

Instabilities in Be star decretion disks

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A Be star is a rapidly rotating B-type star that is ejecting a decretion (outflowing) Keplerian disk. Be/X-ray binaries consist of a Be star in a binary with a companion that is most often a neutron star. X-ray outbursts are observed when material flows on to the neutron star. The disk dynamics in Be/X-ray binaries have some similarities with cataclysmic variables (CVs) since their binary mass ratios are comparable. However, the typically eccentric and misaligned binary orbit leads to many dynamical disk instabilities in Be/X-ray binaries that are not present in CVs. Depending upon the binary orbital parameters and disk properties, possible instabilities include superhump behavior, tilting, nodal precession, warping, Kozai-Lidov oscillations, forced eccentricity growth and eccentric disk breaking. The injection of material into the disk at the stellar equator also affects the disk dynamics. In short-orbital period and high eccentricity binaries, a radially narrow disk can remain locked to the stellar equator, though it may still undergo nodal precession if the star undergoes stellar spin-axis precession. In long-orbital-period binaries with low eccentricity, a radially extended disk can be subject to warping or nodal disk breaking. When the disk breaks, the inner ring remains locked to the Be star equator and the outer disk ring can undergo the dynamical disk instabilities. The complex behavior of Be star disks may explain the observed diversity of light curves and X-ray outbursts.

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1. Introduction

A Be star is a B-type star that is rotating close to its break up rate [1, 2]. The rapid rotation could be primordial, a result of binary mass transfer, or a result of spin-up during the main-sequence B star phase [3]. However, Be stars are typically in a binary system with a neutron star [e.g. 4, 5] and are thought to have been spun up by the accretion of material during the earlier evolution of the companion star [e.g. 6–8]. Material flows from the equator of the Be star into a viscous Keplerian decretion (or outflowing) disk [9–19]. Although stellar winds [20, 21] and disk ejection [22] may aid the spin-down of the star, Be stars are observed at all ages through the main-sequence [23, 24]. Some Be star systems are observed to have stable disks, which implies a constant feeding mechanism, while other systems may have disk build up and decay phases [17].

The mass ratio of a Be/X-ray binary is typically around $q = M_{\text{NS}}/M_* \approx 0.1 - 0.2$, where M_* is the mass of the Be star and M_{NS} is the mass of the neutron star. This is similar to a low-mass ratio cataclysmic variable (CV) in which the disk is also around the higher mass binary component. Therefore, there are some similarities between the Be star disk in a Be/X-ray binary and the disk in a CV system. However, two main differences between the systems are the following:

1. Material flows outwards in a decretion disk around the Be star while in a CV, the material flows inwards onto the white dwarf.
2. The orbit of the Be/X-ray binary can be eccentric and highly misaligned to the orbital plane of the disk.

Since the supernova explosion that formed the neutron star may be associated with a kick, Be/X-ray binaries are often in eccentric orbits with the spin axis of the star misaligned to the binary orbit [25–27]. An eccentric orbit with a large misalignment between the disk and the binary orbit can also lead to a range of dynamical effects that may significantly change the evolution of the disk [e.g. 28–30].

Be star disks are expected to be hot enough for hydrogen to be ionized [e.g. 15] and therefore do not undergo outbursts as a result of the thermal-viscous instability, as some CVs do. However, Be/X-ray binaries can display X-ray outbursts [31, 32] that occur when material is transferred from the Be star disk to the neutron star. These come in two types; Type I outbursts occur each orbital period, while Type II outbursts occur less frequently, but have a much higher luminosity [33–36]. In addition, optical lightcurves show a wide range of behavior. Many Be/X-ray binaries show regular superorbital periods on a timescale of around $20 P_{\text{orb}}$ [37–39], while others have more chaotic behavior [e.g. 40]. We discuss a range of disk instabilities that may help explain the complex observations of Be/X-ray binaries.

2. Be star disk formation and truncation

What is the difficulty with forming a decretion disk from a rapidly rotating Be star? The breakup spin frequency of a star is

$$\Omega_{\text{b}} = \left(\frac{GM_*}{R_*^3} \right)^{1/2}, \quad (1)$$

where R_* is the radius of the star. A star spinning at this rate, or close to this rate with non-radial pulsations, may allow the ejection of a decretion disk [9, 41–45]. However, observations of Be star spin rates suggest that they have an average spin frequency of only $\Omega_* \approx 0.7 - 0.8 \Omega_b$ [17, 46, 47]. Therefore, understanding how the decretion disk forms has been a long standing problem.

