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A New Model for Gamma-Ray Burst Powered by the Blandford-Znajek Process

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Abstract A new model for gamma-ray bursts (GRBs) is discussed by considering the coexistence of the Blandford-Znajek (BZ) process and the magnetic coupling (MC) process, in which the half-open angle $\theta_{\rm BZ}$ of the open magnetic flux on the horizon is determined by the mapping relation between the angular coordinate on the horizon and the radial coordinate on the disk with the assumption that the closed magnetic flux penetrating the disk takes precedence over the open magnetic flux. The GRB is powered by the BZ process with the duration identified as the lifetime of open magnetic flux on the horizon. The powers and torques of the BZ and MC processes are derived by using an improved equivalent circuit. It is shown that the BH is slowed down strongly by the MC process, resulting in a greater average power than other models for GRBs powered by the BZ process. It turns out that the data of several GRBs are well fitted by our model.

Key words: black hole physics — accretion disks — Gamma-ray bursts — Supernovae

1 INTRODUCTION

As is well known, the Blandford-Znajek (BZ) process is an effective mechanism for powering jets from quasars and active galactic nuclei (Blandford & Znajek 1977; Rees 1984). In the BZ process energy and angular momentum are extracted from a rotating BH, and transferred to the remote astrophysics load by the open magnetic field lines. Recently, much attention has been paid on the issue of the long duration GRBs powered by the BZ process (Paczynski 1998; Meszaros & Rees 1997). A detailed model of GRBs invoking the BZ process is given by Lee, Wijers, & Brown 2000, hereafter LWB00).

Recently, a process of extracting energy and angular momentum from the fast-rotating BH to the disk by virtue of closed magnetic field lines coupling the disk with the BH has been proved to be important (Blandford 1999; Putten 1999; Li 2000, 2002; Wang, Xiao & Lei 2002, hereafter W02). The energy mechanism is referred to as the magnetic coupling (MC) process. However, the MC process is not included in LWB00.

In this paper we intend to work out a model for GRB by considering coexistence of the BZ and MC processes (CEBZMC), which is based on our previous work (W02; Wang et al. 2003, hereafter W03a). In our model the BZ process is used for powering GRB, and the MC

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process helps to slow down the BH and halts the accretion. The transferred energy and the duration time for GRB are calculated in the evolving process of the half-opening angle $\theta_{\rm BZ}$ of the magnetic flux on the BH horizon.

Throughout this paper, the geometric units $G = c = 1$ are used.

2 A TOY MODEL FOR GRB BASED ON BH EVOLUTION

Recently, we proposed a model of CEBZMC by considering that the remote astrophysical load in the BZ process and the disk load in the MC process are connected with a rotating BH by open and closed magnetic field lines, respectively (W02; W03a). The poloidal configuration of the magnetic field is shown in Figure 1.

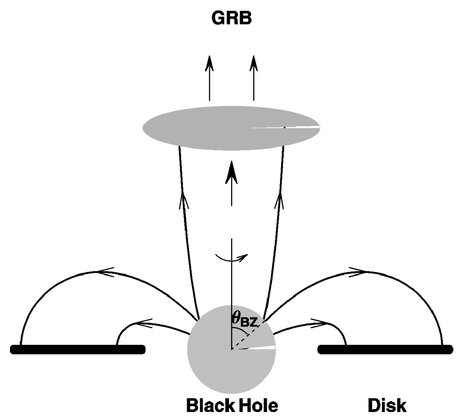

Fig. 1 Poloidal magnetic field connecting a rotating BH with remote astrophysical load and a surrounding disk.

In Figure 1 the angle $\theta_{\rm BZ}$ is the half-opening angle of the open magnetic flux tube, indicating the angular boundary between open and closed field lines on the horizon. In W03a the angle $\theta_{\rm BZ}$ is determined by the mapping relation between the angular coordinate on the horizon and the radial coordinate on the disk with the assumption that the closed magnetic flux penetrating the disk takes precedence over the open magnetic flux, which is expressed as

$$\cos\theta_{\rm BZ} = \int_1^\infty {\rm G}\left(a_*;\xi,n\right)d\xi. \tag{1}$$

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

where $a_* \equiv J/M^2$ is the BH spin defined by the BH mass M and angular momentum J,the parameter n is the power-law index of the magnetic field B_D on the disk, i.e. $B_D \propto \xi^{-n}$, and $\xi \equiv r/r_{\rm ms}$ is the radial coordinate on the disk, which is defined in terms of the radius $r_{\rm ms} \equiv M\chi_{\rm ms}^2$ of the marginally stable orbit (Novikov & Thorne 1973).

