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TOTAL AND JET BLANDFORD-ZNAJEK POWER IN THE PRESENCE OF AN ACCRETION DISK

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ABSTRACT

Rotating black holes probably power ultrarelativistic jets in gamma-ray bursts, relativistic jets from some active galactic nuclei, and jets from some black hole X-ray binaries. Prior estimates of the power output of a black hole have assumed an infinitely thin disk and a magnetic field based upon a slowly rotating black hole and have not self-consistently determined the geometry or magnitude of the magnetic field for a realistic accretion disk. We provide useful formulae for the total and jet Blandford-Znajek (BZ) power and efficiency as determined self-consistently from general relativistic magnetohydrodynamic numerical models. Of all jet mechanisms, we suggest that only the BZ mechanism is able to produce an ultrarelativistic jet.

Subject headings: accretion, accretion disks — black hole physics — galaxies: jets — gamma rays: bursts — X-rays: bursts

1. INTRODUCTION

For Poynting-dominated jets, where field lines tie the black hole to large distances, the energy flux is determined by the Blandford-Znajek (BZ) process (Blandford & Znajek 1977; for reviews, see Ruffini & Wilson 1975; Rees et al. 1982; Begelman et al. 1984; Beskin & Kuznetsova 2000; Punsly 2001; McKinney & Gammie 2004; Levinson 2005). The BZ effect depends on the magnetic field strength near the black hole and the Kerr black hole spin parameter a/M, where $-1 \leq a/M \leq 1$. Self-consistent production of a relativistic Poynting jet likely requires a rotating black hole accreting a thick disk with a disk height (H) to radius (R) ratio of $H/R \gtrsim 0.1$ (Ghosh & Abramowicz 1997; Livio et al. 1999; Meier 2001). As discussed below, a rapidly rotating ($a/M \sim$ 0.5–0.95) black hole accreting a thick ($H/R \gtrsim 0.1$) disk is probably common for jet systems.

However, prior estimates of the BZ power output have assumed the presence of an infinitely thin ($H/R \sim 0$) disk, only apply for $a/M \sim 0$, and do not self-consistently determine the magnetic field strength or field geometry. The purpose of this Letter is to provide useful formulae for the total and jet BZ power for arbitrarily rapidly rotating black holes accreting a realistic disk. We also discuss the dominance of the BZ effect over other relativistic jet mechanisms.

2. BLACK HOLE ACCRETION SYSTEMS

The accretion of a thick disk around a rapidly rotating black hole is often invoked as the engine to power gamma-ray bursts (GRBs) (Narayan et al. 1992; Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999; Narayan et al. 2001; Broderick 2005). Typical GRB models invoke a relatively thick ($H/R \sim$ 0.1–0.9) disk (MacFadyen & Woosley 1999; Popham et al. 1999; Kohri et al. 2005). During the GRB event, the black hole forms with $a/M \sim 0.5$–0.75 and evolves to a rapidly rotating state with $a/M \sim 0.9$–0.95 (Narayan et al. 1992; MacFadyen & Woosley 1999; Shapiro & Shibata 2002; Shibata & Shapiro 2002). GRB models based upon internal shocks require an ultrarelativistic jet with a typical Lorentz factor of $\Gamma \sim 100$–1000 in order to overcome the compactness problem (Lithwick & Sari 2001; Piran 2005), while Compton-drag models require $\Gamma \sim 20$–100 (Ghisellini et al. 2000; Lazzati et al. 2004; Broderick 2005). Direct observations of GRB afterglows show evidence of relativistic motion (Goodman 1997; Taylor et al. 2004, 2005). Large Lorentz factors require a relatively large jet energy flux, which could be BZ-driven and Poynting-dominated rather than neutrino annihilation–driven and enthalpy-dominated (Mészáros & Rees 1997; Popham et al. 1999; Di Matteo et al. 2002; McKinney 2005a, 2005b). Core collapse of a rapidly rotating star leads to an inner disk with a strong uniform (perhaps net) poloidal field.

The accretion of a relatively thick ($H/R \sim 0.9$) disk around a rapidly rotating black hole is probably the engine that powers jets from active galactic nuclei (AGNs) and some black hole X-ray binaries. Both radio-loud AGNs and X-ray binaries in the low-hard state show a correlation between radio and X-ray emission, which is consistent with radio synchrotron emission and hard X-ray emission generated from Comptonization through a thick disk (Merloni et al. 2003). This suggests the disk is geometrically thick when a system produces a jet, where the disk is probably similar to advection-dominated accretion flow models with $H/R \sim 0.9$ (Narayan & Yi 1995).

