Non-axisymmetric Structure of Accretion Disks in Be/X-ray Binaries

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Abstract. The non-axisymmetric structure of accretion disks around the neutron star in Be/X-ray binaries is studied by analyzing the results from three-dimensional (3D) Smoothed Particle Hydrodynamics (SPH) simulations. It is found that ram pressure due to the phase-dependent mass transfer from the Be-star disk excites a one-armed, trailing spiral structure in the accretion disk around the neutron star. The spiral wave has a transient nature; it is excited around the periastron, when the material is transferred from the Be disk, and is gradually damped afterwards. It is also found that the orbital phase-dependence of the mass-accretion rate is mainly caused by the inward propagation of the spiral wave excited in the accretion disk.

Keywords: Accretion and accretion disks, X-ray binaries, Neutron stars, Circumstellar shells, clouds, and expanding envelopes; circumstellar masers

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INTRODUCTION

The majority of high-mass X-ray binaries have been identified as Be/X-ray binaries. These systems generally consist of a neutron star and a Be star with a cool (∼10^4 K) equatorial disk, which is geometrically thin and nearly Keplerian. Be/X-ray binaries are distributed over a wide range of orbital periods (10d ≤ P_{orb} ≤ 300d) and eccentricities (e ≤ 0.9).

Most Be/X-ray binaries show only transient activity in X-ray emission and are termed Be/X-ray transients. Be/X-ray transients show periodic (Type I) outbursts, which are separated by the orbital period and have luminosity L_X = 10^{36−37} erg s^{-1}, and giant (Type II) outbursts of L_X ≥ 10^{37} erg s^{-1} with no orbital modulation. These outbursts have features that strongly suggest the presence of an accretion disk around the neutron star.

Recently, Hayasaki and Okazaki [1] studied the accretion flow around the neutron star in a Be/X-ray binary with a short period (P_{orb} = 24.3 d) and a moderate eccentricity (e = 0.34), using a 3D SPH code and the imported data from [2]. They found that a time-dependent accretion disk is formed around the neutron star. They also discussed the evolution of the azimuthally-averaged structure of the disk, in which a one-armed spiral structure is seen. It is important to note that Be/X-ray binaries are systems with double circumstellar disks (the Be decetration disk and the neutron star accretion disk), which interact mainly via mass transfer, and that this gives a new point of view to understand the interactions in Be/X-ray binaries (see Fig. [1]).
In this paper, we show that ram pressure due to the material transferred from the Be disk around periastron temporarily excites the one-armed spiral wave in the accretion disk around the neutron star in Be/X-ray binaries.

**ONE-ARMED SPIRAL WAVE EXCITED BY A RAM PRESSURE**

Our simulations were performed by using the same 3D SPH code as in [1], which was based on a version originally developed by Benz ([4]; [5]) and later by [6]. In order to study the effect of the ram pressure on the accretion disk, we compare results from model 1 in [1] (hereafter, model A) with those from a simulation (hereafter, model B) in which the mass transfer from the Be disk is artificially stopped for one orbital period. Except for this difference, the two simulations have the same model parameters: The orbital period $P_{\text{orb}}$ is 24.3 d, the eccentricity $e$ is 0.34, and the Be disk is coplanar with the orbital plane. The inner radius of the simulation region $r_{\text{in}}$ is $3.0 \times 10^{-3}a$, where $a$ is the semi-major axis of the binary. The polytropic equation of state with the exponent $\Gamma = 1.2$ is adopted. The Shakura-Sunyaev viscosity parameter $\alpha_{\text{SS}} = 0.1$ throughout the disk.

Fig. 2 gives a sequence of snapshots of the accretion disk around the neutron star for $7 \leq t \leq 8$ in model A, where the unit of time is the orbital period $P_{\text{orb}}$. The left panels show the contour maps of the surface density, whereas the non-axisymmetric components of the surface density and the velocity field are shown in the right panels. Annotated in each left panel are the time in units of $P_{\text{orb}}$ and the mode strength $S_1$, a measure of the amplitude of the one-armed spiral wave, which is defined by using the azimuthal Fourier decomposition of the surface density distribution [see 3, Sec 2.2 for detail]. It is noted from the figure that the one-armed, trailing spiral is excited at periastron and is gradually damped towards the next periastron. The disk changes its topology from circular to eccentric with the development of the spiral wave, and then from eccentric to circular with the decay of the wave during one orbital period.

For comparison, we present the results for model B, in which the mass transfer is
FIGURE 2. Snapshots of the accretion disk for model A. The left panels show the surface density in a range of three orders of magnitude in the logarithmic scale, while the right panels show the non-axisymmetric components of the surface density (gray-scale plot) and the velocity field (arrows) in the linear scale. In the right panels, the region in gray (white) denotes the region with positive (negative) density enhancement. The periastron is in the $x$-direction and the disk rotates counterclockwise. Annotated in each left panel are the time in units of $P_{\text{orb}}$ and the mode strength $S_1$.

FIGURE 3. Same as Fig. 2, but for model B.

artificially turned off for $7 \leq t \leq 8$. Fig. 3 shows the surface density (the left panel) and the non-axisymmetric components of the surface density and the velocity field (the right panel) at the time corresponding to the middle panel of Fig. 2. It should be noted that disk deformation due to the one-armed mode is not seen in model B. The disk is more circular and has a larger radius in model B than in model A. This strongly suggests that the excitation of the one-armed spiral structure in the accretion disk is induced by the ram pressure from the material transferred from the Be disk at periastron.

**Phase dependence of the mass-accretion rate**

After the accretion disk has developed ($t \geq 5$), the mass-accretion rate has double peaks per orbit, a relatively-narrow, low peak at periastron and a broad, high peak afterwards [see Fig. 15(a) of [1]]. While the first low peak at periastron could be artificial, being related to the presence of the inner simulation boundary, the origin of the second high peak was not clear. Below we show that the one-armed spiral wave is responsible for the second peak in the mass-accretion rate.

Fig. 4 shows the time dependence of the mass-accretion rate for $7 \leq t \leq 8$. The thick line denotes the mass-accretion rate in model A, in which the mass transfer from the Be disk is taken into account, whereas the thin line denotes that in model B. The difference between the accretion rate profiles for these two models is striking. The accretion rate in model B monotonically decreases over one orbital period, whereas that of model A shows a broad peak centred at $t \sim 7.32 - 7.35$, which corresponds to the second peak found in [1]. The phase lag of this peak behind the peak of the mass-transfer rate, which
FIGURE 4. Time dependence of the mass-accretion rate for $7 \leq t \leq 8$. The thick and thin lines are for model A and model B, respectively. The right axis shows the X-ray luminosity corresponding to the mass-accretion rate.

occurs at periastron, results from the inward propagation of the wave from the disk outer radius to the inner simulation boundary.

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