Blandford-Znajek process as a gamma ray burst central engine

Hyun Kyu Lee†, R.A.M.J. Wijers, and G.E. Brown

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794, USA

Abstract. We investigate the possibility that gamma-ray bursts are powered by a central engine consisting of a black hole with an external magnetic field supported by a surrounding disk or torus. The rotational energy of the black hole can be extracted electromagnetically as a Poynting flux, a mechanism proposed by Blandford and Znajek (1977). Recently observed magnetars indicate that some compact objects have very high magnetic fields, up to $10^{15}$ G, which is required to extract the energy within the duration of a GRB, i.e., in 1000 s or less. We demonstrate also that the Poynting flux need not be substantially dominated by the disk.

1. Introduction

Gamma ray bursts presently provide great excitement in astronomy and astrophysics as optical observations by way of many instruments give considerable detail of the history of each burst. We are concerned here with the prodigious energy in each burst, the estimate for GRB 971214 being greater than $3 \times 10^{53}$ ergs (Kulkarni et al., 1998), although this could be diminished if considerable beaming is involved in the central engine, as we will discuss.

Amazingly, $2 \times 10^{54}$ ergs is just the rest mass energy of our sun, so it seems immediately clear that the central engine for the GRB must be able to extract a substantial fraction of the rest mass energy of a compact object, neutron star or black hole, and convert it into energy of GRB.

The second criterion for the central engine is that it must be able to deliver power over a long interval up to $\sim 1000$ seconds, since some GRB’s last that long, although other GRB’s last only a fraction of a second. It must also be able to account for the vast diversity in pulses, etc., or, alternatively, one must have a number of diverse mechanisms.

We believe the need to deliver power over the long time found in some bursters to be the most difficult requirement to fulfill, since the final merger time of the compact objects is only a fraction of a second and it is difficult to produce a high energy source of, e.g., $\nu \bar{\nu}$-collisions that goes on for more than two or three seconds.

†Department of Physics, Hanyang University, Seoul 133-791, Korea
For many years mergers of binary neutron stars and of a neutron star with a black hole were considered to be likely sources for the GRB’s. The estimated merger rate in our Galaxy of a few GEM (Galactic Event per Megayear) is of the right order for the occurrence of GRBs. The possible problem with the binary mergers might be the ejected materials during the merging processes. Not more than $\sim 10^{-5}M_\odot$ of baryons can be involved in the GRB, since it would not be possible to accelerate a higher mass of nucleons up to the Lorentz factors needed with the energies available.

We find that the emergence or presence of a black hole during the merging process to be particularly attractive. The baryon number “pollution” problem can be solved by the main part of the baryons going over the event horizon. In the Blandford-Znajek mechanism (Blandford & Znajek 1977) we wish to invoke, a substantial proportion of the rotational energy of the black hole, which will be sent into rapid rotation by swallowing up the neutron star matter, can be extracted through the Poynting vector (Meszaros & Rees 1997). The rate of extraction is proportional to the square of magnetic field strength, $B^2$, as we shall discuss, so that power can be furnished over varying times, depending upon the value of $B$. With substantial beaming, we estimate that $B \sim 10^{15}$G would be sufficient to power the most energetic GRBs with $\sim 10^{53}$ergs.

Failed supernovae were suggested by Woosley (Woosley 1993) as a source of GRB. In this case the black hole would be formed in the center of a massive star, and surrounding baryonic matter would accrete into it, spinning it up. This mechanism is often discussed under the title of hypernovae (Paczynski 1998).

More recently Bethe and Brown (Bethe & Brown 1998) found that in binary neutron star evolutions, an order of magnitude more low-mass black-hole, neutron-star binaries were formed than binary neutron stars. The low-mass black-hole mass of $\sim 2.4M_\odot$ looks favorable for the Blandford-Znajek mechanism.

In some calculations which begin with a neutron star binary, one of the neutron stars evolves into a black hole in the process of accretion, and the resulting binary might also be a good candidate for GRBs. In any case, there are various possibilities furnished by black-hole, neutron-star binaries.

The structure we are proposing as a central engine of the GRB is a system of a black hole surrounded by centrifugally supported material, either an accretion disk or a debris torus left from a recently disrupted object. The rotating black hole is threaded by a strong magnetic field. Along the baryon-free funnel relativistic jets fueled by Poynting outflow give rise to the GRB. The interaction between disk and black hole is characterized by accretion and magnetic coupling. We consider the BZ process only after the main accretion process is completed, leaving an accretion disk of cold residual material, which can support a strong enough magnetic field.

