Active OB Stars: Laboratories for Stellar and Circumstellar Physics
ASP Conference Series, Vol. 361, 2007
S. Štefl, S. P. Owocki and A. T. Okazaki

Interaction between the Viscous Decretion Disk and the Neutron Star in Be/X-ray Binaries

A.T. Okazaki[1] & K. Hayasaki[2,3]

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

[2] *Department of Applied Physics, Graduate School of Engineering, Hokkaido University, Kita-ku, Sapporo 060-8628, Japan*

[3] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, Victoria 3122, Australia*

Abstract. We report on the results from numerical simulations of the interaction between the viscous decretion disk around the Be star and the neutron star in Be/X-ray binaries. For simplicity, both the Be decretion disk and the neutron star accretion disk are assumed to be isothermal and Shakura-Sunyaev's viscosity prescription is adopted. The Be disk is tidally/resonantly truncated at a radius smaller than the periastron distance, except in systems with very high orbital eccentricities and/or large inclination angles. In misaligned systems, the Be disk precesses little when the mass is supplied continuously from the central star, whereas it precesses in the retrograde direction when no mass is supplied. The truncated Be disk in an eccentric orbit makes the mass transfer rate towards the neutron star strongly phase dependent and sensitive to the orbital eccentricity. In highly eccentric systems, a transient accretion disk is formed around the neutron star after every periastron passage. The peak mass-accretion rate in these systems falls within a typical luminosity range of the periodic X-ray outbursts in Be/X-ray binaries. This strongly suggests that, in the framework of the truncated Be disk model for Be/X-ray binaries, periodic X-ray outbursts are a phenomenon most frequently seen in highly eccentric systems.

1. Introduction

Be stars have two-component envelopes: a polar wind and an equatorial disk. In contrast to the highly-supersonic polar wind, the equatorial disk is nearly Keplerian and has small radial flow with the upper limit of $\sim 1\mathrm{km\,s^{-1}}$ (Hanuschik 1994; Hanuschik 2000; Waters & Marlborough 1994). The most likely mechanism to make such a disk around the star is viscosity. The viscous decretion disk model proposed by Lee et al. (1991) explains many observational features of Be disks. According to this model, the central star provides angular momentum to the disk at the innermost radius, and then it is redistributed over the whole disk via viscosity. Thus, in isolated Be stars, the equatorial disk can spread out to a large distance as long as the star can give angular momentum to the disk. On the other hand, in binary Be stars, the companion exerts a negative, resonant torque on the disk at radii where there is a commensurability between the disk and binary orbital periods. Given that the specific angular momentum in a Keplerian disk increases with radius, the negative torque by the companion can truncate the equatorial disk at a resonant radius. The truncation will, then, affect the structure and evolution of the equatorial disk.

The Be/X-ray binaries are one of the most interesting classes of binaries to study the effect of the companion on the dynamics of Be disk. They consist of a Be star and a neutron star with wide ($10\,\mathrm{d} \lesssim P_{\mathrm{orb}} \lesssim 300\,\mathrm{d}$) and mostly eccentric ($e \gtrsim 0.3$) orbits. Most of the Be/X-ray binaries show only transient X-ray activity, one of which are periodic (Type I) X-ray outbursts ($L_{\mathrm{X}} \approx 10^{36-37}\,\mathrm{erg\,s^{-1}}$) separated by the orbital period. Based on the viscous decretion disk model, Negueruela & Okazaki (2001) and Okazaki & Negueruela (2001) semi-analytically showed that the coplanar Be disk in Be/X-ray binaries is truncated at a radius smaller than the periastron distance, as long as $\alpha \ll 1$, where α is the Shakura-Sunyaev viscosity parameter. The result agrees with the observations by Reig et al. (1997) and Zamanov et al. (2001) that there is a positive correlation between the orbital period and the maximum equivalent width of Hα line ever observed in a system, a measure of the maximum disk size around the Be star in the system. The resonantly truncated disk scenario has also been confirmed by numerical simulations for a system with a short orbital period and a moderate orbital eccentricity (Okazaki et al. 2002).

