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ISSUES REGARDING THE BLANDFORD-ZNAJEK PROCESS AS A GAMMA-RAY BURST INNER ENGINE

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ABSTRACT

Several issues regarding the Blandford-Znajek process are discussed to demonstrate that it can be an effective mechanism for powering gamma-ray bursts. Using a simple circuit analysis, it is argued that the disk power increases the effective power of the black hole accretion disk system, although a part of the disk power can be dissipated into black hole entropy. Within the framework of a force-free magnetosphere with a strong magnetic field, a magnetically dominated MHD flow is found to support the Blandford-Znajek process, and it is demonstrated that the possible magnetic repulsion by the rotating black hole will not affect the efficiency substantially.

Subject headings: accretion, accretion disks — black hole physics — gamma rays: bursts — radiation mechanisms: nonthermal

Recently there has been increasing interest in the Blandford-Znajek process (Blandford & Znajek 1977; Thorne, Price, & MacDonald 1986) as one of the viable models of powering the gamma-ray bursts effectively (Lee, Wijers, & Brown 1999). The global picture of a magnetosphere around the rotating black hole suggested by Blandford and Znajek is the force-free configuration of electromagnetic charge and current distributions (MacDonald & Thorne 1982; Okamoto 1992 with the rotating magnetic field lines. The magnetic field is supposed to be supported by the magnetized accretion disk.

To set the Blandford-Znajek process (Lee et al. 1999) working to extract the rotational energy of the black hole, the magnetic field lines and the currents should be anchored onto the horizon (or effectively onto the stretched horizon; Thorne et al. 1986). The toroidal magnetic field, B_ϕ , on the horizon together with the perpendicular component, B_H , to the horizon (or on the stretched horizon) are responsible for the outward Poynting flux in the Blandford-Znajek process, which extracts the rotational energy of the black hole. The boundary condition on the horizon (Znajek 1977), $B_\phi = (\Omega_F - \Omega_H)\tilde{\omega}B_H$,³ implies that the poloidal currents onto the horizon are essential to both the toroidal and the perpendicular components of the magnetic field on the horizon. Therefore it is an interesting question whether current flows onto the horizon can be realized in the relativistic MHD consideration, since the currents consist of charged particles.

The magnetic field on the black hole cannot be supported by the black hole alone. The accretion disk surrounding the black hole is the natural candidate for the supporting system of the strong magnetic field on the black hole. Therefore the disk can put some constraints on the Blandford-Znajek power. One of the simple ways of analyzing the effect of the disk is to adopt a circuit analogy (Thorne et al. 1986; Li 1999). The currents out of the black hole in the

equatorial plane may either go directly to the loading regions or pass through the accretion disk to make the closed circuit of currents together with the inflowing currents onto the horizon from the loading region at infinity. In general, there is also the power from the magnetic braking from the accretion disk, which extracts the disk energy and angular momentum out to the loading region. Hence it increases the power of the black hole–accretion disk system, although a part of it is dissipated into the black hole, in some cases more than the black hole power of the magnetic braking (Li 1999).

The powers from the disk and the black hole depend on the magnetic field strengths. Simple arguments using Ampère’s law and the boundary condition on the black hole show that the poloidal magnetic field on the black hole is larger than the toroidal magnetic field on the inner edge of the accretion disk (r_{in})

$$B_H \gtrsim 2B_\phi^{\text{disk}}(r_{\text{in}}). \quad (1)$$

Similar observations can be found in Ghosh & Abramowicz (1997). Adopting the force-free field configurations suggested by Blandford (1976) or by Ghosh & Abramowicz (1997), one can show that B_H is larger than the poloidal magnetic field on the disk (Lee et al. 1999), which implies that the Blandford-Znajek power is not dominated by the disk power due to the magnetic braking (Li 1999; Livio, Ogilvie, & Pringle 1999). For models in which the disk field generated by disk dynamo effects and turbulence (e.g., Balbus & Hawley 1998) it has been argued that no more energy can be released than the disk binding energy, and that any BZ power from the black hole is smaller than that from the disk (Livio et al. 1999). Lee et al. (1999) showed that for other field configurations, such as that of Blandford (1976) or such as may result from disruption of a neutron star around a black hole, neither of those two limits need apply.

