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Wind-Driven Ablation of Accretion Disks as a Mechanism for State Transitions in Be/X-ray Binaries

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Be/X-ray binaries (BeXRBs), comprising a Be star (a rapidly rotating massive star surrounded by a circumstellar disk) and a neutron star, represent the largest subclass of high-mass X-ray binaries. These systems undergo intermittent X-ray outbursts, while remaining quiescent during the majority of their orbital evolution. The conventional explanation for the transition to quiescence is the centrifugal inhibition of accretion, or the "propeller effect," wherein the neutron star's rapidly rotating magnetosphere prevents inflow of matter. However, this scenario is observationally confirmed in only a few systems with short neutron star spin periods, and its applicability to systems with slowly rotating neutron stars remains uncertain.

In this study, we propose an alternative mechanism for the quiescent state in BeXRBs with misaligned geometries, where the Be disk is inclined relative to the orbital plane. Using three-dimensional hydrodynamical simulations, we demonstrate that the stellar wind from the Be star can ablate the accretion flow and suppress accretion onto the neutron star. Our results show that under typical Be disk conditions, accretion is strongly inhibited by the ram pressure of the stellar wind, effectively halting X-ray activity. A transient accretion disk, and thus an outburst, can only form if the mass-transfer rate is sufficiently high to produce a dense accretion disk capable of withstanding wind-driven ablation.

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1. Introduction

Be/X-ray binaries (BeXRBs) form the largest subclass of high-mass X-ray binaries (HMXBs), accounting for roughly half of the known population [e.g. 8]. They consist of a neutron star (NS) in an eccentric, wide orbit around an early-type Be star, which is surrounded by a geometrically thin, nearly Keplerian decretion disk. Typical orbital periods range from ∼ 10 to ∼ 300 days and eccentricities from $e \sim 0.3$ to 0.7.

The X-ray behavior of BeXRBs is characterized by intermittent outbursts separated by long intervals of quiescence. During most of the orbit the system is faint, with X-ray luminosities $L_X \lesssim 10^{34}$ erg s^{-1}, while during outbursts the luminosity reaches $L_X \gtrsim 10^{36}$ erg s^{-1} or higher. An example is the classical Be/X-ray binary A 0535+26, which exhibits occasional giant outbursts separated by extended low states [e.g. 1].

The conventional explanation for transitions between accretion and quiescent states is the so-called *propeller mechanism*, in which the rapidly rotating magnetosphere of the neutron star centrifugally inhibits accretion when the magnetospheric radius exceeds the corotation radius [2]. In this regime, inflowing matter is expelled or strongly impeded, leading to a dramatic drop in X-ray luminosity.

Although this scenario has been supported by observations in a few BeXRBs with relatively short spin periods ($P_{\rm spin} \sim$ a few seconds), such as 4U 0115+63, V 0332+53 [3, 5, 6], and SMC X-2 [7], the applicability of the propeller mechanism to BeXRBs with slowly rotating neutron stars remains unclear. When the spin period is long ($P_{\rm spin} \gtrsim 100$ s), the corotation radius moves outward and the parameter space in which the system can enter the propeller regime becomes restricted. For many systems, the observed transition luminosities and the expected magnetospheric radii are difficult to reconcile with propeller-driven state changes alone.

In addition, BeXRBs often show properties indicating that mass transfer occurs out of the orbital plane and that the resulting accretion disk around the neutron star is tilted or warped. In such misaligned geometries, the stellar wind from the Be star interacts directly with the accretion disk around the neutron star, potentially affecting its structure and long-term evolution. This raises the possibility that the stellar wind itself might play a role in controlling the accretion state.

In this paper, we explore an alternative or complementary mechanism for state transitions in BeXRBs: *wind-driven ablation* of the accretion disk in systems where the Be disk is misaligned with the orbital plane. Using three-dimensional smoothed particle hydrodynamics (SPH) simulations, we demonstrate that the Be-star wind can strip material from the neutron star accretion disk and, under typical conditions, suppress the formation of a persistent disk. We focus on two representative systems: 4U 0115+63, which has observational evidence for propeller behavior, and A 0535+26, which hosts a more slowly rotating neutron star and a much stronger stellar wind.