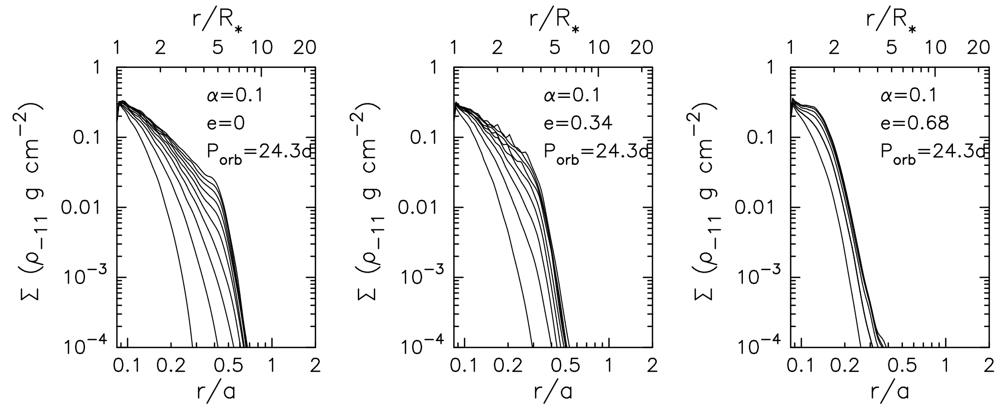
In this paper, we explore the interaction between the Be disk and the neutron star in Be/X-ray binaries, based on the results from three dimensional Smoothed Particle Hydrodynamics (SPH) simulations for a wide range of orbital parameters.

2. Numerical Model

We use a 3D SPH code, in which the Be disk and the accretion disk are modeled by an ensemble of gas particles of negligible masses and the Be star and the neutron star by two sink particles with corresponding masses (Okazaki et al. 2002; Hayasaki & Okazaki 2004; see also Bate et al. 1995). Gas particles which fall within a specified accretion radius are accreted by the sink particle. As the accretion radius, we adopt R_* for the Be star, where R_* is the stellar radius, and $5 \times 10^{-3}a$ for the neutron star, where a is the semi-major axis of the system. For simplicity, we assume that both disks are isothermal at half the effective temperature of the Be star and have the viscosity parameter of $\alpha_{\mathrm{SS}} = 0.1$. The orbital period P_{orb} is fixed to be 24.3 d. We set the binary orbit on the x-z plane with the major axis along the x-axis. At $t = 0$, the neutron star is at the apastron. The mass ejection mechanism from the Be star is modeled by constant injection of gas particles at a radius just outside the equatorial surface. As the Be star, we take a B0V star of $M_* = 18M_\odot$, $R_* = 8R_\odot$, and $T_{\mathrm{eff}} = 26,000\,\mathrm{K}$. For the neutron star, we take $M_X = 1.4M_\odot$ and $R_X = 10^6\,\mathrm{cm}$.

3. Be Disks in Coplanar Systems

Fig. 1 shows the surface density evolution of the viscous decretion disk around the Be star with different eccentricity: (a) $e = 0$, (b) $e = 0.34$ and (c) $e = 0.68$. In these simulations, the Be disk is coplanar with the binary orbital plane. As shown in Fig. 1, the decretion disk around the Be star is tidally/resonantly truncated at a radius depending on the orbital eccentricity. The truncation radius, which is smaller for larger orbital eccentricity, is significantly smaller than the periastron distance. Since the resonant torque prevents disk material from drifting outwards, the disk density increases more rapidly than in disks around isolated Be stars. Note that the truncation is more efficient for a lower orbital eccentricity, as expected from the semi-analytical study. The tidal/resonant truncation does not work in extremely high eccentricity ($e \gtrsim 0.8$).



(a) (b) (c)

Figure 1. Surface density evolution of a coplanar, decretion disk: (a) $e = 0$, (b) $e = 0.34$, and (c) $e = 0.68$. The time interval between adjacent contours is $5P_{\rm orb}$. ρ_{-11} is the disk base density normalized by $10^{-11}{\rm g\,cm^{-3}}$.

The resonant truncation of Be disks in Be/X-ray binaries gives an interesting possibility. A sub-class of dwarf novae show superhumps, which are photometric light humps that repeat with a period slightly longer than the orbital period. These superhumps are caused by the tidally-driven eccentric instability at the 3:1 resonance radius (e.g., Lubow 1991). Given that viscous decretion disks in Be/X-ray binaries with low eccentricity are truncated at the 3:1 resonance radius (see Fig. 1a), we expect similar phenomenon in such Be/X-ray binaries. The discovery of superhumps in low-eccentricity Be/X-ray binaries would give further support for the viscous decretion disk model for Be disks.

4. Be Disks in Misaligned Systems

The resonant truncation also works for misaligned systems as it does for coplanar ones. The truncation, however, is less efficient for a larger inclination angle i. Little truncation is seen for $i > 60°$. When truncated, the surface density evolution of misaligned decretion disks is similar to that of coplanar ones.