Based upon Sołtan-type arguments, AGNs each probably harbor a rapidly rotating ($a/M \sim 0.9$–0.95) black hole (Urry & Padovani 1995; Elvis et al. 2002; Gammie et al. 2004; Shapiro 2005). AGNs are observed to have jets with $\Gamma \lesssim 10$ (Urry & Padovani 1995; Biretta et al. 1999), even $\Gamma \sim 30$ (Begelman et al. 1994; Ghisellini & Celotti 2001; Jorstad et al. 2001), while some observations imply $\Gamma \lesssim 200$ (Ghisellini et al. 1993; Krawczynski et al. 2002; Konopelko et al. 2003). For example, the jet in M87 shows a large-scale opening angle of 10° with $\Gamma \sim 6$ (Junor et al. 1999; Biretta et al. 2002). AGNs probably accrete a uniform field from stellar-wind capture or the interstellar medium (Narayan et al. 2003; Spruit & Uzdensky 2005).

Black hole X-ray binaries might have $a/M \sim 0.5$–0.95 (Gammie et al. 2004), while some may have $a/M \lesssim 0.5$ (Gierliński & Done 2004). X-ray binary systems produce outflows and jets (Mirabel & Rodríguez 1999; McClintock & Remillard 2005). For example, the black hole X-ray binary GRS 1915+105 has a jet with apparently superluminal motion with $\Gamma \sim 1.5$–3 (Mirabel & Rodríguez 1994, 1999; Fender & Belloni 2004; Kaiser et al. 2004). Stellar-wind–capture X-ray binaries probably accrete a uniform field (Narayan et al. 2003).

3. THE BLANDFORD-ZNAJEK EFFECT

Most authors estimate the BZ power based upon the Blandford & Znajek (1977) model of a *slowly* spinning black hole threaded by a *monopole*-based magnetic field and accreting an *infinitely thin disk,* which gives

$$P_{\rm BZ,old} \approx P_0(B^r[{\rm G}])^2(\Omega_H^2/c)r_g^4, \qquad (1)$$

where B^r is the radial field strength, $r_g \equiv GM/c^2$, $\Omega_H = ac/(2Mr_H)$ is the rotation frequency of the hole, $r_H = r_g(1 + [1 - (a/M)^2]^{1/2})$ is the radius of the horizon for angular momentum $J = aGM/c$, and the dimensionless Kerr parameter has $-1 \leq a/M \leq 1$. The parameter $P_0 = 0.01$–0.1, where the uncertainty in P_0 arises because the strength of the magnetic field is not self-consistently determined (see, e.g., MacDonald & Thorne 1982; Thorne & MacDonald 1982; Thorne et al. 1986). Force-free numerical models agree with the above BZ model (Komissarov 2001). General relativistic magnetohydrodynamic (GRMHD) numerical models of slowly spinning, accreting black holes mostly agree with the BZ model for the nearly force-free funnel region of the Poynting-dominated jet (McKinney & Gammie 2004).

The force-free solution for the monopole BZ flux is proportional to $\sin^2\theta$ (Blandford & Znajek 1977), but the accretion of a thick disk diminishes the power output substantially (McKinney & Gammie 2004). This is because the electromagnetic energy accreted as a disk dominates the energy extracted. Some black hole spin energy does escape into the diffuse part of the corona, so the coronal outflow has more Poynting flux for faster spinning holes (McKinney & Gammie 2004; Krolik et al. 2005). For rapidly rotating black holes, the field is no longer monopolar and a significant amount of flux is generated closer to the nearly force-free poles.

HARM (Gammie et al. 2003) was used to evolve a series of otherwise identical GRMHD models with spin a/M from -0.999 to 0.999 and H/R of 0.1, 0.2, 0.5, and 0.9 to determine the total BZ power ($P_{\rm tot}$), jet BZ power ($P_{\rm jet}$), and field strength (B^r). A similar series of models were studied in McKinney & Gammie (2004), which gives a description of the model setup, limitations, and related results. The evolved field geometry is relevant to most black hole systems and corresponds to a turbulent disk field with a self-consistently generated large-scale flux threading the black hole.

Figure 1 shows data and fits described below for $H/R = 0.2$. There is a weak dependence on $H/R \gtrsim 0.1$ for the *jet* BZ power or efficiency, since the thicker the disk, the smaller the black hole solid angle available to the jet, but the field strength there is larger in compensation. The non-jet results for other H/R will be presented in a separate paper.

