# Tidal Truncation of Be-Star Disks in Be/X-Ray Binaries

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**Abstract**

We study the tidal truncation of disks around Be stars in Be/X-ray binaries, assuming that the Be-star disks are formed by viscous decretion. With Shakura-Sunyaev's $\alpha$-viscosity, we find that a critical value of viscosity parameter, $\alpha_{\rm crit}$, exists at each resonance radius. The disk is truncated at a given resonance if $\alpha < \alpha_{\rm crit}$. With the disk radii estimated from the H$\alpha$ observations for A 0535+262 and 4U 0115+634, we evaluate the tidal truncation criterion and find that $\alpha \sim 0.1$ is compatible with those disk radii. By the viscous effect, the decretion disks are overstable for eccentric ($m = 1$) modes.

## 1. Introduction

Be/X-ray binaries form a major subset of high mass X-ray binaries. These are systems consisting of a Be star earlier than B2 and a compact star, which is mostly a neutron star. The orbit is wide and eccentric. The orbital period ranges from several tens of days to several hundred days.

A Be star has two-component envelope, a polar region and an equatorial disk region. 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. Balmer lines arise from the disk region. Some systems exhibit long-term ($1 \sim 2\,$yr) variations in the Balmer line profiles. These variations can be attributed to the $m = 1$ oscillations of Be-star disks (Negueruela et al. 1998a; Clark et al. 1998).

X-ray activity of Be/X-ray binaries is due to the accretion of the envelope of the Be star onto the compact star. Be/X-ray binaries exhibit several types of X-ray activity [See Stella et al. (1986) for details. See also Negueruela et al. (1998a)], which would result from a complicated interaction between the Be star envelope and the compact star.

For Be/X-ray biraries, the maximum equivalent width of the H$\alpha$ line correlates with the orbital period of the system (Reig et al. 1997). This indicates that the equatorial disks around Be stars in Be/X-ray binaries are truncated by something related to the binary separation.

## 2. Viscous Descretion Disk Model for Be Stars

Lee et al. (1991) proposed a viscous decretion disk model for Be stars. In this model, the matter supplied from the equatorial surface of the star drifts outward by the viscous effect, and forms the disk. Basic equations for viscous decretion disks are the same as those for viscous accretion disks, except that the sign of $\dot{M}$ (mass decretion/accretion rate) is opposite. Viscous decretion disks around Be stars are thus geometrically thin and near Keplerian as cool accretion disks are. The outflow is highly subsonic near the star. These features agree well with observed features of Be-star disks. For simplicity, we assume in this paper that the decretion disk is isothermal with the temperature of $0.8T_{\rm eff}$, where $T_{\rm eff}$ is the effective temperature of the Be star.

## 3. Tidal Truncation of Viscous Disks around Be Stars

From the direct comparison of the viscous torque and the tidal torque applied to the gas at a given resonance radius, we have the criterion for marginal tidal truncation as

$$3\pi\alpha\left(\frac{H}{r}\right)^2 = \frac{T_{\rm tidal}}{\Sigma\Omega^2 r^4} \tag{1}$$

(Artymowicz & Lubow 1994), where $H$ is the scale-height of the disk, $T_{\rm tidal}$ is the tidal torque by the compact star, $\Sigma$ is the surface density of the disk, and $\Omega$ is the angular frequency of disk rotation.

We evaluate this criterion for two Be/X-ray binary systems, A 0535+262 and 4U 0115+634. The A 0535+262 system consists of a neutron star orbiting the O9.7IIIe star HD 245770 (=V725 Tau). The orbit is wide ($P_{\rm orb} = 110.3\,{\rm d}$) and eccentric ($e = 0.47$). The 4U 0115+634 system consists of a neutron star orbiting the B0.2Ve star V635 Cas in a relatively close ($P_{\rm orb} = 24.3\,{\rm d}$) and eccentric ($e = 0.34$) orbit. These systems are chosen because the system parameters are observationally well determined. Table 1 lists some resonance radii and the critical values of viscosity parameter, $\alpha_{\rm crit}$, for which the criterion (1) for marginal tidal truncation is met. The disk is truncated at a given resonance if $\alpha < \alpha_{\rm crit}$.

In principle, we can constrain the value of $\alpha$ in decretion disks around Be stars in Be/X-ray binaries by evaluating the criterion (1) at the observed disk sizes. Since no direct measurement of disk sizes has been done for Be/X-ray

Table 1. Criterion for marginal tidal truncation.

| resonance | A 0535+262 | | 4U 0115+634 | |
|---|---|---|---|---|
| | $r/a$ | $\alpha_{\mathbf{crit}}$ | $r/a$ | $\alpha_{\mathbf{crit}}$ |
| 3:1 | 0.47 | $4.1 \cdot 10^{-1}$ | 0.47 | $7.4 \cdot 10^{-1}$ |
| 4:1 | 0.39 | $8.0 \cdot 10^{-2}$ | 0.39 | $1.6 \cdot 10^{-1}$ |
| 5:1 | 0.34 | $2.8 \cdot 10^{-2}$ | 0.33 | $3.3 \cdot 10^{-2}$ |

binaries, we take the size of the H$\alpha$-emitting region, which can be estimated from the separation of double peaks of the line profile, as an approximate value to the disk size.