Inspecting equation (1), we find that the angle $\theta_{\rm BZ}$ can evolve to zero with the decreasing a_* for $3.003 \leq n \leq 5.493$. This implies that the open magnetic flux tube will be shut off when the BH spin decreases to the critical value $a_*^{\rm GRB}$ corresponding to $\theta_{\rm BZ} = 0$. Thus we have a new scenario for powering GRBs in the BZ process: As the BH spin decreases, the open magnetic flux tube for the GRB gets smaller and smaller, and the powering process stops at the critical BH spin a_*^{GRB}.

Considering that the angular momentum is transferred from a rapidly rotating BH to the disk, on which a positive torque exerts, we think the accretion onto the BH is probably halted, and the evolution of the BH is governed by the BZ and the MC processes.

The expressions for the BZ and MC powers and torques are derived in W02 by using an improved equivalent circuit for the BH magnetosphere based on the work of MacDonald and Thorne (1982). Considering the angular boundary θ_{BZ}, we express the BZ and MC powers and torques as follows.

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

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

$$\tilde{P}_{\mathrm{MC}} \equiv P_{\mathrm{MC}}\Big/P_0 = 2a_*^2 \int_{\theta_{\mathrm{BZ}}}^{\pi/2} \frac{\beta\,(1-\beta)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}, \tag{5}$$

$$\tilde{T}_{\mathrm{MC}} \equiv T_{\mathrm{MC}}\Big/T_0 = 4a_*\,(1+q) \int_{\theta_{\mathrm{BZ}}}^{\pi/2} \frac{(1-\beta)\sin^3\theta d\theta}{2-(1-q)\sin^2\theta}, \tag{6}$$

where we have $q \equiv \sqrt{1-a_*^2}$, $P_0 \equiv \left\langle B_H^2 \right\rangle M^2$ and $T_0 \equiv \left\langle B_H^2 \right\rangle M^3$. B_H is the magnetic field on the BH horizon. The parameters k and β are the 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.

Based on the conservation laws of energy and angular momentum we have the following evolution equations of the rotating BH,

$$dM/dt = -(P_{\mathrm{BZ}} + P_{\mathrm{MC}}), \tag{7}$$

$$dJ/dt = -(T_{\mathrm{BZ}} + T_{\mathrm{MC}}). \tag{8}$$

Incorporating equations (7) and (8), we have the evolution equation for the BH spin expressed by

$$da_*/dt = -M^{-2}(T_{\mathrm{BZ}} + T_{\mathrm{MC}}) + 2M^{-1}a_*(P_{\mathrm{BZ}} + P_{\mathrm{MC}}) = B_H^2 M A\,. \tag{9}$$

The sign of A determines whether a_* decreases or increases,and A is given as

$$A = 2a_*\tilde{P}_{\mathrm{mag}} - \tilde{T}_{\mathrm{mag}}. \tag{10}$$

With equation (10) we find the fast-rotating BH will evolve eventually to the equilibrium spin a_*^{eq} corresponding to $A = 0$, and $a_*^{\mathrm{GRB}} > a_*^{\mathrm{eq}}$ holds for $3.003 < n < 5.122$. In our model $3.003 < n < 5.122$ is assumed.

Based on the above discussion on correlation of the BH evolution with the association of GRB, we can calculate the energy E_{GRB} for GRB as follows,

$$E_{\mathrm{GRB}} = 1.79 \times 10^{54}\ \mathrm{erg} \times \left(\frac{M(0)}{M_\odot}\right) \int_{a_*(0)}^{a_*^{\mathrm{GRB}}} \tilde{M}\tilde{P}_{\mathrm{BZ}} A^{-1} da_*, \tag{11}$$

The duration of GRB, t_{GRB}, is regarded as the lifetime of the half-opening angle θ_{BZ}, which is exactly equal to the time for the BH evolving from $a_*(0)$ to a_*^{GRB}, i.e.,

$$t_{\rm GRB} = 2.7\times 10^{3} s \times \left(\frac{10^{15}{\rm G}}{B_H}\right)^2 \left(\frac{M(0)}{M_\odot}\right)^{-1} \int_{a_*(0)}^{a_*^{\rm GRB}} \tilde{M}^{-1} A^{-1} da_*, \qquad (12)$$

where $\tilde{M} \equiv \frac{M}{M(0)}$ is the ratio of the BH mass to its initial value $M(0)$.

