Origin of Two Types of X-Ray Outbursts in Be/X-Ray Binaries. I.
Accretion Scenarios

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Abstract

We propose a new scenario for X-ray outbursts in Be/X-ray binaries that normal and giant outbursts are, respectively, caused by radiatively inefficient accretion flows (RIAFs) and Bondi-Hoyle-Lyttleton (BHL) accretion of material transferred from the outermost part of a Be disk misaligned with the binary orbital plane. Based on simulated mass-transfer rates from misaligned Be disks, together with simplified accretion flow models, we show that mass-accretion rates estimated from the luminosity of normal X-ray outbursts are consistent with those obtained with advection-dominated accretion flows, not with the standard, radiative-cooling dominated, accretion. Our RIAF scenario for normal X-ray outbursts resolves problems that have challenged the standard disk picture for these outbursts. When a misaligned Be disk crosses the orbit of a neutron star, e.g., by warping, the neutron star can capture a large amount of mass via BHL-type accretion during the disk transit event. We have numerically shown that such a process can reproduce the X-ray luminosity of giant X-ray outbursts. In the case of a very high Be disk density, the accretion flow associated with the disk transit becomes supercritical, giving rise to a luminosity higher than the Eddington luminosity.

Key words: stars: binaries, emission-line, Be — stars: pulsars: individual (A 0535+262, 4U 0115+634) — X-rays: binaries

1. Introduction

Be/X-ray binaries are high-mass X-ray sources comprised of a Be star and a neutron star in a wide and, in most cases, eccentric orbit. A Be star is a non-supergiant early type star with a circumstellar disk formed by viscous diffusion of matter ejected from the star. This decretion disk is geometrically thin and Keplerian, as are viscous accretion disks (Lee et al. 1991), and is, in normal condition, truncated by the tidal/resonant interaction with the neutron star (e.g., Okazaki & Negueruela 2001). Because of its eccentric orbit, the neutron star can capture gas from the Be disk only for a short span of time during a close encounter with the Be disk. Such a brief interaction makes the Be/X-ray binaries transient X-ray sources. They show two types of X-ray outbursts: normal (Type I) outbursts, of which the X-ray luminosity \( L_X \sim 10^{36-37} \, \text{erg s}^{-1} \) and the interval is the orbital period, and giant (Type II) outbursts, which are significantly brighter (\( L_X > 10^{37} \, \text{erg s}^{-1} \)) and less frequent than normal outbursts (Stella et al. 1986; Negueruela et al. 1998).

Thanks to long-term, multi-wavelength monitoring observations of Be/X-ray binaries, it is now widely accepted that normal outbursts are triggered by mass transfer from a tidally truncated Be disk at, or near, periastron passage, and that giant outbursts are somehow associated with warping episodes of the Be disk. However, the details of the interaction between the Be disk and the neutron star and the resultant accretion flows remain elusive.

In previous studies, the accretion disk that forms around the neutron star has been implicitly assumed to be modeled by the standard disk (Shakura & Sunyaev 1973). It is geometrically thin and Keplerian, supported by rotation in the radial direction and by gas pressure in the vertical direction, in which heating by viscosity is balanced with cooling by radiation from the disk surface at each radius (e.g., Frank et al. 2002; Kato et al. 2008). Several observed features, however, challenge the standard disk picture for Be/X-ray binaries. For instance, the spin-up episode of the X-ray pulsar in Be/X-ray binaries are, in general, seen only during X-ray outbursts (e.g., Bildsten et al. 1997 for A 0535+262 and GRO J1744+28; Parmar et al. 1989; Wilson et al. 2008 for EXO 2030+375), which often last for a much shorter time than the orbital period. This suggests that the accretion disk, if formed, is transient. Large and rapid flux variations in X-ray outbursts also support the idea of transient accretion disks. In contrast, the standard disk theory suggests that the accretion disk is not transient, but persistent, because the viscous-accretion timescale is generally much longer than the orbital period.

It also remains unclear what mechanism triggers giant X-ray outbursts. There is observational evidence for warping of the outer part of the Be disk before/during giant X-ray outbursts. This episode has most clearly been seen in 4U 0115+634 (Negueruela et al. 2001; Reig et al. 2007), where the H\("\alpha\) emission line profile, which was usually double-peaked, varied between a single-peaked profile and a profile with an absorption core, on a timescale of a year or so. Although
single-peaked profiles and those with absorption core are usually observed for Be stars seen from the polar and the equatorial directions, respectively, the spin axis of the Be star cannot vary with such a short timescale. Thus, this drastic line-profile variation indicates that the angle between the observer and the Be disk plane varies according to the precession of a warped Be disk (Negueruela et al. 2001; Reig et al. 2007).

4U0115+634 is not the only system that has shown a warping episode of the Be disk. Recent spectroscopic monitoring observations of the Be/X-ray binary A0535+262 have detected very complicated changes in the Hα line profiles both during and after the 2009 giant X-ray outburst (Moritani et al. 2011). Analyzing the variability of several line profiles, Moritani et al. (2012) found that the observed features can be explained by a precessing, warped Be disk, which is misaligned with the binary orbital plane.

We note that the association of the warping episode with giant X-ray outbursts favors systems with misaligned Be disks over those with Be disks coplanar with the orbital plane. In misaligned systems, the warping can bend the disk outer part towards the orbital plane, enabling the neutron star to capture more material from the Be disk than it does without warping. On the other hand, in aligned systems where the Be disks are coplanar with the binary orbital plane, it is difficult to understand how the warping of initially coplanar disks can enhance the mass supply to the neutron star. Given that the eccentric orbit of Be/X-ray binaries is attributed to a supernova kick, the same mechanism is also likely to give rise to a misalignment between the Be star’s spin axis and the orbital axis of the binary. Therefore, it is important to study dynamical interactions in misaligned systems, despite that there is little compelling evidence of any misalignment between the Be disk and the binary orbital plane in Be/X-ray binaries.

In this paper, we examine accretion processes in Be/X-ray binaries, with particular attention to A0535+262 and 4U0115+634, two best-studied systems with rather different orbital parameters. Based on the study of these systems, we propose that normal and giant X-ray outbursts in Be/X-ray binaries are respectively caused by radiatively inefficient accretion flows (RIAFs) and Bondi-Hoyle-Lyttleton (BHL) accretion of the material transferred from a Be disk misaligned with the binary orbital plane, and that giant outbursts occur when the tilted Be disk crosses the orbit of the neutron star in the direction of periastron.

The paper is organized as follows. We first argue in section 2 that the standard disk accretion picture does not work as a model for X-ray outbursts of Be/X-ray binaries. Then, in section 3, we show that RIAFs naturally explain characteristic features of normal X-ray outbursts. In section 4, we point out that the accretion rate and timescale evaluated on the basis of our scenario for giant X-ray outbursts are consistent with those observed. We also discuss in this section the possibility of supercritical accretion flows onto the neutron star in Be/X-ray binaries. Section 5 is devoted to discussion about observational implications of our scenarios, and section 6 concludes the paper.

### 2. Classical Picture for X-Ray Outbursts

As summarized in the next section, normal X-ray outbursts last only for a small fraction of the orbital period. This short timescale challenges the classical, standard disk picture for Be/X-ray binaries. In this section, we first show that the standard disk model has a too long accretion timescale to explain the duration time of normal X-ray outbursts. Afterward, we discuss a couple of issues, where the standard disk picture is inconsistent with observations. We present alternative scenarios for X-ray outbursts in later sections.

#### 2.1. Viscous Timescale

In a standard disk, accretion occurs on the viscous timescale, \( t_{\text{vis}} \), which is given by

\[
 t_{\text{vis}} = \alpha^{-1} \left( \frac{r}{H} \right)^2 \frac{1}{\Omega K} \tag{1}
\]

(e.g., Frank et al. 2002; Kato et al. 2008), where \( \alpha \) is the Shakura-Sunyaev’s viscosity parameter, \( r \) is the radius measured from the neutron star, \( H \) is the vertical scale-height of the accretion disk at \( r \), and \( K = (GM_N/r^3)^{1/2} \) with \( M_N \) being the mass of the neutron star. A steady \( \alpha \)-disk solution has a scale-height given by

\[
 H/r = 5.6 \times 10^{-3} \alpha_{0.1}^{-1/2} m_{16}^{3/20} m_{14}^{-1/4} r^{1/8}, \tag{2}
\]

where \( \alpha_{0.1} = \alpha/0.1, m_{16} = M/10^{16} \text{g s}^{-1}, m_{14} = M_N/1.4 M_{\odot} \), and \( r \) is the radius normalized by the Schwarzschild radius \( r_S = 2GM_N/c^2 \approx 4.1 \times 10^{17} m_{14} \text{cm} \). Substituting equation (2) into equation (1), we have

\[
 t_{\text{vis}} = 6.2 \alpha_{0.1}^{-4/5} m_{16}^{-3/10} m_{14}^{1/2} r^{5/4} \text{s}. \tag{3}
\]

In order to evaluate equation (3), we need to estimate the outer radius of the accretion disk and the mass-accretion rate there. In the next subsection, we estimate \( t_{\text{vis}} \) by utilizing results from numerical simulations of tidal interaction in the Be/X-ray binaries A0535+262 and 4U0115+634.

