MAGNETIC INVERSION AS A MECHANISM FOR THE SPECTRAL TRANSITION OF BLACK HOLE BINARIES

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ABSTRACT

A mechanism for the transition between low/hard, high/soft, and steep power law (SPL) spectral states in black hole X-ray binaries is proposed. The low/hard state is explained by the development of a magnetically arrested accretion disk attributable to the accumulation of a vertical magnetic field in a central bundle. This disk forms powerful jets and consists of thin spiral accretion streams of a dense optically thick plasma surrounded by a hot, magnetized, optically thin corona, which emits most of the energy in hard X-rays. State transition occurs because of the quasi-periodic or random inversion of poloidal magnetic fields in the accretion flow supplied by the secondary star. The inward advection of the inverted field results in a temporal disappearance of the central bundle caused by the annihilation of the opposed fields and restoration of the optically thick disk in the innermost region. This disk represents the high/soft state. The SPL state develops at the period of intensified field annihilation and precedes the high/soft state. The continuous supply of the inverted field leads to a new low/hard state because of the formation of another magnetically arrested disk.

Key words: accretion, accretion disks – black hole physics – ISM: jets and outflows – MHD – X-rays: binaries

1. INTRODUCTION

Accretion disks orbiting black holes (BHs) in X-ray binary systems demonstrate a complicated time-dependent behavior, which is typically described as the quasi-periodic transition between three emission states: the low/hard, high/soft, and steep power law (SPL, or otherwise, very high) states (Remillard & McClintock 2006, hereafter RM06; Done et al. 2007). The low/hard state is characterized by a strong hard X-ray emission component in the 2–20 keV range, which takes ≳ 80% of the total flux. A weak, but sizable, thermal component from a cold dense plasma and quasi-periodic oscillations (QPOs) in X-rays may be present or absent. This state is associated with the formation of quasi-steady radio jets (Gallo et al. 2003). The high/soft state shows the dominant thermal component, which is generally consistent with theoretical predictions from the “standard” optically thick accretion disk model (Shakura & Sunyaev 1973). A hard X-ray component is usually present in this state, but is limited to < 25% of the total flux. The SPL state shares some common properties with the high/soft state, such as the thermal component. However, the SPL state is clearly distinguished by the strength of its power-law component and association with high-frequency QPOs (RM06).

While the high/soft state is reasonably well understood theoretically (e.g., Kubota et al. 2005), the nature of the low/hard and SPL states is still a matter of debate. Basically, two classes of phenomenological models were proposed to explain the low/hard state: “truncated-disk” and “corona-and-disk” models. The truncated-disk model assumes that an optically thick disk is truncated at some inner radius \( R_{\text{tr}} \) and the central region, \( R < R_{\text{tr}} \), is filled with a hot (about the virial temperature), optically thin plasma, which produces hard X-rays (e.g., Zdziarski & Gierlinski 2004). Some studies postulate advection-dominated accretion flows (ADAFs, see Narayan & Yi 1994; Abramowicz et al. 1995) or other types of hot accretion disk solutions (Shapiro et al. 1976; Blandford & Begelman 1999; Narayan et al. 2000) as sources of this hot plasma (Poutanen et al. 1997; Esin et al. 1997; Esin et al. 1998, 2001; D’Angelo et al. 2008). Although such studies can provide excellent fits to the combined optical, UV, and X-ray data, the nature of accretion flows in the central region of luminous sources (with \( L \gtrsim 10^{-3} L_{\text{Edd}} \), where \( L_{\text{Edd}} \) is the Eddington luminosity) is unexplained. Mechanisms that produce truncated disks have been discussed by Honma (1996) and Mannoto & Kato (2000), who assumed a radial conductive energy transport that leads to an evaporation of thin disks, and by Meyer et al. (2000), Spruit & Deufel (2002), and Dullemond & Spruit (2005), who considered a vertical evaporation process. In the corona-and-disk models, the optically thick disk remains untruncated and the hard X-rays are generated in a hot, patchy disk corona because of inverse Compton scattering of soft photons that come from the underlying disk (Liang & Price 1977; Galeev et al. 1979; Haardt et al. 1994). To reasonably describe observations, the hot corona should dissipate (probably in magnetic flares) a significant fraction (\( \gtrsim 50\% \)) of the binding energy of the accretion mass. It is assumed that this energy is transported from disk to corona by a magnetic field, but the exact mechanism is unknown (Merloni & Fabian 2001; Uzdensky & Goodman 2008).