One suggestion to overcome this issue is the presence of magnetic fields [48]. With a sufficiently strong stellar magnetic field, the inner parts of the disk are magnetically truncated at the Alfvén radius [49]. Provided that the Alfvén radius is larger than the corotation radius of the star and the disk [but not so large as to destroy the disk, 50], then angular momentum can be transferred from the star to the inner disk and prevent the reaccretion of material. In this model, there is a gap between the star and the inner radius of the disk. This can allow material in small-scale magnetic flaring events on the stellar surface to flow outwards and form the Be star disk [48]. However, current observations have not seen evidence of strong magnetic fields in Be stars [51, 52].

Recently, [53] showed that boundary layer effects in a circumplanetary disk around a planet reduce the rotation rate of the disk in the region close to a planet. This allows for the formation of a decretion disk at spin rates less than the breakup rate. Similar effects occur for a disk around a Be star [22]. Therefore, boundary layer effects may allow the formation of Be star decretion disks at spin rates that are less than the breakup spin rate.

The decretion disk exerts a torque on the star that spins it down. A characteristic Be star spin rate is found by where the timescale that the star spins down on becomes longer than the Be star lifetime. For a disk aspect ratio of $H/R = 0.1$, the characteristic spin frequency is $\Omega_* = 0.7 - 0.8 \Omega_b$ [22]. A smaller disk aspect ratio (meaning a cooler disk) leads to a higher characteristic spin rate.

In a Be/X-ray binary, the radial size of a Be star disk may be limited by the effects of the neutron star. The tidal torque of the neutron star can be strong enough to tidally truncate the disk [14, 33, 54–57] although tidal truncation is weaker if the disk is misaligned to the binary orbit [58–60] and if the disk has a larger aspect ratio [61, 62]. When the tidal truncation is weak, the outer edge of the disk may instead occur where there are close interactions with the neutron star [63].

3. Disk instabilities driven by the companion

In this Section we review some disk instabilities that can occur for a disk around one component of a binary with a mass ratio typical of a Be/X-ray binary, $q = M_{NS}/M_* \approx 0.1$. We consider a range of misalignments between the spin axis of the Be star and the orbital axis, and a range of binary eccentricities. For now, we ignore the torque from the Be star on the disk and consider the disk dynamics driven only by the companion. We note that dynamical instabilities can also occur in the accretion disk around the neutron star [29, 64], but we focus here on the Be star disk.

3.1 Coplanar and circular orbit binaries: Disk eccentricity growth

A system in which the Be star spin axis is aligned to the binary orbital axis and the binary orbit is close to circular has the most similarities with a low mass ratio CV. The disk is radially extended enough to reach the 3:1 resonance. The eccentricity of the disk increases and the disk undergoes prograde apsidal precession [65–67]. This is the driving mechanism of superhump behaviour in CVs.

In a circular orbit Be/X-ray binary, the neutron star accretes material from the Be star disk when it passes close to the disk apastron. Due to prograde disk apsidal precession, this means that Type I X-ray outbursts occur on a timescale slightly longer than the orbital period [19]. This has been observed in a few systems; for example, GS 0834-430 has an orbital eccentricity $e_b = 0.12$ and an orbital period of $P_{\text{orb}} = 105.8$ days and showed five Type I outbursts recurring on a timescale of 107 day [68–70].

3.2 Retrograde coplanar and circular orbit binaries: Retrograde tilt instability

If the Be star spin axis is anti-aligned to the binary angular momentum vector then the Be star disk orbits in a retrograde direction, relative to the binary orbit. A disk orbiting in a retrograde direction relative to a circular orbit binary does not feel the effects of ordinary Lindblad resonances [58, 71]. The interaction time of the gas and the companion is reduced, compared to a prograde orbiting disk. As a result of these differences, the retrograde disk is not *tidally* truncated and instead spreads out until it reaches the orbit of the neutron star [63]. A retrograde disk is therefore much larger than a prograde disk.