2. Blandford and Znajek process

Two decades ago Blandford and Znajek (Blandford & Znajek 1977) proposed a process (BZ) in which rotational energy of a black hole can be efficiently extracted. Consider a half hemisphere (radius $R$) rotating with angular velocity $\Omega$ and a circle on the surface at fixed $\theta$ (in the spherical polar coordinate system).
across which a surface current $I$ flows down from the pole. When the external magnetic field $B$ is imposed to thread the surface outward normally, the surface current feels a force and the torque due to the Lorentz force exerted by the annular ring of width $Rd\theta$ is

$$dT = -\frac{I}{2\pi}d\Psi.$$  

where $d\Psi$ is the magnetic flux through annular ring extended by $d\theta$. From this magnetic braking, we can calculate the rotational energy loss rate

$$P_{rot} = \frac{1}{2\pi} \int \Omega I d\Psi.$$  

Blandford and Znajek demonstrated that such a magnetic braking is possible, provided that the external charge and current distributions around the black hole can support the force-free condition. The Blandford-Znajek process has been reformulated in the frame work of the membrane paradigm (Thorne, Price & MacDonald 1986) in which the complicated physics near the horizon can be expressed in terms physical quantities defined on the stretched horizon. For the axial symmetric and force-free magnetosphere the rotational energy loss rate, $P_{rot}$, and the outgoing power, $P_{BZ}$, are given respectively by

$$P_{rot} = \frac{1}{2\pi} \int \Omega_H I d\Psi, \quad P_{BZ} = \frac{1}{2\pi} \int \Omega_F I d\Psi$$

for a black hole with mass $M$ and angular momentum $J$(angular velocity $\Omega_H = \frac{J}{2M \pi r_H}$) with rigidly rotating magnetic fields (angular velocity $\Omega_F$).

The maximum amount of energy which can be extracted out of the black hole without violating the second law of thermodynamics is the rotational energy, $E_{rot}$, which is defined as

$$E_{rot} = Mc^2 - M_{irr}c^2 = (1 - \sqrt{1 + \sqrt{1 - \tilde{a}^2/2}})Mc^2$$

where $M_{irr} = \sqrt{\frac{A_H c^4}{16\pi G^2}}$ and $A_H$ is the surface area of the black hole(equivalently the black hole entropy, $S_H = \frac{kb^\frac{A_H}{4\pi}}{4\pi}$) and $\tilde{a} = \frac{Jc}{M^2 G}$ is the rotation parameter.

For a maximally rotating black hole ($\tilde{a} = 1$), $E_{rot} = 0.29Mc^2$. However in the physical process a fraction of the rotational energy is dissipated into the black hole increasing the entropy or equivalently irreducible mass:$P_{diss} = P_{rot} - P_{BZ} = \frac{1}{2\pi} \int (\Omega_H - \Omega_F)I d\Psi$. For the optimal process, $\Omega_F \sim 0.5\Omega_H$, the total Blandford-Znajek power is given by (Lee, Wijers & Brown 1999)

$$P = 1.7 \times 10^{50} \tilde{a}^2 f(\tilde{a})(\frac{M}{M_\odot})^2(\frac{<B_H>}{10^{15}{\text{gauss}}})^2 \text{erg/s},$$

where $f(\tilde{a}) = 0(\tilde{a} = 0) \rightarrow 1.14(\tilde{a} = 1)$ and the total energy extracted out is calculated (Phinney 1983, Okamoto 1992) to be

$$E_{BZ} = 0.091 Mc^2 = 1.6 \times 10^{53}(\frac{M}{M_\odot})\text{erg},$$

for a black hole with mass $M$ and angular momentum $J$(angular velocity $\Omega_H = \frac{J}{2M \pi r_H}$) with rigidly rotating magnetic fields (angular velocity $\Omega_F$).
and the time scale $\tau_{BZ} \sim 10^3 \left( \frac{10^{15} \text{ gauss}}{B} \right)^2 \left( \frac{M}{M_\odot} \right) \text{s}$.

The fluences of the recently observed GRB971214 (Kulkarni et al. 1998) and GRB990123 (Kulkarni et al. 1999) correspond to $E_\gamma = [10^{53.5}, 3.4 \times 10^{54}] (\Omega/4\pi) \text{erg}$ which are consistent with $E_{BZ}$ if the considerable beaming is considered. Also the durations of gamma ray bursts suggest that if a strong enough magnetic field ($\sim 10^{15} \text{ G}$) on the black hole can be supported by the surrounding material (accretion disk) the BZ process is a good candidate to provide the powerful energy of the GRB in the observed time interval up to 1000s, which is comparable to the BZ time scale $\tau_{BZ}$.

