

CALORIMETRY OF GAMMA-RAY BURSTS: ECHOES IN GRAVITATIONAL WAVES

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ABSTRACT

Black holes surrounded by a disk or torus may drive the enigmatic cosmological gamma-ray bursts (GRBs). Equivalence in poloidal topology to pulsar magnetospheres shows a high incidence of the black hole luminosity L_H into the surrounding magnetized matter. We argue that this emission is reradiated into gravitational waves at $L_{GW} \approx L_H/2$ in frequencies on the order of 1 kHz, winds, and, potentially, MeV neutrinos. The total energy budget and input to the GRB from baryon-poor jets are expected to be standard in this scenario, consistent with recent analysis of afterglow data. Collimation of these outflows by baryon-rich disk or torus winds may account for the observed spread in opening angles up to about 35° . This model may be tested by future LIGO/VIRGO observations.

Subject headings: black hole physics — gamma rays: bursts — gamma rays: theory — gravitational waves

1. INTRODUCTION

It is now widely believed that progenitors of gamma-ray bursts (GRBs) are massive stars or black hole–neutron star binaries. These systems have ample and well-defined energy in angular momentum to produce the relativistic outflows that drive GRBs. Support for hypernovae in massive stars (Woosley 1993; Paczyński 1997, 1998; Brown et al. 2000) derives from an association with star-forming regions (Paczynski 1998; Bloom, Kulkarni, & Djorgievski 2000), the GRB 980425/SN 1998bw event (although this source exhibits markedly different properties than a typical burst) and a potential GRB/soft X-ray transient (SXT) connection (Brown et al. 2000; G. E. Brown, H. A. Bethe, & H.-K. Lee 2001, in preparation), e.g., as in GRO J1655–40 (Israelian et al. 1999) and V4641 Sgr (Orosz et al. 2001). Chemical abundances in the latter have been attributed to the intercept of hypernova debris by the secondary during the GRB event. A likely outcome of the collapse of a massive star is a black hole surrounded by a disk or torus. The coalescence of black hole–neutron star binaries may likewise produce black hole–torus systems when the black hole spins rapidly (Paczynski 1991). This remains of interest in view of their occurrence rate (Phinney 1991; Narayan, Piran, & Shemi 1991; Brown, Lee, & Bethe 1999), which, although marginally, is consistent with GRB statistics set by estimates of the beaming factors (see below).

In this Letter, we classify the major channels of radiation from black hole–torus systems and provide estimates for their net fluences (see van Putten 2001b for a review). Outflows powered directly by the black hole enables baryon-poor input to the GRBs. Radiation from the torus establishes channels for “unseen” emissions: gravitational radiation, Poynting flux–dominated and baryonic collimating winds, and, possibly, neutrino emissions. In the GRB/SXT association of Brown et al. (2000; G. E. Brown, H. A. Bethe, & H.-K. Lee 2001, in preparation), these emissions are augmented by hypernova disk winds that provide a chemical deposition of metals onto the companion star. We shall find that a dominant fraction of the energy will be liberated in gravitational waves. As predictions for future calorimetry in multiwindow observations, estimates of the fluences in these “unseen” emissions may provide the most stringent observational test of the black hole–torus system. As an observational test for the black

hole–torus association to gamma-ray bursts, we may further consider recovering the present bimodal distribution in durations in the BATSE catalog in these unseen radiation channels.

Recent analysis of afterglow data in GRBs with measured redshifts appears to indicate a standard energy release of prompt gamma rays in long bursts and a rather wide range of observed beaming factors (Frail et al. 2001). Below, we argue that standard energy release and a range of collimation factors is a natural consequence of black hole–torus systems in a suspended accretion state, which we associate with long bursts (van Putten & Ostriker 2001).

In § 2, the basic features of black hole plus disk or torus systems are summarized. Section 3 discusses the clustering and spread in leptonic outflows from black hole–torus systems. Section 4 presents an outlook for unseen emissions in gravitational waves.