The total (disk+corona+jet) BZ power efficiency in terms of the mass accretion rate ($\dot{M}$) for $a/M > 0.5$ is well fitted by

$$\eta_{\rm tot} = \frac{P_{\rm tot}}{\dot{M}c^2} \approx 14.8\% \left[\frac{\Omega_H}{\Omega_H(a/M=1)}\right]^4, \qquad (2)$$

where the coefficient ($\tilde{\eta}$) is obtained by a least-squares fit. Net electromagnetic energy is *accreted* for $a/M \lesssim 0.36$ (including retrograde) when an accretion disk is present. This fact surprisingly agrees with the thin-disk study of Li (2000), who found that $\eta_{\rm tot} > 0$ only if $a/M \gtrsim 0.36$, corresponding to $\Omega_H > \Omega_{\rm K}[{\rm ISCO}]$, the Keplerian angular velocity at the innermost stable circular orbit (ISCO). The sparse-spin study of Krolik et al. (2005) is in basic agreement with our $\eta_{\rm tot}$. Note that the spin dependence of our $\eta_{\rm tot}$ is consistent with McKinney & Gammie (2004) for the fit given by their equation (61) to data shown in Figure 11, where $\eta_{\rm tot} \propto (2 - r_H)^2 \propto (a/M)^4$ was found. Their fit coefficient of 6.8% was inaccurate for $a/M \approx 1$, since they had no model beyond $a/M = 0.97$ and included points with $a/M \lesssim 0.5$ that do not fit well.

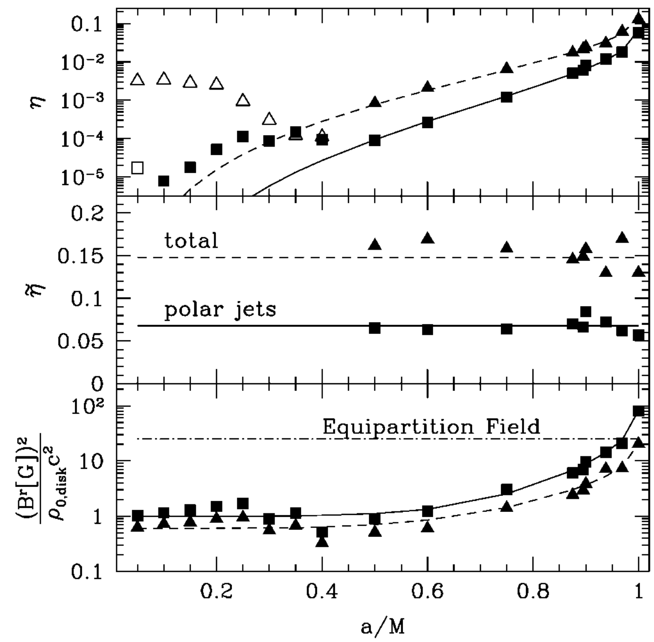

FIG. 1.—*Top*: Total (data, *triangles*; fit, *dashed line*) and jet (data, *squares*; fit, *solid line*) efficiency. Open points represent negative efficiencies. *Middle*: Coefficient ($\tilde{\eta}$) least-squares fit to η-formulae. *Bottom*: Normalized field (in gauss) squared.

The nearly force-free jet region contains field lines that tie the black hole (not the disk) to large distances, leading to the BZ effect and a jet. For $a/M > 0.5$,

$$\eta_{\rm jet} = \frac{P_{\rm jet}}{\dot{M}c^2} \approx 6.8\% \left[\frac{\Omega_H}{\Omega_H(a/M=1)}\right]^5 \qquad (3)$$

over both polar jets. If $a/M \approx 0.9$, then ≈1% of the accreted rest-mass energy is emitted back as a Poynting jet.

In this Letter, the GRMHD numerical models assume the typically used "floor model" of the lowest rest-mass and internal energy density, rather than the more physical pair creation process studied in McKinney (2005a, 2005b). They did not study retrograde spins. Here we find that the rotation of the jet is coupled to the spin of the black hole rather than the rotation of the disk. Hence, even for retrograde spins ($a/M < 0$) the BZ effect produces an outgoing Poynting jet. However, we find that, for example, $\eta_{\rm jet}$ is 10 times less at $a/M = -0.94$ than at $a/M = 0.94$. Thus, clearly the fact that we find that $\eta_{\rm tot} < 0$ for $a/M < 0$ depends on the disk thickness. We expect that for $H/R \lesssim 0.1$ the system can become jet-dominated, and then $\eta_{\rm tot} > 0$ even for $a/M < 0.4$. Note that for all black hole spins and for any disk thickness, we find that the angular momentum extracted agrees with the BZ (i.e., stationary force-free) result of

$$\frac{\dot{L}_{\rm jet}}{\dot{M}r_g c} \approx 4\eta_{\rm jet} \left[\frac{\Omega_H}{\Omega_H(a/M=1)}\right]^{-1}. \qquad (4)$$