2. Propeller Mechanism and Its Limitations

The classical propeller mechanism [2, 3] operates when the magnetospheric radius $R_{\rm m}$

$$R_{\rm m} \approx \left(\frac{\mu^4}{G M_{\rm NS} \dot{M}^2}\right)^{1/7} \approx 4.9 \times 10^8 \, k \, \dot{m}_{16}^{-2/7} m_{1.4}^{-1/7} \mu_{30}^{4/7} \text{ cm} \quad (1)$$

[e.g. 4] lies outside the corotation radius

$$R_{\rm co} = \left(\frac{G M_{\rm NS} P_{\rm spin}^2}{4\pi^2} \right)^{1/3} \approx 1.7 \times 10^8 \, P_{\rm spin}^{2/3} m_{1.4}^{1/3} \; {\rm cm}. \tag{2}$$

Here, $M_{\rm NS}$ is the neutron star mass, $P_{\rm spin}$ is the spin period, $\dot{m}_{16} = \dot{M}/10^{16}\ {\rm g\,s^{-1}}$, $m_{1.4} = M_{\rm NS}/1.4\,M_{\odot}$, $\mu_{30} = \mu/10^{30}\ {\rm G\,cm^3}$ is the normalized magnetic moment, and k is a constant of order unity that depends on the accretion geometry. When $R_{\rm m} > R_{\rm co}$, the Keplerian frequency at $R_{\rm m}$ is lower than the stellar spin frequency, so the magnetosphere rotates super-Keplerian and expels the incoming material.

Accretion onto the neutron star, and therefore X-ray outbursts, can occur only when the mass accretion rate exceeds the gate accretion rate $\dot{M}_{\rm gate}$ corresponding to $R_{\rm m} = R_{\rm co}$:

$$\dot{M}_{\rm gate} \approx 1.4 \times 10^3 \, k^{7/2} P_{\rm spin}^{-7/3} m_{1.4}^{-5/3} \mu_{30}^2 \; {\rm g\,s^{-1}}. \tag{3}$$

The associated limiting X-ray luminosity is

$$L_{\rm X,gate} = \frac{G M_{\rm NS} \dot{M}_{\rm gate}}{R_{\rm NS}} \approx 2.2 \times 10^{38} \, k^{7/2} P_{\rm spin}^{-7/3} r_6^{-1} m_{1.4}^{-2/3} \mu_{30}^2 \; {\rm erg\,s^{-1}}, \tag{4}$$

where $R_{\rm NS}$ is the neutron-star radius and $r_6 = R_{\rm NS}/10^6$ cm.

Observationally, several Be/X-ray binaries with relatively short spin periods, such as 4U 0115+63 ($P_{\rm spin} = 3.61$ s), V 0332+53 ($P_{\rm spin} = 4.38$ s), and SMC X-2 ($P_{\rm spin} = 2.37$ s), show transition luminosities broadly consistent with propeller gating. In these systems, an accretion disk forms and persists during outbursts, but once the accretion rate falls below $\dot{M}_{\rm gate}$ the system enters the propeller regime and the luminosity drops sharply.

However, for systems with longer spin periods, including many persistent or quasi-persistent BeXRBs, equations (3) and (4) imply that the propeller mechanism is unlikely to operate in the same way. Figure 1 summarizes this trend by plotting the gate luminosity given by equation (4) as a function of $P_{\rm spin}$. Here, $k = 0.5$ is adopted for disk accretion. For each system, we compute $L_{\rm X,gate}$ using its observed spin period and the magnetic moment derived from the observed cyclotron resonance scattering features. While the resulting gate luminosities for short-period systems are compatible with the observed transition luminosities, those for many long-period BeXRBs are substantially lower than their observed transition luminosities, indicating that the propeller mechanism alone cannot account for their state transitions.

These considerations motivate the search for additional physical processes that may drive state transitions, especially in systems with slowly rotating neutron stars.

3. Sample Systems

To investigate the role of wind-driven ablation, we focus on two well-observed BeXRBs that occupy different regions in the $P_{\rm spin}$–$L_{\rm X}$ plane and have contrasting wind properties.