3 RESULTS AND DISCUSSION

In our calculations $M(0) = 7M_\odot$, $B_H = 10^{15}G$ and $a_*(0) = 0.998$ are assumed, and the cutoff of $T_{\rm GRB}$ is taken as T_{90}, which is the duration for 90% of the total BZ energy to be carried out (Lee & Kim 2002). By using the expression $E_{\rm rot} = [1-\sqrt{(1+q)/2}]M(0)$(Thorne, Price & Macdonald 1986), we obtain the total rotational energy is $E_{\rm rot} \approx 3.4\times 10^{54} erg$. With equations (11), we have that the energy for GRBs is less than $1.85\times 10^{53} erg$. That means only very a small fraction of $E_{\rm rot}$ is used for powering GRB. Since the true energy of GRB is around $5\times 10^{50} erg$ (Frail et al. 2002), we can fit this energy by taking n=3.194 with the initial half-opening angle $\theta_{\rm BZ}(0)$ less than 24.5^0 in the evolving path of the BH from $a_*(0) = 0.998$ to $a_*^{\rm GRB} = 0.967$.

By using equation (12) we find that the estimated duration of GRB is tens of seconds, which is consistent with the observations. The parameters n and B_H can be adjusted to fit the given true energy E_γ and T_{90}s of several GRBs as shown in Table 1.

Table 1 Power-law index n and magnetic field B_H on the BH horizon derived from the true energy, E_γ, and T_{90} for five GRBs

GRBs	$E_\gamma(10^{51}$ erg) [a]	T_{90}(s) [b]	n	$B_H(10^{15}$G)
990123	1.80	24.34	3.322	0.65
990510	0.248	25.80	3.143	0.44
991208	0.455	39.84	3.187	0.39
991216	0.695	7.51	3.222	0.96
000131	1.30	9.09	3.280	1.00

[a] The true energy E_γ of GRB refers to the sample listed in Table 1 of Frail et al.(2002).
[b] The duration T_{90} of GRB refers to the sample listed in Table 2 of Lee & Kim (2002).

In the previous model for GRBs via the BZ process the duration of GRB is estimated by the time either when the BH stops rotating or when the whole disk is plunged into the BH, and the MC effects have not been taken into account (LWB00; Lee & Kim 2000, 2002; Wang, Lei & Xiao 2002). Compared with these models, the duration of GRB is estimated by the lifetime of the half-opening angle on the BH horizon, and both the BZ and MC processes are playing very important roles in this model for GRN.

We compare the quantities, E_γ, T_{90} and $\bar{P}_\gamma$ (the average power), calculated from three different models for GRBs as listed in Table 2, where the abbreviations **CEBZMC**, **BZO** and **BZACC** represent this model, the model invoking the BZ process only, the model invoking the BZ process with disk accretion, respectively.

From Table 2 we find that the energy provided by model **CEBZMC** is much less than those provided by models **BZO** and **BZACC**, but the duration time and the average power provided by model **CEBZMC** are much less and much greater than those quantities provided by models **BZO** and **BZACC**.

In this paper, we highlight the effect of the BZ process in powering GRB. However, the astrophysical importance of the transferred energy via the MC process is not discussed. Recently the observations demonstrate that long duration GRB are associated with hypernovae (Galama

Table 2 Total energy, duration and average power in different models of GRBs for various $\theta_{\rm BZ}(0)$, with $a_*(0) = 0.998$, $M_H(0) = 7M_\odot$, $B_H = 10^{15}G$ and the initial disk mass $M_D(0) = 3M_\odot$

Model	$\theta_{\rm BZ}(0)$(rad)	$E_\gamma(M_\odot)$	T_{90}(s)	$\bar{P}_\gamma(10^{-4}M_\odot\ {\rm s}^{-1})$
BZO		0.639	9111	0.701
BZACC	0.6	0.059	710	0.825
CEBZMC		0.002	14	1.575
BZO		0.639	3089	2.067
BZACC	0.8	0.149	579	2.579
CEBZMC		0.016	39	4.132
BZO		0.639	1390	4.593
BZACC	1.0	0.288	484	5.941
CEBZMC		0.089	120	7.443

et al. 1998). More recently Brown et al. (2000) worked out a specific scenario for this connection, in which the GRB is powered by the BZ process, and the SN is powered by the MC process. Therefore, we shall improve our model to try to explain the GRB-SN connection in our future work.

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