The horizon value of $B^r \equiv {}^*F^{rt}$, where $^*F$ is the dual of the Faraday tensor, determines the black hole power output (McKinney & Gammie 2004). For all $a/M \geq 0$, the total and jet fields are

$$\frac{(B^r_{\rm tot}[{\rm G}])^2}{\rho_{0,{\rm disk}}c^2} \approx 0.6 + 20\left[\frac{\Omega_H}{\Omega_H(a/M=1)}\right]^4, \tag{5}$$

$$\frac{(B^r_{\rm jet}[{\rm G}])^2}{\rho_{0,{\rm disk}}c^2} \approx 1.0 + 81\left[\frac{\Omega_H}{\Omega_H(a/M=1)}\right]^5, \tag{6}$$

where the equipartition field satisfies $(B^r[{\rm G}])^2/(8\pi) = \rho_{0,{\rm disk}}c^2$, where $\rho_{0,{\rm disk}} \equiv \dot{M}t_g/r_g^3$ and $t_g \equiv GM/c^3$. Hence,

$$P_{\rm tot} \approx 7.4 \times 10^{-3}[(B^r_{\rm tot}[{\rm G}])^2 r_g^2 c - 0.6\dot{M}c^2], \tag{7}$$

$$P_{\rm jet} \approx 8.4 \times 10^{-4}[(B^r_{\rm jet}[{\rm G}])^2 r_g^2 c - 1.0\dot{M}c^2], \tag{8}$$

where since the field is determined self-consistently, no explicit spin dependence appears. This demonstrates the competition between electromagnetic energy extraction and accretion. Notice that no direct comparison can be cleanly made to equation (1), because of the presence of two ambiguities, P_0 and B^r, while our formulae have no ambiguities. Using these formulae requires the mass accretion rate to be determined for each a/M using a model-dependent study, but for $a/M \gtrsim 0.4$ we find that $\dot{M}/M_{\rm disk} \propto \Omega_H^{-1}$ (where $M_{\rm disk}$ is the mass of the disk) and constant for $a/M \lesssim 0.4$, so there is a comparably weak dependence.

For example, for the collapsar model with $M_{\rm BH} \sim 3\ M_\odot$, with $a/M \sim 0.9$ feeding at $\dot{M} = 0.1\ M_\odot\ {\rm s}^{-1}$, we have $\rho_{0,{\rm disk}} \approx 3.4 \times 10^{10}\ {\rm g\ cm^{-3}}$, $B^r_{\rm jet} \approx 10^{16}$ G, and $P_{\rm jet} \approx 10^{51}\ {\rm ergs\ s^{-1}}$. Notice that the neutrino annihilation jet luminosity is $L_{\nu\bar{\nu},{\rm ann,jet}} \sim 10^{50}$–$10^{51}\ {\rm ergs\ s^{-1}}$ (Popham et al. 1999), so these processes are likely both important (but see McKinney 2005a, 2005b). Similar estimates can be made for AGNs and X-ray binaries.

The coefficient in the formulae above depends on the type of accreted-field geometry. As an extreme example, the accretion of a net vertical field leads to an increase in the net electromagnetic efficiency by a factor of 5 (McKinney & Gammie 2004). Also, the accretion of a net toroidal field leads to negligible energy extraction (De Villiers et al. 2005). Future studies should focus on the physical relevance, stability, and long temporal evolution of accreting net toroidal and vertical fields, as done with nonrelativistic MHD simulations (Igumenshchev et al. 2003).

4. DOMINANCE OF THE BLANDFORD-ZNAJEK EFFECT

Figure 2 shows the possible types of field geometries in the disk (see also, e.g., Blandford 2002; Hirose et al. 2004). Field type 1 corresponds to the Balbus-Hawley instability (Balbus & Hawley 1991), which is present in our simulations.

Field type 2 corresponds to models in which the field ties material inside the ISCO to the outer disk (Gammie 1999; Krolik 1999). As these predict, unlike in the α-viscosity model, there is no feature at the ISCO (McKinney & Gammie 2004; Krolik et al. 2005), which impacts any radiative model of the inner radial accretion disk.

Field type 3 corresponds to models that consider the role of the black hole and disk on the disk efficiency (Gammie 1999; Krolik 1999). These suggest that efficiencies of order unity or higher could be achieved by extracting energy from the hole. This field type is present, but the disk efficiency is near the thin-disk efficiency (McKinney & Gammie 2004). Thus, surprisingly, the magnetic field and disk thickness play little role in modifying the disk efficiency. In contrast, the angular momentum accreted is reduced by magnetic field lines that tie from the disk to the hole (McKinney & Gammie 2004; Krolik et al. 2005).

