Gravitational waves from gamma-ray bursts

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ABSTRACT

We present a mechanism for long bursts of gravitational radiation from Kerr black holes surrounded by a torus. These systems are believed to form in core-collapse of massive stars in association with gamma-ray bursts. The torus catalyzes black hole-spin energy mostly into gravitational radiation, with a minor output in winds, thermal and neutrino emissions. Torus winds impact the remnant envelope of the progenitor star from within, which may account for X-ray emission lines and leaves a supernova remnant. The frequency in gravitational radiation satisfies

\[ f_{gw} = 470 \text{Hz} \left( \frac{E_{SNR}}{4 \times 10^{51}} \right)^{1/2} (0.1/\beta)^{1/2} (7M_\odot/M_H)^{3/2}, \]

where \( E_{SNR} \) is the kinetic energy in the SNR, \( M_H \) is the black hole mass and \( \beta \approx 0.1 \) the initial ejection velocity, as detected in GRB 011211. Ultimately, this leaves a black hole binary surrounded by a SNR, which is conceivably illustrated by RX J050736-6847.8.

1. Introduction

There is increasing evidence for a GRB-supernova association with young massive stars. These events are probably associated with the prompt formation of a Kerr black hole in core-collapse (Woosley 1993). The dissipative timescale of spin-energy in the horizon of the black hole agrees with the durations of tens of seconds of long GRBs, and a small fraction of the baryon-free energy in angular momentum released along the axis of rotation is consistent with the inferred baryon-poor input to the observed \( E_\gamma \approx 3 \times 10^{51} \text{erg} \) in GRB-energies (van Putten, 2001; van Putten & Levinson, 2003).

Kerr black holes produce luminous output in gravitational radiation, winds, thermal and neutrino emissions through a surrounding torus. These torus emissions are contemporaneous with forementioned minor output in baryon-poor outflows along the axis of rotation of the black hole. Gravitational radiation forms a major output of the system, representing approximately 10% of the rotational energy \( E_{rot} \) of the black hole. About \( 1 - 2\% E_{rot} \) is emitted in MeV-neutrinos. Both these emissions do not affect the environment. The output in torus
winds of about $1\% E_{\text{rot}}$ impact the remnant stellar envelope from within with continuum radiation and with kinetic energy. We recently suggested that this continuum radiation from within may be the source of X-ray line-emissions, when the envelope has expanded and goes through a transition from optically thick to optically thin. This proposal is similar but not identical to the reflection model, as discussed by (Lazzati et al., 2002) where line-emission is excited by incidence of continuum radiation on the surface of an optically thick slab. The efficiency of continuum-to-line emission is generally on the order of a few percent in such reflection processes.

Based on Lazzati et al. (2002), Ghisellini et al. (2002) discuss a model-dependent analysis of required continuum-energies $E_c$ for excitation of line-emissions in GRB 970508 (Piro et al., 1999), GRB 970828 (Yoshida et al., 1999), GRB 991216 (Piro et al., 2000), GRB GRB 000214 (Antonelli 2000) and GRB 011211 (Rees et al. 2002). This indicates energies $E_c \geq 4 \times 10^{52}$erg in GRB 991216, pointing towards an energy reservoir in excess of that required for the GRB-energies $E_\gamma$, assuming a canonical efficiency of kinetic energy-to-gamma rays of about 15%. This supports the notion that the GRB inner engine is processing other channels of emissions, in addition to and in excess of baryon-poor input to GRB-afterglow emissions.

The predicted long burst in gravitational radiation associated with GRB-supernovae (“hypernovae”) may be detected by upcoming gravitational wave-experiments. We mention broad band laser interferometric instruments LIGO (Abramowici1992), VIRGO (Bradaschia 1992), TAMA (Massaki 1991) and GEO (e.g., Schutz & Papa, 1999), and bar or sphere detectors presently under construction. Calorimetry on this energy output provides a method for testing the existence of Kerr black holes as objects in nature.

Calorimetry on hypernova remnants may further provide constraints on the angular velocity of the torus and hence its frequency in gravitational radiation. This serves to design and optimize specific search strategies for the accompanying bursts of gravitational radiation. Remnants of hypernovae are predicted to be black hole binaries surrounded by a supernova remnant. An example of this morphology is RX J050736-6847.8 (Chu et al. 2001).

