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The model for the state transitions of the X-ray binaries GRO J1655-40 based on cosmic battery

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Abstract. A toy model for the state transitions of X-ray binaries (XRBs) is proposed by considering the effects of cosmic battery. In our model, we present an explanation for the origin of the magnetic field: some electric currents flowing around a Kerr black hole in the equatorial plane generates the poloidal magnetic field which exists on the black hole and the accretion disk. And the magnetic field is very important for explaining the state transitions. We discuss the different configurations of magnetic field corresponding to different states of the XRBs—GRO J1655-40. It turns out that the Poynting-Robertson cosmic battery could be the key factor for explaining the state transitions of XRBs.
Key words: black hole – accretion disks – X-ray binaries

1. Introduction

As it is well known, most X-ray binaries (XRBs) are transient systems that undergo occasional outbursts, which display complex spectral and timing features. Generally, an outburst can be divided into three spectral states (along with the time duration): low/hard (LH) state, intermediate state and high/soft (HS) state (Zdziarski 2000; McClintock & Remillard 2006). The HS state is characterized by a strong thermal emission and a weak power-law component. However, the thermal emission is normally weak in the LH state and most of the radiation comes from a nonthermal power-law component. And jets can be observed in the LH state, but cannot be in the soft one. The intermediate state is a transient state from the LH to HS state (or the opposite), of which both the thermal component and the power-law component are strong. The hard X-ray photon index of the intermediate state is around 2.5-3.0 and, therefore, it is also referred to as the steep power law (SPL) state (Remillard & McClintock 2006). And it has been pointed out that high frequencies Quasi-Periodic Oscillations (HFQPOs) are generally associated with the SPL states of XRBs.

Some authors discussed the reasons of the state transitions of XRBs. Esin et al. (1997) indicated that a self-consistent model of accretion flows around a black hole (BH) that unified all of the three states mentioned above. Their model consistently treats the dynamics of the accreting gas, the thermal balance of the ions and electrons in the two-temperature disk and corona, and the radiation processes that produce the observed spectrum. Except for the self-consistent model, there are alternative models of the Xray states, and many of them invoke a dynamic accretion disk corona that is fed by magneto hydrodynamics instabilities in the disk (Matteo 1999; Merloni & Fabian 2001a, b).

In one word, it is well accepted that accretion rate is a key factor in governing the state transitions of XRBs. However, the main features cannot be described only by accretion rate, while magnetic fields are regarded as another key parameter in state transitions of XRBs (Spruit & Uzdensky 2005; King et al. 2012).

Recently, we also argued that the magnetic field is very important to state transitions in XRBs (Ye et al. 2016; Huang et al. 2016). Unfortunately, the origin of magnetic fields in BH systems has been a puzzle in astrophysics, and the configuration of magnetic field corresponding to state transitions of XRBs is still obscure. Generally, there exist two models for the origin of magnetic field. The first model for the origin of magnetic fields in accretion flows is the dynamo mechanism, by which the large scale ordered magnetic fields are produced from the seed magnetic fields frozen in the turbulent conducting fluid (Moffatt 1978; Parker 1979). The second model is the so called Poynting-Robertson cosmic battery (PRCB) proposed by Contopoulos & Kazanas (1998), which is based on the Poynting-Robertson drag effect on the electrons of the innermost plasma orbiting a BH, or a neutron star. The revisits and modifications of the PRCB mechanism and its application to astrophysics are given in a series of works (Contopoulos et al. 2006; Christodoulou et al. 2008; Contopoulos et al. 2009).

Enlightened by the above works we intend to study the configurations of magnetic field base on the PRCB, and discuss the state transitions of XRBs—GRO J1655-40.

This paper is organized as follows. In section 2 we indicate how to calculate the configuration of magnetic field base on the PRCB. In section 3 the different magnetic field configurations corresponding to different states of the XRBs—GRO J1655-40—are given. It is shown that the different magnetic field configurations could fit the state transitions of XRBs. In section 4 we summarize our main results. Throughout this paper the geometric units $G = c = 1$ are used.

2. The model base on PRCB

Following Huang et al. (2016), we have the current intensity created by the PRCB mechanism as follows

$$I_{PRCB} = \Delta s j_{PRCB} = \frac{en\Delta t\Delta s}{m_e}\frac{F\sigma_T\nu_K}{c^2}. \tag{1}$$

From equation (1) we know that there exists a current on the disk surrounding a BH. Not long ago, Li (2002) considered a toy model to probe the magnetic coupling mechanism by assuming a toroidal current flowing in the equatorial plane of a Kerr BH. Following Li (2002), we can calculate the configurations of magnetic field corresponding to the different currents on the disk.