#### 2.2. Accretion Timescale Estimated from Numerical Simulations

##### 2.2.1. Numerical method

The simulations presented below were performed with a 3D SPH code, which is a particle method that divides the fluid into a set of discrete “fluid elements” (=particles), and is flexible in setting various initial configurations. The code is the same as that used by Okazaki et al. (2002) (see also Bate et al. 1995). Using a variable smoothing length, the SPH equations with a standard cubic-spline kernel are integrated with an individual time step for each particle.

In our code, the Be disk is modeled by an ensemble of gas particles with negligible self-gravity. For simplicity, the gas particles are assumed to be isothermal at \( 0.6 T_{\text{eff}} \) with \( T_{\text{eff}} \) being the effective temperature of the Be star (Carciofi & Bjorkman 2006). We model the mass ejection process from the star by injecting gas particles at a constant rate just outside the equatorial surface of the star. Once injected, gas particles interact with each other. As a result, most of the injected particles fall back on to the Be star by losing angular momentum, and...
a small fraction of particles drift outwards, obtaining angular momentum from the other particles.

On the other hand, the Be star and the neutron star are represented by sink particles with appropriate gravitational mass. Gas particles that fall within a specified accretion radius are accreted by the sink particle. We assume that the accretion radius of the Be star is equal to the stellar radius, \( R_\text{Be} \), while for the neutron star, we adopt a variable accretion radius of \( r_\text{L} \), where \( r_\text{L} \) is the Roche-lobe radius, given approximately by

\[
r_\text{L} = D \frac{0.49q^{2/3}}{0.69q^{2/3} + \ln(1 + q^{1/3})}
\]

(Eggleton 1983). The mass ratio is \( q = M_\text{N} / M_\text{Be} \), where \( M_\text{N} \) is the mass of the neutron star, and the instantaneous distance between the stars is \( D \).

In simulations described in this paper, we adopted artificial viscosity parameters of \( \alpha_{\text{SPH}} = 1 \) or \( \beta_{\text{SPH}} = 0 \), which roughly corresponds to the Shakura-Sunyaev viscosity parameter \( \alpha = 0.1 \), except in very-low density regions (e.g., Okazaki et al. 2002). We set the binary orbit on the \( x-y \) plane with the major axis along the \( x \)-axis (the apastron is in the \( +x \)-direction). At \( t = 0 \), the neutron star is at apastron. It orbits about the Be star primary with the orbital period \( P_\text{orb} \) and the orbital eccentricity \( e \).

2.2.2. A 0535+262

A 0535+262 consists of an O9.7IIIe star and an X-ray pulsar with a relatively wide \( [P_\text{orb} = 110.2 \text{ d (Moritani et al. 2010)}] \) and eccentric [\( e = 0.47 \) (Finger et al. 1994)] orbit. As the mass and radius of the Be star, we take \( 25 M_\odot \) and \( 15 R_\odot \) from Vacca et al. (1996). With these parameters, the semi-major axis is \( a = 2.0 \times 10^{13} \text{ cm} \). The magnetic field strength of the neutron star is \( 4.3 \times 10^{12} \text{ G} \) from the observed cyclotron resonance scattering features (Makishima et al. 1999). Table 1 summarizes system parameters used in this paper.

| Table 1. System parameters for A 0535+262 and 4U 0115+634.* |
|-------------------------------------------------------------|
| **Be star parameters**                                      |
| Name             | V725 Tau  | V635 Cas  |
| Spectral type    | O9.7IIIe† | B0.2Ve‡  |
| Mass \( M_\text{Be} \) \( (M_\odot) \) | 25§       | 19§       |
| Radius \( R_\text{Be} \) \( (R_\odot) \) | 15§       | 8§        |
| Effective temperature (K) | 26000 | 26000 |
| **Be disk parameters**                                     |
| Temperature \( T_\text{D} \) (K) | 15600 | 15600 |
| **Neutron star parameters**                               |
| Mass \( M_\text{N} \) \( (M_\odot) \) | 1.4      | 1.4       |
| Radius \( R_\text{N} \) \( (cm) \) | \( 10^6 \) | \( 10^6 \) |
| Spin period \( P_\text{s} \) (s) | 103³    | 3.6²     |
| Magnetic field strength (G) | \( 4.3 \times 10^{12}** \) | \( (0.87–1.07) \times 10^{12}†† \) |
| **Orbital parameters**                                    |
| Orbital period \( P_\text{orb} \) (d) | 110.2‡‡ | 24.3‡   |
| Orbital eccentricity \( e \) | 0.47³‡  | 0.34³   |
| Mass ratio \( q \) | 0.056   | 0.074   |
| Semi-major axis \( a \) \( (cm) \) | \( 2.0 \times 10^{13} \) | \( 6.7 \times 10^{12} \) |

* References: † Gianfranca et al. (1980), ‡ Negueruela and Okazaki (2001), § Vacca et al. (1996), ¶ Coe et al. (1975), †† Rappaport et al. (1978), ** Makishima et al. (1999), †‡ Ferrigno et al. (2009), ‡‡ Moritani et al. (2010), ‡‡ Finger et al. (1994).
produce a peak X-ray luminosity of $\sim 2 \times 10^{37} \rho_{-11} \text{erg s}^{-1}$ in the coplanar case, and $4 \times 10^{36} \rho_{-11} \text{erg s}^{-1}$ in the misaligned case, if the accretion time of the captured material on to the neutron star were negligible. Here, we calculated the X-ray luminosity by $L_X = \frac{GM_X}{R_X} \approx 1.0 \times 10^{-2} \dot{m}_{16} L_{\text{Edd}}$, with $L_{\text{Edd}}$ being the Eddington luminosity given by

$$L_{\text{Edd}} = \frac{4\pi c GM_X}{\kappa_{\text{es}}} \approx 1.8 \times 10^{38} \rho_{1.4} \text{ erg s}^{-1},$$

(5)

where $c$ is the speed of light and $\kappa_{\text{es}}$ is the opacity of the electron scattering. We take $R_X = 10^6 \text{ cm}$ as the radius of the neutron star.

Since the Roche-lobe radius, $r_L$, is larger than the neutron-star radius by many orders, the accretion time from this radius to the neutron star surface could significantly reduce the peak amplitude, and broaden the shape of the accretion rate. It is thus interesting to estimate the accretion rate at the neutron star radius. For this purpose, we first calculated the circularization radius, $r_{\text{circ}}$, from the specific angular momentum of captured material, $j$, by assuming that $r_{\text{circ}}$ is approximately given by $r_{\text{circ}} = j^2 / (GM_X)$. Then we evaluated the viscous timescale, $t_{\text{vis}}$, at $r = r_{\text{circ}}$, using equation (3). In our simulations, the mass-weighted average of $r_{\text{circ}}$ was $r_{\text{circ}} \approx 3 \times 10^{11} \text{ cm} \sim 0.02a$ (coplanar case) and $r_{\text{circ}} \sim 7 \times 10^{10} \text{ cm} \sim 0.004a$ (misaligned case). The lower panels of figure 1 show the resultant $t_{\text{vis}}$ as a function of the orbital phase. In both simulations, the viscous (i.e., accretion) timescale turned out to be longer than the orbital period at most phases, in particular, $t_{\text{vis}} \sim 5 \text{--} 6 \text{ } P_{\text{orb}}$ at the peak mass-transfer phase.

Using the phase dependence of the mass-capture rate and viscous timescale, we estimated the accretion rate on to the neutron star as follows. With the mass-capture rate, $\dot{M}_{\text{cap}}(t)$, at $t$, we approximated the amount of mass captured for a short span of time between $t = t_0$ and $t = t_0 + \Delta t$ by $\dot{M}_{\text{cap}}(t_0) \Delta t$. As a very rough approximation of the viscous accretion process, we assumed that this amount of mass is accreted by the neutron star over $t_{\text{vis}}$ between $t_0 + t_{\text{vis}} / 2$ and $t_0 + 3t_{\text{vis}} / 2$ at a constant rate of $\dot{M}_{\text{cap}}(t_0) \Delta t / t_{\text{vis}}$. Note that in this treatment the accretion timescale is taken as being independent of the mass capture/accretion history. The method is
thus expected to provide a reasonable estimate of the accretion rate, when the accretion timescale increases with the orbital phase, or slowly decreases with the phase with the changing timescale being longer than the accretion timescale, itself. However, this might create an artificial, spiky feature in the resulting accretion rate in case the accretion timescale rapidly decreases with the orbital phase, where in real systems the rapid accretion of newly captured material would certainly be prevented by an already existing accretion disk with a longer accretion timescale.