2. NONTHERMAL EMISSIONS FROM BLACK HOLE–TORUS SYSTEMS

The black hole–torus system represents hypernovae, or the expected outcome of black hole–neutron star coalescence. The torus forms as remnant matter of a fallback envelope of a massive star or as the debris of a neutron star. A net magnetic flux carried by the torus supports a similarly shaped magnetosphere. Surrounded by a magnetic field with net poloidal magnetic flux, the central black hole assumes an equilibrium magnetic moment (van Putten 2001b)

$$\mu_H^e \sim aBJ_H, \quad (1)$$

where $a = J_H/M$ denotes the specific angular momentum of a black hole with angular momentum J_H and mass M , and B is the field strength of the torus magnetosphere. The magnetic moment given by equation (1) is no “fourth hair” of the black hole (Carter 1968); it is generated by an equilibrium charge $q^e \sim BJ_H$ of the black hole (Wald 1974; Dokuchaev 1987; Lee, Lee, & van Putten 2001). This magnetic moment serves to regulate an essentially uniform and maximal horizon flux, preserved at arbitrary rotation rates. This permits the horizon to couple to the inner face of the torus and to support an open

flux tube to infinity (van Putten 2001b). The net horizon luminosity L_H is, correspondingly, the sum of a luminosity L_T into the torus and a luminosity L_p to infinity.

Equivalence in poloidal topology to pulsar magnetospheres indicates a high incidence of the black hole luminosity—by way of Maxwell stresses—into the surrounding magnetized matter (adapted from Goldreich & Julian 1969; Thorne, Price, & McDonald 1986; van Putten 1999; G. E. Brown, H. A. Bethe, & H.-K. Lee 2001, in preparation):

$$L_T = \omega_T(\omega_H - \omega_T)f_T^2A_H^2, \quad (2)$$

where f_T denotes the fraction of poloidal horizon flux $2\pi A_H$ that connects to the torus, and ω_T and ω_H denote the angular velocities of the torus and the black hole, respectively. A suspended accretion state arises when ω_H/ω_T is sufficiently large (van Putten & Ostriker 2001).

Leptonic outflows are produced by rotating black holes in an open flux tube along their axis of rotation, in response to differential frame-dragging (van Putten 2000, 2001b; Heyl 2001). This open flux tube is endowed with conjugate radiative-radiative boundary conditions, at the horizon and finity. Global closure of the current—asymptotically null in the force-free sections on the horizon and infinity—over an outer flux tube supported by the torus gives rise to a net luminosity in $e^\pm\gamma$ given by (van Putten 2001b)

$$L_p = \frac{1}{2}\omega_T(\omega_H - 2\omega_T)f_o^2A_H^2, \quad (3)$$

where f_o denotes the fraction of poloidal horizon flux that supports the open flux tube. This in situ creation of leptonic outflows takes place whenever the black hole rotates faster than *twice* the angular velocity of a torus in prorated rotation.

The energetic coupling (eq. [2]) permits a high luminosity L_{GW} in low-frequency gravitational wave emissions from the torus, by generic nonaxisymmetric deformations. A time-averaged luminosity can be estimated in the suspended accretion state (van Putten & Ostriker 2001). When most of the magnetic field on the horizon is anchored to the surrounding matter, i.e., $f_T \approx 1$, we have $L_H \approx L_T$ and hence (van Putten 2001b)

$$L_{GW} \approx \omega_T^2A_T^2 \approx L_H/2, \quad (4)$$

where $2\pi A_T$ denotes the net poloidal flux in the torus. Here $\omega_T/\omega_H \approx f_H^2/2$ in terms of the fraction f_H of the flux supported by the torus that connects to the horizon of the black hole (van Putten 2001a).

An appreciable fraction of equation (2) may dissipate in the disk, probably giving rise to emission of neutrinos if maintained at high enough temperatures and perhaps other forms of radiation. The torus may lose baryon-rich material at a substantial rate. This may provide a baryonic collimating wind launched along the open flux tubes (see below) and a chemical deposition of metals onto the companion star.

