ON PERIODIC X-RAY OUTBURSTS IN Be/X-RAY BINARIES

A.T. Okazaki[1] and 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 numerically study the accretion flow around the neutron star in Be/X-ray binaries, using a three dimensional Smoothed Particle Hydrodynamics code. We find that the viscous decretion disk around the Be star is tidally truncated at a radius smaller than the periastron distance for a wide range of orbital parameters. 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 and the inclination angle. In systems with low to moderate eccentricity, the accretion rate is too low to cause periodic X-ray outbursts. Such systems are likely to stay in quiescence normally and show only temporal X-ray outbursts when they have an enhanced mass-transfer from the Be star. In contrast, in highly eccentric systems, the peak accretion rate falls in a typical range of acretion rate for the periodic X-ray outbursts in Be/X-ray binaries unless the misaligned angle between the Be disk and the binary orbital plane is too large. This strongly suggests that, in the framework of the truncated Be disk model for Be/X-ray binaries, periodic X-ray outbursts are the phenomenon most frequently seen in highly-eccentric, coplanar systems.

Key words: accretion disks; Be/X-ray binaries; X-ray outbursts.

1. INTRODUCTION

The Be/X-ray binaries form the largest subclass of high mass X-ray binaries. They consist of a Be star and a neutron star. The orbit is wide ($10\,\mathrm{d} \lesssim P_{\mathrm{orb}} \lesssim 400\,\mathrm{d}$) and mostly eccentric ($e \gtrsim 0.3$). Most of the Be/X-ray binaries show only transient X-ray activity due to transient accretion from the circumstellar disk of the Be star. Each Be/X-ray binary exhibits some or all of the following three types of X-ray activity:

1. periodic (Type I) X-ray outbursts, coinciding with periastron passage ($L_{\mathrm{X}} \approx 10^{36-37}\,\mathrm{erg\,s^{-1}}$),

2. giant (Type II) X-ray outbursts ($L_{\mathrm{X}} \gtrsim 10^{37}\,\mathrm{erg\,s^{-1}}$), which show no clear orbital modulation,

3. persistent low-luminosity X-ray emission ($L_{\mathrm{X}} \lesssim 10^{34}\,\mathrm{erg\,s^{-1}}$)

(Stella et al. 1986; see also Negueruela et al. 1998). These features imply a complicated interaction between the Be-star envelope and the neutron star.

Be/X-ray binaries are also important as a laboratory for studying the physics of the tidal interaction, the mass transfer and the accretion process in eccentric binaries. They are unique in the sense that the neutron star is fed by the overflow from the circumstellar disk around the Be star, which is geometrically thin and nearly Keplerian. The radial velocity of the Be disk is smaller than a few $\mathrm{km\,s^{-1}}$, at least within ~ 10 stellar radii (Hanuschik 1994; Hanuschik 2000; Waters & Marlborough 1994). These features are in good agreement with the viscous decretion disk model proposed by Lee et al. (1991) (Porter 1999; see also Okazaki 2001). In this model, the matter supplied from the equatorial surface of the star drifts outwards because of the viscous effect and forms the disk. Until recently, little work has been done on the interaction in these unique objects. See Fig. 1 for a schematic diagram of the interactions in Be/X-ray binaries.

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 size and the maximum equivalent width of Hα ever observed in a system, a measure of the maximum disk
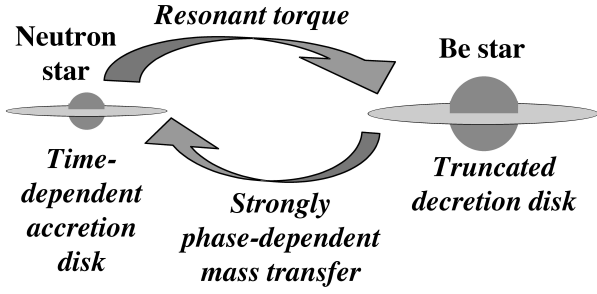
Figure 1. Schematic diagram of the interactions in Be/X-ray binaries.

size around the Be star in the system. It has also been confirmed by numerical simulations for a system with a short orbital period and a moderate orbital exccentricity (Okazaki et al., 2002).

