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Hyperaccretion after the Blandford-Znajek Process: A New Model for GRBs with X-Ray Flares Observed in Early Afterglows *

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Abstract We propose a three-stage model with Blandford-Znajek (BZ) and hyperaccretion process to interpret the recent observations of early afterglows of Gamma-Ray Bursts (GRBs). In the first stage, the prompt GRB is powered by a rotating black hole (BH) invoking the BZ process. The second stage is a quiet stage, in which the BZ process is shut off, and the accretion onto the BH is depressed by the torque exerted by the magnetic coupling (MC) process. Part of the rotational energy transported by the MC process from the BH is stored in the disk as magnetic energy. In the third stage, the MC process is shut off when the magnetic energy in the disk accumulates and triggers magnetic instability. At this moment, the hyperaccretion process may set in, and the jet launched in this restarted central engine generates the observed X-ray flares. This model can account for the energies and timescales of GRBs with X-ray flares observed in early afterglows.

Key words: accretion, accretion disks — black hole physics — magnetic fields — gamma-rays: bursts

1 INTRODUCTION

Recently, flares in early X-ray afterglows have been discovered in both long and short bursts with the X-ray telescope (XRT) on board Swift. These flares appear at about tens to hundreds seconds after the triggerring of the GRBs and last about several hundred seconds (for a review of the Swift results and, in particular, the X-ray flares, see Zhang 2007). Their rapid variability has been interpreted as the inner engine being active much longer than the duration of the GRB itself (Zhang et al. 2006). Therefore, it is needed that after the prompt gamma-ray emission has ceased, the central engine can be restarted (Fan & Wei 2005; Zhang et al. 2006).

For the case of long GRBs, King et al. (2005) suggested that the X-ray flares could be produced from a fragmentation of the collapsing stellar core in a modified hypernova scenario. The fragment subsequently merges with the main compact object formed in the collapse, releasing extra energy. In this two-stage collapse model, the time delay between the burst and the flare reflects the gravitational radiation time scale for the orbiting fragment to be dragged in.

For the case of short GRBs, MacFadyen, Ramirez-Ruiz & Zhang (2005) suggested that the flares could be the result of interaction between the GRB outflow and a non-compact stellar companion. In this model, the short GRBs result from the collapse of a rapidly rotating neutron star in a close binary system. On the other hand, Dai et al. (2006) suggested that the flares in short GRBs are produced by differentially rotating, millisecond massive pulsars after the merger of the binary neutron star. The differential rotation leads to windup of interior poloidal magnetic fields and the resulting toroidal fields are strong enough to float up and break through the stellar surface. Magnetic reconnection-driven explosive events then occur, leading

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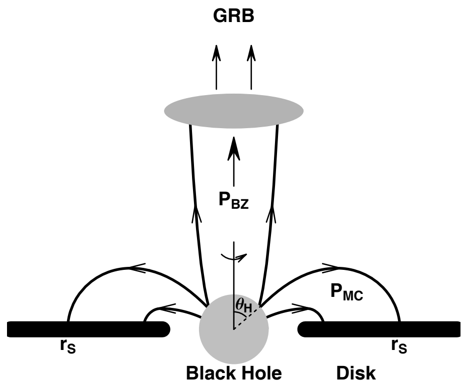

Fig. 1 A schematic drawing of the magnetic field configuration for the three-stage model.

to multiple X-ray flares minutes after the original gamma-ray burst. Gao & Fan (2006) also suggested a short-lived supermassive magnetar model to account for the X-ray flares following short GRBs. In their model, X-ray flares are powered by the dipole radiation of the magnetar.

Motivated by the fact that flares are observed in both long and short duration GRBs, Perna et al. (2006) suggested that the flares could be produced due to subsequent accretion of blobs of materials in a hyperaccreting accretion disk, which initially circularize at various radii and subsequently evolve viscously. Proga & Zhang (2006), on the other hand, conjectured that energy release could be repeatedly stopped and then restarted by the magnetic flux accumulated around the accretor, which leads to the X-ray flares.

Although the main features of the X-ray flares can be interpreted successfully in the above scenarios, a quantitative model with a clear physical process for restarting the central engine remains lacking.