In this note, we discuss the effect of the disk on the Blandford-Znajek process using a simple circuit analysis, and also the effect of the magnetic field on the horizon of the black hole in the framework of MHD (Takahashi et al. 1990; Hirotani et al. 1992), to show that the Blandford-Znajek process from the black hole–accretion disk system can be effective enough to power the observed GRBs.

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³ Ω_F and Ω_H are the angular velocities of the rotating black hole and the magnetic field lines, respectively, and $\tilde{\omega}$ is the “cylindrical radius” in the Kerr metric; $g_{\phi\phi} = \tilde{\omega}^2$.

The Poynting flux out of the horizon is carried out to the load region along the poloidal magnetic field lines. Consider the Poynting flux through the funnel between the magnetic surfaces with magnetic flux $\Delta\Psi$ (Thorne et al. 1986). One can replace the complexity of the load region by the equivalent resistance ΔR_L , which can be formally defined by

$$\frac{1}{2\pi} \Omega_F \Delta\Psi = I \Delta R_L, \quad (2)$$

where I is the current along the magnetic field line and ΔR_L is the equivalent resistance across the load region at infinity encompassed by two magnetic surfaces with the magnetic flux $\Delta\Psi$. In the circuit analogy, the left-hand side of equation (2) is the voltage drop, ΔV_L , across the load region. On the horizon the magnetic braking induces the electromotive force $\Delta\mathcal{E}_H$,

$$\Delta\mathcal{E}_H = \frac{1}{2\pi} \Omega_H \Delta\Psi, \quad (3)$$

and the dissipation ΔP_H into the horizon to increase the entropy, S , of the black hole with temperature T_H ($\Delta P_H \Delta t = T_H \Delta S$), which can be written as

$$\Delta P_H = \frac{(\Delta V_H)^2}{\Delta R_H}, \quad (4)$$

using the voltage drop ΔV_H on the horizon between the magnetic surfaces ($\Delta V_H = I \Delta R_H$) and the horizon resistivity R_H . The electromotive force is the sum of the voltage drops, ΔV , across the horizon and the load region in the circuit, which can be written as

$$\Delta V = \Delta V_L + \Delta V_H, \quad (5)$$

and the power delivered to the load region by the Poynting flux is

$$\Delta P_L = I^2 R_L = \left(\frac{\Delta V}{\Delta R_L + \Delta R_H} \right)^2 \Delta R_L. \quad (6)$$

The Blandford-Znajek process is a sum of these circuits over the magnetic surfaces. For a simple analysis we will consider the equivalent circuit for the Blandford-Znajek power, where the electromotive forces are summed to be an electromotive force $\mathcal{E}_H$: the current I (total current flowing into the black hole), the total horizon surface resistance R_H , and the equivalent load resistance R_L (Fig. 1a). Then, from equation (6) the Blandford-Znajek power out of the rotating black hole can be written as

$$P_{\text{BZ}}^H = I_H^2 R_L = \left(\frac{V_L + V_H}{R_L + R_H} \right)^2 R_L, \quad (7)$$

where the electromotive force of the black hole is $\mathcal{E}_H = V_L + V_H$. Since the magnetic field lines do not cross each other, there are no interference effects between the magnetic fields and we may simply sum the contributions from all field lines.

A similar analysis can be applied to the Poynting power from the magnetic braking of the magnetized accretion disk (Blandford 1976). For the case in which there are no magnetic field lines from the black hole horizon (no magnetic braking of the black hole), the load region is anchored by the magnetic field lines from the disk. The electromotive

FIG. 1.—Three schematic circuits corresponding to the rotating black hole-accretion disk system in a force-free magnetosphere. The load region is approximated by the resistance R_L . The electromotive forces (resistances) of the black hole and the accretion disk are denoted by $\mathcal{E}_H(R_H)$ and $\mathcal{E}_D(R_D)$, respectively. The currents I_H , I_D , and I_{HD} are flowing out of the black hole into the accretion disk and then to the loading region, coming back to the black hole to complete the circuit. (a) A system consisting of the rotating black hole alone. (b) A black hole-accretion disk system but without the Blandford-Znajek power from the black hole. (c) A black hole-accretion disk system with both the Blandford-Znajek power of the black hole and the accretion disk.