In this paper, we study the origin of the periodic (Type I) X-ray outbursts in Be/X-ray binaries, performing three dimensional Smoothed Particle Hydrodynamics (SPH) simulations. Our results suggest that, in the framework of the truncated Be disk model for Be/X-ray binaries, the periodic X-ray outbursts are the phenomenon most frequently seen in highly-eccentric, coplanar systems.

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. We assume that the Be star has the accretion radius of R_*, where R_* is the radius of the Be star. For the neutron star, we adopt the accretion radius of $r = 5 \times 10^{-3}a$, where a is the semi-major axis. For simplicity, we assume that both disks are isothermal at the temperature of half the effective temperature of the Be star and have the viscosity parameter $\alpha_{SS} = 0.1$. 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 $T_{\rm eff} = 26,000$ K. For the neutron star, we take $M_X = 1.4M_\odot$ and $R_X = 10^6$ cm.

3. TRUNCATION OF THE Be DISK

Until recently, models for periodic (Type I) X-ray outbursts in Be/X-ray binaries had assumed a large disk around the Be star so that the neutron star can accrete gas

when it passes through the disc near periastron. However, as mentioned above, Negueruela & Okazaki (2001) and Okazaki & Negueruela (2001) semi-analytically showed that the Be disk in Be/X-ray binaries is truncated at a radius smaller than the periastron distance. The truncation is due to the resonant torque exerted by the neutron star, which removes the angular momentum from the disk.

Fig. 2 shows the surface density evolution of the viscous decretion disk around the Be star. Panels (a) and (b) are for $e = 0.34$ and $e = 0.68$, respectively. In these simulations, the orbital period $P_{\rm orb}$ is 24.3 d and the Be disk is coplanar with the binary orbital plane. Each simulation finally had about 150,000 SPH particles. As shown in Fig. 2, the decretion disk around the Be star is tidally/resonantly truncated at a radius 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. The wavy patterns seen in the surface density distribution in the left panel is due to the tightly wound spiral density wave excited in the disk. Note that the truncation is more efficient for a lower orbital eccentricity, as expected from the semi-analytical study. We have found that the tidal/resonant truncation works, except for systems with extremely high eccentricity ($e \gtrsim 0.8$).
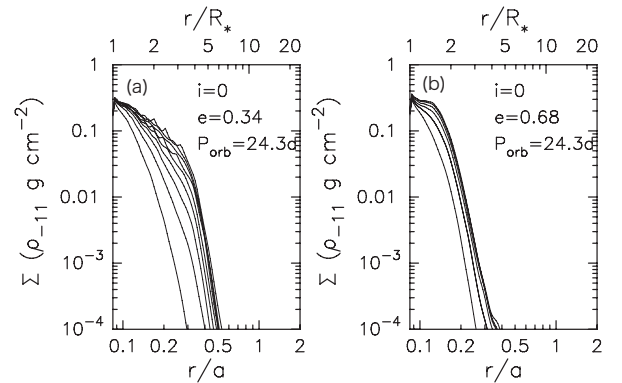

Figure 2. Surface density evolution of the Be decretion disk for (a) $i = 0°$ and $e = 0.34$ and (b) $i = 0°$ and $e = 0.68$, where i is the angle between the mid-plane of the Be disk and the orbital plane. The orbital period $P_{\rm orb} = 24.3$ d. The time interval between adjacent contours is $5P_{\rm orb}$. $\rho_{-11} = \rho_0/10^{-11}{\rm g\,cm}^{-3}$, where ρ_0 is the base density of the disk.