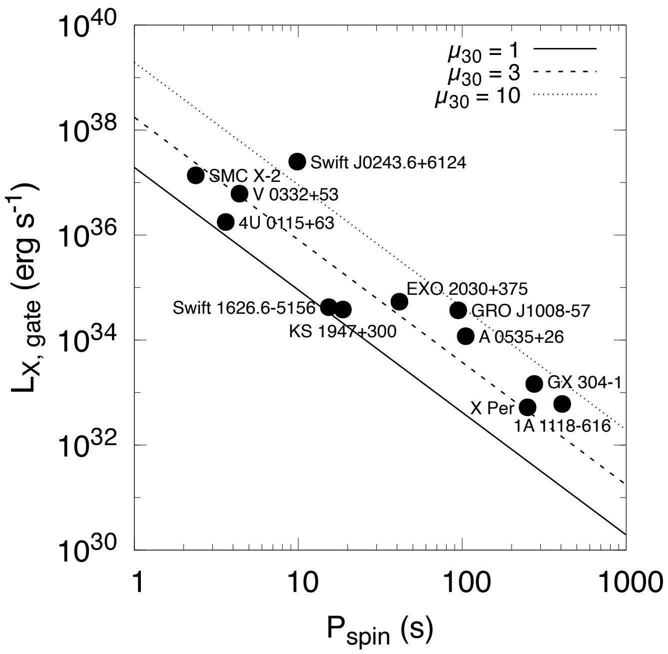

Figure 1: Gate X-ray luminosity for the propeller mechanism as a function of the neutron star spin period, calculated from equation (4). The curves show $L_{X,\mathrm{gate}}$ for three representative magnetic moments, $\mu_{30} = 1$, 3, and 10 (solid, dashed, and dotted lines; $k = 0.5$, $m_{1.4} = 1$, $r_6 = 1$). The symbols mark the propeller gate luminosities computed from equation (4) using the observed spin period and the magnetic moment inferred from the observed cyclotron resonance scattering features for individual systems. For short-period systems such as 4U 0115+63, V 0332+53, and SMC X-2, the predicted gate luminosities are broadly consistent with the observed transition luminosities, whereas many long-period BeXRBs would have propeller transitions at luminosities much lower than those actually observed, suggesting that additional mechanisms are at work in these systems.

3.1 4U 0115+63

4U 0115+63 is a classical transient BeXRB consisting of a B0.2 Ve star and a neutron star with spin period $P_{\mathrm{spin}} = 3.61$ s in an eccentric orbit with orbital period $P_{\mathrm{orb}} = 24.3$ d and eccentricity $e = 0.34$. The system exhibits recurrent outbursts and has provided some of the clearest observational evidence for transitions between accretion and propeller regimes [3, 5, 6]. The stellar wind mass-loss rate derived from recent prescriptions is $\dot{M}_{\mathrm{w}} \approx 5.7 \times 10^{-10}\, M_\odot\,\mathrm{yr}^{-1}$ [9].

3.2 A 0535+26

A 0535+26 hosts an O9.7 IIIe star and a more slowly rotating neutron star with $P_{\mathrm{spin}} \simeq 104$ s. The orbital period is $P_{\mathrm{orb}} = 110$ d with eccentricity $e = 0.47$. The system shows occasional giant outbursts separated by long intervals of quiescence and moderate activity [e.g. 1]. The stellar wind is significantly stronger than in 4U 0115+63, with an estimated mass-loss rate $\dot{M}_{\mathrm{w}} \approx 7.2 \times 10^{-8}\, M_\odot\,\mathrm{yr}^{-1}$ [9].

Because of its long spin period and strong wind, A 0535+26 is a promising candidate for a system in which the stellar wind, rather than the propeller mechanism, plays a dominant role in controlling the accretion state.

4. Numerical Method

We perform three-dimensional hydrodynamical simulations using the smoothed particle hydrodynamics (SPH) method to model the interaction of the Be-star decretion disk and wind with the accretion flow around the neutron star. The code is the same as that used by [10, 11]. The basic numerical setup is as follows.

We take the orbital plane as the xy-plane, with the $+x$-direction being the direction of apastron. At time zero, the neutron star is at the apastron. The rotation axis of the Be star is tilted by 45° about the x-axis. This misalignment is motivated by previous studies of BeXRBs and ensures that the neutron star encounters a tilted disk and that the resulting accretion flow is likely to form a warped or tilted disk around the neutron star. In our SPH framework, binary star components are modeled as sink particles with appropriate masses and specified accretion radii. An ensemble of gas particles is continuously injected from the Be star into both the decretion disk and the stellar wind. For the disk, particles are injected axisymmetrically in the equatorial plane just outside the star. These particles initially have only the azimuthal velocity component equal to the local Keplerian speed, but due to the viscous interaction among particles, a fraction of the particles diffuses outward to form a disk.