Lei et al. (2005a, hereafter L05; 2005b) proposed a scenario for GRBs in Type Ib/c SNe, invoking the coexistence of the Blandford-Znajek (BZ, Blandford & Znajek 1977) and Magnetic Coupling (MC, Blandford 1999; van Putten 1999; Li 2000, 2002; Wang et al. 2002) processes. The BZ process can provide "clean" energy for the prompt GRB by extracting rotating energy from a BH (Lee et al. 2000). In L05, the accretion onto the BH is depressed by the torque exerted by the BH through MC process. It is found that the BZ process will be shut off before the MC process because the half-opening angle closing on the BH horizon. Recently, van Putten & Levinson (2003, hereafter PL03) suggested that the magnetic energy accumulated by the MC process can trigger magnetic instability, which results in the cessation of the MC process (Eikenberry & van Putten 2003).

Based on L05 and PL03, we suggest that the pause and the restart of the central engine arise from the MC process, and propose a three-stage model to interpret the GRBs and their flares, in which the prompt GRB and the X-ray flare are powered by the BZ process and the subsequent hyperaccretion, respectively.

2 THE THREE-STAGE MODEL

In this section, we present the three-stage model for the inner engine for GRBs. The magnetic field configuration is shown in Figure 1, — it is adapted from van Putten (2001).

In Figure 1 the angle $\theta_{\rm H}$ is the half-opening angle of the open magnetic flux tube, representing the angular boundary between open and closed field lines on the horizon. The angle $\theta_{\rm H}$ can be determined by (Wang et al. 2003)

$$\cos\theta_{\rm H} = \int_1^{\xi_S} {\rm G}\,(a_*;\xi,n)\,d\xi\,, \tag{1}$$

where $a_* \equiv J/M^2$ is the BH spin defined in terms of the BH mass M and the angular momentum J, n is the power-law index for the variation of $B_{\rm D}^P$, i.e., $B_{\rm D}^P \propto \xi^{-n}$, and $\xi \equiv r/r_{\rm ms}$ is the radial coordinate on the disk, in units of the radius, $r_{\rm ms} \equiv M\chi_{\rm ms}^2$, of the marginally stable orbit (Novikov & Thorne 1973), $\chi_{\rm ms}$ depends only on a_* (Novikov & Thorne 1973):

$$\chi_{\rm ms}^4 - 6\chi_{\rm ms}^2 + 8a_*\chi_{\rm ms} - 3a_*^2 = 0\,. \tag{2}$$

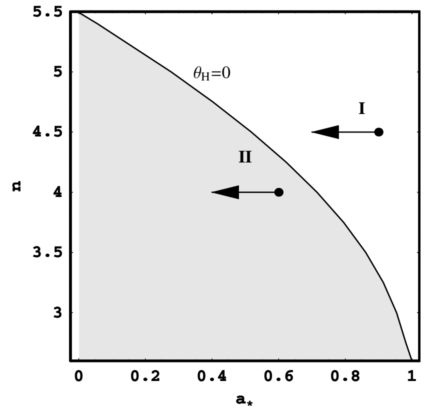

Fig. 2 Critical line for screw instability divides the parameter space into regions **I** and **II**. Each filled circle with arrowhead in the two regions represents one evolutionary state of the BH.

The function G $(a_*;\xi,n)$ is given by

$$\mathrm{G}\,(a_*;\xi,n)=\frac{\xi^{1-n}\chi_{\mathrm{ms}}^2\sqrt{1+a_*^2\chi_{\mathrm{ms}}^{-4}\xi^{-2}+2a_*^2\chi_{\mathrm{ms}}^{-6}\xi^{-3}}}{2\sqrt{\left(1+a_*^2\chi_{\mathrm{ms}}^{-4}+2a_*^2\chi_{\mathrm{ms}}^{-6}\right)\left(1-2\chi_{\mathrm{ms}}^{-2}\xi^{-1}+a_*^2\chi_{\mathrm{ms}}^{-4}\xi^{-2}\right)}}\,. \tag{3}$$

