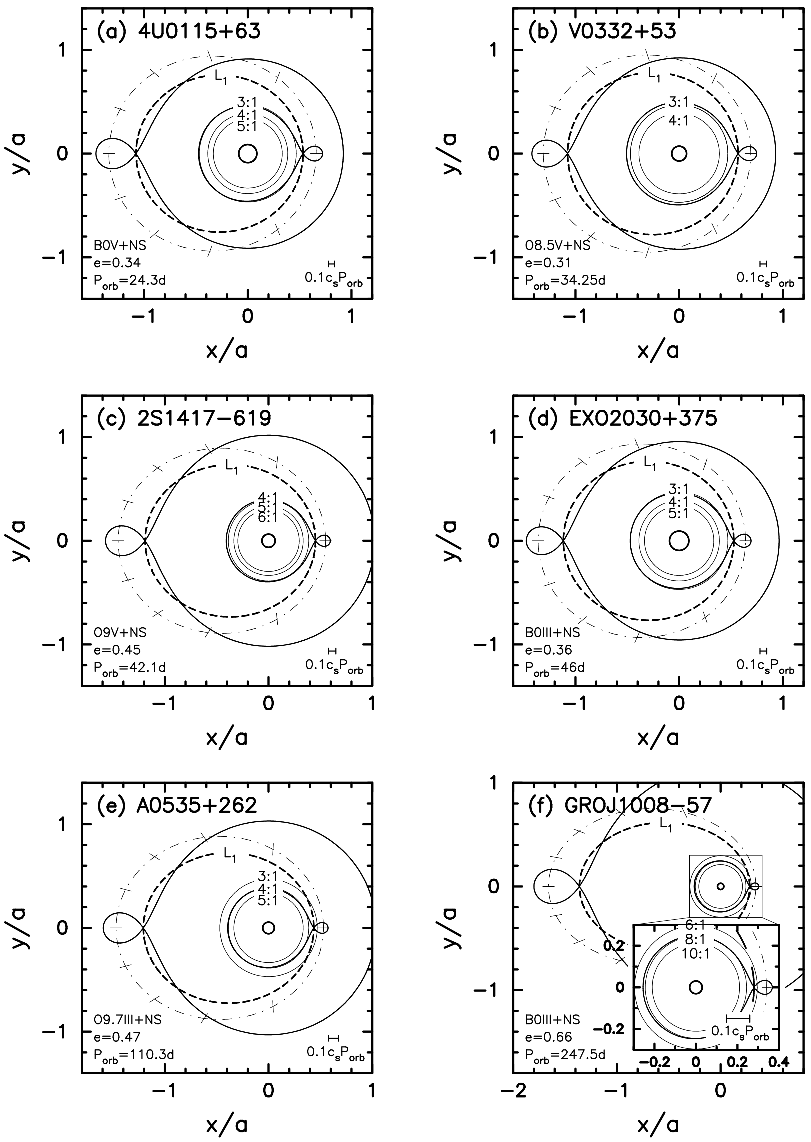

FIGURE 2. Truncated disk radii and orbital models for some Be/X-ray binaries. The dash-dotted line represents the orbit of the neutron star. The dashed line represents the L_1 point around the orbit. The thick solid lines denote the effective Roche lobes of the two stars at apastron and periastron. The thin solid lines denote the radii of the resonantly-truncated Be disk. They are for $\alpha = 0.3$, 0.1, and 0.03 from outside. Also shown is an upper limit of the distance over which the disk outer radius can expand during one orbital period.

disk rotation, and $T_{\rm reson}$ the resonant torque by the neutron star. [See Negueruela and Okazaki (2000) for details about how to compute the resonant torque.]

In Figure 1, we plot $\alpha_{\rm crit}$ at the $n:1$ resonance radii for seven Be/X-ray binary systems. The resonant torques at the $n:1$ radii are stronger than those at radii with other period commensurabilities located nearby. Figure 1 shows that the Be disk in Be/X-ray binaries should be truncated at a radius which depends on the orbital parameters and viscosity.

In Figure 2, we show the truncated disk radii and orbital models for six systems among the seven shown in Figure 1. We also show the distance scale corresponding to $0.1c_{\rm s}P_{\rm orb}$ in each panel, where $c_{\rm s}$ and $P_{\rm orb}$ are the sound speed and the orbital period, respectively. This scale should be taken as an upper limit of the distance over which the disk outer radius can expand during one orbital period, because the outflow velocity in Be disks is certainly much smaller than a few $\mathrm{km\,s^{-1}}$.

From Figure 2, we observe that the neutron star never passes through the disk at periastron, as has been described by many authors; the Be disk cannot be that large because of the resonant truncation.

4. SCENARIOS FOR TYPE I OUTBURSTS

Although the viscous decretion is a very slow process, in systems with wide orbits like A 0535+262, GROJ 1008-57, and 2S 1845-024, the outer radius of the resonatly-truncated Be disk can expand significantly during the neutron star orbits far from periastron. Such systems will exhibit regular periodic (Type I) outbursts around periastron, if the viscosity is large enough ($\alpha \gtrsim 0.1$) to allow the disk outer radius to expand beyond the L_1 point. Systems with close orbits can also show regular Type I outbursts, if the viscosity is so large ($\alpha \lesssim 1$) that the truncated disk almost fills the effective Roche lobe at periastron.

For other systems such as wide orbit systems with small viscosity ($\alpha \ll 0.1$) or close orbit systems without very high viscosity ($\alpha \lesssim 0.1$), we expect no Type I outbursts as long as the disk is axisymmetric. Be disks are, however, known to often suffer global $m = 1$ perturbations and become elongated. If the $m = 1$ perturbation makes the disk elongated toward periastron by chance, the Roche lobe overflow can occur around periastron passage. In such systems, we will observe transient and/or irregular Type I outbursts.

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