Both truncated-disk and corona-and-disk models have advantages and disadvantages to explain the observed data (see Done et al. 2007). To overcome the disadvantages, several more sophisticated models were developed, some of which included the elements of both classes of models described above (Taam et al. 2008) and others considered jets that emit in radio and X-rays (Markoff et al. 2001; Ferreira et al. 2006). The transition between emission states in the truncated-disk models is assumed by means of shifting the truncation radius \( R_{\text{tr}} \), to or out of the BH (e.g., Petrucci et al. 2006). The parameter, or a set of parameters, that triggers the transition is unknown. For example, the triggering mechanism’s dependence on the luminosity, or accretion rate, is ruled out by observations that show that many sources can have about same total luminosity at different states (Done & Gierlinski 2003).

This Letter proposes a detailed mechanism for spectral variability of BH X-ray binaries. The mechanism uses a recently found dynamical model of magnetized accretion disks.
The key ingredient of the model is a bipolar magnetic field that is supplied with accretion flows at the outer boundary. Such flows were modeled by I08 using combined two-dimensional/three-dimensional (2D/3D) numerical MHD simulations. The simulations assume a permanent injection of mass and poloidal magnetic field into a slender equatorial torus located at \( R_{\text{m}} \) near the outer boundary \( R_{\text{m}} = 220 R_g \), where \( R_g = 2GM/c^2 \) and \( M \) is the BH mass. The injected mass and field form a magnetized accretion disk that carries the vertical magnetic field inward. At the inner numerical boundary, \( R_{\text{in}} = 2 R_g \), the mass is absorbed by the BH, but the vertical field, which cannot be absorbed, is accumulated in a central bundle. When the field \( B_0 \) in the bundle approaches the equipartition level,

\[
\frac{B_0^2}{8\pi} \sim \rho \frac{GM}{R_g},
\]

where \( \rho \) is the density, the accretion flow is arrested by the field. Further accumulation of the field results in the growth of the outer radius of the arrested region, \( R_{\text{m}} \). This type of accretion flow was anticipated in previous theoretical and numerical studies (Bisnovatyi-Kogan & Ruzzmaikin 1974, 1976; INA03; Narayan et al. 2003) and was called the magnetically arrested disk. Most of the volume in such a disk is filled with a hot (with temperature \( T \sim GMm_p/R_g \), where \( m_p \) is the proton mass), highly magnetized (with plasma \( \beta \ll 1 \)), low-density plasma. The accretion disk interacts with this plasma at \( R_{\text{m}} \) and forms geometrically thin and dense streams, which accrete into the BH on spiral trajectories, flowing around low-density “magnetic islands” (see Figures 4 and 6 in I08). The flow pattern is highly variable because of the development of Rayleigh–Taylor and Kelvin–Helmholtz instabilities. The infall velocity of the dense plasma in streams is a large fraction (\( \sim 0.5 \)) of the free-fall velocity, which is why the streams are geometrically thin and occupy only a small fraction of the volume in a magnetically arrested disk. The high infall velocity also indicates that there is an efficient “braking” of the rotating flow by means of the vertical field. This braking results in the transfer of the rotational energy of the flow to the field energy and the release of the latter energy in the form of bipolar Poynting jets. The simulations of I08 demonstrated that \( \sim 1\% \) of \( Mc^2 \), where \( M \) is the mass accretion rate, can go into the jets in the case of magnetically arrested disks orbiting non-rotating BHs. Note that the jet power can be substantially enhanced in the case of fast rotating BHs with properly aligned spins because of the “ergospheric disk” mechanism (Punsly & Coroniti 1990; Punsly et al. 2009).