To summarize, the work performed by the black hole as it sheds off its angular momentum in the course of the evolution to a lower energy state (by the Rayleigh criterion) is liberated through two important channels (van Putten 2001b):

1. Baryon-poor outflows along open flux tubes supported by the spin energy of the black hole (van Putten 2000, 2001b; Heyl 2001), which, we conjecture, provide the free energy source that powers GRBs. This work is proportional to $f_o^2 =$

$(\Omega_H/4\pi)^2 \ll 1$, whereby the remaining fraction $f_T \approx 1$. The important GRB emissions form a small fraction of the total luminosity L_H of the black hole.

2. Gravitational wave emissions from nonaxisymmetric deformations in the torus, powered by about one-third of the black hole luminosity. These frequencies are correlated with the Keplerian angular velocity of the torus and, hence, are on the order of 1 kHz—low frequencies relative to the quasi-normal mode oscillations of the black hole.

In the hypernova model of Brown et al. (2000; G. E. Brown, H. A. Bethe, & H.-K. Lee 2001, in preparation), a third channel consists of disk winds providing chemical depositions of metals onto the companion star. The energy of $\sim 10^{52}$ ergs in these winds (Maeda et al. 2001) may derive from L_T by a safe margin (see below). Unknown is the role of analogous baryonic winds from black hole–torus systems formed in mergers of black hole–neutron star binaries.

3. THE TRUE ENERGY BUDGET AND CLUSTERING AND SPREAD IN OUTFLOWS

The fraction of the hole rotational energy liberated as leptonic outflows is approximately $(\Omega_H/4\pi)^2 \ll 1$, where Ω_H is the solid angle on the horizon occupied by an open flux tube (van Putten 2001b). The remaining spin-down energy is deposited in the torus as described in point 2 above. By the first law of black hole thermodynamics, the efficiency of delivering spin energy into the surrounding torus is given by the ratio of angular velocities $\omega_T/\omega_H = 2/[(R/M_H)^{3/2} + 1]$ of the torus and black hole, respectively, for a maximally spinning black hole. Here R denotes the radius of the torus and M_H the mass of the black hole, assuming the torus to be in approximately Keplerian motion. For a conservative value $\omega_T/\omega_H \sim 0.1$, the available black hole energy of a maximally rotating black hole is

$$E_H \approx 4 \times 10^{53} (M_H/7 M_\odot) \text{ ergs}. \quad (5)$$

Here the fiducial scale of $7 M_\odot$ is motivated by the range of about 4–14 M_\odot in dynamically determined masses of black hole candidates in X-ray novae (see van Putten 2001b for a recent update).

The suspended accretion state is expected to result in a relatively thick torus, as it will be hot and in a state of super-/sub-Keplerian motion at the inner/outer face due to the powerful competing torques acting on it. This promotes a radially slender and a poloidally extended shape. It should be mentioned that the torus mass and magnetic-to-kinetic energy ratio are the two main uncertain parameters, also in regard to the timescale of the suspended accretion state (van Putten & Ostriker 2001).

A relatively thick torus produces a funnel surrounding the black hole. The horizon solid angle Ω_H of the open flux tube on the horizon will depend on the poloidal structure of the torus magnetosphere surrounding the black hole—as supported by the inner face of the torus in its immediate vicinity. Tori with inner faces larger than the black hole size are expected to give rise to a similar poloidal topology of the torus magnetosphere surrounding the black hole and hence similar solid angles Ω_H . This leads to the expectation that both the total black hole energy, E_H , and the fraction that emerges along the open flux tubes, E_p , should be standard. Adopting the estimate by (Frail et al. 2001) for the true energy of prompt emission— $\bar{E}_\gamma \approx 5 \times 10^{50}$ ergs (in bipolar outflows)—we obtain

$$\Omega_H/4\pi = (E_p/E_H)^{1/2} \approx 0.1(M_H/7 M_\odot)^{-1/2}(\epsilon/0.1)^{-1/2}, \quad (6)$$