At first, our discussion is based on a stationary, axisymmetric magnetosphere anchored in a Kerr BH and its surrounding disk. So we can give the concerned Kerr metric parameters as follow (Macdonald & Thorne 1982)

$$A = \left(r^2 + a^2\right)^2 - a^2 \Delta \sin^2\theta, \qquad \rho^2 = r^2 + a^2\cos^2\theta, \qquad \Delta = r^2 + a^2 - 2Mr,$$
$$\varpi = (A/\rho)^{1/2}\sin\theta, \qquad \alpha = (\rho\Delta/A)^{1/2}. \tag{2}$$

Following Ge et al. (2008), the equations about the calculation of configuration are given by

$$J^\alpha = (I/r)(\Delta/A)^{1/2}(\partial/\partial\phi)^\alpha[\delta(r - r_1^{'}) + \delta(r - r_2^{'})]\delta(\cos\theta), \tag{3}$$

which is the four-current vector corresponding to two counter oriented toroidal electric currents flow on circles of $r = r_1^{'}$ and $r = r_2^{'}$ in the equatorial plane of a Kerr BH;

$$\Psi(a_*, r, \theta, r_1^{'}, r_2^{'}) = 2\pi[A_\phi(a_*, r, \theta, r_1^{'}) + A_\phi(a_*, r, \theta, r_2^{'})], \tag{4}$$

which is the magnetic flux penetrating into the surface of a circle with radius r, where $A_\phi(a_*, r, \theta, r_1^{'})$ and $A_\phi(a_*, r, \theta, r_1^{'})$ are the toroidal components of the electric vector potential produced by the electric currents located at $r_1^{'}$ and $r_2^{'}$, respectively (Li 2002; Zanjek 1978; Petterson 1975; Linet 1979); and

$$B_D^P = -\frac{1}{2\pi}(\frac{\Delta}{A})^{1/2}\frac{d\Psi(a_*, r, \theta, r_1^{'}, r_2^{'})}{dr}, \tag{5}$$

which is the poloidal magnetic field with the spherical coordinate (r, θ) related to the magnetic flux.

Following Ge et al. (2008), and incorporating equations (2)–(5), we have the magnetic field configurations, which are produced by the two electric currents.

3. The magnetic field configurations and state transitions of the XRBs—GRO J1655-40

Based on our model, we can get the different magnetic field configurations with different distribution of electric currents. And then, we can give some explanations for the astronomical observations of XRBs in different states depending on the different magnetic field configurations. In this paper, we focus on the observations of XRBs—GRO J1655-40, which correspond to three different states:

the LH state, the SPL state and the HS state. In the following calculations, the BH spin is fixed at 0.7 and the BH mass is 6.3, which is in unit of the solar mass (Remillard & McClintock 2006; Shafee et al. 2006; Ozel et al. 2010).

3.1. The LH state of GRO J1655-40

Considering the accretion disk to be far away from the BH in the initial phase of the burst in the XRBs, we assume that the inner electric current is located at $8.7r_{ms}$, where r_{ms} is the innermost stable circular orbit, and the outer electric current is located at $8.7r_{ms} + L_0$ (Novikov & Thorne 1973), where L_0 is a parameter to adjust the interval of the two currents. In the following calculation, we set $L_0 = 20$, whose unit is the gravitational radius r_g.

Combining equations (2)—(5), we have the configuration of magnetic field based on two electric currents as shown in Fig. 1. In Fig. 1 and the following figure about the configuration of magnetic field, the unit of coordinate is r_g.

From Fig. 1 we found that there exist many open lines in the configuration of magnetic field, which correspond to the Blandford–Znajek (BZ) process and the Blandford–Payne (BP) process (Blandford & Znajek 1977; Blandford & Payne 1982). As we all know there are relativistic jets in the LH state of GRO J1655-40 (Hjellming 1995; Hannikainen et al. 2000). Miller et al. (2006) reported that an X-ray-absorbing wind discovered in an observation of GRO J1655-40 must be powered by a magnetic process that can also drive accretion through the disk. The disk wind could be powered by the pressure generated by magnetic viscosity internal to the disk or magneto-centrifugal forces. Recently, Stuchlík & Kološ (2016) indicated a new mechanism for the jet, in which the large-scale magnetic field is very important for the formation of the jet by accelerating the charged particles. So it is reasonable that the open poloidal large-scale magnetic fields are helpful to power and collimate the jets associated with LHS via the BZ and BP processes.