The magnetically arrested disk model is a promising candidate to explain BH binaries in the low/hard state because of its specific properties. This model can have an outer optically thick disk that is naturally truncated at \( R_{\text{m}} \), similar to what is postulated in the phenomenological truncated-disk model. Inside \( R_{\text{m}} \), a soft X-ray emission from the disk is suppressed because of fast accretion of the mass in spiral streams, which an optically thick medium cannot efficiently radiate because of the long Thomson-scattering diffusion time of photons in comparison with the accretion time (I08). Instead, the binding energy of the accretion flow is transformed into the energy of toroidal MHD waves that feed the Poynting jets and heat the low-density plasma, which surrounds the dense accretion streams, via magnetic flares. This plasma can emit hard X-rays via bremsstrahlung and Compton scattering of soft photons from the dense streams. Such emission properties plus the presence of the dense plasma in the vicinity of the BH cause the magnetically arrested disk model to resemble another phenomenological model for the low/hard state, corona-and-disk model.

The existence of magnetically arrested disks is determined only by the presence or absence of strong vertical magnetic fields. The thermal and emission properties of plasma in these disks are not relevant in this respect. Therefore, magnetically arrested disks can exist in a wide range of luminosities and accretion rates, from significantly sub- to significantly super-Eddington rates. This is unlike the case of optically thin ADAF models that become thermally unstable at moderate and high luminosities, \( L \gtrsim 10^{-3}L_{\text{Edd}} \) (Abramowicz et al. 1995).

The magnetically arrested disk model can be used to explain low-frequency (\( \sim 0.1–30 \) Hz) QPOs that are often found in BH binaries in the low/hard state (RM06). The spiral accretion streams in magnetically arrested disks form patterns that have almost solid-body rotations with frequencies determined as a fraction (\( \sim 0.5 \)) of the Keplerian frequency at \( R_{\text{m}} \) (I08). Relating this rotation with low-frequency QPOs, one can estimate the QPO frequency,

\[
\nu \sim 10^4 \left( \frac{M}{M_\odot} \right)^{-1} \left( \frac{R_{\text{m}}}{R_g} \right)^{-3/2} \text{Hz.}
\]

Note that Tagger & Pellat (1999) and Tagger et al. (2004) proposed a similar mechanism of the solid-body rotating structure for low-frequency QPOs. However, the nature of their structure, which is formed by a spiral-wave generated because of the “accretion–injection” instability, is different from the nature of magnetically arrested disks. Estimating \( R_{\text{m}} \) from Equation (2) in the case of Cyg X-1, which is characterized by \( M \sim 10 M_\odot \) and \( \nu \sim 1–3 \) Hz (Rutledge et al. 1999), one obtains \( R_{\text{m}} \sim 30 R_g \). The latter estimate agrees with the estimates of \( R_{\text{m}} \) in Cyg X-1 obtained from interpretations of X-ray spectra (Gierliński et al. 1997; Axelsson et al. 2008).

### 3. TRANSITION MECHANISM

The flow that feeds an accretion disk orbiting the primary (BH) is supplied by the secondary (star) and, therefore, can carry a magnetic field, whose strength and topology are determined by the strength and topology of the stellar magnetic field and relative orbital motions of binary components. In this circumstance, the poloidal component of the supplied fields can be inverted in time randomly (depending on the secondary’s magnetic activity) and/or quasi-periodically (with the time scale \( \sim \) the orbital time). The field inversion can result in a temporal
disappearance of a magnetically arrested disk, because of the annihilation of opposed fields, and in a restoration of an optically thick disk that extends down to the last stable circular orbit of the BH. This can explain the transition between the low/hard state, which is characterized by the presence of a magnetically arrested disk, and the high/soft state, which is the manifestation of an untruncated Shakura–Sunyaev-type disk.