where ϵ denotes the conversion efficiency of bulk energy of the leptonic outflow into gamma rays. While existing models vary in their estimates of ϵ , an approximate mean value of about 0.15 appears to be reasonable for GRB emission from internal shocks (Kobayashi, Piran, & Sari 1997; Daigne & Mochkovitch 1998; Guetta, Spada, & Waxman 2001; Panaitescu & Kumar 2000). Radiative viscosity mediated through the agency of some background radiation field (a component that may be particularly relevant for the class of models considered here) may enhance the efficiency of internal shocks considerably (Levinson 1998). Alternatively, high efficiency (as well as a preferable νF_ν peak of prompt emission) can be naturally achieved in compact fireball models, whereby prompt GRB gamma rays near the peak of the spectral energy distribution are produced on compact scales, prior to the acceleration of the fireball to its terminal Lorentz factor (Eichler & Levinson 2000). Thus, a value of $\Omega_H/4\pi \sim 0.1$, corresponding to an opening angle

$$\theta_H \approx 35^\circ, \quad (7)$$

seems reasonable. Given the observed mean beaming factor, $f_b \sim 2 \times 10^{-3}$, this generally implies that the baryon-poor outflow should be further collimated into a solid angle $\Omega_j \sim \Omega_H/30$. Further collimation may proceed through interactions with the baryon-rich wind surrounding it (Levinson & Eichler 2000). If the disk or torus is initially hot (at MeV temperatures) and dense, as anticipated if it forms as a result of collapse of a massive star or coalescence of compact objects, then it will first cool down over a timescale of several seconds via neutrino emission. During this process, a fraction η (a few percent) of a solar mass will be blown off, carrying a total energy of order $\eta M_\odot c^2$ (Levinson & Eichler 1993). Additional mass loss may arise from the interaction of the black hole and the torus, as mentioned above.

The degree of collimation depends on the parameters of the baryonic wind, which in turn might be sensitive to the conditions in the disk (as well as its structure) and is, therefore, expected to exhibit large variations. This can explain the diversity of beaming factors exhibited by the sample studied in (Frail et al. 2001). Preliminary analysis (Levinson & Eichler 2000) shows that the opening angle of the fireball thereby collimated is proportional to the ratio of luminosities of the baryon-poor and baryon-rich outflows. For a GRB having a beaming factor on the order of the mean found by Frail et al. (2001); e.g., GRB 990123, we find that the energy E_{CW} on the confining wind is roughly

$$E_{CW} \approx (2f_b)^{-1/2} E_j \epsilon^{-1} \approx 5 \times 10^{52} \text{ ergs}, \quad (8)$$

below the total energy deposition in the torus by a safe margin (see eq. [5]). Further work is needed to quantify the relation between the collimation factor and the luminosity of the baryonic wind for a broader range of physical conditions and for different assumptions on the boundary conditions.

4. GRAVITATIONAL WAVE BURSTS FROM BLACK HOLE SPIN IN LONG GRBS

There are at least five aspects to a black hole–torus system that suggest considering their potential as LIGO/VIRGO sources of gravitational radiation, produced by emissions from the torus. (1) By equivalence in poloidal topology to pulsar magnetospheres, the torus is strongly coupled to the spin energy of the black hole (van Putten 1999; van Putten & Ostriker

2001). (2) Nonaxisymmetric deformations in the torus will produce gravitational and radio emissions (modulations) at low frequencies (relative to those of the quasi-normal modes of the horizon), e.g., at twice the Keplerian frequency if produced by lumpiness. (3) Compact magnetized objects that reach their Schwarzschild radius with gravitationally weak magnetic fields radiate predominantly in gravitational rather than electromagnetic waves (see young pulsars; e.g., Shapiro & Teukolsky 1983, p. 283). (4) Nonaxisymmetric deformations in the torus are expected by instabilities, such as self-gravity, and are consistent with the requirement for intermittency at the source (Piran 1999, 2000). (5) The true rate of GRBs should be frequent, as inferred from their large beaming factor (Frail et al. 2001).