Applying the above procedure to the phase-dependent mass-capture rate and viscous timescale, we obtained the orbital modulation of the accretion rate estimated at the neutron-star radius. The result is shown by the thin (red) lines in the upper panels of figure 1. As expected from the fact that the viscous timescale is much longer than the orbital period, the obtained mass accretion rate is mostly constant, and exhibits only short and small enhancements at phases with short accretion timescales. These simulated features contradict with the observational characteristics of normal X-ray outbursts, which exhibit a large and rapid change in the X-ray flux.

2.2.3. 4U 0115+634

4U 0115+634 consists of a B0.2Ve star and an X-ray pulsar with a relatively narrow ($P_{\text{orb}} = 24.3$ d) and eccentric ($e = 0.34$) orbit (Rappaport et al. 1978). As the mass and radius of the Be star, we take $19 M_\odot$ and $8 R_\odot$ from Vacca et al. (1996). With these parameters, the semi-major axis is $a = 6.7 \times 10^{12}$ cm, which is about three-times smaller than that of A 0535+262. These system parameters are summarized in table 1.

As for A 0535+262, we performed two simulations for 4U 0115+634, i.e., a coplanar disk simulation and a simulation with a Be disk misaligned by 45° about the semi-minor axis. Both simulations were run over 50 $P_{\text{orb}}$ until the Be disk become fully developed, and started to show a regular orbital modulation in the mass-capture rate by the neutron star. The number of gas particles at the end of coplanar and misaligned simulations were ~140000 and ~110000, respectively.

Figure 2 shows the result from (a) the coplanar disk simulation and (b) the misaligned disk simulation. The format of the figure is the same as that of figure 1.
of A 0535+262 does. For the same reason, the pre-periastron peak, which is caused by a pre-periastron close encounter of the neutron star to the Be disk, disappeared in the misaligned simulation of 4U0115+634. The stronger tidal interaction in 4U0115+634 also gives rise to longer viscous timescale (lower panels), because the captured material has a larger specific angular momentum. As a result, in 4U0115+634 the mass-accretion rate estimated at the neutron star surface (red lines) is much lower and less variable than in A 0535+262 (the pre-periastron spike in figure 2a is an artificial feature arising from our simplified treatment). Apparently, these simulated features are inconsistent with the observational characteristics of normal X-ray outbursts.

2.3. Direct Accretion vs. Propeller Regimes

Although we have shown in the above sections that the standard disk scenario does not agree with the observed short duration and large and rapid X-ray flux variations of normal X-ray outbursts, one may argue that the onset of the propeller regime can truncate the accretion regime, and hence make the standard disk model still viable. Given a strong positive correlation between the spin period of the pulsar and the orbital period of the binary seen in Be/X-ray binaries (e.g., Corbet 1986), it is likely that the propeller effect of the rotating magnetosphere of the pulsar plays an important role in systems with short orbital periods. Indeed, in 4U0115+634, Campana et al. (2001) witnessed a very rapid increase of the X-ray flux to be attributed to the transition from the propeller regime to the direct accretion regime. It is not clear, however, whether the same mechanism plays an important role in the X-ray behavior of systems with much longer orbital periods, such as A 0535+262.

Below we examine whether the propeller effect also works for A 0535+262, truncating the accretion regime short and making a large difference between the quiescent and outburst X-ray fluxes. For this purpose, we compare the corotation radius, $r_C$, where the local Keplerian frequency is equal to the rotation frequency of the magnetosphere, with the magnetospheric radius, $r_M$, obtained by equating the magnetic-field pressure of the neutron star to the gas pressure of the accretion disk. For $r_M < r_C$, the velocity of a rigidly rotating magnetic field is sub-Keplerian at the magnetospheric radius, which permits the material in the accretion disk to fall on to the neutron star along the magnetic field lines. The system is then in the direct accretion regime. On the other hand, for $r_M > r_C$, the magnetosphere rotating at a super-Keplerian speed expels disk material, thus prohibiting accretion to occur. This regime is called the propeller regime.

The corotation radius, $r_C$, is given by

$$r_C = \left( \frac{GM_X P_{\text{spin}}^2}{4\pi^2} \right)^{1/3} \approx 1.4 \times 10^8 P_{\text{spin}}^{2/3} m_{1.4}^{1/3} \ \text{cm},$$

(6)

where $P_{\text{spin}}$ is the spin period of the neutron star.

Assuming the magnetic field of the neutron star to be a dipole-like field, the magnetospheric radius, $r_M$, is written as

$$r_M \approx 4.9 \times 10^8 k \ m_{16}^{-2/7} m_{1.4}^{-1/7} \mu_{30}^{4/7} \ \text{cm}$$

(7)

(e.g., Frank et al. 2002). Here, $\mu_{30} = \mu / 10^{30} \text{[G cm}^3\text{]}$ is the normalized magnetic moment and $k$ is a constant of order unity that depends on the physics and geometry of accretion. For spherical accretion, $k \sim 1$. For disk accretion, however, the previous results range from $k \sim 0.5$ to $k \sim 1$. In this paper, we adopt $k = 1$ as a conservative value for disk accretion, which gives rise to an upper limit of the magnetospheric radius for a given $\dot{m}$. The system is in the accretion regime when the normalized accretion rate satisfies the following condition:

$$\dot{m}_{16} > 1.4 \times 10^3 k^{7/2} P_{\text{spin}}^{-7/3} m_{1.4}^{-5/3} \mu_{30}^2.$$

(8)

For disk accretion in A 0535+262, where $P_{\text{spin}} = 103$ s and $\mu_{30} = 4.3$, we have $\dot{m}_{16} \gtrsim 0.5$ for the direct accretion regime.

In figure 3, we compare $r_M$ with $r_C$ using the mass-accretion rate estimated from the observed X-ray flux of A 0535+262. We utilized the X-ray observations by Swift/BAT (15–50 keV),1 converting its count rates to the energy fluxes. We assumed that $1 \text{Crab} = 1.386 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1}$, modeling the Crab spectra with $\Gamma_{12} = 0.26 \times 10^{22} \text{cm}^{-2}$, $\Gamma = 2.1$, and power-law normalization being 10.0. Figure 3 shows the ratio of the magnetospheric radius, $r_M$, to the corotation radius, $r_C$.

The figure clearly shows that the system is almost always in the accretion regime when the duration time is a small fraction of the orbital period, typically 0.2–0.3 $P_{\text{orb}}$. Sometimes

![Fig. 3. Long-term variation of the ratio of the magnetospheric radius $r_M$ to the corotation radius $r_C$ for A 0535+262. The magnetospheric radius is estimated from the observed flux with Swift with a conservative value of $k = 1$.](http://swift.gsfc.nasa.gov/docs/swift/results/transients/1A0535p262/)

3. Origin of Normal X-Ray Outbursts

The observed features of normal X-ray outbursts are summarized as follows. They occur at or near the periastron passage. The X-ray luminosity increases by about one order of magnitude with respect to the pre-outburst state ($L_X \sim 10^{36} \text{erg s}^{-1}$). The duration time is a small fraction of the orbital period, typically 0.2–0.3 $P_{\text{orb}}$. Sometimes
the precursors and flares occur prior to the main outbursts (Klochkov et al. 2010a and 2010b for EXO 2030+375; Caballero et al. 2008 for A 0535+262; Campana et al. 2001 for 4U 0115+634). Among those, the flares are interpreted to be caused by the instability of magnetosphere (e.g., Postnov et al. 2008).

Although it is widely accepted that normal X-ray outbursts are triggered by the mass transfer from the Be disk at or near periastron, the accretion mechanism still remains an open question. As shown in the previous section, the standard disk scenario fails to explain the observational features noted above. Below we propose that the normal X-ray outbursts are caused by RIAFs onto the neutron star from a tidally truncated Be disk.

3.1. Radiatively Inefficient Accretion Flows

In the context of the standard disk model, the viscous-heating rate per unit area, $Q_+$, is assumed to balance with the radiative cooling rate per unit area, $Q_{\text{rad}}$, in the energy equation. This approach is justified when the accretion disk is geometrically thin, so that $Q_{\text{adv}} \sim (H/r)^2 Q_+$ can be neglected, where $Q_{\text{adv}}$ represents the advective cooling rate per unit area. However, in hot accretion flows with $H/r \approx c_s/v_K \sim 1$, where $c_s$ and $v_K$ are the sound speed and Keplerian velocity of the disk, respectively, the advection cooling cannot be neglected in the energy equation.