In Section 2, we review radiation from Kerr black holes surrounded by a torus. In Section 3, we calculate a supernova connection from the the impact of the torus winds on the remnant envelope of the progenitor star. We propose a remnant in Section 4, and conclude with suggestions for future observations in Section 5.
Fig. 1.— Shown is the histogram of redshift corrected durations of 27 long bursts with individually determined redshifts from their afterglow emissions. We identify these long durations with the lifetime of rapid spin of a Kerr black hole in a state of suspended accretion. These durations are effectively defined by the rate of dissipation of black hole-spin energy in the horizon – an unobservable sink of energy – subject to a new magnetic stability criterion for the torus. (Reprinted from M.H.P.M. van Putten, 2002, ApJ, 575, L71.)
2. Black hole-beauty

A torus around a rotating black hole becomes radiant by *three-fold equivalence to pulsars*: in poloidal topology, causality and ms rotation periods. In accord with Mach’s principle, the inner face of the torus hereby receives input from the black hole – a nearby compact infinity with non-zero angular velocity – and the outer face radiates to asymptotic infinity. In response, conservation of energy and angular momentum causes the black hole to spin down, i.e.: *the black hole becomes luminous*. See (van Putten & Levinson, 2003) for a theory on tori surrounding rapidly spinning black holes.

The torus develops a state of suspended accretion, while the black hole spins rapidly. The equations of suspended accretion permit solutions with a positive gravitational wave-luminosity, produced by multipole mass-moments in the torus. These emissions in gravitational radiation and winds are further accompanied by thermal and neutrino emissions, as dissipation in the torus develops MeV-temperatures.

Most of the spin-energy of the black hole is dissipated in the horizon. This dissipation is rate-limited, and sets a lower bound of tens of seconds on the lifetime of its spin and, hence, the emissions by the torus. Most of the black hole-luminosity is incident onto the torus, whereby the torus’ emissions form the major energy output of the system. Gravitational radiation, in turn, defines most of the output from the torus, and represents about 10% of the spin-energy of the black hole.

A small fraction of black hole-spin energy is released along the axis of rotation in the form of baryon-poor outflows along an open magnetic flux-tube. This magnetic flux-tube extends from the horizon to infinity. A horizon half-opening angle corresponding to the curvature in poloidal topology of the inner torus magnetosphere defines an energy output in baryon-poor outflows of about 0.1% of the rotational energy of the black hole. This is in quantitative agreement with the observed value of $E_\gamma \simeq 3 \times 10^{51}$ erg in GRB-energies, assuming a canonical efficiency of kinetic energy-to-gamma rays of about 15%.

We stress that our model for GRBs from rotating black holes accounts quantitatively for both the long durations relative to the Keplerian timescale (order parameter $\sim 10^4$), as well as the small output in GRB-energies relative to the rotational energy of the black hole (order parameter $\sim 10^{-3}$).

The model predicts a correlated output in gravitational radiation and torus winds. In particular, their energies satisfy (van Putten (2003), corrected and simplified)

$$\frac{E_{gw}}{E_{rot}} \simeq \frac{\alpha \eta}{\alpha(1 + \delta) + \eta^2} \sim \eta$$

(1)
in the limit of strong viscosity (large $\alpha$) and small slenderness (small $\delta$). Here $f_w$ denotes the fraction of open magnetic flux supported by the torus which connects to infinity, $\delta = b/2a$ is a ratio of minor-to-major radius of the torus and $\eta$ denotes the ratio of the angular velocity of the torus to that of the black hole, which satisfies $\eta \sim 1/4\alpha$ for large $\alpha$. The energy emissions in winds satisfies

$$\frac{E_w}{E_{rot}} \sim \frac{\eta f_w^2 (1 - \delta)^2}{\alpha (1 + \delta) + f_w^2} \sim \eta^2$$  \hspace{1cm} (2)

in the same limit considered in (1), applied to the case of a symmetric flux-distribution with $f_w = \frac{1}{2}$. In dimensionful form, these energy emissions are $E_{gw} \simeq 4 \times 10^{53} \text{erg} \left(\eta/0.1\right) \left(M_H/7M_\odot\right)$ and $E_w \simeq 4 \times 10^{52} \text{erg} \left(\eta/0.1\right)^2 \left(M_H/7M_\odot\right)$. The frequency of quadrupole gravitational radiation $f_{gw}$ and the energy in winds are related by

$$f_{gw} \simeq 470 \text{Hz} \left(\frac{E_w}{4 \times 10^{52} \text{erg}}\right)^{1/2} \left(\frac{7M_\odot}{M_H}\right)^{3/2}. \hspace{1cm} (3)$$

For the purpose of calorimetry on $E_w$, we set out to identify observable signatures of the impact of the torus winds on its surroundings.

3. Black hole-supernovae

Prompt core-collapse in young massive stars in binaries may produce Kerr black holes surrounded by a disk or torus, formed from matter stalled against an angular momentum barrier (Brown et al., 2000). Prompt collapse takes place on a free-fall time, or less through the agency of magnetic fields (see, e.g., van Putten & Ostriker 2001). As a result, the newly formed black hole-torus system is initially surrounded by a remnant stellar envelope. Spin-energy of the black hole released in the form of torus winds promptly impacts this stellar envelope from within.