Clark et al. (1998) studied the long-term variability of A 0535+262 and found that the H$\alpha$ line profiles taken from 1994 September to 1996 Feburuary were relatively stable. The peak separation of the H$\alpha$ line during this period varied around 5.2Å. Taking the stellar parameters from Vacca et al. (1996) and the inclination angle of 46° (Negueruela, private communication), we have the disk size $r_{\rm disk}/a \sim 0.57$ for A 0535+262, which can be marginally consistent with being the 3:1 resonance radius.

For 4U 0115+634, Negueruela et al. (1997) reported that the peak separation of the H$\alpha$ line was about 440km s$^{-1}$ and did not change noticeably in 1992 and 1993. Using the stellar parameters and the inclination angle of Negueruela et al. (1998b), we obtain $r_{\rm disk}/a \sim 0.35$ for 4U 0115+634. The Be-star disk of 4U 0115+634 can be truncated at ∼4:1 resonance radius. Note that $\alpha \sim 0.1$ is compatible with the observed disk sizes for these systems.

## 4. Eccentric ($m = 1$) Modes in Viscous Decretion Disks

Figure 1(a) shows the steady structure of the viscous decretion disk around the Be star of A 0535+262. The disk structure of the Be star of 4U 0115+634 is quite similar to that of A 0535+262. In viscous, isothermal decretion disks, the surface density decreases as $r^{-2}$, the radial velocity, which is highly subsonic, increases as $r$, and the rotaion velocity is near Keplerian.

By the viscous effect, decretion disks are overstable for eccentric ($m = 1$) modes, of which the growth rate is of the order $\alpha(H/r)^2\Omega$. Figure 1(b) shows the fundamental eccentric mode in the Be-star disk of A 0535+262. The eccentric mode in the Be-star disk of 4U 0115+634 is similar to that of A 0535+262. The characteristics of the modes agree with the long-term ($1 \sim 2\,$yr) variabilities of the Balmer line profiles observed for these Be/X-ray binaries.

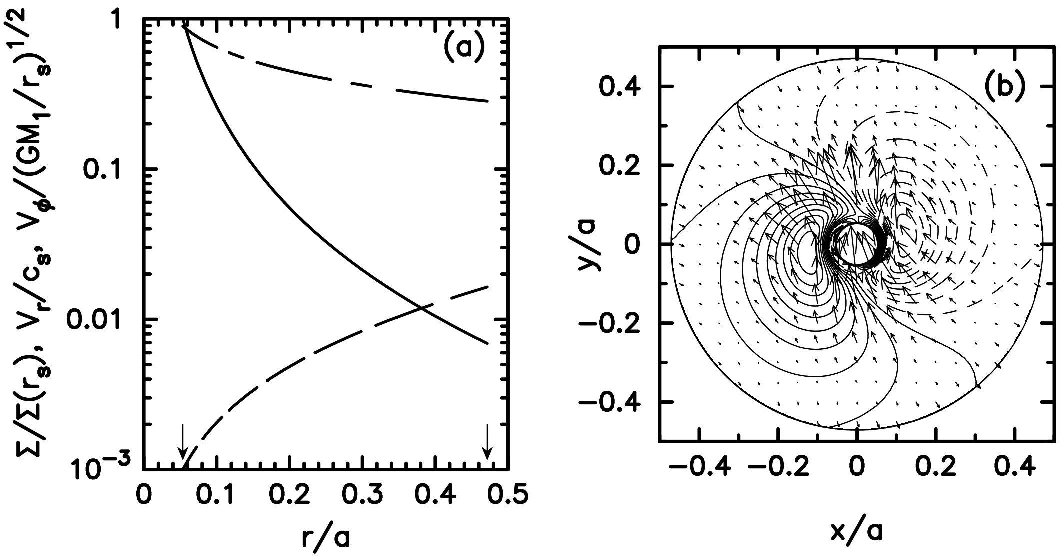


Fig. 1. (a) Steady structure of a viscous decretion disk around the Be star of A 0535+262. Solid, dashed, and dash-dotted lines denote $\Sigma/\Sigma(r_{\rm s})$, $V_r/c_{\rm s}$, and $V_\phi/(GM_1/r_{\rm s})^{1/2}$, respectively, where $M_1$ and $r_{\rm s}$ are the mass and radius of the Be star, respectively, $V_r$ and $V_\phi$ are the radial and azimuthal velocity components, and $c_{\rm s}$ is the isothermal sound speed. We adopt $\alpha = 0.1$ and $V_r(r_{\rm s})/c_{\rm s}(r_{\rm s}) = 10^{-3}$. The radiative force in the form of $\eta(r/r_{\rm s})^\epsilon \times GM_1/r^2$ with $(\eta, \epsilon) = (0.2, 0.1)$ is included. Two downward arrows denote the inner and outer disk radii. (b) Linear, fundamental $m = 1$ mode in the Be-star disk of A 0535+262. The period of the mode is 1.5 yr and the growth time is 9.3 yr. The disk rotates counterclockwise. The contours denotes the relative density perturbation in linear scale. The solid (dashed) contours are for the region with positive (negative) density enhancement. The arrows show velocity vectors associated with the perturbation.

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