Abramowicz et al. (1995) found that there are two families of advection-dominated accretion flow solutions. One family consists of optically thin, advection-dominated accretion flows (ADAFs), while the other consists of optically thick, advection-dominated accretion flows, so-called slim disks. Both families are thermally and viscously stable. From figure 3 of Abramowicz et al. (1995), ADAF solutions exist if $\dot{m} \equiv \dot{M}/(L_{\text{Edd}}/c^2) \lesssim 1$ (or equivalently $\dot{m}_{16} \lesssim 20 m_{14}$) whereas there are slim disk solutions if $\dot{m} \gtrsim 10$ (or $\dot{m}_{16} \gtrsim 200 m_{14}$). In the following, we consider ADAF solutions as the RIAF model for normal X-ray outbursts. We also discuss slim disk solutions in subsection 4.4.

3.1.1. Self-similar ADAF solutions

Narayan and Yi (1994) derived a set of solutions of self-similar, optically thin ADAFs with $Q_{\text{adv}} = fQ_+$, where $f$ exhibits the extent to which the flow is advection dominated. These flows give us most of the important properties of the general solutions, although $Q_{\text{rad}}$ is not explicitly shown.

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**Fig. 4.** ADAF model for A 0535+262 with (a) a coplanar Be disk and (b) a Be disk misaligned with the orbital plane by 45° about the semi-minor axis. The format of the figure is the same as that of figure 1, except that the thin (red) lines in the upper panels denote the estimated mass-accretion rate at the neutron star radius using the ADAF solution and that the lower panels show the infall timescale of the ADAF at the circularization radius of captured material (solid lines) and the mass-weighted average of the ADAF timescale (dashed lines).
in their solutions. Therefore, we model accretion flows onto the neutron star by the self-similar ADAFs when they have low accretion rates $\dot{m} \lesssim 1$ (or $\dot{m}_{16} \lesssim 20m_{14}$). By adopting the self-similar scaling law proposed by Narayan and Yi (1994, 1995), we obtain a set of solutions for $\alpha \ll 1$ as

$$v_r \approx -2.1 \times 10^9 c_1 \alpha_{0.1} \dot{r}^{-1/2} \text{ cm s}^{-1}, \quad \rho \approx 4.2 \times 10^5 c_1^{1/2} m_{14} \dot{r} \text{ cm},$$

$$H \approx 2.1 \times 10^{-6} c_1^{-1/2} m_{16}^{1/2} \alpha_{0.1}^{-1} m_{14}^{-2} \dot{r}^{-3/2} \text{ g cm}^{-3},$$

$$T \approx 2.7 \times 10^{12} c_3 \dot{r}^{-1} \text{ K},$$

where $v_r$ is the radial velocity, $\rho$ is the density, $T$ is the disk temperature, and $c_1 \approx 0.53$, $c_2 \approx 0.34$, and $c_3 \approx 0.35$ are numerical constants.

### 3.1.2. Observational implications

The inflow timescale of the ADAF is evaluated by

$$t_{\text{ADAF}} = \frac{r}{|v_r|} \approx 2.0 \times 10^{-4} m_{14} \alpha_{0.1}^{-1} \dot{r}^{-3/2} \text{ s}.$$  \hspace{1cm} (13)

Applying equation (13) to the same simulation data as in figures 1 and 2 for A 0535+262 and 4U 0115+634, respectively, we calculated the mass-accretion rate profiles in the case of ADAFs. The results are shown in figure 4 for A 0535+262 and figure 5 for 4U 0115+634. From the results for A 0535+262, we note that the ADAF solutions provide X-ray profiles with similar duration and amplitude to those of observed normal outbursts. The pre-periastron spike of the mass-accretion rate in the coplanar simulation is also reminiscent of an observed short spike prior to periastron (e.g., Camero-Arranz et al. 2012). Comparing the mass-accretion rate in the upper panel with the $t_{\text{ADAF}}$ plot in the lower panel, we note that the spiky feature is caused by the material with very low specific angular momentum.

The simulated accretion rate for 4U 0115+634 also has the accretion timescale in agreement with that of the observed normal outbursts. The X-ray luminosity obtained for the typical Be disk density ($10^{11} \text{ g cm}^{-3}$ at the base of the disk), however, seems too low to be consistent with the observations. This might explain why this system has shown normal X-ray outbursts only when the Be disk was fully developed.

Next, we consider the Bolometric X-ray luminosity of ADAFs. For simplicity, we assume that the X-ray radiation emitted from the ADAF is produced only by Bremsstrahlung cooling. The cooling due to other processes, such as the Synchrotron radiation and Inverse Compton process, will be discussed in a forthcoming paper in the context of high-energy...
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emissions. The Bremsstrahlung cooling rate per unit surface area is given by

\[ Q_{\text{br}} = \epsilon_{\text{br}} \rho^2 T_1^{1/2} H \]
\[ \approx 7.7 \times 10^{22} c_1^{-2} a_1^{-2} m_{1.4}^2 \dot{m}_{1.6}^{-5/2} \text{erg s}^{-1} \text{cm}^{-2}. \]  (14)

where \( \epsilon_{\text{br}} \approx 1.2 \times 10^{21} \text{erg s}^{-1} \text{cm}^{-2} \) is the emissivity of the Bremsstrahlung radiation. Then, the Bolometric X-ray luminosity is given by

\[ L_{\text{ADAF}} = 2\pi r_S^2 \int_{r_{\text{in}}}^{r_{\text{out}}} \dot{r} Q_{\text{br}} d\dot{r} \]
\[ \approx 1.7 \times 10^{34} a_1^{-2} r_1^{-1/2} m_{1.4}^{4/7} \mu_{30}^{-2/7} m_{16}^{8/7} \text{erg s}^{-1} \]  (15)

for \( r_M < r_{\text{circ}} \).

On the other hand, the X-ray luminosity, \( L_X \), emitted from the surface of the neutron star is calculated with equation (5) by

\[ L_X = \epsilon_X m_{1.4} L_{\text{Edd}} \approx 1.8 \times 10^{36} m_{1.4} \dot{m}_{16} \text{erg s}^{-1}. \]  (16)

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4. Accretion Mechanism for Giant X-Ray Outbursts

In the previous section, we proposed that normal X-ray outbursts are caused by ADAFs of material transferred from a truncated Be disk. The peak mass-transfer rate obtained by numerical simulations was in the range \( 10^{16-17} \text{g s}^{-1} \). This rate, together with the accretion timescale of ADAFs, gives rise to a peak X-ray luminosity on the order of \( 10^{36} \text{erg s}^{-1} \). As summarized below, however, it is about one order of magnitude lower than that of giant X-ray outbursts. In other words, a mass-transfer rate comparable to \( 10^{37-18} \text{g s}^{-1} \) is required to explain the peak X-ray luminosity of giant X-ray outbursts.

At first glance, it seems to be very unlikely for a truncated Be disk to provide such a high mass-transfer rate, because there is a gap between the neutron-star orbit and the Be disk. However, in misaligned systems, where the tidal torque is weaker than that in coplanar systems, the truncation radius could be larger than the periastron separation, depending on the tilt angle and the azimuth of tilt. If such a disk is warped towards the orbital plane, and if its direction happens to be near the periastron direction, the neutron star could capture gas at a sufficiently high rate for a giant X-ray outburst, when it passes through the warped part of the Be disk. Indeed, disk warping episodes associated with giant X-ray outbursts have been observed, as mentioned in section 1, and also summarized in subsection 4.1.

There are two possible mechanisms to make a Be disk warped: radiation-driven warping (Pringle 1996; Porter 1999) and tidally driven warping (Martin et al. 2011). Unfortunately, our SPH code cannot currently handle either of these mechanisms, although there are SPH codes in which one of these mechanisms is implemented [Foulkes et al. (2010) for radiation-driven warping simulations; Lodato and Price (2010) for tidal warping simulations]. Hence, as a first step towards modeling giant X-ray outbursts, we consider below the interaction between the neutron star and a rigidly tilted disk that extends beyond the neutron star orbit. After summarizing observational characteristics of giant X-ray outbursts, we first consider the Bondi-Hoyle-Lyttleton accretion of Be-disk material as a simplest approach for modeling the passage of the neutron star through the Be disk, and then numerically study accretion flows from differentially rotating Be disks for more detailed modeling. Whereas numerical simulations enable us to quantitatively compare results, the analytical approach provides a qualitatively better understanding of the physics behind the numerical result. We also discuss the possibility that the accretion flows become supercritical if the Be disk density is very high.