It is known that accretion disks misaligned with respect to the orbital plane are known to precess in the retrograde direction because of the tidal torque by the companion. When the sound-crossing times-scale is shorter than the precession time-scale, rigid-body, retrograde precession of an accretion disk is possible (Papaloizou & Terquem 1995). It is interesting to see whether this is also the case with Be decretion disks.

Fig. 2 shows the long-term change in the tilt angle β (dashed line) and azimuth of the tilt γ (solid line) of a misaligned Be disk. In this simulation, the rotation axis of the Be star is tilted about y-axis by 30 degrees (i.e., initially $\beta = \pi/6$ and $\gamma = 0$). Gas particles are injected at the equatorial surface of the star at a constant rate for the first $50\,P_{\mathrm{orb}}$ (Panel a), and then the injection of particles is turned off for the next $50\,P_{\mathrm{orb}}$ (Panel b). In Fig. 2b, the theoretical precession rate of an accretion disk (Bate et al. 2000) is also shown by the dash-dotted line for the same density distribution and orbital parameters. As shown in Fig. 2a, the Be disk shows little precession when the mass is continuously supplied. The rotation axis of the disk is kept aligned with that of the central star. When the mass supply is shut off, however, the disk begins to precess in the retrograde direction. The precession rate increases towards an asymptotic value, which coincides with the theoretical precession rate of an accretion disk.

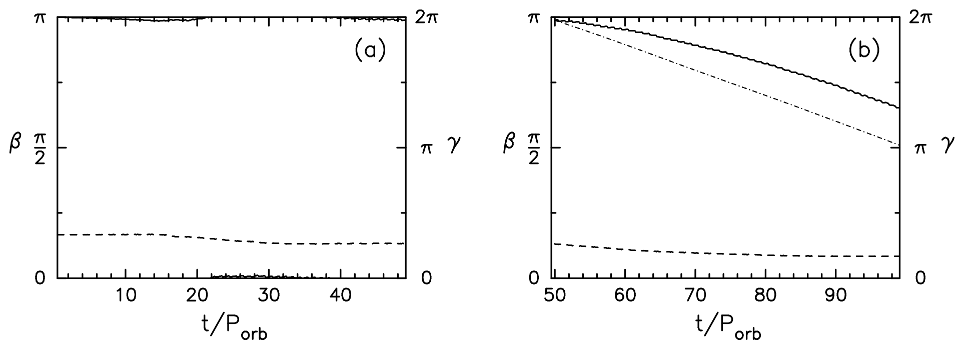


Figure 2. Long-term evolution of the tilt angle β (dashed lines) and azimuth of the tilt γ (solid lines) of a misaligned Be disk. The rotation axis of the Be star is tilted about y-axis by 30 degrees. Gas particles are injected at the equatorial surface of the star at a constant rate for the first $50\,P_{\mathrm{orb}}$ (Panel a), and then the particle injection is turned off for the next $50\,P_{\mathrm{orb}}$ (Panel b). The dash-dotted line in Panel b shows the theoretical precession rate for an accretion disk with the same density distribution and orbital parameters.

5. Accretion Disks in Moderately Eccentric Systems

Okazaki & Negueruela (2001) discussed that the X-ray behavior of moderately eccentric Be/X-ray binaries depends on rather subtle details of system parameters. Systems with the Be disk truncated in the vicinity of the critical lobe will frequently exhibit X-ray outbursts after periastron passage, whereas those with the Be disk significantly smaller than the critical lobe will normally show no periodic outburst.

Recently, Hayasaki & Okazaki (2004, 2005, 2007) studied the accretion flow around the neutron star in a Be/X-ray binary with a short period ($P_{\mathrm{orb}} = 24.3\,\mathrm{d}$) and a moderate eccentricity ($e = 0.34$), performing SPH simulations. These orbital parameters are for 4U 0115+63, one of the best studied Be/X-ray binaries. They found that, in this particular system, the peak accretion rate onto the neutron star falls below an observed luminosity range of periodic X-ray outbursts. Thus, the system is likely in the quiescent state, which explains the normal in-activity of 4U 0115+63 in X-rays. They also found that a persistent accretion disk is formed and grows secularly. This suggests that Be/X-ray binaries with moderate orbital eccentricity have a persistent accretion disk around the neutron star, even if they are in the quiescent state.

6. Accretion Disks in Highly Eccentric Systems

The mass-accretion rate onto the neutron star is expected to be higher in systems with a higher eccentricity. In order to study whether highly eccentric systems have the mass-accretion rate large enough to exhibit periodic X-ray outbursts, we have run a simulation for a coplanar system with $e = 0.68$.