The gravitational wave luminosity can be calculated in a suspended accretion state (van Putten 2001b). The frequencies will be, to leading order, related to the Keplerian angular velocity of the torus. On the secular timescale of spin-down of the black hole, these frequencies will trace a horizontal branch in the $f(f)$ -diagram (van Putten & Sarkar 2000). In particular, lumpiness in the torus produces a gravitational wave frequency at twice the Keplerian frequency (van Putten 2001b):

$$f_{gw}(t) \sim 1\text{--}2 \text{ kHz}/(1+z), \quad df_{gw}(t)/dt = \text{const.} \quad (9)$$

Here canonical values are used for a black hole–torus system at redshift z . Other frequencies may arise as described in studies of quasi-periodic oscillations (see Stella 2001). If the torus is unstable against breaking up in clumps, or if the torus shows violent expansions in its mean radius, the gravitational waves will be episodic, and will correlate with subbursts in long GRBs. It should be mentioned that the horizontal branch may be above or below the f -axis, corresponding to a positive or negative linear chirp in the frequency dynamics. This uncertainty results from the uncertainty in the details of the radial dependence of the fraction of interconnecting field lines between the black hole and the inner face of the torus as a function of major radius of the torus.

The torus is expected to be luminous also in winds and, when sufficiently hot, neutrino emissions. The energy liberated in gravitational radiation, winds, and neutrinos may be roughly equal (van Putten 2001b). By equation (4), the black hole luminosity (eq. [5]) into the torus serves as an estimate for the energy released in gravitational waves:

$$E_{GW} \approx 10^{53} (M_H/7 M_\odot) \text{ ergs}. \quad (10)$$

Since gravitational wave emission is essentially unbeamed, the beaming factor of ~ 500 found by Frail et al. (2001) suggests that long GRBs, observed at redshifts of order unity, take place as gravitational wave bursts at a rate of a few times 10^5 yr^{-1} , or a few times per year within a distance of 100 Mpc. With the gravitational emissions (eq. [10]) in the frequency range given by equation (9), this suggests that long GRBs are potentially powerful LIGO/VIRGO burst sources of gravitational radiation (van Putten 2001b).

The above suggests at least three aspects to future LIGO/VIRGO observations. LIGO/VIRGO may quantitatively probe the innermost structure of black hole–torus systems by tracking the secularly evolving frequencies. A link to GRBs may be established by comparing duration statistics from these LIGO/VIRGO detections with the BATSE catalog (after redshift corrections). A link to a binary progenitor system may be made by searching for a progenitor chirp to the emissions from the torus. If it is present, it would be of interest to consider ex-

tracting the individual binary masses by combining the chirp mass from precursor emissions with the black hole mass determined from the (secularly evolving) frequencies from the torus.

5. SUMMARY AND CONCLUSIONS

A black hole surrounded by a disk or torus is a likely outcome of the collapse of a massive star or coalescence of compact objects and may power the enigmatic GRBs. The rotational energy of the black hole should be released both along the axis of rotation and into the equatorial plane owing to its interaction with the surrounding disk or torus. Baryon-poor outflows are expected to be produced along the axis of rotation, while Maxwell stresses dominate the energetics onto the surrounding magnetized matter. A torus will radiate the latter in gravitational waves, winds and, possibly, neutrinos.

Sufficiently thick tori should yield a similar poloidal structure of the magnetosphere in the neighborhood of the black hole and, hence, roughly similar opening angles of the outflow on the horizon, leading to the extraction of a standard fraction of the spin energy in the form of outflows that power GRBs. This can quite naturally account for the inferred clustering of GRB energies. The initial cooling of the torus, and subsequent dissipation of some fraction of the unseen hole energy, will drive considerable mass loss of baryons from the torus. Collisions of the baryon-poor outflows and the baryon-rich winds can provide a collimation mechanism. As the degree of collimation

depends on the wind parameters, and might be sensitive to the specific conditions in the torus, it should lead to a range of opening angles for the collimated leptonic outflows, which may explain the observed spread of beaming factors. The same power input to the disk or torus is expected to expel baryonic winds in the equatorial plane, which may account for the chemical depositions in metals onto the companion star (Brown et al. 2000; G. E. Brown, H. A. Bethe, & H.-K. Lee 2001, in preparation).

A standard total hole energy and the fraction powering the associated GRB determines the solid angle Ω_H occupied by the open flux tubes near the horizon. This relates to gravitational waves as a potentially new observable and to the true energy of the prompt GRB emission. If Ω_H is indeed similar in all sources, it will appear as a break in the distribution of opening angles (eq. [7]) that may be observable in a large enough sample and can serve as an important test for this model.