A retrograde disk around one component of a circular orbit binary is unstable to tilting [63]. The largest tilt growth occurs in the outermost radii of the disk, closest to the neutron star. The inclination growth may be the result of a retrograde Lindblad resonance. This tilting instability may affect the accretion on to the neutron star since the disk is tilted away from the binary orbital plane. X-ray outbursts in retrograde systems are therefore expected to be weaker than those in prograde systems [see also 72].

3.3 Misaligned binary-disk: Nodal precession and warping

When the spin axis of the Be star is misaligned to the binary angular momentum vector, the disk forms in a plane that is misaligned to the binary orbital plane, and such a disk can undergo retrograde nodal precession [e.g. 73]. A misaligned test particle orbit with orbital radius R undergoes retrograde nodal precession on a timescale

$$t_{\text{prec}} = \frac{2\pi}{\omega}, \quad (2)$$

where the precession frequency is

$$\omega = \frac{3}{4} \frac{M_{\text{NS}}}{\sqrt{M_* M}} \frac{\Omega_{\text{orb}}}{(1 - e_b^2)^{3/2}} \left(\frac{R}{a_b}\right)^{3/2} \cos i \quad (3)$$

[73, 74], the total binary mass is $M = M_* + M_{\text{NS}}$, the binary eccentricity is e_b , the binary semi-major axis is a_b , the misalignment is i , and the binary angular frequency is $\Omega_{\text{orb}} = 2\pi/P_{\text{orb}}$.

The disk can undergo solid body precession on an angular momentum weighted average timescale if the communication timescale across the radial extent of the disk is faster than the precession timescale [75–77]. In Be star disks, the high viscosity means that the communication is likely through viscosity (rather than wave-like communication). Observations suggest that the Shakura-Sunyaev [78] viscosity parameter is $\alpha \approx 0.3$ in Be star disks [15, 79–81]. The precession rate depends sensitively on the distribution of material within the disk. If the disk communication is poor, then the disk can be unstable to warping (where the disk has a radially varying tilt) and

even breaking (where the disk breaks into disjoint rings that can behave independently) [82–84]. For typical Be star disk parameters, nodal disk breaking is unlikely (however, see Section 4 for the additional effect of the torque from the Be star).

3.4 Highly misaligned binary-disk: Kozai-Lidov instability

Above a critical misalignment angle, a misaligned test particle orbit around one component of a binary is unstable to Kozai–Lidov (KL) oscillations. The particle’s inclination is periodically exchanged for eccentricity [85–87]. During this process, the component of the angular momentum that is perpendicular to the binary orbital plane is conserved, which is expressed as

$$\sqrt{1 - e^2} \cos i \approx \text{const}, \quad (4)$$

where i is the inclination of the orbital plane of the particle relative to the binary orbit plane and e is the eccentricity of the orbit of the test particle. A test particle that is initially on a circular and highly misaligned orbit undergoes oscillations of its orbital plane that involve closer alignment and, therefore, higher values of its eccentricity. For these oscillations to occur, the initial inclination of the orbit of the test particle i_0 must satisfy $\cos^2 i_0 < 3/5$. This condition requires $39^\circ \lesssim i_0 \lesssim 141^\circ$. The maximum eccentricity that an initially circular particle orbit can achieve is given by

$$e_{\text{max}} = \sqrt{1 - \frac{5}{3} \cos^2 i_0} \quad (5)$$

[88]. The timescale for KL oscillations is given approximately by

$$t_{\text{KL}} = \frac{M_* + M_{\text{NS}}}{M_{\text{NS}}} \frac{P_{\text{orb}}^2}{P_p} (1 - e_b^2)^{3/2} \quad (6)$$

[89], where P_p is the orbital period of the particle.

Similarly, a highly misaligned disk around one component of a binary can undergo global KL disk oscillations where the inclination and eccentricity of the disk are exchanged [90]. The timescale for disk KL oscillations is an angular momentum weighted average of the local rates [90–92]. For the case of a fluid disk, the KL instability also depends on the aspect ratio of the disk, as the effects of pressure modify the apsidal precession rate [93, 94]. In a Be/X-ray binary system, if the disk misalignment is large enough for KL oscillations to occur, the disk can become highly eccentric [28, 30]. The neutron star can have a strong interaction with the highly eccentric disk and gain significant material over a short period of time. This is a possible explanation for Type II X-ray outbursts [95].