The minimum magnetic flux that is required to form a magnetically arrested disk can be estimated using Equation (1):

$$\Phi_0 \sim \pi R_s^2 B_0 \sim \pi R_s^2 \left( \frac{Mc}{\theta R_s^2} \right)^{1/2} \approx 4 \cdot 10^{20} \theta^{-1/2} \left( \frac{M}{M_\odot} \right)^{3/2} \left( \frac{\dot{M}}{M_{\text{Edd}}} \right)^{1/2} \text{Mw}, \quad (3)$$

where $\theta = H/R_s < 1$, $H$ is the disk thickness near the BH horizon, and $M_{\text{Edd}} = L_{\text{Edd}}/c^2$. For comparison, the magnetic flux in the Crab pulsar is estimated to be $\sim 10^{25}$ Mw. The flux (Equation (3)) comes from the outer accretion radius $R_s = 2GM/v_s^2$, where it is collected during the time $\tau$, so that

$$\Phi_0 \sim B_s R_s v_s \tau, \quad (4)$$

where $B_s$ and $v_s$ are the magnetic induction and accretion velocity at $R_s$, respectively. The estimate of $B_s$, depending on the accumulation time $\tau$ and other parameters of the problem, can be obtained by substituting Equation (3) into Equation (4), yielding

$$B_s \sim 10^{-3} \theta^{-1/2} \left( \frac{v_s}{c} \right) \left( \frac{\tau}{\text{year}} \right)^{-1} \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{\dot{M}}{M_{\text{Edd}}} \right)^{1/2} \text{G}. \quad (5)$$

Let us consider the example of Cyg X-1 and use the following parameters: $v_s \sim 10^8$ cm s$^{-1}$, $\tau \sim 1$ year, $\theta \sim 0.1$, and $M \sim 0.1 M_{\odot}$. Then, the estimate of the inner field yields $B_0 \sim 10^8$ G. This field magnitude agrees with the magnitude derived from polarimetric observations of Cyg X-1 (Gnedin et al. 2003). The estimate of the outer field yields $B_s \sim 10^{-5}$ G. This estimate demonstrates how small the field supplied into the accretion disk can be to initiate the formation of a magnetically arrested disk in Cyg X-1. For comparison, the typical observed stellar fields are $\sim 1–100$ G.

An evolution of the inverted fields in accretion disks has been studied using axisymmetric 2D MHD simulations. Although these simulations do not correctly reproduce the 3D structure of magnetically arrested disks (I08), they qualitatively correctly model the global evolution of the fields and, therefore, are adequate here. The employed numerical method is described in I08 and the simulation setup is assumed to be the same as in Model B from there, except that the present simulations consider an inversion of the injected field. Figure 1 presents the evolution of magnetic fluxes in the midplane of the model inside the five specific radii: $210 R_g (= R_{\text{inj}})$, $100 R_g$, $50 R_g$, $25 R_g$, and $2 R_g (= R_{\text{inj}})$ (the black, red, green, blue, and magenta curves, respectively). The time is given in units of the orbital time at $R_{\text{inj}}$. The spikes seen in the magenta curve are due to a cycle accretion in the magnetically arrested region. This cycle accretion is an artifact of the assumed axisymmetry and is not present in 3D simulations (I08). Initially, the magnetic fluxes are gradually increased with time because of the inward advection of the vertical field. The moment of the field inversion is chosen at $t = 5.1$, which is clearly distinguished as the abrupt jump of the black curve in Figure 1. Other curves, which correspond to the fluxes at smaller radii, are changed in time with delays and more gradually. The field inversion results in a temporal suppression of the accretion flow at large radii (because more injected mass leaves the computational domain through the outer boundary) and development of a wide radial gap, $\sim R_{\text{inj}}/2$, between the outer edge of the “old” disk and the inner edge of a “new” disk, which carries the inverted field. As the mass accumulated in the old disk is reduced, the accretion rate into the BH is also reduced. The increased time intervals between the spikes seen at $t \approx 6$ to 7.5 in Figure 1 correspond to this reduction. At $t \approx 7$, the new disk is fully developed and quickly fills the radial gap, forming a continuous disk. This disk has the vertical fields, which are inverted at some disk radius. Figure 2 represents this stage of evolution, showing the density distribution and magnetic lines in the meridional cross-section of the model at $t = 8.52$. The central magnetic bundle is large and the flow is magnetically arrested. The inverted field (see Figure 2(b)) closely approaches the bundle, resulting in an intensive reconnection dissipation, which heats plasma in a narrow interface between the opposed fields. At $t \approx 9.5$, the central bundle is completely annihilated and the dense disk extends all the way inward to $R_{\text{inj}}$. The simulations show that the accretion into the BH is continuous, without signs of the cycle accretion, from $t \approx 9$ to 10. Figure 3 illustrates this evolution stage, showing the model at $t = 10.08$. The simulations were finished at $t = 10.75$. At this moment, the inverted field builds up another central magnetic bundle, which arrests the accretion flow. It becomes apparent that the further evolution of this model will basically repeat the initial evolution.