A major fraction of the rotational energy of the black hole is predicted to be liberated in gravitational waves that overlap with the bandwidth of the advanced LIGO/VIRGO. Determining this power output promises true calorimetry of black hole-torus systems.

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REFERENCES

- Bloom, J. S., Kulkarni, S., & Djorgovski, S. G. 2000, *AJ*, submitted (astro-ph/0010176)
- Brown, G. E., Lee, C.-H., & Bethe, H. A. 1999, *NewA*, 4, 313
- Brown, G. E., Lee, C.-H., Wijers, R. A. M. J., Lee, H. K., Israelian, G., & Bethe, H. A. 2000, *NewA*, 5, 191
- Carter, B. 1968, *Phys. Rev.*, 174, 1559
- Daigne, F., & Mochkovitch, R. 1998, *MNRAS*, 296, 275
- Dokuchaev, V. I. 1987, *Soviet Phys.—JETP Lett.*, 65, 1079
- Eichler, D., & Levinson, A. 2000, *ApJ*, 529, 146
- Frail, D. A., et al. 2001, *Nature*, submitted (astro-ph/0102282)
- Goldreich, P., & Julian, W. H. 1969, *ApJ*, 157, 869
- Guetta, D., Spada, M., & Waxman, E. 2001, *ApJ*, in press (astro-ph/0011170)
- Heyl, J. S. 2001, *Phys. Rev. D*, 63, 064028
- Israelian, G., Rebolo, R., Basri, G., Casares, J., & Martín, E. L. 1999, *Nature*, 401, 142
- Kobayashi, S., Piran, T., & Sari, R. 1997, *ApJ*, 490, 92
- Lee, H. K., Lee, C.-H., & van Putten, M. H. P. M. 2001, *MNRAS*, in press
- Levinson, A. 1998, *ApJ*, 507, 145
- Levinson, A., & Eichler, D. 1993, *ApJ*, 418, 386
- . 2000, *Phys. Rev. Lett.*, 85, 236
- Maeda, K., et al. 2001, *ApJL*, submitted (astro-ph/0011003)
- Narayan, R., Piran, T., & Shemi, A. 1991, *ApJ*, 379, L17
- Orosz, J. A., et al. 2001, *ApJ*, submitted (astro-ph/010345)
- Paczynski, B. P. 1991, *Acta Astron.*, 41, 257
- . 1997, preprint (astro-ph/9706232)
- . 1998, *ApJ*, 494, L45
- Panaitescu, A., & Kumar, P. 2000, *ApJ*, 543, 66
- Phinney, E. S. 1991, *ApJ*, 380, L17
- Piran, T. 1999, *Phys. Rep.*, 314, 575
- . 2000, *Phys. Rep.*, 333, 529
- Shapiro, S. L., & Teukolsky, S. A. 1983, *Black Holes, White Dwarfs, and Neutron Stars* (New York: Wiley)
- Stella, L. 2001, in *Proc. X-Ray Astronomy 1999: Stellar Endpoints, AGN and the Diffuse Background*, ed. G. Malaguti, G. Palumbo, & N. White (Singapore: Gordon & Breach), in press (astro-ph/0011395)
- Thorne, K. S., Price, R. H., & McDonald, D. A. 1986, *Black Holes: The Membrane Paradigm* (New Haven: Yale Univ. Press)
- van Putten, M. H. P. M. 1999, *Science*, 284, 115
- . 2000, *Phys. Rev. Lett.*, 84, 3752
- . 2001a, *Phys. Rev. Lett.*, submitted
- . 2001b, *Phys. Rep.*, 345, 1
- van Putten, M. H. P. M., & Ostriker, E. C. 2001, *ApJ*, 552, L31
- van Putten, M. H. P. M., & Sarkar, A. 2000, *Phys. Rev. D*, 62, 041502(R)
- Wald, R. M. 1974, *Phys. Rev. D*, 10, 1680
- Woosley, S. E. 1993, *ApJ*, 405, 273