In Equation (1) $\xi_S \equiv r_S/r_{\mathrm{ms}}$ is the critical radius of screw instability in the MC process, which is determined by the criteria for the screw instability, given by Wang et al. (2004),

$$\frac{B_{\mathrm{D}}^P}{B_{\mathrm{D}}^T}<\frac{L}{2\pi\varpi_{\mathrm{D}}}\,, \tag{4}$$

where L is the poloidal length of the closed field line, ϖ_{D} the cylindrical radius on the disk, B_{D}^P and B_{D}^T are the poloidal and toroidal components of the magnetic field on the disk, and $L/2\pi\varpi_{\mathrm{D}}$ and $B_{\mathrm{D}}^P/B_{\mathrm{D}}^T$ are respectively expressed as (Wang et al. 2004):

$$B_{\mathrm{D}}^P/B_{\mathrm{D}}^T=\frac{\xi^{1-n}\,(1+q)\left[2\csc^2\theta-(1-q)\right]}{2a_*\,(1-\beta)}\sqrt{\frac{1+a_*^2\chi_{\mathrm{ms}}^{-4}\xi^{-2}+2a_*^2\chi_{\mathrm{ms}}^{-6}\xi^{-3}}{1+a_*^2\chi_{\mathrm{ms}}^{-4}+2a_*^2\chi_{\mathrm{ms}}^{-6}}}\,, \tag{5}$$

$$\frac{L}{2\pi\varpi_{\mathrm{D}}}=\frac{1}{4\xi\sqrt{1+a_*^2\xi^{-2}\chi_{\mathrm{ms}}^{-4}+2a_*^2\xi^{-3}\chi_{\mathrm{ms}}^{-6}}}\int_{\xi_{\mathrm{H}}}^{\xi}\frac{d\xi}{\sqrt{1+a_*^2\xi^{-2}\chi_{\mathrm{ms}}^{-4}-2\xi^{-1}\chi_{\mathrm{ms}}^{-2}}}\,. \tag{6}$$

By using Equation (1) we have the critical lines for the half-opening angle $\theta_{\mathrm{H}}=0$ in a_*-n parameter space shown in Figure 2.

An interesting feature shown in Figure 2 is that the angle θ_{H} can evolve to zero (the shaded region) with decreasing a_* for $2.616\le n\le 5.493$. This evolutionary feature implies that the BZ process will be shut off when the BH spin decreases to the critical value a_*^{GRB} corresponding to $\theta_{\mathrm{H}}=0$. The lifetime of the half-opening angle θ_{H} is defined as the evolution time of the BH from the initial spin $a_*(0)$ to a_*^{GRB}.

2.1 Stage 1: the Prompt Emission of GRB

In the first stage, the BZ process works together with the MC process and the evolution state of the BH is located in region **I** of Figure 2.

Since angular momentum is transferred from the rapidly rotating BH to the disk, a very strong torque will be exerted on the inner disk in the MC process. The accretion onto the BH will be depressed by the

MC process (van Putten & Ostriker 2001; PL03; Li 2002). Therefore, in this stage, the accretion rate is very low, and the prompt emission of GRB is mainly powered by the BZ process.

The powers and torques for the BZ and MC processes are expressed as (Wang et al. 2002; Wang et al. 2003)

$$\tilde{P}_{\rm BZ} \equiv P_{\rm BZ}/P_0 = 2a_*^2 \int_0^{\theta_{\rm H}} \frac{k\,(1-k)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}\,, \tag{7}$$

$$\tilde{T}_{\rm BZ} \equiv T_{\rm BZ}\Big/T_0 = 4a_*\,(1+q) \int_0^{\theta_{\rm H}} \frac{(1-k)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}\,, \tag{8}$$

$$\tilde{P}_{\rm MC} \equiv P_{\rm MC}\Big/P_0 = 2a_*^2 \int_{\theta_{\rm H}}^{\pi/2} \frac{\beta\,(1-\beta)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}\,, \tag{9}$$

$$\tilde{T}_{\rm MC} \equiv T_{\rm MC}\Big/T_0 = 4a_*\,(1+q) \int_{\theta_{\rm H}}^{\pi/2} \frac{(1-\beta)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}\,, \tag{10}$$

where $q \equiv \sqrt{1-a_*^2}$, $P_0 \equiv B_{\rm H}^2 M^2$ and $T_0 \equiv B_{\rm H}^2 M^3$. $B_{\rm H}$ is the magnetic field on the BH horizon. Parameters k and β are ratios of the angular velocities of the open and closed magnetic field lines to that of the BH, respectively. Usually, $k = 0.5$ is taken for the optimal BZ power.