The SPL state is similar in some respects to the high/soft state (see Section 1). This motivates us to explain the SPL state as a final phase of the more extended period of field annihilation that precedes the high/soft state. Unfortunately, no supporting 3D simulations of this period have been done yet and our discussion is only limited by the following qualitative statements. (1) At the final phase, the radius $R_{\text{inj}}$ is small and the optically thick disk can extend deep inside, providing a sizable spectral thermal component. (2) A significant fraction of the disk emission can be provided by the reconnection dissipation of the stored magnetic energy. This can explain the specific steep power-law spectral
Figure 2. Distribution of density (a) and magnetic lines (b) in the meridional plane at $t = 8.52$ from axisymmetric 2D simulations of the accretion disk model. The black hole is located on the left side of the images, and the small open circles there correspond to the inner boundary around the black hole at $R_{in} = 2R_g$. The axis of rotation is in the vertical direction. The domain shown has the radial extent $R_{out} = 220R_g$ along the equatorial plane and vertical extent from $-R_{out}/2$ to $R_{out}/2$. The color bar on the right in (a) indicates the scale for log $\rho$ (in arbitrary units). The lines in (b) have been plotted using the method of Cabral & Leedom (1993). The field carried inward by the disk and the field in the central magnetic bundle have inverted vertical components (b). The central bundle arrests the accretion flow and forms a truncated disk (a).

Figure 3. Same as in Figure 2, but at $t = 10.08$. The central magnetic bundle seen in Figure 2(b) has disappeared because of the annihilation with the incoming inverted field (b). The disk is untruncated and extends all the way inward to $R_{in}$ (a).

4. SUMMARY

This Letter proposes a detailed mechanism for emission state transition in BH X-ray binaries. The mechanism is based on a dynamical model of a magnetically arrested disk obtained in recent 3D MHD simulations (I08) that can describe the low/hard state. In this state, the central region of an optically thick accretion disk orbiting the BH is filled with a strong (equipartition) vertical magnetic field that arrests the flow, resulting in a truncated disk. The accretion, however, is not suppressed in this disk but takes the form of thin spiral streams that penetrate through a highly magnetized, hot, low-density plasma. The spiral flow twists the vertical field and produces powerful Poynting jets. Radiation from the disk is dominated by hard X-rays emitted by the hot plasma and includes a radio component from the jets. The magnetically arrested disk is capable of explaining low-frequency QPOs.

The transition from the low/hard to high/soft state occurs when the magnetic field at the outer boundary is inverted. An annihilation of this field, carried inward by the flow, and the central field results in a temporal disappearance of the magnetically arrested disk. For a moment, the optically thick disk extends inward to the last stable orbit of the BH and no jets are produced. This represents the high/soft state, which ends as soon as the continuous supply of the inverted field results in the formation of another magnetically arrested disk. The SPL state and associated high-frequency QPOs develop in this scenario at the period of intensive annihilation of the inverted fields, which precedes the high/soft state. Quasi-periodic or random inversion of magnetic fields in the accretion flow supplied by the secondary star can explain the observed spectral transitions of BH X-ray binaries.

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