4.1. Observational Characteristics of Giant Outbursts

The observed features of giant X-ray outbursts are summarized as follows. The X-ray luminosity increases by a factor \( \gtrsim 10^2 \) with respect to the quiescent state \( (L_X \gtrsim 10^{37} \text{erg s}^{-1}) \). It sometimes rises up by a factor of \( 10^{3-4} \) to a level comparable to the Eddington luminosity of the neutron star. The duration time is several tens of days \( (\gtrsim 0.5 P_{\text{orb}}, \text{sometimes over one orbital period}) \). No orbital modulation has been detected. The fact that the large spin-up of the neutron star is seen in giant X-ray outbursts provides strong evidence for the presence of a transient accretion disk during the giant outburst. Quasi-periodic oscillations (QPOs) detected in some systems (e.g., Takeshima et al. 1994; Finger et al. 1996; Heindl et al. 1999) also support the transient accretion-disk scenario.

In some systems, the warping of a Be disk associated with the giant outburst has been observed (Negueruela et al. 2001; Reig et al. 2007; Moritani et al. 2011). Negueruela et al. (2001) and Reig et al. (2007) made long-term monitoring observations of the H\textalpha emission line profile from the optical counterpart of 4U 0115+634 in 1995–2005, and found that before and during giant X-ray outbursts, it changed from the usual double-peaked profile to a single-peaked or shell-line profile on a timescale of a year or so. As mentioned in section 1, this profile variability is most likely to originate from the precession of a warped Be disk. Moreover, high-resolution H\textalpha profiles of the optical counterpart of A0535+262 observed during the giant X-ray outburst in 2009 had an enhanced component, which together with the double-peaked component, appeared as a triple peak. Further analysis of these profiles indicates that the Be disk
became tidally warped (Martin et al. 2011), and intersected with the binary orbital plane near the periastron during the giant X-ray outburst (Moritani et al. 2012).

4.2. Bondi-Hoyle-Lyttleton Accretion

We consider the Bondi-Hoyle-Lyttleton (BHL) accretion process where the neutron star captures gas from an initially uniform flow of density $\rho$ and relative speed $v_{\text{rel}}$. The BHL accretion was first analyzed by Bondi and Hoyle (1944), and has been extensively studied since then (see Edgar 2004 for references and a modern review).

In the classical BHL accretion, the material with an initial impact parameter smaller than a critical value of

$$b \equiv \frac{2GM_X}{v^2_{\text{rel}}} \approx 3.7 \times 10^{12} m_{1.4} \left(\frac{v_{\text{rel}}}{100\text{ km s}^{-1}}\right)^{-2} \text{cm} \quad (17)$$

has a negative total energy, and is eventually accreted onto the central object. This leads to a simple BHL formula for the expected mass accretion rate,

$$\dot{M}_0 = \rho v_{\text{rel}} \pi b^2$$

$$= 4.4 \times 10^{18} m_{1.4} \left(\frac{\rho}{10^{-14}\text{ g cm}^{-3}}\right) \times \left(\frac{v_{\text{rel}}}{100\text{ km s}^{-1}}\right)^{-3} \text{g s}^{-1}. \quad (18)$$

In order to emulate the accretion process from an extended tilted disk, we adopt the disk gas density and velocity evaluated at the position of the neutron star, assuming the Be disk to cross the orbit at this position (see figure 6 for the model geometry). In the calculation, the Be disk is assumed to rotate at the Keplerian speed and have the density distribution in the form

$$\rho = \rho_0 \times \left(\frac{r}{R_*}\right)^{-n} \quad (19)$$

with typical Be disk parameters: $\rho_0 = 10^{-11}\text{ g cm}^{-3}$ and $n = 7/2$. Here, $r$ is the distance from the Be star. For simplicity, we neglect the velocity shear and the density gradient around the neutron star.

As an example, in the top panels of figure 7 we show the relative speed, $v_{\text{rel}}$, between the neutron star and a Be disk with a tilt angle of $\beta = 45^\circ$ as a function of the azimuth of the ascending node, $\gamma + \pi/2$. The left panel is for A 0535+262, while the right panel is for 4U 0115+634. In both calculations, we assumed that the disk rotates in the prograde direction. Note that the plot shows the dependence of the relative velocity on the azimuth of tilt, $\gamma$, of the Be disk, not on the orbital phase of the neutron star. For $\gamma + \pi/2 = 0$, the neutron star passes through the Be disk at the apastron, while for $\gamma + \pi/2 = \pi$ the periastron is the location of the disk transit.

We mentioned above that the material with an initial impact parameter smaller than $b$ accretes to the neutron star. In binaries, however, only material inside the Roche radius of the neutron star, $r_L$, given by equation (4), can be accreted. Thus, for BHL accretion in binaries, the accretion rate is given by

$$\dot{M}_{\text{BHL}} = \dot{M}_0 \times \min \left[1, \left(\frac{r_L}{b}\right)^2\right]. \quad (20)$$

where $\dot{M}_0$ is the classical BHL accretion rate, given by equation (18). The middle panels of figure 7 compare these two radii, $b$ (blue line) and $r_L$ (red line). The solid part of
Fig. 7. Characteristic quantities of the BHL accretion as a function of ascending-node azimuth $\gamma + \pi/2$, at which the neutron star passes through the Be disk: (a) A 0535+262 and (b) 4U 0115+634. Top panels: Relative velocity between the neutron star and the Be disk. Middle panels: Comparison between BHL accretion radius $b$ (blue line) and Roche radius $r_L$ (red line) of the neutron star. Bottom panels: Mass-accretion rate, $M_{\text{BHL}}$, given by equation (20). In these calculations, the tilt angle, $\beta$, is fixed at $45^\circ$. The base density and the density gradient index of the Be disk are assumed to be $10^{11} \text{ g cm}^{-3}$ and 7/2, respectively.

These lines indicate the effective accretion radius, i.e., the smaller radius of $b$ and $r_L$, inside which the gas accretes onto the neutron star. We note that for $\beta = 45^\circ$, the accretion radius in A 0535+262 is controlled by $b$ when the neutron star passes through the disk around the periastron, while it is equal to $r_L$ otherwise. In our model, this transition occurs only for moderate values of tilt angle. This is also the case in 4U 0115+634, although in this smaller system with a higher relative velocity, the accretion radius in the particular case of $\beta = 45^\circ$ is controlled by $b$ for any value of azimuth of tilt $\gamma$. For $\beta \ll 45^\circ$, because of a small relative velocity, the critical radius, $b$, for the BHL accretion exceeds the Roche radius, $r_L$, at any azimuth of the disk plane, so that the accretion radius is always given by $r_L$. On the other hand, for $\beta \gg 45^\circ$ (including all cases of retrograde disk rotation), the relative velocity is so high that the BHL accretion radius, $b$, is always smaller than...
the Roche radius, $r_{12}$, as in the case of stellar-wind accretion.

The bottom panels of figure 7 present the accretion rate, $M_{\text{BHL}}$, calculated by using equation (20). Note that in A 0535+262, the mass-accretion rate of $\gtrsim 10^{37} \, \text{g s}^{-1}$, and hence the accretion luminosity of $\gtrsim 10^{37} \, \text{erg s}^{-1}$, is obtained for a wide range of azimuth of a misaligned disk. In contrast, in 4U 0115+634, such a high accretion rate is obtained only if the Be disk density is significantly higher than the typical density.

Figure 8 shows the mass-accretion rate as a function of the tilt angle, $\beta$. In these calculations, the azimuth of tilt, $\gamma$, was fixed at 90°, for which the neutron star passes through the Be disk at the periastron. The solid and the dashed lines denote $M_{\text{BHL}}$ for A 0535+262 and 4U 0115+634, respectively. From the figure, we note that in A 0535+262 and 4U 0115+634, respectively. In these calculations, the azimuth of tilt, $\gamma$, was fixed at 90°, for which the neutron star passes through the Be disk at the periastron.

4.3. Accretion from Differentially Rotating Be Disks

Although very simplified, the above analytical model provides useful information about the mass captured by the neutron star when it passes through a tilted Be disk. The resultant mass-capture rate is on the order of $10^{37} \, \text{erg s}^{-1}$ for a wide range of tilt angles. This rate is comparable to the mass accretion required for the observed luminosity of giant X-ray outbursts.