4. ACCRETION DISKS IN SYSTEMS WITH MODERATE ECCENTRICITY

Based on semi-analytical results for several Be/X-ray binaries with known orbital parameters, Okazaki & Negueruela (2001) discussed that the X-ray behavior of systems with moderate eccentricity depends on rather subtle details: Systems in which the disk is truncated in the vicinity of the critical lobe will regularly display
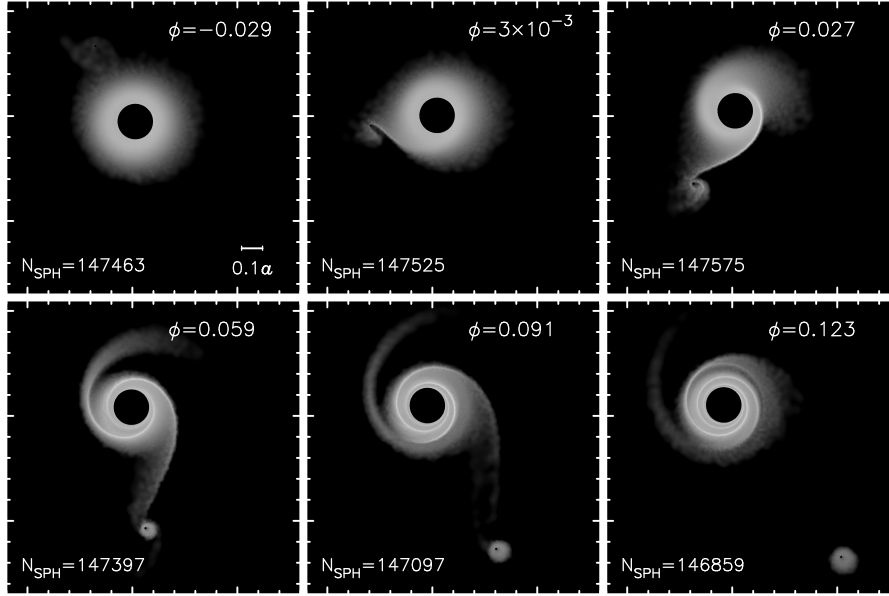
Figure 3. Snapshots of the accretion disk formation in a coplanar Be/X-ray binary with $P_{\mathrm{orb}} = 24.3\,\mathrm{d}$ and $e = 0.68$, which cover $\sim 0.15 P_{\mathrm{orb}}$ around the periastron passage. Each panel shows the surface density in a range of 5 orders of magnitude in the logarithmic scale. Annotated in each panel are the orbital phase and the number of SPH particles.

Type I outbursts, whereas those with the disk significantly smaller than the critical lobe will show Type I outbursts onlys when the disk is strongly disturbed.

Recently, Hayasaki & Okazaki (2004) and Hayasaki & Okazaki (2005) 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 ($e = 0.34$), using a 3D SPH code and the simulation data by Okazaki et al. (2002) as the outer boundary condition. They found that the peak accretion rate on to the neutron star in their moderately eccentric system ($3 \times 10^{-11} M_{\odot}\,\mathrm{yr}^{-1}$) is much smaller than that corresponding to a typical luminosity range of Type I outbursts ($L_{\mathrm{X}} \approx 10^{36-37}\,\mathrm{erg\,s}^{-1}$), which implies that this system is normally in quiescent state. They also found that a time-dependent accretion disk is formed and grows secularly, because the mass-accretion rate on to the neutron star is much smaller than the mass-transfer rate from the Be disk. Their results suggest that Be/X-ray binaries with moderate orbital eccentricities are likely to have persistent accretion disks around the neutron star, even if they exhibit no periodic (Type I) X-ray outbursts.

5. ACCRETION DISKS IN SYSTEMS WITH HIGH ECCENTRICITY

The mass-accretion rate on to the neutron star is expected to be higher in systems with a higher eccentricity. In order to study the effect of the orbital parameters on the accretion rate, we have run three simulations for highly eccentric systems with different orbital period P_{orb} and inclination angle i. In these simulations, the eccentricity

e was fixed at 0.68.

5.1. Coplanar System with a Short Orbital Period

Fig. 3 gives snapshots covering $\sim 0.15 P_{\mathrm{orb}}$ around the periastron passage, which occurs at phase $\phi = 0$, in a coplanar system ($i = 0$) with $P_{\mathrm{orb}} = 24.3\,\mathrm{d}$ and $e = 0.68$. Each panel shows the logarithm of the surface density. The dark spot near the center is the Be star. Annotated in each panel are the orbital phase and the number of SPH particles. As seen in Fig. 3, an accretion disk is formed around the neutron star at periastron, when the material is transferred from the Be disk for a short period of time. Most of the material transferred from the Be disk accretes on to 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.