For the wind, particles are ejected in a spherically symmetric fashion except for the region that ejects disk particles. An external force is introduced to emulate an accelerating wind with the β-velocity law, $v_{\rm wind}(r) = v_\infty(1 - R_*/r)^\beta$, where $\beta = 1$ is adopted and v_∞ is assumed to be equal to $2.6v_{\rm esc}$ [12], with $v_{\rm esc} = (2GM_*/R_*)^{1/2}$ being the escape velocity of the star. Here, M_* and R_* are the mass and radius of the Be star, respectively. The mass-loss rates adopted are those estimated by [9]: $\dot{M}_{\rm w} = 5.7 \times 10^{-10}\, M_\odot\,{\rm yr}^{-1}$ for 4U 0115+63 and $\dot{M}_{\rm w} = 7.2 \times 10^{-8}\, M_\odot\,{\rm yr}^{-1}$ for A 0535+26, as mentioned in the previous section.

We adopt artificial viscosity parameters $\alpha_{\rm SPH} = 3$ and $\beta_{\rm SPH} = 2$ to emulate a Shakura–Sunyaev viscosity parameter $\alpha_{\rm SS} \simeq 0.3$ in the disk region [13]. Each simulation starts from a diskless state and is evolved until the Be disk becomes sufficiently developed to show regular interaction with the neutron star.

The binary orbit is taken to be Keplerian with the observed orbital elements $(P_{\rm orb}, e)$ appropriate for each system. We parameterize the Be-disk density by a characteristic midplane density ρ_0 at the base of the disk, hereafter referred to as the base density, and consider both a "typical" Be-disk density ($\rho_0 \sim 10^{-11}$ g cm^{-3}) and a disk that is ten times denser ($\rho_0 \sim 10^{-10}$ g cm^{-3}) to explore the dependence of the accretion dynamics on the mass-transfer rate.

To enhance the spatial resolution of the accretion flow around the neutron star, we employ a particle-splitting technique: when a particle enters the Roche lobe of the neutron star, it is split into thirteen particles following the method of [14]. This allows us to resolve the structure of the accretion disk while keeping the total number of particles manageable.

In the misaligned configuration, the stellar wind collides with the tilted neutron-star accretion disk. The ram pressure of the wind can ablate material from the disk surface and, if sufficiently strong, can prevent the disk from growing or even destroy it between successive periastron passages.

To characterize the accretion state, we measure the mass accretion rate onto the neutron star and estimate the corresponding X-ray luminosity via $L_X \simeq GM_{NS}\dot{M}_{acc}/R_{NS}$. We also monitor the spatial distribution of gas around the neutron star and the Be star, including the morphology and persistence of any accretion disk, using two-dimensional surface density maps in the orbital (xy) plane and in the two orthogonal vertical planes (xz and yz).

5. Results

5.1 Runs without stellar wind

As a reference, we first consider simulations in which the stellar wind is switched off. In both 4U 0115+63 and A 0535+26, the neutron star captures gas from the Be disk primarily around periastron. In the absence of wind, the captured gas settles into a persistent accretion disk around the neutron star, regardless of whether we adopt the typical ($\rho_0 \sim 10^{-11}$ g cm^{-3}) or ten-times denser Be-disk density.

Figure 2 shows snapshots of the surface density distribution in the orbital plane near periastron for both systems. In each figure, the Be star is near the origin and the neutron star is on its left, surrounded by an accretion disk, as shown in the inset plot, where the neutron star is at the center. In each case with a typical base density, the neutron star is surrounded by a well-defined accretion disk whose outer radius and mass gradually grow over successive orbits. The accretion rate onto the neutron star remains relatively high, implying that, in the absence of wind, both systems would tend to maintain an accreting state for a wide range of parameters. The same conclusion would apply to coplanar systems, where the stellar wind does not impact the accretion disk.

5.2 4U 0115+63 with stellar wind

When the stellar wind is included, the dynamics of the accretion flow change significantly. Figure 3 illustrates the surface density distribution around the neutron star after periastron in 4U 0115+63, for (*left*) a typical ($\rho_0 \sim 10^{-11}$ g cm^{-3}) and (*right*) a ten times denser ($\rho_0 \sim 10^{-10}$ g cm^{-3}) Be disk. We find that for a typical-density Be disk, the accretion disk forms only briefly near periastron and is quickly eroded by the stellar wind afterwards. Even if the Be disk is ten times denser, the accretion disk is compact and transient, with its mass and radial extent substantially reduced compared to the no-wind case. The corresponding X-ray luminosity varies between $L_X \sim 5 \times 10^{34}$ and $\sim 4 \times 10^{36}$ erg s^{-1}, depending on the Be-disk density.