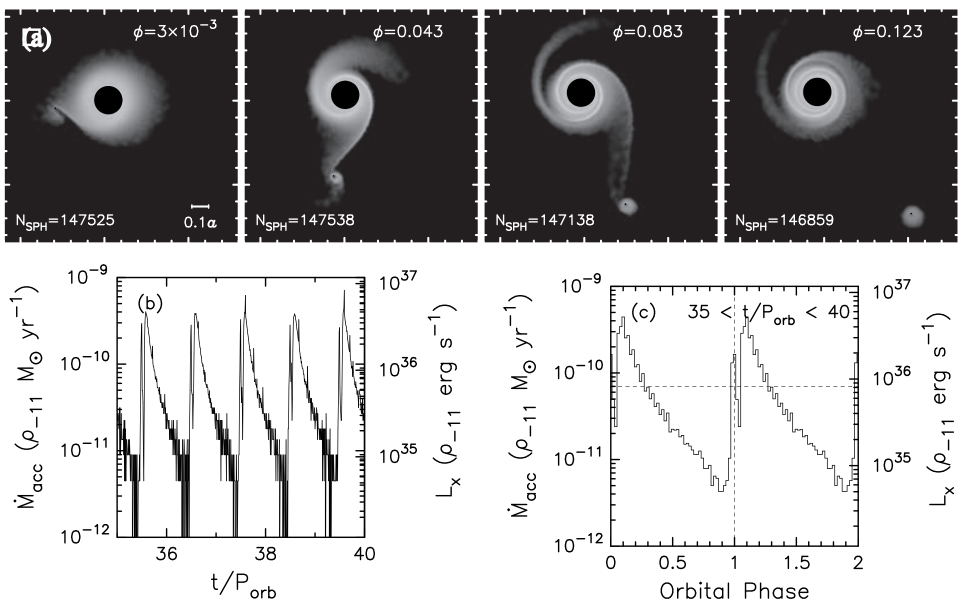


Figure 3. (a) Snapshots of the accretion disk formation in a coplanar Be/X-ray binary with $e = 0.68$, which cover $\sim 1/8P_{\rm orb}$ after a periastron passage. Each panel shows the surface density in a range of five orders of magnitude in the logarithmic scale. Annotated in each panel are the orbital phase and the number of SPH particles. (b) Variation in the accretion rate onto the neutron star from the same simulation. The neutron star is at apastron at $t = nP_{\rm orb}$ with integer n. (c) Orbital-phase dependence of the accretion rate. To reduce the fluctuation noise, the data is folded on the orbital period over $5P_{\rm orb}$. The periastron passage of the neutron star, which occurs at phase 0, is denoted by the vertical dashed line. The right axis shows the X-ray luminosity L_X given by $L_X = GM_X\dot{M}_{\rm acc}/R_X$.

Fig. 3a gives snapshots covering $\sim 1/8P_{\rm orb}$ after a periastron passage. Each panel shows the logarithm of the surface density. As seen in Fig. 3a, an accretion disk is formed around the neutron star by the material transferred from the Be disk for a short period of time after the periastron passage. Most of the material transferred from the Be disk is accreted by the neutron star by the next periastron passage. Thus, the accretion disk in this highly eccentric system is transient, unlike the counterparts in moderately eccentric systems.

Fig. 3b shows variations in the accretion rate over $5P_{\rm orb}$ from the same simulation, whereas Fig. 3c gives an orbital-phase dependence of the accretion rate and the corresponding X-ray luminosity averaged over the same period of time. It should be noted that the X-ray luminosity ($\sim 5 \times 10^{36}$erg s^{-1}) corresponding to the maximum accretion rate of about $4 \times 10^{-10} M_\odot\,{\rm yr}^{-1}$ falls within a typical luminosity range of the periodic X-ray outbursts in Be/X-ray binaries. Thus, this system is likely to show an X-ray outburst after every periastron passage. This is exactly what is expected for highly eccentric systems.

Figs. 3b and c also show that the accretion rate has two peaks per orbit; an initial spike followed by the major peak. This feature is stable, although the accretion rates of these peaks vary from cycle to cycle. The presence of two peaks is related to the fact that the specific angular momentum of the material transferred from the Be disk takes minimum just before the periastron passage and increases rapidly as the neutron star moves away from the periastron. It is interesting to note that Camero Arranz et al. (2005) recently reported on a similar feature in the light curve of periodic X-ray outbursts of EXO 2030+375.