Following Wang et al. (2004), we have all equations about the BZ and BP powers as follows

$$P_{BZ}/P_0 = 2a_*^2 \int_{\theta_1}^{\theta_2} \frac{k(1-k)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}, \tag{6}$$

where $q = \sqrt{1-a_*^2}$, $k = \Omega_F/\Omega_H$ is the ratio of the angular velocity of the open field lines to that of the horizon, and the angular coordinate of the open field lines is assumed to vary from θ_1 to θ_2, or

$$P_{BP}/P_0 = \int_1^{\xi_{out}} f(a_*, \xi, n) d\xi, \tag{7}$$

where the function $f(a_*, \xi, n)$ is expressed by (Wang et al. 2004)

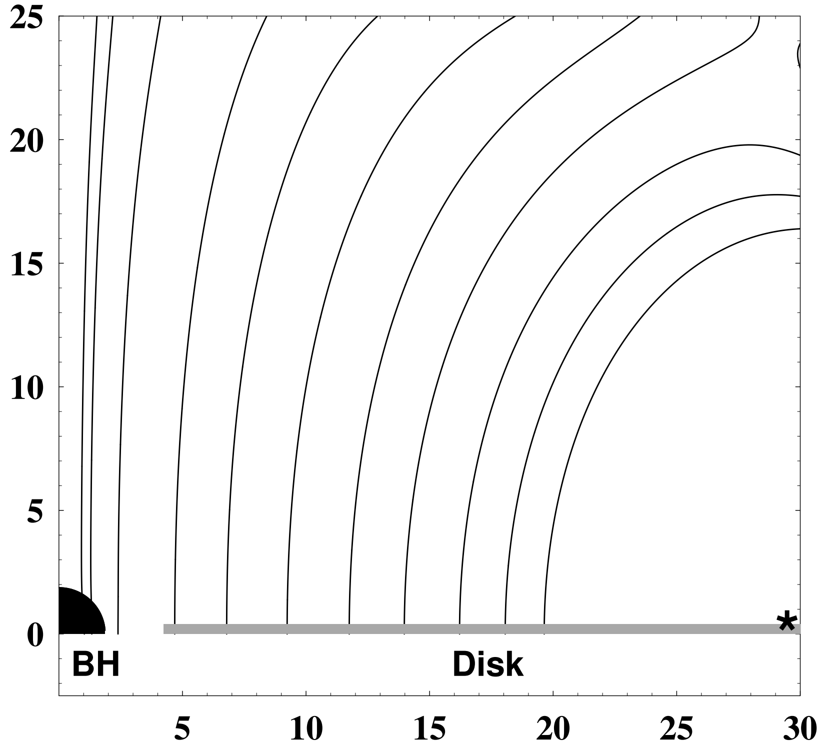

Figure 1. A magnetic field configuration on the disk is produced by the two currents at $8.7r_{ms}$ and $8.7r_{ms}+20$, respectively. The symbol "$*$" represents the electric current located at $8.7r_{ms}$. The second electric current is not shown in the figure, because it is too far away from the BH.

$$f(a_*,\xi,n)=\frac{(1+q)^2(1+\xi^{-2}\chi_{ms}^{-4}a_*^2+2\xi^{-3}\chi_{ms}^{-6}a_*^2)\xi^{-2n}}{2\chi_{ms}^2(1+a_*\xi^{-3/2}\chi_{ms}^{-3})^2(1-2\xi^{-1}\chi_{ms}^{-2}+\xi^{-2}\chi_{ms}^{-4}a_*^2)}; \qquad (8)$$

here n is the power-law index indicating the degree of concentration of the magnetic field in the central region of the disk, $\xi\equiv r/r_{ms}$ is a dimensionless radius of the disk in terms of the radius of the last stable circular orbit, $r_{ms}=M\chi_{ms}^2$, where M means the BH mass, and $\chi_{ms}=\sqrt{r_{ms}/M}$ means a dimensionless radial parameter on the disk.

$$P_0=(B_H^2)M^2\approx B_4^2m_{BH}^2\times 6.59\times 10^{28}erg\cdot s^{-1}, \qquad (9)$$

where B_4 and m_{BH} are B_H and M in the units of 10^4 $Gauss$ and one solar mass, respectively. And the poloidal magnetic fields on the horizon, B_H, are estimated by the following relation (Beskin 1997)

$$B_H \approx 10^{8.5} m_{BH}^{-1/2} Gauss. \tag{10}$$

In calculations, we set $\theta_1 = 0.3$, $\theta_2 = 1.45$, and $\xi_{out} = 100$. Combining equations (6)—(10), we can get the jet power, which is from the BZ and BP processes. The result is shown in Fig. 2.

