One-armed spiral structure of accretion discs induced by a phase-dependent mass transfer in Be/X-ray binaries

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ABSTRACT

We study non-axisymmetric structure of accretion discs in Be/X-ray binaries, performing three dimensional Smoothed Particle Hydrodynamics simulations for a coplanar system with a short period and a moderate eccentricity. We find that ram pressure due to the phase-dependent mass transfer from the Be-star disc excites a one-armed, trailing spiral structure in the accretion disc around the neutron star. The spiral wave is transient; it is excited around the periastron passage, when the material is transferred from the Be disc, and is gradually damped afterwards. The disc changes its morphology 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. It turns out that the inward propagation of the spiral wave significantly enhances the mass-accretion rate onto the neutron star. Thus, the detection of an X-ray luminosity peak corresponding to the peak in enhanced mass-accretion rate provides circumstantial evidence that an accretion disc is present in Be/X-ray binaries.

Key words: accretion, accretion discs – hydrodynamics – methods: numerical – binaries: general – stars: emission-line, Be – X-rays: binaries

1 INTRODUCTION

About two-thirds 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 ($\sim 10^4$ K) equatorial disc, which is geometrically thin and nearly Keplerian. Be/X-ray binaries are distributed over a wide range of orbital periods ($10^4 < P_{\text{orb}} < 300$ d) 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 $L_X \gtrsim 10^{37}$ erg s\(^{-1}\) with no orbital modulation. These outbursts have features that strongly suggest the presence of an accretion disc around the neutron star.

Recently, Hayasaki & Okazaki (2004, hereafter paper I) studied the accretion flow around the neutron star in a Be/X-ray binary with a short period ($P_{\text{orb}} = 24.3$ d) and a moderate eccentricity (e = 0.34), using a three dimensional Smoothed Particle Hydrodynamics (SPH) code. They found that a time-dependent accretion disc is formed around the neutron star. They also discussed the evolution of the azimuthally-averaged structure of the disc, although the disc is significantly eccentric in spite of the nearly Keplerian rotation. The non-axisymmetric structure seen in the disc is considered to result from a phase-dependent mass transfer from the Be disc.

Tosa (1994) showed numerically that ram pressure due to an intergalactic gas excites the one-armed spiral structure in the non-selfgravitating, galactic $V$-constant disc. Then Kato & Tosa (1994) showed analytically that the excitation of the one-armed mode is caused by the same resonant instability mechanism as the tidally induced eccentric instability which explains the superhump phenomena in dwarf novae systems (Hirose & Osaki 1989, Lubow 1991). In the context of accretion disc theory, Lubow (1994) investigated the effect of time varying mass-transfer on the eccentricity of an accretion disc in a circular binary. However, it has never been explicitly studied how phase-dependent mass transfer affects the eccentricity of an accretion disc in an eccentric binary.

In this letter, we study the non-axisymmetric structure of the accretion disc around the neutron star in Be/X-ray binaries. In Section 2 the development of the one-armed
spiral structure is demonstrated with 3D SPH simulations. The strength of several modes excited in the disc, the orbital modulation of the disc radius and the phase dependence of the mass-accretion rate are also analyzed in this section. Our conclusions are presented in Section 3.

2 RAM-PRESSURE-DEFORMED ACCRETION DISCS

In this section, we show that ram pressure due to the material transferred from the Be disc around periastron temporarily excites the one-armed spiral wave in the accretion disc around the neutron star in Be/X-ray binaries.

Our simulations were performed using the same 3D SPH code as in paper I, which was based on a version originally developed by Benz (Benz 1990; Benz et al. 1990) and later by Bate, Bonnell & Price (1995). In order to investigate the effect of ram pressure on the accretion disc, we compare results from model 1 in paper I (hereafter, model A) with those from a simulation (hereafter, model B) in which the mass transfer from the Be disc 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 disc is coplanar with the orbital plane. The inner radius of the simulation region \( r_m \) is 3.0 \( \times 10^{-3} a \), where \( a \) is the semi-major axis of the binary. A polytropic equation of state with the exponent \( \Gamma = 1.2 \) is adopted. The Shakura-Sunyaev viscosity parameter \( \alpha_{SS} = 0.1 \) throughout the disc. There is also a bulk viscosity \( \nu_b = 5 \Omega S S c_s H / 3 \), where \( c_s \) is the polytropic sound speed and \( H \) is the scale-height of the disc.

Fig. 1 gives a sequence of snapshots of the accretion disc 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 \( P_{\text{orb}} \). For comparison, we present the results for model B, \( 8 \leq t \leq 9 \), in which the mass transfer is artificially turned off for \( 7 \leq t \leq 8 \). Fig. 2 shows the surface density (the left panel) and the non-axisymmetric components of the surface density 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 disc rotates counterclockwise. Annotated in each left panel are the time in units of \( P_{\text{orb}} \).