These results are broadly consistent with a scenario in which the propeller mechanism controls the state transition in 4U 0115+63: the accretion disk, already weakened by wind-driven ablation, becomes susceptible to centrifugal inhibition as the accretion rate declines. Nevertheless, the simulations underscore that the stellar wind has a strong dynamical effect and cannot be neglected, even in systems where the propeller effect is observationally supported.

5.3 A 0535+26 with stellar wind

In A 0535+26, the impact of the stellar wind is even more pronounced because of the much higher wind mass-loss rate. The strong wind even affects the Be-disk structure, requiring significantly higher mass injection rates to form a dense enough Be disk that can survive wind-driven

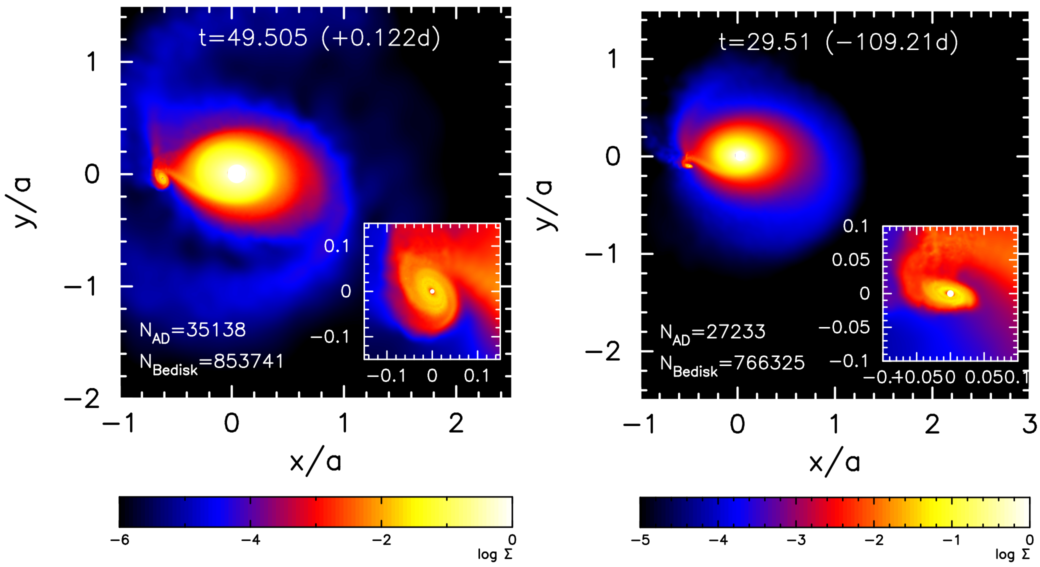

Figure 2: Surface density maps in the orbital plane for 4U 0115+63 (left) and A 0535+26 (right) just after periastron, in simulations without stellar wind. In each figure, the white filled circle near the origin denotes the Be star, while the neutron star is a small white dot on the left of the Be star and is surrounded by gas transferred from the Be disk. The inset shows a zoom-in view of the accretion flow in the vicinity of the neutron star. In both systems, a persistent accretion disk develops around the neutron star for typical Be-disk densities.