The rotation parameter of the black hole can be estimated by assuming a substantial part of the angular momentum of the merging compact binary systems or collapsars (a fraction $(x)$ of the specific angular momentum) can be imparted onto the black hole when a fraction $(y)$ of the mass collapses into the black hole. From the semi-quantitative estimation (Lee, Wijers & Brown 1999) we get $\tilde{a} = 0.53 \frac{x}{y}$ for BH-NS merger with $M_{BH} = 2.5 M_\odot$, $M_{NS} = 1.5 M_\odot$ and the tidal radius $\sim 10^6 \text{ cm}$, $\tilde{a} = 0.67 \frac{x}{y}$ for NS-NS merger, and $\tilde{a} = 2.3 \frac{x}{y}$ for collapsars with massive rapidly spinning progenitors ($M_o \sim 40 M_\odot$). Hence it is very plausible to have a rapidly rotating black hole as a resulting object in the center in the merging systems and also in hypernovae of large angular momentum progenitors, but a precise value of $\tilde{a}$ will be difficult to calculate.

3. Magnetized accretion disk

The presence of the accretion disk is important for the BZ process because it is the supporting system of the strong magnetic field on the black hole, which would disperse without the pressure from the fields anchored in the accretion disk. Recent numerical calculations (Popham, Woosley & Fryer 1999) show that accretion disks formed by various merging processes are found to have large enough pressure such that they can support $\sim 10^{15} \text{ G}$ assuming a value of the disk viscosity parameter $\alpha \sim 0.1$, where $\alpha$ is the usual parameter in scaling the viscosity.

The discovery that soft gamma ray bursts are magnetars (Kouveiotou et al. 1998) also supports the presence of the strong magnetic fields of $\sim 10^{15} \text{ G}$ in nature. It is also possible that existing magnetic fields can be increased by the dynamo effect. The identification by now of three soft gamma repeaters as strong-field pulsars indicates that there may be a large population of such objects: since the pulsar spindown times scale as $B^{-1}$, we would expect to observe only 1 magnetar for every 1000 normal pulsars if they were formed at the same rate, and if selection effects were the same for the two populations. We see 3 magnetars and about 700 normal pulsars, but since they are found in very different ways the selection effects are hard to quantify. It is nonetheless clear that magnetars may be formed in our Galaxy at a rate not very different from that of normal pulsars.

The life time of the accretion disk determined by the accretion rate is also very important for the GRB time scale because it supports the magnetic field on the black hole. The strong magnetic field perpendicular to the disk produces a high accretion rate $\dot{M} = 10^{-4} M_\odot \text{s}^{-1}$ (Lee, Wijers & Brown 1999). However
the total accretion is less than $10^{-1} M_{\odot}$ during the GRB time scale and it may not change the disk structure for the Blandford-Znajek process significantly. According to numerical simulations of merging systems which evolve eventually into black hole - accretion disk configuration (Popham, Woosley & Fryer 1999) the viscous life times are 0.1 - 150 s, which are not inconsistent with the GRB time scale. Also it has been pointed out (Meszaros, Rees & Wijers 1998) that a residual cold disk of $\sim 10^{-3} M_{\odot}$ can support $10^{15} G$, even after the major part of the accretion disk has been drained into the black hole or dispersed away.

The current conservation condition, namely that the total current flows onto the black hole should go into the inner edge ($r_{in}$) of the accretion disk, implies

$$2MB_\phi^H(\theta = 2\pi) = \tilde{\omega}(r_{in}) B_{\phi}^{disk}(r_{in}).$$  \hspace{1cm} (7)

Since the cylindrical radius in Kerr geometry $\tilde{\omega}(r_{in}) > 2M$, we can see that $B_\phi^H$ is larger than $B_{\phi}^{disk}$. From the boundary conditions on the horizon in the optimal case and on the accretion disk (Blandford 1976) with angular velocity $\Omega_D$ respectively

$$B_\phi^H = -\Omega_H MB_H, \quad B_{\phi}^{disk} = -2\Omega_D r B_{z}^{disk},$$  \hspace{1cm} (8)

we get

$$\frac{B_z(r_{in})}{B_H} = \sqrt{\frac{GM}{r_{in} c^2}} \frac{\tilde{\omega} r_{in}}{2 r_H c^2} < 1,$$  \hspace{1cm} (9)

and the power of the disk magnetic braking $P_{disk} = \frac{2}{f(\theta)} \left(\frac{GM}{r_{in} c^2}\right)^2 P_{BZ}$. It shows that the magnetic field on the horizon cannot be smaller than that on the inner edge of the accretion disk and the disk power need not be substantially larger than that from the black hole (Livio, Ogilvie & Pringle 1998; Ghosh & Abramowicz 1997; Lee, Wijers & Brown 1999).

The energy outflow from the disk is mostly directed vertically from the disk where the baryon loading is supposed to be relatively high enough to keep the baryons from being highly relativistic. Therefore the BZ process from the disk can be considered to have not much to do with gamma ray burst phenomena. However the BZ from the disk could power an outflow with lower $\Gamma$, but nonetheless high energy, which could cause an afterglow at large angles. That would lead to more afterglows being visible than GRBs, because the afterglows are less beamed.