For comparison, we present the results for model B. In which the mass transfer is artificially turned off for \( 7 \leq t \leq 8 \). Fig. 2 shows the surface density (the left panel) and the non-axisymmetric components of the surface density and the velocity field (arrows) at the time corresponding to the middle panel of Fig. 1. The format of the figure is the same as that of Fig. 1. It should be noted that the disc deformation due to the one-armed mode is not seen in model B. The disc 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 disc is induced by ram pressure from the material transferred from the Be disc at periastron.

2.1 Mode strength

In this subsection, we analyse the orbital-phase dependence of the disc eccentricity by decomposing the surface density distribution into Fourier components which vary as \( \exp(i m \phi) \), where \( m \) is the azimuthal harmonic number.

Following Lubow (1991), we define the mode strength by

\[
S_{f,m}(t) = \frac{2}{M_d(1 + \delta_{m,0})} \int dr \int_0^{2\pi} r d\phi \Sigma(r, \phi, t) f(m \phi),
\]

where \( f \) is either \( \sin \) or \( \cos \) and \( M_d \) is the total disc mass given by \( \int dr \int_0^{2\pi} r d\phi \Sigma(r, \phi, t) \). Then, the total strength of the mode \( m \) is defined by

\[
S_m(t) = (S_{\cos, m}^2 + S_{\sin, m}^2)^{1/2}.
\]

Note that our definition of the mode strength slightly differs from that of Lubow (1991). He decomposed the surface density distribution into double Fourier components.
with the azimuthal and time harmonic numbers, whereas we did it with only the azimuthal harmonic number. This is because our purpose is to analyze the time dependence of the non-axisymmetric structure of the accretion disc in detail. Note also that the definition of the mode strength is not unique, so Eq. (2) gives only a rough measure of the amplitude of each mode. If the spiral wave is tightly winding, Eq. (2) will underestimate the amplitude significantly.

Fig. 3 shows the evolution of several non-axisymmetric modes for model A, in which the phase-dependent mass transfer from the Be disc is taken into account. The solid, dashed and dotted lines denote the strengths of the disc radius (0 ≤ t ≤ 8). The contribution be-

The middle panel of Fig. 4 shows the azimuth ωp between the position vector of the maximum value of the non-axisymmetric component of the surface density and the eccentric vector of the binary orbit (hereafter, the azimuth of the maximum density perturbation). As in the other panels, the thick and thin lines are for model A and model B, respectively. It should be noted that ωp in both models shifts little over one orbital period. This is a typical characteristic of the one-armed modes in nearly Keplerian discs (Kato 1983).

2.2 Orbital modulation in the disc radius

In paper I, we found that the disc size modulates with the orbital phase; the disc shrinks at periastron and gradually restores its radius afterwards. Our interpretation of this orbital modulation was that the decrease in the disc radius at periastron is due to a negative torque by the Be star, while the later expansion is due to the viscous diffusion. For the reason described below, this interpretation must be corrected.

The bottom panel of Fig. 4 shows the time dependence of the disc radius for 7 ≤ t ≤ 8, which is defined in the same way as in paper I (equation 5). As in the other panels, the thick and thin lines are for model A and model B, respectively. From the figure, we note that the disc radius in model B monotonically increases with time and shows no orbital modulation. This is in sharp contrast to the orbital modulation in the disc radius seen in model A. Since the only difference between model A and model B is that the mass transfer from the Be disc is included in model A, while it is not in model B, it is most likely that the reduction in the disc radius after periastron passage is related to the mass transfer from the Be disc. Apparently, the negative torque by the Be star has little effect on the accretion disc radius in these models.

How can the mass transfer from the Be star reduce the accretion disc size? As shown in Fig. 3 of paper I, the circularization radius of the material transferred from the Be disc is smallest around the periastron. It is much smaller than the accretion disc radius shown in the bottom panel of Fig. 4. In other words, the specific angular momentum of the material transferred from the Be disc is much smaller than that of the material at the outer radius of the accretion disc. Accretion of such material onto the disc outer radius will temporarily reduce the disc radius. This mechanism, together with the

Figure 2. Same as Fig. 1 but for model B.

Figure 3. Evolution of several non-axisymmetric modes for 0 ≤ t ≤ 8. The solid, dashed and dotted lines denote the strengths of the m = 1, m = 2 and m = 3 modes, respectively.
periastron could be artificial, being related to the presence 
wards [see Fig. 15(a) of paper I]. While the first low peak at 
narrow, low peak at periastron and a broad, high peak after-
accretion rate has double peaks per orbit, a relatively-
high peak was not clear. Below we show that the one-armed 
of the inner simulation boundary, the origin of the second 
accretion disc is developed (T ≥ 5), the mass-
viscous diffusion, naturally explains the orbital modulation 
in the disc radius found in paper I.

2.3 Phase dependence of the accretion rate

After the accretion disc is developed (t ≥ 5), the mass-
accretion rate has double peaks per orbit, a relatively-
low peak at periastron and a broad, high peak after-
wards [see Fig. 15(a) of paper I]. 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 ≤ t ≤ 8. The thick line denotes the mass-accretion 
rate in model A, in which the mass transfer from the Be disc 
is taken into account. For comparison, the mass-accretion 
rate in model B, in which the mass transfer from the Be disc 
is artificially turned off at t = 7, is also shown by 
the thin line. The difference between the accretion rate pro-
files 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 ∼ 7.32 − 7.35, which corresponds to the second peak found 
in paper I.