As can be seen in sub-subsection 2.2.2, however, high mass-capture rates do not necessarily mean high mass-accretion rates. If the accretion time is comparable to or longer than the orbital period, the accretion luminosity will stay more or less constant at a level much lower than that calculated from the peak mass-capture rate. Hence, it is important to examine the accretion timescale of mass captured by the neutron star. It is, however, not a trivial task to estimate the accretion rate and timescale, given the presence of differential rotation in the Be disk and the eccentricity of the neutron star orbit. For a quantitative study of these quantities, we carried out SPH simulations of accretion processes from misaligned Be disks for a limited range of parameter space for A 0535+262 and 4U 0115+634.

4.3.1. Numerical model

The initial configuration of the simulations was as follows. For simplicity, we considered a rigidly-tilted, isothermal Be disk to model the interaction between the neutron star and a misaligned disk. In order to simulate a direct collision of the neutron star with the Be disk with good spatial resolution, we concentrated SPH particles in a ring-like region across the periastron separation $r = (1 - e)a$, from $r \sim 0.65 (1 - e)a$ to $r \sim 1.2 (1 - e)a$. We distributed SPH particles such that the Be disk would have an equatorial density distribution in the form of equation (19) with $\rho_0 = 10^{-11} \, \text{g cm}^{-3}$ and $n = 7/2$, and would be in hydrostatic equilibrium in the direction normal to the disk mid-plane. The disk temperature was set to $0.6 T_{\text{eff}}$, as in sub-subsection 2.2.1. We tilted the Be disk about the semi-major axis (i.e., $\gamma = 90^\circ$) to study the strongest interaction case for each tilt angle. The accretion radius of the neutron star was set to $0.01 a \approx 2 \times 10^5 R_X$. The initial number of SPH particles was $7 \times 10^5$. We ran each simulation from 0.1 $P_{\text{orb}}$ prior to the periastron through 0.1 $P_{\text{orb}}$ after it.

4.3.2. Numerical results

We ran simulations for five different tilt angles of $\beta = 0^\circ$, 20°, 40°, 60°, and 90° for each system. The peak accretion rates obtained in these simulations are plotted by filled circles in figure 8. In contrast to the analytical result, the simulated peak accretion rate monotonically decreases with increasing misaligned angle. Compared with the analytical rate, the simulated rate is significantly high in the coplanar ($\beta = 0^\circ$) case, comparable for $\beta = 20^\circ$ and 90°, and significantly low for $\beta = 40^\circ$ and 60°.

In order to understand the cause(s) of these differences, we compare the simulation results for tilt angles of $\beta = 20^\circ$ and $\beta = 40^\circ$ in more detail in figures 9 (A 0535+262) and 10 (4U 0115+634). In each figure, the upper panels show the orbital-phase dependence of the mass-accretion rate on to the neutron star. In each panel, the thick (blue) line denotes the rate of mass inflow through the inner simulation boundary.
Fig. 9. Simulation result for the BHL accretion from a tilted Be disk in A 0535+262: (a) $\beta = 20^\circ$ and (b) $\beta = 40^\circ$, where $\beta$ is the tilt angle. The azimuth of tilt, $\gamma$, is fixed at $90^\circ$ for which the neutron star passes through the Be disk at the periastron. Each simulation has run from orbital phase $-0.1$ to $+0.1$. Upper panels: The orbital-phase dependence of the mass-inflow rate through the inner simulation boundary [thick (blue) lines] and the estimated accretion rate at the neutron star radius [thin (red) lines]. The right axis shows the X-ray luminosity corresponding to these rates. Lower panels: The orbital-phase dependence of the accretion timescale [thick (red) lines]. The standard and the ADAF accretion timescales are also shown by the upper and lower thin (black) lines, respectively. The horizontal (red) dashed line in each lower panel denotes the mass-weighted average of the accretion timescale.

For $\beta = 20^\circ$, the simulated accretion rate rises rapidly, has a pre-periastron peak, and then decays slowly. On the other hand, for $\beta = 40^\circ$ there are two peaks. The lower pre-periastron peak is followed by the higher post-periastron peak. After the post-periastron peak, the rate decreases gradually. In both cases, the initial accretion is of the BHL type, but later (after the neutron star passes through the disk) the accretion is via an accretion disk formed by material that catches up with the neutron star from behind, which has significantly larger specific angular momentum than the material accreted before and during the disk transit. The initial BHL accretion and the subsequent accretion via the accretion disk form the rapidly rising part and the slowly decline part of the simulated accretion rate profile, respectively.

As can be seen in figure 8, the analytical model predicts a higher accretion rate for $\beta = 30^\circ$–$40^\circ$ than for $\beta = 20^\circ$. The simulations, however, have revealed the opposite trend. The simulated accretion rate for $\beta = 20^\circ$ is 2–3 times as high as that for $\beta = 40^\circ$ in both systems. Examining the interaction more closely, we found that in the case of small tilt angles, the tidal torque by the neutron star starts exciting a tidal stream in the Be disk significantly before the disk crossing event, which collides with the neutron star at a very small impact parameter. Since the density in the tidal stream is much higher than in the background disk gas, this collision enhances the mass-accretion rate significantly. In contrast, for $\beta \gtrsim 40^\circ$, where the tidal torque is weaker, the tidal stream grows more slowly. By the time it becomes strong, the neutron star is already passing the periastron and the streaming gas, which has a relatively large impact parameter, forms an accretion disk, not directly running on to the neutron star, and thus unable to significantly enhance the mass-accretion rate.

Since the accretion radius set in these simulations is $0.01a \sim 2 \times 10^5 R_X$, and still very far from the neutron-star, the accretion time the flow takes from this radius to the neutron star surface could significantly modify the amplitude and shape of the accretion rate profile. Thus, we estimated the accretion rate at the neutron-star radius (hereafter, the final accretion rate) using the same procedure as that described in sub-subsection 2.2.2. In deriving the final accretion rate, we assumed that the accretion flow is of standard-disk type.
in the period of \( \dot{m} > 1 \) (or \( \dot{m}_{16} > 20 \)) and afterwards, while it is of ADAF type otherwise. In the former (latter) case, the accretion takes place in the viscous (ADAF) timescale given by equation (3) [equation (13)], with the circularization radius derived from the specific angular momentum of accreted SPH particles. The phase dependence of the accretion timescale, \( t_{\text{acc}} \), is shown by the thick (red) lines in the lower panels of figures 9 and 10, where for comparison purpose the viscous and ADAF timescales are also denoted by the upper and lower thin lines, respectively. The resultant, final accretion rate is shown by the thin (red) lines in the upper panels. From the figures we note that the final accretion rate profile changes little from the simulated profile at \( r = 0.01a \), except for cases where the accretion rate exceeds the upper limit for ADAF solutions, so that the accretion flow is of the standard-disk type. For typical Be disk parameters, the latter case occurred only in \( \beta \leq 20^\circ \) simulations for A 0535+262.

The above-described simulations of accretion from differentially rotating Be disks have important observational implications. The peak accretion rates obtained for \( \beta \lesssim 20^\circ \) and typical Be disk density (\( \rho_{-11} \sim 1 \)) agree with those required for the observed X-ray luminosity of giant X-ray outbursts. In other words, Be disks of typical density have potential to cause giant outbursts if the tilt angle is small. On the other hand, if the tilt angle is large, say \( \beta \sim 40^\circ \), the Be disk has to be several-times denser than typical in order to supply a sufficient amount of gas for giant X-ray outbursts. Otherwise, the outbursts would appear as normal X-ray outbursts.

4.4. Supercritical Accretion

In the previous section, we assume that the accretion of mass captured by the BHL-type accretion occurs via the standard disk or optically thin ADAF. This assumption is reasonable as long as the mass-capture rate is on the order of \( 10^{17} \text{ g s}^{-1} \) or less. If the mass-capture rate exceeds the Eddington rate (\( \sim 10^{18} \text{ g s}^{-1} \)), however, the accretion flow drastically changes to being supercritical. In this section, we consider the possibility that Be/X-ray binaries have supercritical accretion flows.

Recent X-ray observations have revealed the existence of bright X-ray sources, such as GRS 1915+105, in our Galaxy with luminosities over the Eddington luminosity (c.f., Done et al. 2007). Such large luminosities can be explained by a supercritical accretion flow onto a black hole or neutron star (cf. Watarai et al. 2000).

In an optically thick accretion flow with an accretion rate much higher than the Eddington accretion rate, the photons...
are trapped and restored as the entropy in the accreting gas without being radiated away. Such a flow is called a slim disk, where the advective cooling dominates the radiative cooling. The slim-disk model was first proposed by Abramowicz et al. (1988) as a thermally stable, advection-dominated, supercritical accretion flow. Then, its self-similar solution has been derived by Wang and Zhou (1999) and Watarai (2006).

