

State transitions triggered by inverse magnetic field: probably applied in high-mass X-ray binaries?

Shuang-Liang Li and Zhen Yan

Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China; *lisl@shao.ac.cn*, *zyan@shao.ac.cn*

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Abstract Previous works suggested that the state transitions in an X-ray binary can be triggered by accreting an inverse magnetic field from its companion star. A key point of this mechanism is the accretion and magnification of large-scale magnetic fields from the outer boundary of a thin disk. However, how such a process can be realized is still an open question. In this work, we check this issue in a realistic X-ray binary system. According to our calculations, a quite strong initial magnetic field, $B \sim 10^2 - 10^3$ G, is required in order to assure that the large-scale magnetic field can be effectively dragged inward and magnified with the accretion of gas. Thus, such a picture probably can be present in high-mass X-ray binaries possessing a strong stellar magnetic field, e.g., Cyg X-1.

Key words: accretion, accretion disks — black hole physics — (magnetohydrodynamics) MHD — X-rays: binaries

1 INTRODUCTION

It is well known that black hole (BH) X-ray binaries (XRBs) have shown different X-ray spectral states (see reviews by Remillard & McClintock 2006; Belloni 2010; Zhang 2013). The two fundamental X-ray spectral states are the low/hard (LH) and high/soft (HS) states, where the X-ray emission in LH state is dominated by a non-thermal component coming from a hot accretion flow (Narayan & Yi 1994; Yuan & Narayan 2014), and the X-ray emission in HS state is dominated by a thermal component coming from an optically thick and geometrically thin disk (Shakura & Sunyaev 1973). During the transition between LH and HS states, both thermal and non-thermal components are important, which is usually called intermediate state. Though the mechanism for the transition between these two X-ray spectral states has been widely studied, it is still an open question so far.

Mass accretion rate has long been believed to be the dominant parameter in determining spectral state transitions (Esin et al. 1997). In this kind of truncated disk model, the accretion geometry in the LH state is an inner hot accretion flow plus an outer thin disk (Meyer et al. 2000; Done et al. 2007; Liu et al. 2011; Yuan & Narayan 2014), where the hot accretion flow only survives below $0.01L_{\text{Edd}}$ (Esin et al. 1997), or up to $0.1L_{\text{Edd}}$ by adopting an alternative solution in Yuan et al. (2007). So, the state transition occurs at a nearly constant luminosity (several percent of Eddington luminosity), which is inconsistent with the observation that the hard-to-soft transition luminosity varies by up to two orders of magnitude (Homan

et al. 2001; Gierliński & Done 2003; Zdziarski et al. 2004; Yu & Yan 2009). Therefore, many other parameters have been proposed. The Comptonizing region constrained from timing variability has been considered to be the other independent parameter needed to determine the state transition behavior (Homan et al. 2001); the recent accretion history may play an important role in determining the transition luminosity (Homan & Belloni 2005); the disk mass has been suggested as the initial condition in determining the state transitions (Yu et al. 2004; Yu & Dolence 2007; Yu & Yan 2009); and the process of disk tearing could produce a variety of behaviors capable of explaining state transitions (Nixon & Salvesen 2014). But there is no conclusive evidence for either argument, so this subject still remains a mystery. In this work, we are going to discuss another promising parameter: magnetic field.

Large-scale magnetic fields, which are believed to accelerate the jet (see reviews of jet formation models by Yuan & Narayan 2014), should be present in LH state. Recently, strong disk winds were found to exist in the HS state of some X-ray binaries (Ponti et al. 2012), which may also be driven by the ordered magnetic field. Thus, it is possible that the magnetic field can be another parameter affecting the state transitions. Igumenshchev (2009) and Dexter et al. (2014) suggested that a magnetosphere could form in the inner region of a disk by accumulating enough magnetic flux (Narayan et al. 2003; McKinney et al. 2012) and that the state transition could be triggered by accreting an inverted magnetic field from a companion star. The LH state can correspond to a truncated accretion disk with a large truncation radius R_{tr} . Recently, the advection of