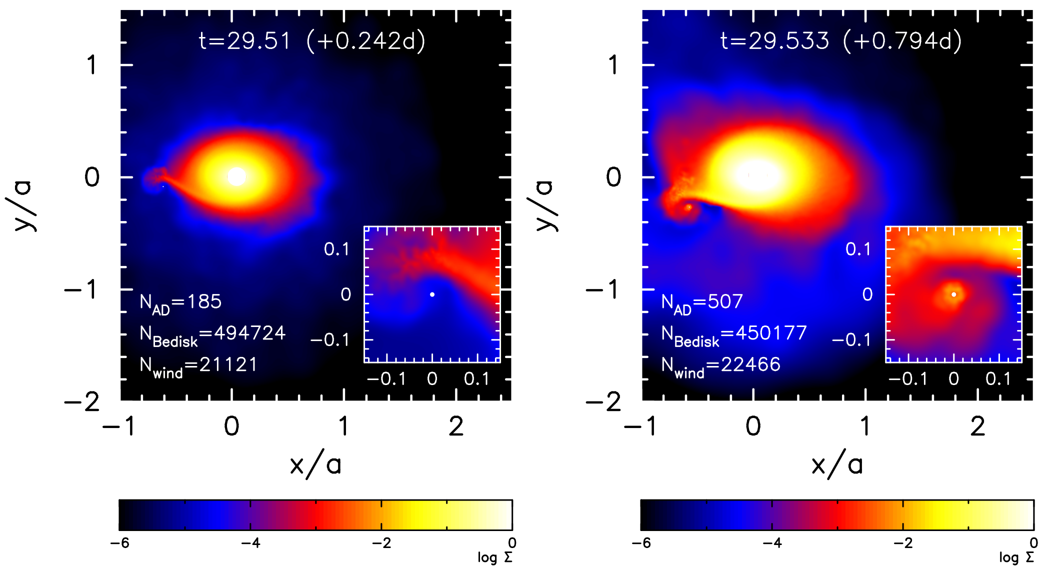

Figure 3: Snapshots of the accretion flow around the neutron star after periastron in 4U 0115+63 with stellar wind included, for a typical-density Be disk (left) and a ten times denser disk (right). The wind ablates the accretion disk, which forms only briefly near periastron and largely disappears before the next periastron passage.

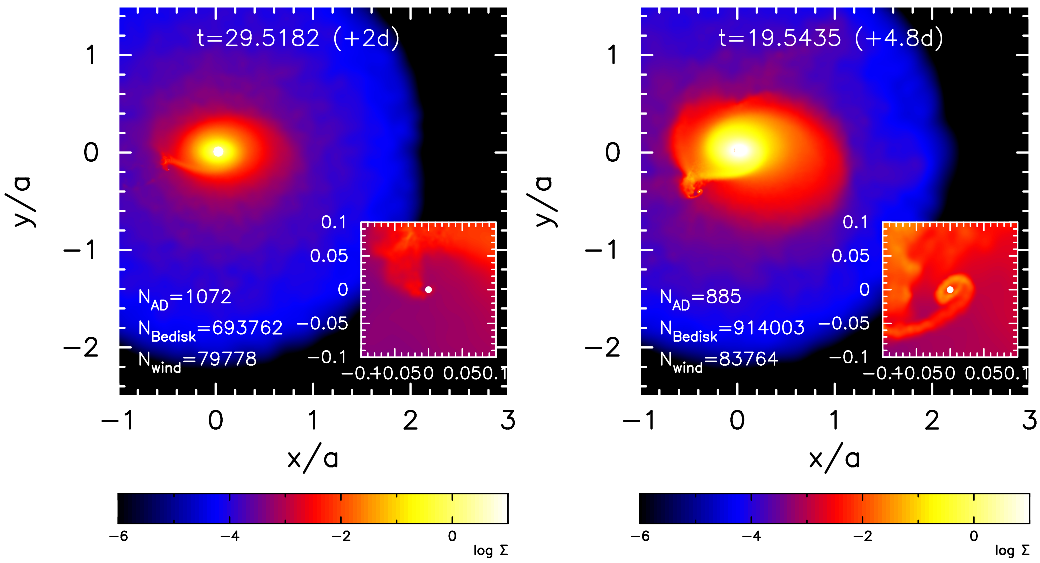

Figure 4: Accretion simulations for A 0535+26 with stellar wind. The left panel is for a Be disk slightly denser than typical ($\rho_0 \sim 2 \times 10^{-11}$ g cm^{-3}), while the right panel is for a Be disk with ten times higher density ($\rho_0 \sim 2 \times 10^{-10}$ g cm^{-3}). In both cases, the strong wind prevents the formation of a long-lived accretion disk around the neutron star; only at the highest densities does a transient, dense accretion disk form, leading to outburst-level X-ray luminosities.

ablation in the long term. For a resulting typical-density Be disk, the accretion flow onto the neutron star is strongly suppressed, so that an accretion disk forms only temporarily. Even when the Be disk is more than ten times denser, the wind continuously strips material from the vicinity of the neutron star, preventing the accretion disk from surviving between periastron passages.