4. Conclusion

We have evaluated the power and energy that can be extracted from a rotating black hole immersed in a magnetic field, the Blandford-Znajek process. We improve on earlier calculations to find that the power from a black hole of given mass immersed in an external field is ten times greater than previously thought. The amount of energy that can be extracted from a black hole in this way is limited by the fact that only 29% of the rest mass of a black hole can be in rotational energy, and that the optimal efficiency with which energy can be extracted from the hole via the Blandford-Znajek effect is 31%. The net amount
of energy that can be optimally extracted is therefore 9% of the rest energy of the black hole. We consider various scenarios for the formation of rotating black holes in gamma-ray burst engines, and while the resulting angular momenta are quite uncertain in some cases, it seems that the required values of the rotation parameter, \( \tilde{a} > 0.5 \), are achievable.

The rate at which angular momentum is extracted depends on the magnetic field applied to the hole. A field of \( 10^{15} \) G will extract the energy in less than 1000 s, so time scales typical of gamma-ray bursts can be obtained. Since the black hole cannot carry a field, there must be an ambient gas in which the field is anchored that drives the Poynting flux from the black hole. The most obvious place for it is the accretion disk or debris torus surrounding the black hole just after it formed.

It has been argued that a field turbulently generated in the disk would not give a strong Blandford-Znajek flux (Livio, Ogilvie & Pringle 1998), because the disk would dominate the total Poynting output, and no more than the disk’s binding energy could be extracted. We show explicitly that a field in the disk could be much greater, for example if it is derived from the large, ordered field of a neutron star that was disrupted. The field distribution proposed by Blandford (Blandford 1976) for such a case would allow the field on the hole to be larger than on the disk, such that the Poynting flow would not be dominated by the disk and not subject to any obvious limits imposed by the disk.

Recent hydrodynamic simulations (Ruffert & Janka 1998) of merging binaries show that along the rotation axis of the black hole an almost baryon-free funnel is possible. This can be easily understood since the material above the hole axis has not much angular momentum so that it can be drained quickly, leaving a baryon-free funnel. Hence relativistically expanding jets along the funnel, fueled by Poynting outflow which is collimated along the rotation axis, can give rise to gamma ray bursts effectively. Recent observation (Kulkarni et al. 1999) seems to provide an evidence of beaming for GRB990123. It is also interesting to note that the beaming via Blandford-Znajek process with the possible disk precessing can be applied to simulate the temporal structures of the gamma ray bursts (Portegies-Zwart, Lee & Lee 1999).

We also note that a Poynting flow may provide an alternative way of providing a very large magnetic field for the shocked material that radiates the afterglow and the gamma-ray burst itself: the standard assumption is that the required high fields grow turbulently in the shocked gas, up to near-equipartition values. But the field in the Poynting flow only decreases as \( 1/r \), so if it is \( 10^{15} \) G at \( r = 10^5 \) cm, it could be as high as \( 10^4 \) G at the deceleration radius \( (10^{16} \) cm), ample to cause an energetic gamma-ray burst.

We are grateful to Roger Blandford, Sterl Phinney and Kip Thorne for guidance and useful discussions. This work is supported by the U.S. Department of Energy under Grant No. DE-FG02-88ER40388. HKL is supported also in part by KOSEF-985-0200-001-2 and BSRI-98-2441.

References

Bethe, H & G.E. Brown, G.E. 1998, ApJ 506, 780
Blandford, R.D. 1976, MNRAS 176, 465
Blandford, R.D., & Znajek, R.L. 1977, MNRAS 179, 433
Ghosh, P. & Abramowicz. M.A. 1997, MNRAS 292, 887
Kouveliotou, C. et al. 1998, Nature 393, 235
Kulkarni, S.R. et al. 1998, Nature, 393, 35
Kulkarni, S.R. et al. 1999, astro-ph/9902272 v2
Lee, H.K., Wijers, R.A.M.J. & Brown, G.E. 1999, in preparation
Livio, M., Ogilvie, G.I. & Pringle, J.E. 1999, ApJ 512, 100L
Meszaros, P., Rees, M.J.1997, ApJ 482, L29
Meszaros, P., Rees, M.J., & Wijers, R.A.M.J. 1998 astro-ph/9808106
Okamoto, I. 1992, MNRAS 294, 192
Paczynski, B. 1998, ApJ 494, L45
Phinney, S. 1983, PhD thesis
Popham, R., Woosley, S.E., & Fryer, C.L. 1999, astro-ph/9807028
Portegies-Zwart,S., Lee, C.-H. & Lee, H.K. 1999, ApJ in press(astro-ph/9808191)
Ruffert,M. & Janka,H.-Th. 1998, astro-ph/9804132
Thorne, K.S., Price, R.H. & MacDonald, D.A. 1986, Black Holes; The Membrane Paradigm
Woosley, S.E. 1993, ApJ 405, 273