the magnetic field from the outer disk region has been believed to be a promising way to form a large-scale field in the accretion disk. Nevertheless, how it forms in a thin disk has been a long-standing debatable issue. Thus, the key point in this picture is the accretion and magnification of large-scale magnetic fields from the outer boundary of a thin disk. Due to the low radial velocity and long advection timescale, the accretion of a standard thin disk had been found to be ineffective in magnifying the field (van Ballegooyen 1989; Lubow et al. 1994). Spruit & Uzdensky (2005) suggested that the advection of the field can be accelerated by some strong bundles of flux threading the disk because they can simultaneously increase the radial velocity by taking away the angular momentum of the disk and decrease the diffusion by suppressing the turbulence. Cao & Spruit (2013) considered a thin disk with a moderately weak large-scale magnetic field, where the angular momentum is totally transferred by disk winds, and found that the advection efficiency of the field can also be greatly increased. This mechanism was revisited by considering the effects of winds on the disk structures in Li & Begelman (2014). They found that the advection timescale of the field can be smaller than the diffusion timescale for the main reason that the disk temperature is greatly decreased because the winds take away most of the viscous dissipated energy, resulting in a decrease of the magnetic diffusivity η and an increase of the diffusion timescale (see Sect. 2 for details). Except for the models mentioned above, the other mechanism to solve the field diffusion problem associated with the formation of large scale fields in a thin disk is the coronal mechanism (e.g., Rothstein & Lovelace 2008, Beckwith et al. 2009), which suggested the field can be advected inwards through the corona region, thus avoiding the diffusion problem. In this work, we try to check whether the large-scale magnetic field on a thin disk can be magnified in realistic X-ray binary systems.

2 MODEL

We consider a realistic thin disk which accretes gas from the companion star in X-ray binaries. Whether the magnetic field can be effectively dragged inwards depends on the competition between advection timescale and diffusion timescale. If the advection timescale τ_{adv} is far smaller than diffusion timescale τ_{dif} , the field can be magnified. The diffusion timescale τ_{dif} can be given by $\sim RH\kappa_0/\eta$ (Cao & Spruit 2013; Li & Begelman 2014), where $\eta \sim \nu$ (ν is the viscosity coefficient) as suggested by recent MHD simulations (Fromang & Stone 2009; Guan & Gammie 2009). When the magnetic torque is far larger than the viscous torque and thus dominates the transportation of disk angular momentum, the strong disk winds driven by magnetic torque will take away lots of energy released in the disk, which results in the decrease of ν ($\sim \alpha c_s H$) and the increase of diffusion timescale. Therefore, the field can be effectively magnified when the magnetic torque dominates the viscous torque.

Considering a thin disk with a very weak field, the magnetic and viscous torques are given by $T_m = B_p B_\phi R / 2\pi$ (Livio et al. 1999; Cao 2002) and $W_{R\phi} = 2H\alpha P_{\text{tot}}$, respectively. Thus, the ratio of magnetic torque to viscous torque is

$$\frac{T_m}{W_{R\phi}} \sim \frac{0.2R}{H\alpha\beta_p} \sim \frac{130}{\beta_p} \quad (1)$$

with $B_\phi = 0.1B_p$ and $\alpha = 0.1$, where $\beta_p = (P_{\text{gas}} + P_{\text{rad}})/(B_p^2/8\pi)$ and $H/R \sim 1.6 \times 10^{-2}$ are adopted. Here the disk scale height H is given by

$$\begin{aligned} H &= 1.5 \times 10^3 \alpha^{-1/10} \dot{m}^{3/20} m^{9/10} r^{9/8} \\ &\quad (1 - r^{-1/2})^{3/20} \\ &= 4.7 \times 10^8 \text{cm}, \end{aligned} \quad (2)$$