The orbital-phase dependence of the accretion rate on to the neutron star is shown in Fig. 5(a). To reduce the fluctuation noise, the data is folded on the orbital period over $5P_{\mathrm{orb}}$. The periastron passage of the neutron star is denoted by the vertical dashed line. The right axis shows the X-ray luminosity L_X given by $L_X = GM_X \dot{M}_{\mathrm{acc}}/R_X$. It is important to note that the X-ray luminosity ($\sim 5 \times 10^{36}\,\mathrm{erg\,s}^{-1}$) corresponding to the peak accretion rate of about $4 \times 10^{-10} M_{\odot}\,\mathrm{yr}^{-1}$ enters a typical luminosity range of the Type I X-ray outbursts in Be/X-ray binaries. Note also that the the accretion rate profile has an initial spike followed by the major peak. This is because the specific angular momentum of the transferred mass from the Be disk rapidly increases with phase. Sim-
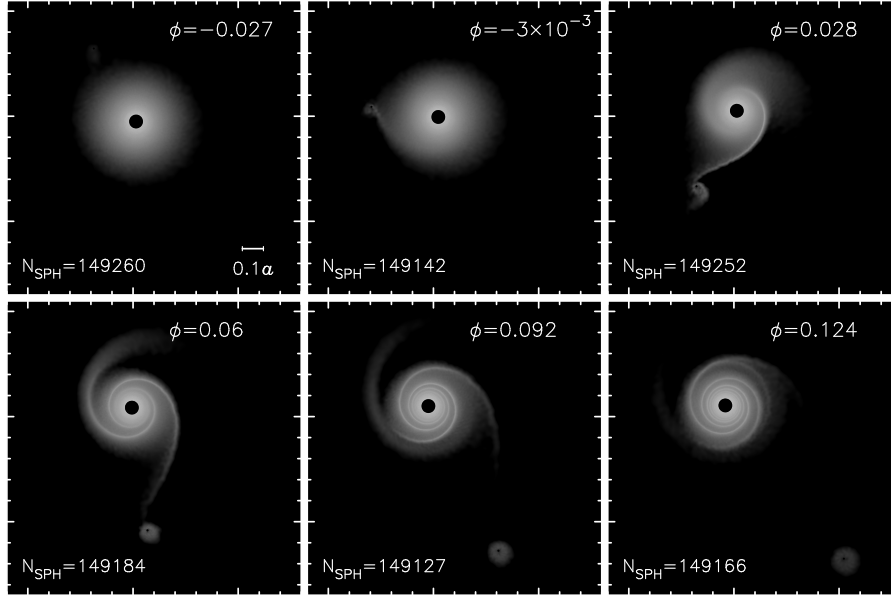
Figure 4. Same as Fig. 3, but for $P_{orb} = 100$ d.

ilar feature was recently found in EXO 2030+375 by Camero Arranz et al. (2005).

5.2. Coplanar System with a Long Orbital Period

Fig. 4 gives snapshots covering $\sim 0.15 P_{orb}$ around the periastron passage in a coplanar system ($i = 0$) with $P_{orb} = 100$ d and $e = 0.68$. The format of the figure is the same as that of Fig. 3. In this simulation, a transient accretion disk is also formed around the neutron star at periastron.

The orbital-phase dependence of the accretion rate on to the neutron star is shown in Fig. 5(b). To reduce the fluctuation noise, the data is folded on the orbital period over $5 P_{orb}$. In this simulation, the X-ray luminosity corresponding to the peak accretion rate of about $2 \times 10^{-10} M_{\odot}\,yr^{-1}$ is about $2 \times 10^{36} erg\,s^{-1}$, which also enters a typical luminosity range of the Type I X-ray outbursts. As in the short orbit case, the accretion rate profile has two peaks, although the dip between the two peaks is much inconspicuous.