force $\mathcal{E}_D$ on the disk with the resistance R_D , and the load region resistance R_L , establish a circuit (Fig. 1b). Then the power at the load region is given by

$$P^D = I_D^2 R_L = \left(\frac{V_D + V_L}{R_L + R_D} \right)^2 R_L, \quad (8)$$

where V_D is the voltage drop across the disk with effective resistance R_D ,

$$V_D = I_D R_D, \quad (9)$$

$$\mathcal{E}_D = V_D + V_L. \quad (10)$$

If the circuit of current flows includes the horizon from near the black hole's cap to the equator, then the dissipation due to the horizon resistivity should be taken into account. Then

$$\mathcal{E}_D = V_L + V_D + V_H, \quad (11)$$

and the power at the load region becomes

$$P^{DH} = \left(\frac{V_L + V_D + V_H}{R_L + R_D + R_H} \right)^2 R_L. \quad (12)$$

Now considering the magnetic fields both on the horizon of the rotating black hole and on the accretion disk, there are two electromotive forces, $\mathcal{E}_H$ and $\mathcal{E}_D$ (Fig. 1c). The load region where the magnetic field lines are anchored is now divided into two parts, of which effective resistance can be denoted by R_L^H and R_L^D , respectively, according to the origin of the magnetic field lines (from the horizon or the accretion disk). The magnetic field lines do not cross each other, and we can sum the powers from each region to get the total power. Since it is equivalent to the series connection of two resistances, we can take $R_L = R_L^H + R_L^D$ for the total power. Then we have

$$\mathcal{E}_H + \mathcal{E}_D = V_L + V_D + V_H, \quad (13)$$

$$V_L = I_{HD} R_L, \quad (14)$$

and the power at the load region is given by

$$P_{BZ}^{HD} = I_{HD}^2 R_L = \left(\frac{V_L + V_D + V_H}{R_L + R_D + R_H} \right)^2 R_L. \quad (15)$$

This is the power at the loading region powered by the system of the rotating black hole and the magnetized accretion disk. Assuming high conductivity of the accretion disk, we can take R_D to be negligible compared to R_H and R_L ($V_D \sim 0$). It is easy to see that the power is enhanced by the addition of the accretion disk:

$$\frac{P_{BZ}^{HD}}{P_{BZ}^H} = \left(1 + \frac{\mathcal{E}_D}{\mathcal{E}_H} \right) > 1. \quad (16)$$

Taking $\mathcal{E}_D \sim \mathcal{E}_H$, the power from the black hole–accretion disk circuit would give ~ 4 times that through the black hole alone. It is also interesting to compare P_{BZ}^{HD} with the power of the load region with the disk battery only, P^D , in order to see how the power is constrained by the disk power. From equations (8) and (15) we get

$$\frac{P_{BZ}^{HD}}{P^D} = \left(\frac{R_L}{R_H + R_L} \right)^2 \left(1 + \frac{\mathcal{E}_H}{\mathcal{E}_D} \right)^2. \quad (17)$$

Since the electromotive forces are induced by the magnetic braking, the ratio $\mathcal{E}_H/\mathcal{E}_D$ depends on how we estimate the magnetic fields on the disk and the horizon. The comparison of these two powers is possible because the magnetic fields on the black hole and the disk are supposed to be related. The estimation in Li (1999) gives a bound

$$\mathcal{E}_H/\mathcal{E}_D < 1.7, \quad (18)$$

and for the optimal case

$$2.5 < \frac{P_{BZ}^{HD}}{P_{BZ}^H}, \quad (19)$$

$$\frac{P_{BZ}^{HD}}{P^D} < 1.8. \quad (20)$$

On the other hand, the estimation using the boundary conditions on the horizon and the disk leads to different results (Lee et al. 1999). For example, for $\tilde{a} \sim 0.5$ we get

$$\mathcal{E}_H/\mathcal{E}_D \sim 3, \quad (21)$$

$$\frac{P_{BZ}^{HD}}{P_{BZ}^H} \sim 1.7, \quad (22)$$

$$\frac{P_{BZ}^{HD}}{P^D} \sim 4. \quad (23)$$

One can see that the difference in the estimates is found to be only a factor of 2 (not an order of magnitude or more) for the moderate range of the angular momentum parameter $0.5 < \tilde{a} < 1$. Hence the power loss from the disk into the black hole may not be a serious problem in powering a GRB at the load region as shown in equation (16).