where $r = R/R_g$, $R = 10^4 R_g$, $\dot{m} = 1$ ($\dot{m} = \dot{M}/\dot{M}_{\text{crit}}$, $\dot{M}_{\text{crit}} = 1.5 \times 10^{17} \text{m g s}^{-1}$, $m = M/M_\odot$) and $m = 10$ (Kato et al. 1998). Therefore, if the field is strong enough, e.g., $\beta_p \sim 1 - 10$, the magnetic torque will dominate the transportation of disk angular momentum. For a standard thin disk with the same disk parameters, the disk pressure is dominated by gas pressure and can be approximately described by (Kato et al. 1998)

$$\begin{aligned} P_{\text{gas}} &\simeq 3.12 \times 10^{17} \alpha^{-9/10} \dot{m}^{17/20} m^{-9/10} R^{-21/8} \\ &\quad \times (1 - R^{-1/2})^{17/20} \\ &= 1.38 \times 10^6 \text{g cm}^{-1} \text{s}^{-2}. \end{aligned} \quad (3)$$

However, as pointed out by Li (2014), the pressure of a thin disk could be 10^2 times smaller than that of a standard disk because the most energy released in the disk is taken away by disk winds, resulting in the decrease of gas pressure (see figure 2 in Li (2014)). Thus, the disk pressure at the outer radius will reduce to $\sim 1.38 \times 10^4 \text{g cm}^{-1} \text{s}^{-2}$ for a thin disk with strong disk winds. For $B = 10^3 \text{G}$, the corresponding magnetic pressure is $P_m = B_p^2/8\pi \simeq 4 \times 10^4 \text{g cm}^{-1} \text{s}^{-2}$, which corresponds to $\beta_p < 1$ when $B_\phi = 0.1B_p$ is adopted.

Thus, a field strength of $B \sim 10^2 - 10^3 \text{G}$ from the outer boundary of a thin disk is required in order to assure the dominant role of magnetic torque. It is reasonable to assume that the accreting gas at the outer boundary carries a similar magnetic field as the companion star. Therefore, the scenario of this model looks probable in systems with companion stars having a high magnetic field. As far as we know, most Galactic BH XRB systems harbor a low mass companion star. Among BH low-mass X-ray binaries (LMXBs) with reliable measurements, most of the companion stars are K-type stars (Ritter & Kolb 2003; Casares & Jonker 2014). We found the magnetic field strengths of stars with different spectral types in the catalog of Bychkov et al. (2009) roughly follow a normal distribution on a logarithmic scale. The average magnetic field strength of K-type stars is $\sim 20 \text{G}$, which is smaller than the requirement of Igumenshchev (2009)'s model according to our calculations. Cygnus X-1 is the only currently known Galactic BH

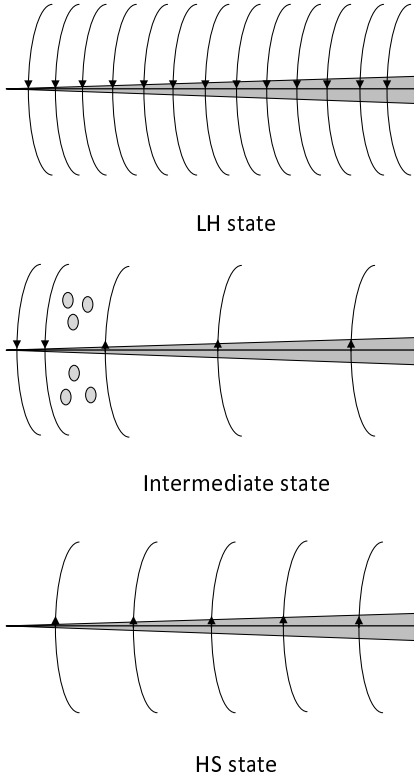


Fig. 1 Schematic diagram of the magnetic field threading the disk during state transitions.