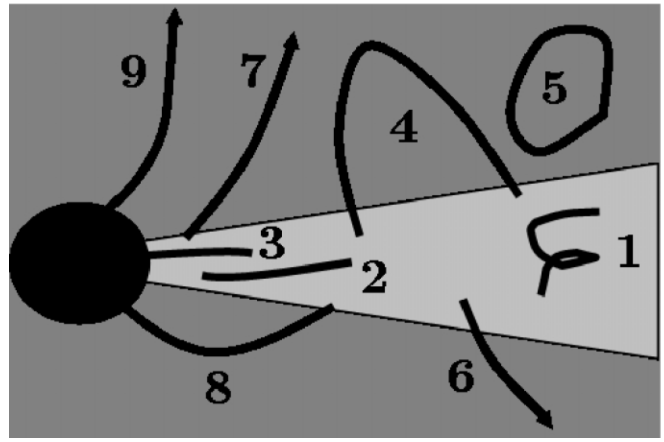

FIG. 2.—Possible field geometries. Type 9 dominates in GRMHD numerical models and is associated with the Blandford-Znajek effect. Types 1, 2, 3, 5, and 6 are dynamically important. Type 4 is transient. Types 7 and 8 are not dynamically stable.

Field types 4 and 5 correspond to surface reconnections. Type 4 geometries are temporary, and type 5 is common. Thus, reconnection efficiently removes large loops that tie the disk to itself.

Field type 6 corresponds to the Blandford-Payne–type model (Blandford & Payne 1982). We find that the lab-frame $|B| \propto r^{-5/4}$ as in their model, but the lab-frame $\rho \propto r^{0.0}$ instead of their $\rho \propto r^{-3/2}$. Also, there are few stable type 6 field lines because the inner radial corona is convectively unstable and magnetically unstable to magnetic buoyancy. Thin disks likely have more stable surfaces that might allow for a stable wind.

Field type 7 corresponds to coronal outflows or ergosphere-driven winds (Punsly & Coroniti 1990a, 1990b). There are no dynamically stable field lines that tie the inner radial disk to large distances. Even for $a/M = 0.999$, no additional Poynting flux is created in the ergosphere, and the electromagnetic energy at infinity completely dominates the hydrodynamic energy at infinity associated with the MHD Penrose process, in basic agreement with the results of Komissarov (2005) and counter to the results of Koide et al. (2002) and Punsly (2005). Koide et al. (2002) evolved for much too short a time. Punsly (2005) used the three-dimensional GRMHD near-horizon results of Krolik et al. (2005), but their near-horizon results could have numerical artifacts associated with their use of Boyer-Lindquist coordinates. However, there is a convectively and magnetically unstable, self-consistently mass-loaded, collimated, mildly relativistic ($v/c \lesssim 0.95$) coronal outflow (McKinney & Gammie 2004; De Villiers et al. 2005a). A rotating black hole is not required for nonrelativistic ($v/c \lesssim 0.6$) coronal outflows (McKinney & Gammie 2002, 2004).

Field type 8 corresponds to Uzdensky (2005) type models. These field geometries appear rarely and do not transfer a significant amount of energy or angular momentum. Such geometries may be more important for thin disks.

Field type 9, the dominant feature, is associated with the Blandford-Znajek model. Since the magnetic field confines the disk matter away from the polar region, the rest-mass flux there is arbitrarily low. The large BZ flux to low rest mass flux ratio can translate into an arbitrarily fast jet. The mass loading of this jet is considered in McKinney (2005a, 2005b).

Note that for accretion models with a net vertical field, the resulting structure is essentially identical (McKinney & Gammie 2004). Reconnection efficiently erases the initial geometric differences.

5. CONCLUSIONS

Typical BZ power output estimates assume an infinitely thin disk and a slowly rotating black hole, and they do not self-consistently determine the magnitude or geometry of the magnetic field. We have used GRMHD numerical models to self-consistently determine the total and jet BZ efficiency when a disk is present. There is a significantly stronger dependence on black hole spin than prior estimates suggest.

Near the rotating black hole, the field geometry of the accretion system is dominated by the field that leads to the BZ effect. Since the polar region is magnetically confined against disk material and the BZ power is large, the jet Lorentz factor can be arbitrarily large. This is unlike disk-related jet mechanisms that are directly loaded by disk material.

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