Although it is obvious that the above peak is caused by 
the mass transfer from the Be disc, the mass transfer rate has 
a narrow peak at periastron. What mechanisms connecting 
the mass transfer from the Be disc and the mass accretion 
onto the neutron star lead to a phase delay of ∼ 0.3? There 
are two possibilities. Either the disc is the viscously adjusting 
to the addition of low-angular momentum material. How-
ever, even if the angular momentum of the material trans-
ferred from the Be disc is the lowest, its viscous time scale at 
the circularization radius is over 7 binary periods [see Fig. 3 
of paper I]. Thus, the viscous accretion of the lowest-angular 
momentum material could play no key role of the enhance-
ment of the accretion rate at an orbital phase of about 0.35.
Or, the second possibility is that the one-armed spiral wave 
is excited by ram pressure of the transferred material from 
the Be disc and then the spiral wave travels inwardly. The 
excitation of the spiral wave takes about ∼ (0.1 − 0.2)P_{\text{orb}} 
(see the top panel of Fig. 4) and the difference of the peak 
position on the orbital phase between the mode strength and 
the accretion rate results from the wave propagation from 
the disc outer radius to the inner simulation boundary.

The time-scale for wave propagation is roughly esti-
mated by using the dispersion relation of the one-armed 
oscillation in the nearly Keplerian discs [Kato 1983]. Its fre-
quency ω is written by ω ∼ − Ω_{\text{orb}} (k_r H)^2/2, where k_r is the 
radial wavenumber and Ω_{\text{orb}} is the orbital angular velocity. 
Finally, the time-scale for a global, one-armed perturbation 
to travel across the disc is 2π/ω ∼ 0.13P_{\text{orb}} at r ∼ 0.05a 
at t ∼ 7.1. Therefore, combining the time-scales for wave 
excitation and propagation, we expect that the peak of the 
mass-accretion rate lags behind that of the mass-transfer 
rate by (0.2 − 0.3)P_{\text{orb}}, which is in good agreement with the 
phase of the second peak of mass-accretion rate shown in 
Fig. 4.

3 CONCLUSIONS

In this letter, we have investigated non-axisymmetric struc-
ture in the accretion disc around the neutron star in Be/X-
ray binaries, analysing the results from a simulation per-
formed by Hayasaki & Okazaki [2004]. We have adopted the 
phase-dependent, mass-transfer rate from a high-resolution 
simulation by Okazaki et al. [2002] for a coplanar system 
with a short period (P_{\text{orb}} = 24.3d) and a moderate eccen-
tricity (e = 0.34), which targeted 4U0115+63, one of the 
best studied Be/X-ray binaries.

We have found that a one-armed, trailing spiral wave
is excited in the accretion disc by ram pressure from the strongly phase-dependent mass-transfer from the Be disc. The spiral wave is transient; it is excited at periastron passage, when mass transfer from the Be disc takes place, and is gradually damped afterwards. The one-armed perturbation pattern in the accretion disc precesses little over one orbital period, which is consistent with the theory of global, one-armed oscillations in nearly Keplerian discs \cite{kato1993}.

The eccentric ($m = 1$) mode dominates the other non-axisymmetric modes throughout the run ($0 \leq t \leq 8P_{\text{orb}}$). In the initial stage of disc development ($0 \leq t \leq 5P_{\text{orb}}$), elliptical orbits of the gas particles transferred from the Be disc make the accretion disc significantly eccentric. After the disc is well developed ($t \gtrsim 5$), however, the one-armed spiral wave gives the major contribution to the eccentric deformation of the accretion disc. Then, the strength of the deformation significantly modulates with the orbital phase, corresponding to the rapid excitation and the subsequent gradual damping of the one-armed wave.

The system we studied differs from that of \cite{kato1993} in the sense that our accretion disc is nearly Keplerian and ram pressure of the material transferred from the Be disc exerts on the accretion disc only briefly around periastron and ram pressure of the material transferred from the Be disc enhances the inward mass flux in the accretion disc, and is therefore responsible for this high peak in the accretion rate. The X-ray luminosity peak corresponding to the high peak in accretion rate has never been identified in Be/X-ray binaries. However, if this peak is detected, it could be understood as strong circumstantial evidence for the presence of an accretion disc in Be/X-ray binaries.

In this letter, we have reported on the effects of ram pressure on the accretion disc, including the excitation of the one-armed spiral wave, which enhances the accretion rate. These results are based on the simulations, of which the run time was much shorter than the viscous time-scale. In longer simulation runs, new features/interactions are expected to appear. While the deformation of the accretion disc by ram pressure is expected to become small as the disc mass increases, the excitation of the eccentric mode directly driven by the one-armed bar potential, which is not seen in our simulations, will become important. The tidal/resonant torque by the Be star may begin to work on the outer part of the accretion disc, as the disc size increases. In a subsequent paper, we will investigate the long-term evolution of the accretion disc in Be/X-ray binaries in detail.

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Figure 5. 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.