5.3. Misaligned System with a Short Orbital Period

In order to study the effect of the inclination angle on the accretion on to the neutron star, we have run a simulation for $P_{orb} = 24.3$ d, $e = 0.68$ and $i = 30°$ about y-axis, where i is the angle between the mid-plane of the Be disk and the orbital plane. We have found that the inclined Be disk is resonantly truncated as in coplanar systems. We have also found that the accretion disk formed around the neutron star is inclined from the orbital plane with an angle different from that of the Be disk.

Figure 5(c) shows the phase dependence of the accretion rate on to the neutron star. To reduce the fluctuation noise, the data is folded on the orbital period over $3 P_{orb}$. In this simulation, the X-ray luminosity corresponding to the peak accretion rate of about $8 \times 10^{-11} M_{\odot}\,yr^{-1}$ is about $10^{36} erg\,s^{-1}$, which is roughly equal to the lower end of the luminosity range of Type I X-ray outbursts. Thus, the accretion rate is sensitive to the inclination angle i. Since the accretion rate decreases with increasing i, systems with large misalignment angles ($\gg 30°$) are unlikely to exhibit Type I X-ray outbursts unless the Be disk is strongly disturbed. The accretion rate profile shows a two-peaked feature, but it is very modest compared with the profiles for coplanar systems.

6. CONCLUSIONS

We have performed three dimensional SPH simulations in order to study the accretion flow around the neutron star in Be/X-ray binaries. We have found that an accretion disk is formed around the neutron star whether or not the accretion rate is high enough to cause a Type I X-ray outburst. Due to the truncation of the Be disk and the eccentric orbit of the neutron star, the accretion rate on to the neutron star is strongly phase dependent, and is sensitive to the orbital eccentricity and the inclination angle. In systems with low to moderate eccentricity, the accretion rate is too small to cause periodic (Type I) 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 in a typical range of acretion rate for the Type I X-ray outbursts in Be/X-ray binaries. Since the accretion rate decreases with increase of orbital period and inclination angle, highly eccentric systems with small misaligned angles are most favorable
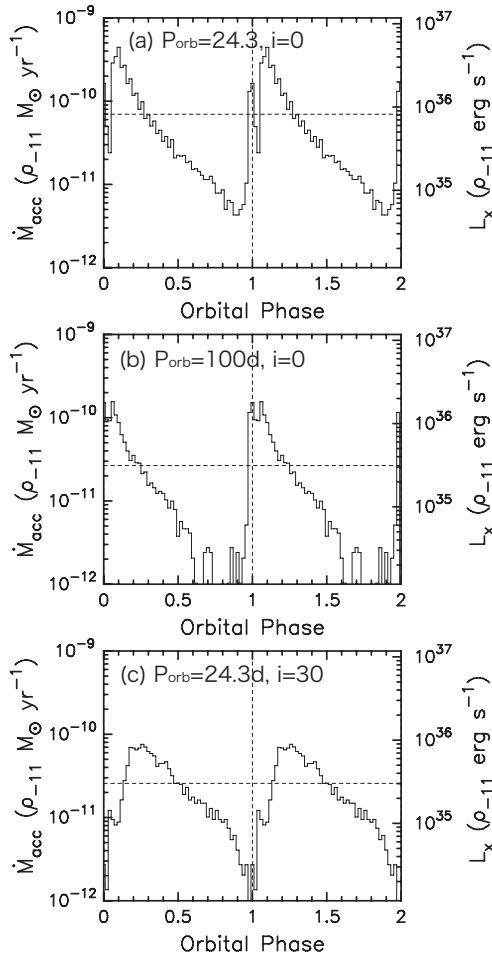
Figure 5. Orbital-phase dependence of the accretion rate on to the neutron star: (a) $P_{orb} = 24.3\,\mathrm{d}$ and $i = 0°$, (b) $P_{orb} = 100\,\mathrm{d}$ and $i = 0°$, and (c) $P_{orb} = 24.3\,\mathrm{d}$ and $i = 30°$ about y-axis. To reduce the fluctuation noise, the data is folded on the orbital period over $3 - 5P_{orb}$. 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 luminocity corresponding to the mass-accretion rate.

for Type I X-ray outbursts.

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