In this analysis we have assumed an ideal efficiency of the disk power. In the realistic case, the effective electromotive force $\mathcal{E}_D^{\text{eff}}$ should be smaller than the total magnetic braking power. It is also interesting to note that a part of the disk power may come from the rotational energy of the black hole due to the possible magnetic coupling of the black hole and accretion disk around the equatorial plane (Gammie 1999). Hence it is not clear how the efficiency of the Blandford-Znajek process can be affected substantially by the accretion disk.

In the Blandford-Znajek process, the energy and the angular momentum flows along the poloidal field lines are dominated by the magnetic field. However, the magnetosphere proposed by Blandford and Znajek should be supported by the currents, which are carried by the fluid particles although they carry only negligible energy and angular momentum compared to the Poynting flux. Therefore it is important to see whether it is dynamically possible that the fluid particles can flow onto the horizon of the black hole, since the currents anchored to the horizon are essential for the Blandford-Znajek process to work in extracting the rotational energy of the black hole. The question on whether the current flows in the Blandford-Znajek process can be realized in the relativistic MHD consideration is related also to the issue of magnetic flux repulsion due to the black hole rotation.

Assuming a steady and axially symmetric magnetosphere around the rotating black hole, Takahashi et al. (1990) and Hirotani et al. (1992) discussed the physical characteristics of the flow along the poloidal magnetic field lines. The particle flows are constrained by several critical points, which the fluid particles should cross without causing any divergences to get onto the horizon or to infinity. The poloidal velocity of the fluid particle, u_p , and the derivatives along the field line define the Alfvén point and the fast magnetosonic points, respectively (Takahashi et al. 1990). It has been shown that the negative energy flow into the horizon is possible if

$$0 < \Omega_F < \Omega_H, \quad (24)$$

and if the Alfvén points are inside the ergosphere. This same condition also defines the range of Ω_F for which energy is extracted out of the rotating black hole via the Blandford-Znajek process. The fluids which pass through the Alfvénic point inside the ergosphere with negative energy and angular momentum should cross the fast magnetosonic point to fall into the horizon. Hirotani et al. (1992) investigated the case with the fast magnetosonic point very near to the horizon to show that the magnetically dominated MHD flow, which supports the poloidal currents onto the horizon for the Poynting flow in the Blandford-Znajek process, is possible.

There has been a series of works (Wald 1974; King, Lasota, & Kundt 1975; Bicak & Janis 1985) which seem to imply that magnetic flux repulsion can suppress the efficiency of the Blandford-Znajek process substantially for the extreme Kerr black hole.⁴ The effect of the flux expulsion when the rotating black hole is immersed in the external uniform magnetic field along the rotational axis of the black hole can be expressed as

$$\Phi_{\tilde{a}} = (1 - \tilde{a}^4)\Phi_{\tilde{a}=0}, \quad (25)$$

which shows that there is no magnetic field flux through the black hole (half-hemisphere) for the extremely rotating black hole, $\tilde{a} = 1$. One can see easily that the effect gets reduced rapidly as $\tilde{a}$ decreases. For example, if we take $\tilde{a} = 0.5$, then $\Phi_{0.5}/\Phi_0 = 0.94$. Hence, for the practical purpose of explaining the gamma-ray burst power, where the black holes in the center are rapidly rotating but not necessarily at the extreme rotation, it is not a severe restriction.

In summary, it is most likely that off the equatorial plane the Blandford-Znajek process is at least as effective as in the original formulation, which has enough efficiency for powering gamma-ray bursts, provided that there is a strongly magnetized accretion disk. It is also interesting to note that the interaction between the black hole and the

⁴ More discussions with a different point of view for the force-free environment can be found in Lee, Wijers, & Brown (1999).

accretion disk is also important, since it may affect the Blandford-Znajek process.⁵ The transition region between the horizon and the inner edge of the accretion disk is quite complicated compared to the off-equatorial plane up to near the rotational axis of the black hole. The possible magnetic coupling between the horizon and the accretion disk may result in constraints on the rotation of the black hole and the accretion disk. The effect of a magnetic field on the matter in the accretion disk considerably complicates the discussion, but some recent attempts have been made to incorporate this into the models (Punsly 1998; Krolik 1999; Gammie 1999).

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⁵ For example, the effect of the accretion on the Blandford-Znajek power evolution has been discussed recently by Moderski, Sikora, & Lasota (1998) and Cavaliere & Malquori (1999) for the systems with super-massive black holes.

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