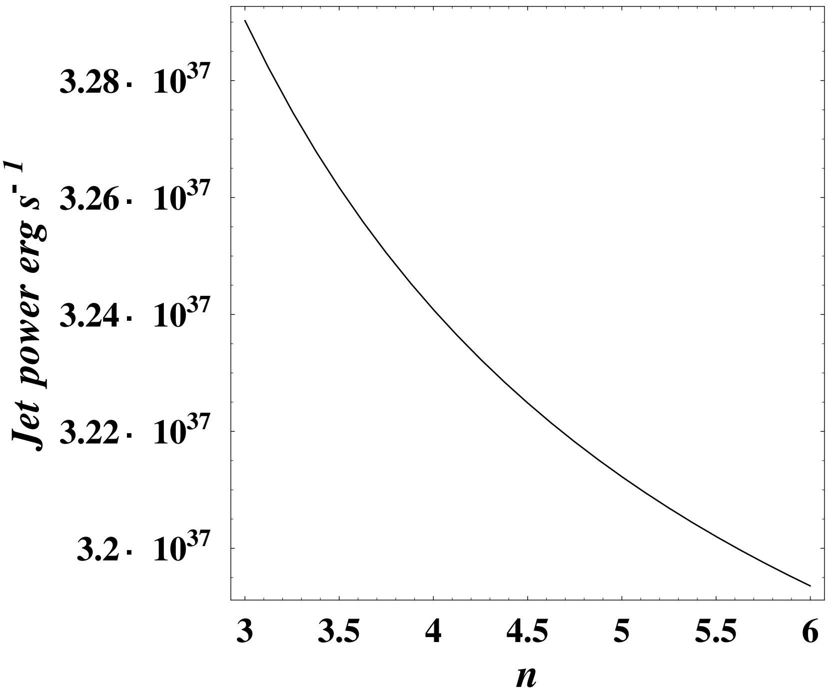

Figure 2. Jet power versus n with $a_* = 0.7$

It is reasonable that the compact jet in XRBs is responsible for the hard X-ray emission, which comes from the base of the jet (Markoff et al. 2004; Markoff & Nowak 2004; Markoff et al. 2005). From Takahashi et al. (2008) we know that the X-ray luminosity in GRO J1655-40 is about $5.1 \times 10^{36} erg \cdot s^{-1}$. Considering the transferring efficiency between the jet power and X-ray luminosity to be about 0.1 to 0.2, our result of jet power fits the observations.

3.2. The SPL state of GRO J1655-40

Along with the accretion duration, the radii of the two currents are closer and closer to the BH. Then we assume that the inner electric current is located at r_{ms} and the outer electric current is located at $r_{ms} + 5$, which corresponds to the middle phase of the outburst of the XRBs.

Following equations (2)—(5) and the parameters mentioned above, we have the configuration of magnetic field as shown in Fig. 3.

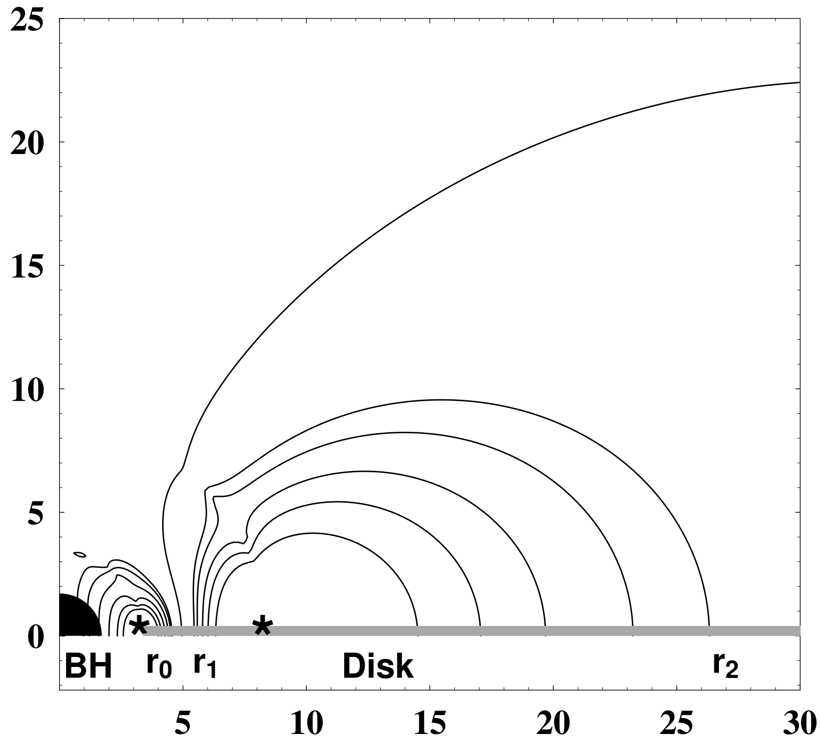

Figure 3. A magnetic field configuration on the disk produced by the two currents at r_{ms} and $r_{ms}+5$, respectively. The symbols " $*$ " represent the electric currents located at r_{ms} and $r_{ms} + 5$, respectively.