3.5 Eccentric orbit binaries: Forced eccentricity growth

A test particle around one component of an eccentric binary experiences a forced eccentricity due to the binary potential [96]. An initially circular orbit test particle undergoes eccentricity oscillations. Similarly, a disk around one component of a binary may undergo global oscillations driven by forced eccentricity [e.g. 97]. Forced eccentricity growth of the disk occurs for both prograde and retrograde disks, although the oscillations are stronger for retrograde disks because the disk is more radially extended and closer to the perturbing binary companion [98]. A retrograde

disk can even be subject to eccentric disk breaking where the disk breaks into disjoint rings that have different eccentricities and longitude of pericenter but remain coplanar to each other [see also 99].

Variability in the size, eccentricity, and structure of the disk causes changes in the observed emission spectra. These effects may be seen in the evolution of the equivalent width of the H α line [100–103]. Changes in the outer edge of the disk impact the accretion flow onto the neutron star, which may lead to variability in the X-ray outbursts. If the eccentricity of the disk oscillates, there may be periodic changes in the X-ray observations.

4. Disk dynamics with mass injection from the Be star

The injection of material from the Be star into the inner parts of the disk can affect the disk dynamics described in the previous section. The injection exerts a torque on the inner parts of the disk that aligns the disk with the Be star equator. This torque competes with the torque from the companion. In this Section we discuss some possible outcomes.

4.1 Stellar spin-axis precession

If the injection torque dominates the torque from the companion, then the disk may remain aligned to the equator of the Be star. This is possible if the disk is radially narrow such that the viscous timescale is much shorter than the timescale for the dynamical effects described in Section 3. The truncation radius of Be star disk scales with $a_b(1 - e_b)$ [55] and so the disk is radially narrower for high binary eccentricity and short orbital period.

However, in a misaligned system, the Be star itself can undergo stellar spin-axis precession. The spin axis of the star precesses around the angular momentum vector of the binary with precession frequency given by

$$\omega_{\text{stellar}} = \frac{3}{2}k\Omega_* \left(\frac{M_{\text{NS}}}{M_*} \right) \left(\frac{R_*}{a_b(1 - e_b^2)^{1/2}} \right)^3 \cos i \quad (7)$$

[e.g. 104, 105], where $k \approx 0.5$ is a constant that depends upon the stellar interior [e.g. 106, 107]. The precession timescale is

$$t_{\text{stellar}} = \frac{2\pi}{\omega_{\text{stellar}}}. \quad (8)$$

Fig. 8 shows the stellar spin axis precession timescale as a function of the binary orbital period and the binary eccentricity. This effect is particularly important for shorter orbital period and larger eccentricity binaries.

A disk that remains locked to the stellar equator can undergo nodal precession on the timescale of the stellar spin axis precession [108]. This may provide an explanation for the very regular superorbital periods observed in the lightcurves of short-orbital-period, highly eccentric, Be/X-ray binaries such as A0538-66 [109–111].

4.2 Disk warping and breaking

In a system with longer orbital period and smaller eccentricity, the disk is more radially extended and the torque from the companion on the disk becomes more important. For typical Be