The energy $E_{\rm BZ}$ extracted in the BZ process can be calculated during the evolution of GRB. The true energy for GRBs, E_γ, is given by L05,

$$E_\gamma = \varepsilon_\gamma E_{\rm BZ} = 2.69 \times 10^{53}\ {\rm erg} \times \left(\frac{M(0)}{} M_\odot\right)\left(\frac{\varepsilon_\gamma}{0.15}\right) \int_{a_*(0)}^{a_*^{\rm GRB}} \frac{\tilde{M}\tilde{P}_{\rm BZ}}{-\tilde{T}_{\rm mag} + 2a_*\tilde{P}_{\rm mag}} da_*\,, \tag{11}$$

where $\tilde{P}_{\rm mag} \equiv \tilde{P}_{\rm BZ} + \tilde{P}_{\rm MC}$, $\tilde{T}_{\rm mag} \equiv \tilde{T}_{\rm BZ} + \tilde{T}_{\rm MC}$, and $\tilde{M} \equiv M/M(0)$ is the ratio of the BH mass to its initial value. Following van Putten et al. (2004), we take the efficiency $\varepsilon_\gamma = 0.15$ in calculations.

The duration of GRB, $t_{\rm GRB}$, is defined as the lifetime of the half-opening angle $\theta_{\rm H}$, which is exactly equal to the time for the BH spin evolving from $a_*(0)$ to $a_*^{\rm GRB}$, i.e.,

$$t_{\rm GRB} = 2.7 \times 10^3\,{\rm s} \times \left(\frac{10^{15}\ {\rm G}}{B_{\rm H}}\right)^2 \left(\frac{M_\odot}{M(0)}\right) \int_{a_*(0)}^{a_*^{\rm GRB}} \frac{\tilde{M}^{-1}}{-\tilde{T}_{\rm mag} + 2a_*\tilde{P}_{\rm mag}} da_*\,. \tag{12}$$

The energy and duration of the prompt emission can be obtained by taking $M(0)$, $a_*(0)$, n and $B_{\rm H}$ into Equations (11) and (12). In the following calculations the initial BH mass and spin are assumed to be $M(0) = 7\,M_\odot$ and $a_*(0) = 0.9$.

By adopting proper values of parameters n and $B_{\rm H}$, our model can explain both long and short bursts, such as GRB 050219A and GRB 050709 (see Table 1).

Table 1 GRB 050219A and GRB 050709

GRBs	Type	T_{90}(s)	$E_\gamma(10^{50}$ erg)	n	$B_{\rm H}(10^{15}$ G)
50219A	Long	23.6[1]	$> 4.8^a$	>3.545	>0.7
050709	Short-hard	0.07[2]	0.021^b	3.330	2

From Table 1 we find that the shorter duration and lesser energy of the short burst can be fitted with a smaller value of n and a greater value of $B_{\rm H}$. Some long bursts have been fitted in L05 by reasonable values of n and $B_{\rm H}$.

2.2 Stage 2: Accretion Depressed by the MC Process

At this stage, the MC process is still active, and it depresses the accretion onto the BH. Following PL03, the magnetic field energy of the disk, ε_B, will build up in response to the power received from the BH, i.e.,

$$\varepsilon_B(t) = \int_0^t \eta P_{\rm MC} dt\,, \tag{13}$$

where η is the ratio of the rate of increase of the magnetic field energy to the total MC power, and we have $\eta \ll 1$ since most of the rotational energy of a Kerr BH is emitted in gravitational radiation and MeV neutrino emissions (van Putten 2001).

According to PL03 the magnetic instability of the disk will occur if

$$\varepsilon_B/\varepsilon_{\rm K} > 1/15\,, \tag{14}$$

where $\varepsilon_{\rm K}$ is the kinetic energy of the disk. Once this instability is triggered, the magnetic field lines connecting the BH horizon and the disk will disconnect quickly, i.e., the MC process will cease.

As the accretion in the inner part of the disk is blocked by the MC process the inner region will pile up at the accretion rate corresponding to the radius r_S, and a torus might form due to the matter accumulation.