XRB to harbor a high mass companion star, the spectral type of which is O9.7 (Bolton 1972; Orosz et al. 2011). The average magnetic field strength of O-type stars in Bychkov et al. (2009) is ≈ 340 G. Fortunately, Karitskaya et al. (2010) measured the $\langle B_z \rangle \sim 600$ G at the outer radius of the accretion disk ($2 \times 10^5 R_g$), which is high enough to satisfy the condition $\beta_p < 10$. Therefore, we think this model is promising in explaining the spectral state transition in high-mass X-ray binaries possessing a strong stellar magnetic field, such as Cyg X-1.

3 SUMMARY AND DISCUSSION

In this work, we investigate whether an ordered magnetic field can be magnified from the outer boundary of a thin disk, which is the key point for the mechanism that a state transition can be triggered by accreting an inverse magnetic field from a companion star. According to our calculations, a quite strong initial magnetic field of $B \sim 10^2 - 10^3$ G is required in order to assure the dominant role of magnetic torque in transferring angular momentum. Thus, such a picture is probably present in some high-mass X-ray binaries.

Interestingly, as presented in Li (2014), the disk winds driven by a large-scale magnetic field can take away most of the energy released in the disk and thus help to cool the disk.

The radiative efficiency of a thin disk with winds could be 10^3 times smaller than that of a standard thin disk. Thus, the thermal component of a disk will disappear if there are strong disk winds (see Fig. 1). Such a state seems to correspond to the LH state in X-ray binaries, which is similar to what is suggested in Livio et al. (2003). The system will gradually change into the intermediate state once the accretion with the opposite field starts. The transient jets in the intermediate state can come from acceleration by changing the field to bubbles/outflows, which are produced by magnetic reconnection (Igumenshchev 2009; Dexter et al. 2014; Khiali et al. 2015), or from the magnetic rope where the energy reaches a threshold (Yuan et al. 2009). When the accretion of the inverted field starts, the former large-scale field will gradually vanish due to magnetic annihilation with the inverted field. After the disappearance of the original field but before the transformation to the inverted large-scale field, the thin disk will become radiatively efficient again and enter the HS state. Wind can be easily launched from the surface of a radiatively inefficient accretion flow due to the positive Bernoulli parameter of the gas (Narayan & Yi 1994; Blandford & Begelman 1999; Yuan et al. 2012; Gu 2015). However, other conditions, e.g., radiation pressure and/or large-scale magnetic field, are required in order to drive winds from a thin disk (Murray et al. 1995; Blandford & Payne 1982).

In the case of an ordered magnetic field, the inclination angle of field lines with respect to the surface of the disk is required to be smaller than 60° in order to launch winds from a cold thin disk (Blandford & Payne 1982), but radiation pressure can help to realize this process as suggested by Cao (2012, 2014). Strong disk winds have been verified by the discovery of highly ionized absorbers in the HS states of some X-ray binaries (Ponti et al. 2012), which may be driven by a large-scale magnetic field.

The typical magnetic flux of a thin disk threaded by a large-scale field is $\Phi \sim 10^{22}$ G cm $^{-2}$ as suggested by Igumenshchev (2009). With the presence of a large-scale field, the radial velocity of a thin disk is about $V_R \sim 10^5$ cm s $^{-1}$ at $R \sim 10^4 R_g$, which is one-two orders of magnitude larger than that of a standard thin disk (Li & Begelman 2014). Thus, the timescale to accumulate the observed magnetic flux is $\tau \sim \Phi / BV_R R \sim 10^4 - 10^6$ s for a field strength of $B \sim 10^2 - 10^3$ G. The observed transition timescales between LH and HS states in Cyg X-1 are several days (Grinberg et al. 2013), which is roughly consistent with the results of our model. In order to avoid the formation of a magnetically-arrested accretion flow (MAD, McKinney et al. 2012), a balance of magnetic field advection and diffusion should be required. However, how such a balance can be achieved and kept stable is still unclear (e.g., Bisnovatyi-Kogan & Lovelace 2012; Cao & Spruit 2013). If the answer is it does not, a MAD will be built naturally in the inner disk region. In such a case, the timescale of the accumulated flux, $\sim 10^4 - 10^6$ s, is also roughly consistent with the timescale of an outburst in X-ray binaries.

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