In what follows, we first describe the condition in which the supercritical accretion occurs in an accretion flow around the neutron star in the context of Be/X-ray binaries. We then derive the accretion timescale based on the self-similar solutions of slim disk model (Watarai 2006). We finally evaluate the Bolometric X-ray luminosity emitted from the slim disk.

### 4.4.1. Condition for supercritical accretion

At luminosities close to, or higher than, the Eddington luminosity, the scale-height of the accretion disk is comparable to the radius, i.e., \( H/r \sim 1 \). Hence, in the following analysis, we do not distinguish between spherically symmetric accretion and disk accretion.

In a very optically thick medium, photons are trapped if their diffusion timescale, \( t_{\text{diff}} \), is longer than the accretion timescale, \( t_{\text{acc}} \). If the medium is disk-like, \( t_{\text{diff}} \) of photons near the equatorial plane is given by

\[
t_{\text{diff}} \sim \frac{3H^2}{c\lambda} \sim \frac{3H\tau}{c} \sim \frac{3H\Sigma}{2c}
\]

(e.g., Kato et al. 2008), where \( \lambda \) is the mean free path of photons, \( \tau \) is the vertical optical depth, \( \kappa \) is the opacity, and \( \Sigma \) is the surface density. In deriving the last equation, we used \( \tau \sim \kappa \Sigma/2 \). As the opacity \( \kappa \), we use that of the electron scattering, \( \kappa_{\text{es}} \) (\( \sim 0.4 \)).

On the other hand, the accretion timescale is written as

\[
t_{\text{acc}} \sim \frac{r}{v_r} \sim \frac{2\pi r^2 \Sigma}{M}.
\]

Equating equation (21) with equation (22) and using equation (5), we obtain the photon-trapping radius \( r_{\text{trap}} \) as

\[
r_{\text{trap}} = \frac{3H}{2} \frac{Mc^2}{2r_L} \approx 3.2 \times 10^4 m_{16} \text{ cm},
\]

where \( H/r \sim 1 \) at high luminosities. In order for the supercritical accretion to occur, \( r_{\text{trap}} \) should be larger than the magnetospheric radius, \( r_M \), from which we have the following condition:

\[
m_{16} > m_{16,sc},
\]

where we define

\[
m_{16,sc} = 1.7 \times 10^3 \kappa^{7/9} \beta^{1/9} \gamma^{4/9} m_{14}^{0.4}. \]

From equation (25), the mass-capture rate must be higher than \( \sim 2 \times 10^{19} \text{ g s}^{-1} \) in order that the accretion flow becomes supercritical before it reaches the magnetosphere of the neutron star. To realize such a huge mass-capture rate, the base density of the Be disk should be by two orders of magnitude higher than the typical \( \rho_0 = 10^{-11} \text{ g cm}^{-3} \). Note that this is not an unrealistic condition. For instance, figure 9a shows that in the case of A 0535+262 with \( \beta = 20^\circ \) and \( \gamma = 90^\circ \), the accretion flow can be supercritical at orbital phases from \( -0.04 \) to \( 0.02 \) with respect to the periastron, if the base density is \( 10^{-9} \text{ g cm}^{-3} \) or \( \rho_{-11} = 100 \).

### 4.4.2. Observational implications

In this subsection, we evaluate the Bolometric X-ray luminosity emitted from the slim disk. We assume that the condition \( m > m_{16} \) is satisfied, so that the slim disk state holds from the photon-trapping radius down to the magnetospheric radius.

According to a self-similar solution of the slim disk (Watarai 2006), the radial velocity is given by

\[
|v_r| \approx 3.2 \times 10^9 f \alpha_0 \gamma^2 r^{-1/2} \text{ cm s}^{-1},
\]

where we recall that \( f = Q_{\text{adv}}/Q^+ \). Then, the accretion timescale is calculated as

\[
t_{\text{SCAF}} = \frac{r_{\text{trap}}}{|v_r|} \approx 2.7 \times 10^{-6} f^{-1} \alpha_0^{-1} m_{14}^{-1/2} m_{16}^{1/2} \text{ s}. \]

The distribution of the effective temperature of the slim disk is given by the self-similar solution as

\[
T_{\text{eff}} \approx 4.9 \times 10^7 f^{1/8} m_{14}^{-1/4} \gamma^{-1/2} \text{ K}
\]

(Watarai 2006), so that the cooling rate of the slim disk, \( Q_{\text{rad}} \), is given by

\[
Q_{\text{rad}} = 2\sigma T_{\text{eff}}^4 \approx 1.1 \times 10^{26} f^{1/2} m_{14}^{-1} \gamma^{-2} \text{ erg s}^{-1} \text{ cm}^{-2}. \]

The Bolometric X-ray luminosity emitted from the slim disk is then estimated as

\[
L_{\text{slim}} = 2\pi r_S^2 \int_{r_M} r_{\text{trap}} d\hat{r} \approx 1.2 \times 10^{38} f^{1/2} m_{14} \ln \left( \frac{r_{\text{trap}}}{r_M} \right) \text{ erg s}^{-1}. \]

From equation (27), the timescale of the supercritical accretion is much shorter than the orbital period of any Be/X-ray binaries. Hence, if the mass-capture rate satisfies the condition given by equation (24), the resultant supercritical accretion flow would have the same final accretion rate profile as those shown by the thick (blue) lines in the upper panels of figures 9 and 10 with the amplitude proportional to the base density of the Be disk. From equation (30), the luminosity is then estimated to be on the order of \( 10^{38} \text{ erg s}^{-1} \), even if \( r_{\text{trap}}/r_M \approx 10 \). Note that the light curves of supercritical accretion flows in Be/X-ray binaries are thus quite different from those expected for standard disk accretion.

### 5. Discussion

In Be/X-ray binaries, the Be disk is tidally/resonantly truncated by the gravitational force of the neutron star, except in highly eccentric systems and those with Be disks highly inclined from the orbital plane (Okazaki & Negueruela 2001). Such a truncation produces a gap between the Be disk and the neutron star orbit. In a system with a gap, the neutron star captures gas from a tidally elongated part of the disk. Since the tidal deformation is a dynamical process, and there occurs no redistribution of the angular momentum by viscosity, the rotation velocity in the elongated part decreases more rapidly with radius than in a Keplerian disk. This makes the relative velocity between the neutron star and the captured material larger than in the case where the neutron star captures mass from an extended Keplerian disk without a gap. As a result, the material captured from a truncated Be disk forms a large
accretion disk around the neutron star. If the accretion disk is radiative-cooling dominated, its accretion timescale easily exceeds the orbital period. In such a situation the system will exhibit no rapid nor large X-ray flux changes seen in normal X-ray outbursts. In fact, in section 2, we have shown that this is the case for the Be/X-ray binaries A 0535+262 and 4U0115+634, by using results from numerical simulations.

One might argue that the magnetosphere of the neutron star controls the accretion flows, causing rapid and large variations of the X-ray luminosity. When the magnetospheric radius is larger than the corotation radius of the accreting matter, the matter is expelled by the rotating magnetosphere (the propeller effect), and the systems is in the quiescent state. The gate opens only if the Be disk supplies a large enough mass so that the resultant accretion flow can push back the magnetosphere inside the corotation radius. In fact, in 4U0115+63 a sudden transition from the quiescence to a normal outburst has been witnessed, which is consistent with this idea (Campana et al. 2001).

However, as shown in section 2, A 0535+262 is almost always in the direct accretion regime (figure 3), because the propeller effect does not work for this slowly rotating X-ray pulsar. The system is therefore one of best candidates to study more direct relationship between the accretion flows onto the neutron star and the resultant X-ray variability. Given that standard disks have accretion timescales much longer than the orbital period, we can safely rule out the possibility that the material from the truncated Be disk forms a standard disk around the neutron star.

The problem with rapid and large X-ray variability is resolved if the accretion flow is radiatively inefficient (RIAF). In section 3, using results from numerical simulations, we have shown that mass transfer from truncated Be disks with typical density parameters gives rise to accretion rates in agreement with those expected from X-ray luminosity of normal outbursts, and that these rates are significantly lower than the critical rate above which no RIAF solution exists. The accretion timescale is also consistent with the duration of normal outbursts.

The RIAF model for normal X-ray outbursts opens a new research field on Be/X-ray binaries. In this paper, we assumed that the magnetospheric radius for self-similar ADAF solutions is about the same as that for the disk accretion. Given that the magnetospheric interaction affects the accretion onto the neutron star in many ways, including even the possibility of launching jets, it is very important to investigate this phenomenon in detail. There is also a possibility to detect high energy emission from RIAFs, e.g., synchrotron emission in X-rays from accelerated particles in the layer above the magnetosphere and the GeV/TeV emission via the inverse Compton scattering of soft photons from the Be star and/or the accretion disk, although Fermi and VERITAS detected no emission above 0.1 GeV from A0535+262 during the 2009 giant outburst (Acciari et al. 2011). We will analyze it in a forthcoming paper.