In the case without the depression by the MC process the accretion rate can be estimated by considering the balance between the pressure of the magnetic field and the ram pressure of the innermost part of the accretion flow (Moderskin et al. 1997), i.e.,

$$B_{\rm H}^2/(8\pi) = P_{\rm ram} \sim \rho c^2 \sim \dot{M}_{\rm D}/(4\pi r_{\rm H}^2)\,. \tag{15}$$

As seen in Figure 1, the MC torque mainly affects the accretion flow within the radius ξ_S. As a simple model, we assume the accretion rate of the disk beyond ξ_S can also be estimated by Equation (15). The time of forming a torus in the suspended accretion state can be estimated as

$$\tau_{\rm torus} \approx \frac{M_{\rm T}}{\dot{M}_{\rm D}} = \alpha B_{15}^{-2} m_{\rm H}^{-1} \frac{2}{(1+q)^2} 2.7\times 10^3\,{\rm s}\,, \tag{16}$$

where $M_{\rm T}$ is the mass of the torus, and $m_{\rm H} \equiv M/M_{\odot}$, $\alpha \equiv M_{\rm T}/M$, and $B_{15} \equiv B_{\rm H}/10^{15}\,{\rm G}$. For $M_{\rm T} = 0.1\,M_{\odot}$, $B_{\rm H} = 10^{15}\,{\rm G}$ and $a_* = 0.5$, we have $\tau_{\rm torus} \approx 3.2\,{\rm s}$. Thus a torus will form either after or during the prompt emission of GRB according as the burst is short or long. The kinetic energy of the torus, $\varepsilon_{\rm K}$, can be estimated as (PL03)

$$\varepsilon_{\rm K} = \frac{M_{\rm TM}}{2r_{\rm T}}\,, \tag{17}$$

where the radius of the torus $r_{\rm T}$ can be estimated by $r_{\rm T} \approx r_{\rm ms}$.

Once the magnetic field energy of disk, ε_B, satisfies Equation (14), the instability sets in and the magnetic field lines connecting the BH horizon and the disk will be disconnected quickly. At this time, the MC process ceases. The BH spin at this instant is denoted by $a_*^{\rm acc}$.

2.3 Stage 3: Hyperaccretion as the Restarting Engine for X-Ray Flares

The torque to depress the accretion flow will disappear immediately once the MC process stops. At this stage the viscous torque is dominant, and the hyperaccretion will occur due to an abrupt loss of angular momentum of the disk matter.

Since the BZ process ceased at the end of the first stage due to the shutting-off of the half-opening angle $\theta_{\rm H}$, the only operating energy process at this time (the third stage) is hyperaccretion.

We assume that the X-ray flares are powered by the hyperaccretion. Let the hyperaccretion start at time $t_{\rm acc}$ (in the frame of central engine). In addition, we assume that $t_{\rm acc}$ is determined by the duration for the BH spin evolving from $a_*(0)$ to $a_*^{\rm acc}$.

Let the observed starting time of the flare be $t_{\rm flare}$. We relate $t_{\rm acc}$ to the radius for the new ejecta (produced by the hyperaccretion process) to catch up with the previous merged shell of GRB prompt stage by

$$R_f \sim \gamma^2 c t_{\rm acc}. \tag{18}$$

Here the Lorentz factors of the ejected shells etc. are all assumed to be of the same order γ (Sari & Piran 1995). Considering that the observed time is $t_{\rm flare} \approx R/\gamma^2 c$, we can regard $t_{\rm acc}$ as the time of observing the X-ray flare, i.e., $t_{\rm flare} \sim t_{\rm acc}$.

In our model $t_{\rm acc}$ is sensitive to the values of n, $B_{\rm H}$ and η. Now, n and $B_{\rm H}$ are obtained by fitting the energy and duration of the GRB prompt emssion (see the discussion in stage 1). Therefore, only η is determined by $t_{\rm acc}$ or $t_{\rm flare}$ for a given GRB. For GRB 050219A and GRB 050709, the X-ray flares are observed at $t_{\rm flare} \sim 100\,{\rm s}$ after the trigger of the bursts. The values of η are respectively taken as 0.05 and 0.01 for GRB 050219A and GRB 050709 in our calculations.

For other bursts, the values of η are of the same order. This can be proved by the following estimation. For $M_{\rm T} = 0.1\,M_\odot$, the critical magnetic energy is $\varepsilon_B = \varepsilon_{\rm K}/15 \approx 10^{51}$ erg. The MC power can be estimated as $P_{\rm MC} \sim B^2 M^2 \approx 6.59 \times 10^{50}$ erg s^{-1}. If $t_{\rm flares} \sim 100\,{\rm s}$, we have $\eta \sim 0.02$.