As it is well known, the 3:2 HFQPOs pairs have been observed in several XRBs, including GRO J1655-40 ($450Hz$: $300Hz$)(Remillard et al. 1999; Strohmayer, 2001; Remillard & McClintock 2006). Some authors discussed that the 3:2 HFQPOs pairs could be explained in XRBs by the epicyclic resonance model (Abramowicz & Kluźniak 2001; Abramowicz et al. 2003; Kluźniak et al. 2004; Török et al. 2005). Recently, in the GRO J1655-40, some authors indi-

Table 1. Fitting HFQPOs in GRO J1655-40.

Source	a_*	m_{BH}	r_H/r_g	r_0/r_g	r_1/r_g	r_2/r_g	ν_{QPO1}	ν_{QPO2}
GRO J1655-40	0.7	6.3	1.7	4.1	6.0	26.5	450	300

cated that the 3:2 HFQPOs pairs could be explained along with the related low frequency QPOs by the relativistic precession model, or its variants (Motta et al. 2014; Stuchlík & Kološ 2016a, b). In our model, we could give an explanation for the 3:2 HFQPOs pairs too. From Fig. 3, it is found that there are two regions, which correspond to two kinds of magnetic coupling (MC). Following Zhao et al. (2009), considering that the magnetic reconnection arises from the twist of the closed field lines of MC in the two regions, we infer that the flares occur most probably in the critical field lines of the two regions, which could produce the HFQPOs in XRBs. There are some equations about the frequencies as follow

$$\nu_{QPO1} = \nu_0[\frac{a}{2(1+q)} - (\xi_0^{3/2}\chi_{ms}^3 + a_*)^{-1}], \tag{11}$$

$$\nu_{QPO2} = \nu_0[(\xi_1^{3/2}\chi_{ms}^3 + a_*)^{-1} - (\xi_2^{3/2}\chi_{ms}^3 + a_*)^{-1}], \tag{12}$$

where $\nu = (m_{BH})^{-1} \times 3.23 \times 10^4 Hz$. ν_{QPO1} is produced by the magnetic connection between the radius of the BH horizon r_H and r_0, and ν_{QPO2} is produced by the magnetic connection between r_1 and r_2.

From Fig. 3, we can set the parameters as listed in Table.1. And then we can fit the observations about 3:2 HFQPOs pairs in GRO J1655-40.

3.3. The HS states of GRO J1655-40

At the last phase of the outburst of the XRBs, all accretion matter falls into the BH, then it is reasonable that we assume that all electric currents fall into the BH.

That means there is no magnetic field in the disk. This result is benefit for explaining that the HS state is dominated by the thermal component in the spectral. And that is reason for some authors to indicate that the HS state means the thermal state (Remillard & McClintock 2006).

4. Conclusion and discussion

Based on PRCB, we calculated some configurations of magnetic field. And we found that the state transitions of the XRBs—GRO J1655-40 are due to the changing of electric currents along with the duration of accretion. The LH state is produced by the two currents, which are far away from the BH. And then, the two closing electric currents produce the SPL state. At last, the HS state follows, because there is no electric current in the disk.

There are some issues we need to discuss.

Firstly, some authors indicated that the mass of the GRO J1655-40 black hole estimated by the optical methods reads 5.3, which is in unit of solar mass. And the spin is less than 0.7 (Beer et al. 2002; Motta et al. 2014). In our model, following equations (11) and (12), we found that the frequencies are porportional to the spin and inversely porportional to the mass. So less mass makes higher frequencies, and less spin makes lower frequencies. As listed in Table. 1, there are some other parameters that could affect the frequencies, which correspond to the location of magnetic connection. That means the location of electric currents in the disk would be different for that shown in Fig. 3 if we want to fit the 3:2 HFQPOs pairs based on the new mass and spin in GRO J1655-40.

Secondly, we just explained one XRBs, and we just discussed the jet power and HFQPOs in GRO J1655-40. Some other details of state transitions of the XRBs are not discussed in our paper, such as the details of the spectra in different states of the XRBs.

We hope to discuss these details and improve our model for more XRBs in future work.

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