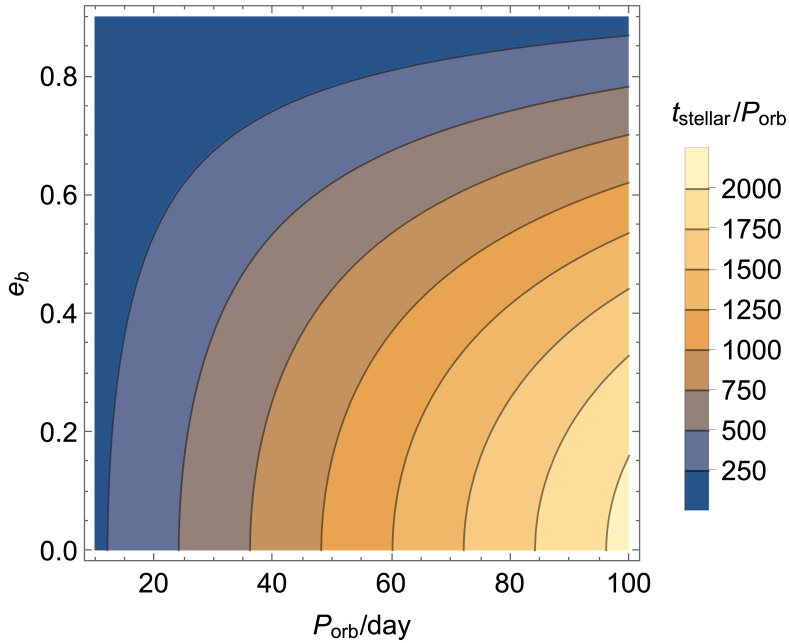


Figure 1: The stellar spin axis precession timescale (equation (8)) as a function of the binary orbit period, P_{orb} , and the binary eccentricity, e_b . The Be star has mass $M_1 = 8.84 M_{\odot}$, radius $R_* = 6 R_{\odot}$, and spin frequency $\Omega_* = 0.8 \Omega_b$. The neutron star companion has mass $M_2 = 1.44 M_{\odot}$.

star parameters, in the absence of injection, nodal disk breaking is not expected to occur. However, when the star itself provides a torque on the disk from the injection of material, this can lead to disk warping and even disk breaking [30, 82, 112]. The inner ring of the disk remains locked to the binary equator, while the outer ring can nodally precess independently [74, 112, 113]. The outer ring feels the torque from the companion and can undergo the dynamical effects described in Section 3.

Disk breaking may explain the short precession timescale observed in Pleione [83]. The nodal precession timescale of a particle is shorter in an orbit farther away from the Be star, closer to the companion (see equation (2)). The outer edge of the outer disk ring is likely at the tidal truncation radius. The larger the break radius (which is equal to the inner disk radius of the outer ring), the faster the nodal precession timescale of the outer disk ring.

5. Conclusions

Be star decretion disks in Be/X-ray binaries display a wide range of dynamical behaviors that arise from the combined effects of binary eccentricity, spin–orbit misalignment, and mass injection from the rapidly rotating Be star. Although these systems share some similarities with low–mass ratio CVs, the presence of an eccentric and/or misaligned neutron-star companion fundamentally changes the disk evolution and introduces many instabilities not present in CVs.

In circular and coplanar binaries, the disk may extend to the 3:1 resonance and develop eccentricity, similar to the driving mechanism of superhump behavior in CVs. Type-I X-ray outbursts then occur on a timescale slightly longer than the orbital period. Retrograde coplanar

disks, which are not tidally truncated, can become much more extended and are susceptible to a retrograde tilt instability that weakens their interaction with the neutron star.

When the spin axis of the Be star is misaligned with the binary orbit, the disk can undergo nodal precession which can also lead to disk warping. At higher misalignments, Kozai–Lidov oscillations can develop, driving the disk to high eccentricity and potentially supplying large amounts of material for Type-II outbursts. In eccentric binaries, both prograde and retrograde disks are subject to forced eccentricity oscillations that may introduce strong secular changes in disk structure, including eccentric disk breaking in the retrograde case.

The injection of material from the Be star further modifies these dynamical processes. In short–period systems with high binary eccentricity, the disk is radially narrow and remains locked to the stellar equator, so it may inherit the stellar spin-axis precession, offering a natural explanation for the highly regular superorbital periods found in some short-orbital-period, high eccentricity Be/X-ray binaries. In long-orbital–period systems with low binary eccentricity, the disk can be radially extended and susceptible to nodal disk breaking, allowing the outer ring to evolve independently of the inner ring that is locked to the stellar equator.

Overall, the variety of dynamical instabilities that can occur in Be star decretion disks may explain the complex optical and X-ray variability of Be/X-ray binary systems. Differences in orbital period, misalignment, binary eccentricity, disk temperature, and viscous communication naturally lead to diverse disk morphologies and time-dependent behaviors. Future work combining hydrodynamical simulations with multi-wavelength observations will be essential for connecting these disk instabilities to the observed phenomenology of individual systems.

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