It has been argued that the hyperaccreting torus can power the X-ray flares via neutrino annihilation (e.g. Ruffert & Janka 1998). The jet luminosity driven by this mechanism depends very sensitively on the mass accretion rate, since the neutrino emission is related very closely to the density and the temperature of the torus. For accretion rates ($\tilde{M}_{\rm D}$) between 0.01 and $0.1\,M_e\,{\rm s}^{-1}$, the $\nu\bar{\nu}$ annihilation luminosity can be well fitted by (Popham et al. 1999; Fryer et al. 1999; Janiuk et al. 2004):

$$\log L_{\nu\bar{\nu}}\ ({\rm erg}\cdot{\rm s}^{-1}) \approx 43.6 + 4.89 \log\left(\frac{\dot{M}}{0.01\,M_\odot\,{\rm s}^{-1}}\right) + 3.4a_* \,. \tag{19}$$

During this stage, the BH spin must be $a_*^{\rm acc}$, or about 0.5.

The total energy of the flare is also typically smaller than that of the prompt emission, although in some cases the two can be comparable (e.g. for GRB 050502B). Based on Equation (19), a torus with a mass of $0.1\,M_\odot$ can provide 10^{50} erg via neutrino annihilation if its accretion rate is about $0.1\,M_\odot\,{\rm s}^{-1}$. This energy is enough to power the X-ray flares in the GRB afterglow.

The duration of the flare can be estimated as follows. Following Zou, Dai & Xu (2006), we assume that the emission of X-ray flares comes from the reverse shock of the internal shock. For a relativistic reverse shock, the duration of the shock in the observer's frame is $\Delta t_{\rm flare} \simeq \Delta/c$ (Sari & Piran 1995), while the depth of shell for the spreading case is $\Delta \simeq R/\gamma^2$. Thus, the duration of a given flare is

$$\Delta t_{\rm flare} \simeq R_f/\gamma^2 c \simeq t_{\rm flare}. \tag{20}$$

It is interesting to note that the three time scales are approximately equal, $\Delta t_{\rm flare} \sim t_{\rm flare} \sim t_{\rm acc}$, and are all independent of the Lorentz factors. This result is in agreement with the observations.

In general, the afterglow light curves are characterized by multiple flares. This feature can be understood by the hyperaccretion restarting repeatedly, provided that the disk may be fragmented by the gravitational instability as proposed by Perna et al. (2006), or the accretion can be repeatedly stopped and then restarted by the accumulated magnetic flux as shown by Proga & Zhang (2006).

Moreover, the durations of these flares seem to be positively correlated with the starting time of the flares: the later the starting epoch, the longer the duration. This is particularly evident in GRB 050502B and the short-hard GRB 050724. In both cases, there is an early flare with duration the same order of the peak time (several 100 s for GRB 050502B and several 10 s for GRB 050724), and there is also a very late flare at tens of thousands seconds with a duration of the same order. The above properties of the flares could be interpreted by Equation (20), which predicts that the arrival time of each new flare should directly correlate with its total duration.

3 DISCUSSION

In this paper, we propose a three-stage model for the inner engine of GRBs. The prompt emission of GRB is explained by the BZ process and the X-ray flares by a later hyperaccretion process. One of the features of our model is the MC effects on the accretion process: both the depressed accretion and the start of the hyperaccretion process are related intimately to the MC mechanism. It turns out that some features of the X-ray flares in the early afterglow after the prompt gamma ray emission can be interpreted.

Comparing with the models of Perna et al. (2006) and Proga & Zhang (2006), our model can describe the stopping and restarting of the central engine in a quantitative way. While the former have their advantages in explaining the multiple flares, our model can also interpret the multiple flares if the MC process can be stopped and restarted repeatedly. Although the restart of the MC process is very speculative, it is possible since the magnetic filed can be recovered by the dynamo process (Hawley et al. 1995) or by the accumulation of the magnetic flux (Spruit, Stehle & Papaloizou 1995).

In our model, the X-ray flares are powered by the hyperaccretion process. However, Fan et al. (2005) argued that this process is not efficient for short GRBs. Instead, the BZ process would work well, and a similar result can be found in Xie et al. (2007). Like the MC process, the restart of the BZ process is also possible.

From the above discussion we find that the rebuilding of the magnetic field is essential to our model, and we intend to address this issue in our future work.

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