Another interesting possibility also emerges from the RIAF model for normal X-ray outbursts. In section 3, we used numerical results for a typical Be disk with a base density of $10^{-11}$ g cm$^{-3}$ and a density gradient index of $n = 7/2$. There is, however, a large range of observed base density ($10^{-12}$–$10^{-10}$ g cm$^{-3}$) and density gradient index (2.5–4.5) (e.g., Jones et al. 2008). If the mass-transfer rate from the Be disk exceeds the critical rate above which no RIAF solution exists, a standard accretion disk would form. Thus, the transition between the standard disk state and the RIAF state can occur, depending on the base density and the density gradient of the Be disk. Observationally, this transition would be seen as a sudden drop/rise of the X-ray luminosity by about one order of magnitude. Since the mass-transfer rate decreases with increasing angle between the Be disk and the binary orbital plane, the coplanar Be disk systems are most favorable to see this transition.

In section 4, we have proposed that giant X-ray outbursts can be triggered by the BHL accretion of material from a tilted Be disk. Although the RIAF model with truncated Be disks works for normal X-ray outbursts, it cannot be applied to giant X-ray outbursts by two reasons. One reason is that because of the disk truncation, the mass-transfer rate is lower than that required for giant X-ray outbursts, unless the Be disk density is much higher, or its distribution is much flatter than typical values. The other, more crucial reason is that the accretion rate estimated from the luminosity of bright giant X-ray outbursts exceeds by a factor of few the highest mass-accretion rate for RIAFs. Moreover, there is observational evidence that the Be disk is warped when giant outbursts occur (Negueruela et al. 2001; Reig et al. 2007; Moritani et al. 2011).

Our model for giant X-ray outbursts is based on the idea that the warped shape of the Be disk naturally results in enhanced mass accretion, if the disk is inclined from the orbital plane, and its warped part gets across the orbit of the neutron star from above or below the orbital plane. In real systems, the accretion rate should depend on the local density and the velocity distribution of gas around the neutron star. For a warped disk picture, however, no such information is easily available. Therefore, as a first order of approximation, we modeled the warped Be disk by a rigidly-tilted, Keplerian disk with a power-law density distribution in the radial direction. The Be disk was assumed to have an outer radius larger than the periastron separation. With a simplified analytical treatment, we found that the accretion radius of the neutron star is limited by the Roche lobe radius for small tilt angles, while for large tilt angles the neutron star accretes material inside the BHL accretion radius.

Numerical simulations also revealed a new feature of the BHL accretion in Be/X-ray binaries. For Be disks with small tilt angles ($\beta \lesssim 20^\circ$), the tidal torque of the neutron star rapidly excites a collimated gas flow in the Be disk, and the neutron star collides with this tidal stream at a very small impact parameter. Since the density in the tidal stream is much higher than in the background disk gas, this collision greatly enhances the mass-accretion rate. This does not happen for larger tilt angles ($\beta \gtrsim 40^\circ$). Consequently, the accretion rate is much higher for small tilt angles than for large tilt angles.

Using simulation data, we estimated the time-dependent accretion rate at the neutron-star radius. It turns out that for typical Be disk parameters, only long-period systems, such as A0535+262, with small tilt angles ($\beta \lesssim 20^\circ$) can have mass-accretion rates as high as those estimated for giant X-ray
outbursts. In order for systems with large tilt angles ($\beta \geq 40^\circ$) and/or short periods, such as 4U 0115+634, to exhibit giant X-ray outbursts, the Be disk density has to be higher than the typical one by a factor of several or more around the neutron star orbit. Otherwise, the outburst luminosity of these systems falls into the range of normal X-ray outbursts.

In this paper, we have assumed the upper limit for the ADAF solutions to be $\dot{m} = M/(L_{\text{edd}}/c^2) = 1$ (or $M \sim 2 \times 10^{17}$ g s$^{-1}$). With this criterion, the accretion flow is radiative-cooling dominated (i.e., a standard disk) only for relatively bright ($\gtrsim 4 \times 10^{37}$ erg s$^{-1}$) giant outbursts. For less-bright ($\lesssim 4 \times 10^{37}$ erg s$^{-1}$) giant outbursts, and all normal outbursts, the accretion flow is advection-dominated. The type of the accretion flow, standard-disk type or ADAF type, thus depends only on whether the mass-accretion rate is higher than the limiting rate for ADAF solutions or not.

From the sensitiveness of the accretion rate on the local tilt angle, a working hypothesis comes up for a series of X-ray activities consisting of a few normal X-ray outbursts and a giant X-ray outburst. This series of X-ray activity has sometimes been observed in Be/X-ray binaries. As mentioned in subsection 4.1, 4U 0115+634 has shown observational evidence of precession of a warped Be disk before and during giant X-ray outburst (Negueruela et al. 2001; Reig et al. 2007). When a warped disk precesses, it is likely that the local tilt angle, i.e., the angle between the neutron star’s motion and the motion of material in the Be disk, varies from cycle to cycle. If the tilt angle is large at the beginning, the system exhibits an X-ray outburst at a level considered to be a normal outburst. If the warped structure survives over several orbital cycles, there will be a good chance for the neutron star to pass through the disk at a small tilt angle in due course. This encounter will give rise to a giant X-ray outburst. Later on, the system will show a few outbursts at the level of normal X-ray outbursts until the azimuth of the disk plane ($\gamma + \pi/2$) moves too far away from the periastron. In this way, our model for giant X-ray outbursts naturally, though qualitatively, explains a sequence of X-ray outbursts, i.e., the occurrence of a few normal X-ray outbursts before and after a giant X-ray outburst, which has been observed in 4U 0115+634, A 0535+262, and some other Be/X-ray binaries.

Finally, there is a possibility of supercritical accretion in Be/X-ray binaries, as discussed in subsection 4.4. Throughout the present work, we fixed the base density and the density gradient index of the Be disk at $10^{-11}$ g cm$^{-3}$ and 7/2, respectively. As mentioned previously, however, there is a large scatter in the distribution of the Be-disk base density and its density gradient. For Be disks with a very high base density and/or significantly flatter density distribution, the model predicts that the accretion becomes supercritical, triggering super-Eddington luminosity. As long as we know, no Be/X-ray binaries have shown super-Eddington luminosity. Nevertheless, we have seen no mechanism that can prevent Be disks from supplying mass at supercritical rates. If the supercritical accretion takes place, the luminosity will exceed, or be comparable to, the Eddington luminosity and photon trapping will veil all features related to magnetic fields of the neutron star such as X-ray pulsation and cyclotron resonance scattering features. Once such characteristic changes are observed, a fertile research field will arise from it. It is therefore important to carry out more detailed modeling of supercritical accretion in Be/X-ray binaries. Be/X-ray binaries thus provide a unique opportunity where in one system one can study the physics of various types of accretion, including standard disks, Bondi-Hoyle-Lyttleton accretion, RIAFs, and even supercritical accretion flows, in relation to the geometry and dynamics of the mass donor.

6. Conclusions

We have studied the origins of normal and giant X-ray outbursts in Be/X-ray binaries. Based on the results from 3D SPH simulations, we first showed that the accretion via the standard disk cannot produce the observed rapid and large X-ray flux variation. Then, by using analytical studies as well as numerical ones, we proposed the following scenarios for these two types of X-ray outbursts:

1. The normal X-ray outbursts are caused by RIAFs from tidally truncated Be disks. The resultant luminosity and time variability are consistent with those observed, because RIAFs have accretion timescales much shorter than the orbital period, so that the rapid and large variation in the mass-transfer rate from the truncated Be disk is conserved during the accretion process.

2. Giant X-ray outbursts occur in systems where the Be disk is misaligned with the binary orbital plane and is sufficiently developed. When the outermost part of such a disk is warped, and crosses the orbit of the neutron star near the periastron, the neutron star can capture a large amount of gas via BHL accretion. This process results in the formation of a very small standard disk, or ADAF, depending on the mass-capture rate, in which the accretion timescale is much shorter than the orbital period.

In the present work, we focused on the mass-transfer process from the Be disk to the neutron star, as well as the subsequent accretion processes. There are, however, observational hints that the giant X-ray outburst is not a single independent event, but is a highlight of a much longer cycle of events. For instance, a giant X-ray outburst is often accompanied by smaller scale X-ray outbursts, and the Be disk emission starts declining sometime before the giant outburst. In our next paper, we will consider how the giant X-ray outbursts and these associated events are related to the evolutionary cycle of the Be disk.

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