Figure 4 shows representative snapshots of the surface density in the orbital plane for two Be-disk densities: (*left*) the base density twice as large as typical ($\rho_0 \sim 2 \times 10^{-11}$ g cm^{-3}) and (*right*) the base density twenty times larger than typical ($\rho_0 \sim 2 \times 10^{-10}$ g cm^{-3}). The accretion structures around the neutron star are transient and fragmented, and the mass accretion rate is highly variable, leading to intermittent X-ray activity. The strong wind ram pressure effectively acts as a gate: only when the mass-transfer rate from the Be disk becomes sufficiently high can a dense, compact disk form that partially withstands wind-driven ablation and produces an outburst-level luminosity ($L_X \sim 10^{36}$–10^{37} erg s^{-1}).

These results support the idea that in A 0535+26, and perhaps in many other long-P_{spin} BeXRBs with strong winds, the stellar wind plays a key role in controlling the state transitions, independently of the classical propeller regime.

6. Discussion

Our simulations suggest that wind-driven ablation of the neutron-star accretion disk is a robust mechanism in misaligned BeXRBs. The basic ingredients, i.e., a decretion disk around the Be star, a tilted accretion disk around the neutron star, and a line-driven stellar wind, are ubiquitous in BeXRBs, although the quantitative impact depends on the wind strength, disk density, and degree of misalignment.

For systems with relatively weak winds and short neutron star spin periods, such as 4U 0115+63, the classical propeller mechanism can still be the primary driver of state transitions, but wind-driven ablation modifies the structure of the accretion disk and shortens its lifetime. In systems with strong winds and long spin periods, exemplified by A 0535+26, the propeller condition is harder to satisfy, and our results point to a picture in which the stellar wind itself effectively controls whether the system is in an accreting or quiescent state.

Observationally, this scenario may help explain the wide luminosity gap between outburst and quiescence seen in many BeXRBs, as well as the diversity of outburst patterns. A strong wind can maintain the system in a low state for extended periods, with occasional episodes during which enhanced mass transfer from the Be disk overwhelms wind-driven ablation and triggers an outburst. Changes in the Be-disk density or geometry, driven by stellar activity or disk oscillations, could then lead to complex, long-term variability.

Further work is needed to explore a wider range of system parameters, including different tilt angles and azimuths of tilt, wind strengths, and orbital periods and eccentricities, and to compute synthetic observables that can be directly compared with X-ray and optical monitoring data. Including more realistic thermodynamics and radiative cooling as well as implementing physical viscosity would also improve the modeling of the ablation process and the evolution of Be and accretion disks.

7. Conclusions

We have investigated the role of wind-driven ablation of accretion disks in Be/X-ray binaries using three-dimensional SPH simulations of misaligned Be-neutron star systems. As sample systems, we have selected two BeXRBs with contrasting properties: 4U 0115+63, which is comprised of a Be star with modest stellar wind and a neutron star with a relatively short spin period, and A 0535+26, which has a Be star with a much stronger wind and a slowly rotating neutron star. Our main conclusions are as follows:

1. Given the broad distribution of neutron star spin periods in BeXRBs, centrifugal inhibition of accretion (the propeller mechanism) is unlikely to be the sole mechanism responsible for state transitions between outburst and quiescence, especially in systems with slowly rotating neutron stars.

2. In the absence of stellar wind, a persistent accretion disk tends to form around the neutron star in both 4U 0115+63 and A 0535+26, even for relatively low Be-disk densities. This would favor prolonged accretion and X-ray activity. The same conclusion would apply to coplanar systems, where the stellar wind does not strike the accretion disk.

3. When the Be-star wind is included, the ram pressure of the wind ablates the accretion flow. In 4U 0115+63, the accretion disk forms only briefly near periastron and does not survive to the next periastron passage. The corresponding X-ray luminosity can be as low as several times 10^{34} erg s^{-1}, which is well below the transition luminosity. Thus, the result is consistent with a scenario in which the propeller mechanism controls the state transition in 4U 0115+63.

4. In A 0535+26, where the stellar wind is about two orders of magnitude stronger than in 4U 0115+63, the wind dominates the accretion dynamics. No persistent accretion disk forms even for a Be disk ten times denser than typical; only transient accretion disks capable of driving outburst-level luminosities can form when the mass-transfer rate is very high.

5. We propose that wind-driven ablation of the neutron-star accretion disk is a key mechanism for state transitions in BeXRBs with misaligned Be disks, particularly in systems with strong winds and slowly rotating neutron stars.

Wind-driven ablation thus provides a natural extension of the classical propeller picture and may help to unify the diverse phenomenology of BeXRBs across a wide range of spin periods and wind properties.

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