7. Conclusions

We have numerically studied the interaction between the Be disk and the neutron star in Be/X-ray binaries, based on the viscous decretion disk scenario. We have found that the Be disk is truncated at a radius smaller than the periastron distance, unless the eccentricity is extremely high ($e > 0.8$) or the inclination angle between the disk plane and the orbital plane is large ($i > 60°$). Because of the resonant truncation, the disk density in Be/X-ray binaries increases more rapidly than in disks around isolated Be stars.

We have also found that a persistent accretion disk is formed around the neutron star, whether or not the accretion rate is large enough to cause X-ray outbursts. Due to the truncation of the Be disk and the eccentric orbit of the neutron star, the accretion rate is strongly phase dependent and is sensitive to the orbital eccentricity. In systems with low to moderate eccentricity, the accretion rate is too small to display periodic X-ray outbursts. Such systems are likely to stay in quiescence normally. On the other hand, in highly eccentric systems, the peak accretion rate falls within a typical range of accretion rate for the periodic X-ray outbursts. Thus, in the framework of the truncated Be disk model for Be/X-ray binaries, periodic X-ray outbursts are a phenomenon most frequently seen in highly eccentric systems.

Acknowledgments. This work has been supported in part by Grant-in-Aid for the 21st Century COE Scientific Research Programme on "Topological Science and Technology" from the Ministry of Education, Culture, Sports, Science and Technology of Japan and by Grant-in-Aid for Scientific Research (16540218) of Japan Society for the Promotion of Science.

References

Bate, M. R., Bonnell, I. A., & Price, N. M. 1995, MNRAS, 285, 33
Bate, M. R., Bonnell, I. A., Clarke, C. J., et al. 2000, MNRAS, 317, 773
Camero Arranz, A., Wilson, C. A., Connell, et al. 2005, A&A, 441, 261

Hanuschik R. W. 1994, in Balona L.A., Henrichs H., Le Contel J.M., ed. Pulsation, Rotation and Mass Loss of Early-Type Stars, IAU Symp. 162, Kluwer Academic Publishers, Dordrecht, p.265
Hanuschik R. W. 2000, in Smith M. A., Henrichs H.F., Fabregat J., ed. Be Phenomenon in Early-Type Stars, IAU Colloq. 185, ASP, San Francisco, p.518
Hayasaki, K. & Okazaki, A. T. 2004, MNRAS, 350, 971
Hayasaki, K. & Okazaki, A. T. 2005, MNRAS, 360, L15
Hayasaki, K. & Okazaki, A. T. 2007, these proceedings, p. 428.
Lee, U., Saio, H., & Osaki, Y. 1991, MNRAS, 250, 432
Lubow, S. H. 1991, ApJ, 381, 259
Negueruela I., Reig P., Coe M.J., & Fabregat J. 1998, A&A, 336, 251
Negueruela, I. & Okazaki, A. T. 2001, A&A, 369, 108
Okazaki A. T. 2001, PASJ, 53, 119
Okazaki, A. T. & Negueruela, I. 2001, A&A, 377, 161
Okazaki, A. T., Bate, M. R., Ogilvie, G. I., & Pringle, J. E. 2002, MNRAS, 337, 967
Papaloizou, J. C. B. & Terquem, C. 1995, MNRAS, 274, 987
Porter J.M. 1999, A&A, 348, 512
Reig, P., Fabregat, J., & Coe, M. J. 1997, A&A, 322, 193
Waters L. B. F. M. & Marlborough J. M., 1994, in Balona L. A., Henrichs H., Le Contel J. M., ed. Pulsation, Rotation and Mass Loss of Early-Type Stars, IAU Symp. 162, Kluwer Academic Publishers, Dordrecht, p.399
Zamanov, R. K., Reig, P., Mart, J., et al. 2001, A&A, 367, 884

Discussion

T. Rivinius: In Be binaries, not Be/X-ray binaries, we sometimes see a phenomenon of phase-locked V/R variability. If I understand it correctly, this does not happen if you consider only orbital mechanics. I wonder if the phase-locking mechanism is more radiative than just orbit-mechanical.

A. Okazaki: I agree with you that our simulations can't explain the phase-locked V/R variability in some Be binaries. But resonantly truncated disk model naturally leads to the idea of superhumps in low-eccentricity Be/X-ray binaries. So, we are still looking for an observational evidence for the superhump phenomenon in Be/X-ray binaries.

A. ud-Doula: It seems to me that you used only 150,000 particles in your simulations. This is quite low resolution for 3D simulations. Did you do any resolution study by increasing or decreasing number of particles to obtain similar results?

K. Hayasaki: With about half the number of particles, I have obtained similar results.