The kinetic energy and radial momentum of the torus winds provides a powerful mechanism to eject matter, producing a supernova associated with the underlying GRB. GRB 991216 and GRB 011211 both show initial ejection velocities $\beta \simeq 0.1$, relative to the velocity of light, as observed in blue-shifted X-ray line-emissions. This blue-shift defines the efficiency $\beta/2$ of conversion of an energy $E_w$ in essentially luminal torus winds to a kinetic energy $E_{SNR}$ of matter ejecta. This leaves $E_{SNR} \simeq (1/2)\beta E_w \sim \text{few } \times 10^{51} \text{ erg}$ from $E_w = \text{few } \times 10^{52} \text{ erg}$. These values are remarkably similar to the kinetic energies in non-GRB supernova remnants. Because the efficiency $\beta$ of $E_w$ to $E_{SNR}$ is somewhat larger than the efficiency of continuum-to-line emissions, it is a preferred method for calorimetry on torus winds.
The energetic impact on the envelope provides a source of continuum emission for excitation of X-ray lines, and deposits kinetic energy. The above shows that both of these processes are remarkably inefficient. Excitation of X-ray lines by continuum emissions has an estimated efficiency of less than one percent (Ghisellini 2002). Deposition of kinetic energy by approximately luminal torus winds has an efficiency of $\beta$, denoting the ejection velocity relative to the velocity of light.

Matter ejecta in both GRB 991216 (Piro et al., 2000) and GRB 011211 (Reeves, 2002) show an expansion velocity of $\beta \approx 0.1$. The efficiency of kinetic energy deposition of the torus wind onto this remnant matter is hereby $\beta/2 = 5\%$. With $E_w$ as given in (2), this predicts a supernova remnant with $E_{SNR} \approx \frac{3}{2} \beta E_w \approx 2 \times 10^{51}$ erg, which is very similar to energies of non-GRB supernovae remnants. We emphasize that ultimately, this connection is to be applied the other way around: obtaining estimates for $E_w$ from kinetic energies in a sample of supernova remnants around black hole binaries, by assuming that $\beta \sim 0.1$ holds as a representative value for the initial ejection velocity obtained from $E_w$. This assumption may be eliminated by averaging over observed values of $\beta$ in a sample of GRB-supernova events with identified line-doppler shifts.

4. Remnants of beauty

The angular momentum in rapidly spinning black holes produced in core-collapse probably derives from orbital angular momentum, following prior interaction of the young massive star with a binary companion (Paczynski 1998; Brown 2000). Therefore, the end product of the black hole-supernova is a black hole binary (a black hole and a low mass companion) surrounded by a supernova remnant, accompanied by a burst of gravitational radiation as an echo in eternity.

It becomes of interest, therefore, to search for black hole binaries in supernova remnants. A particularly striking example of an X-ray binary surrounded by a supernova remnant is RX J050736-6847.8. The above suggests that this X-ray binary may harbor a black hole.

5. Conclusions

We present a mechanism for long-duration bursts (of tens of seconds) of gravitational radiation powered by Kerr black holes. This emission is catalyzed by a surrounding torus, in association with minor outputs in winds, thermal and MeV neutrino emissions. A small fraction of the black hole-spin energy is released contemporaneously along the axis of rotation.
We propose this as a model for GRB-supernovae (“hypernovae”), following Woosley’s (1993) scenario of black hole formation in core-collapse of massive stars (Paczynski 1998, Brown 2000).

The proposed model accounts quantitatively for the secular timescale of long GRBs and the relatively small GRB-energies. The torus emissions in various energy channels are correlated with the Keplerian angular velocity, which establishes a relation between wind-energies and the frequency of quadrupole gravitational radiation. This provides an avenue to use calorimetry on torus winds and its remnants in support of predicting frequencies of gravitational radiation. This is intended for designing optimal detection and search strategies in upcoming gravitational wave-experiments. The interaction of the torus wind with the remnant envelope may further produce a burst in radio emission, which could be a source of interest for LOFAR/SKA. Some constraints might be placed on the statistics of these bursts by the recent analysis of Levinson et al. (2002).

The model predicts hypernova remnants in the form of black hole binaries surrounded by a supernova remnant. A candidate of particular interest is RX J050736-6847.8. It becomes of interest to pursue searches for a sample of such X-ray binaries surrounded by supernova remnants, of which some may harbor black hole binaries.

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Fig. 2.— A tree of black hole-spin energy, catalyzed by a torus: most energy is dissipated in the horizon, most of the output is in gravitational radiation, accompanied by a minor output in winds, thermal and neutrino emissions. A small fraction is released in baryon poor outflows as input to GRB-afterglow emissions. Direct measurement of gravitational radiation by upcoming gravitational wave-experiments provides a calorimetric test for Kerr black holes (dark connections). Calorimetry on torus winds (below the dashed line, incomplete or unknown) provides an avenue for constraining the angular velocity of the torus, and hence its frequency of gravitational radiation. Ultimately, this leaves a black hole binary, possibly an SXT, surrounded by an SNR. (Reprinted from van Putten & Levinson, ApJ, 2003, in press.)
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