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OFF-AXIS PROPERTIES OF SHORT GAMMA-RAY BURSTS

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ABSTRACT

Based on recent models of relativistic jet formation in BH-torus systems as remnants of compact binary mergers, the relation between the on- and off-axis appearance of short, hard gamma-ray bursts (GRBs) is discussed in terms of energetics, duration, average Lorentz factor, and probability of observation assuming that they are produced by neutron star (NS+NS) or neutron star-black hole (NS+BH) binary mergers. As a consequence of the interaction with the torus matter at the jet basis and the subsequent expansion of the jets into an extremely low-density environment, the collimated ultrarelativistic outflows possess flat core profiles with only little variation of properties, and are bounded by very steep lateral edges. Owing to the rapid decrease of the isotropic-equivalent energy near the jet edges, the probability of observing the lateral, lower Lorentz factor wings is significantly reduced and most short GRBs should be seen with on-axis-like properties. Taking into account cosmological and viewing angle effects, theoretical predictions are made about the short-GRB distributions with redshift, fluence, and apparent energy. The detection of short GRBs with low Lorentz factors is statistically disfavored, suggesting a possible reason for the absence of soft short bursts in the duration-hardness diagram. It appears unlikely that the subenergetic GRB 050509b can be explained by off-axis observation.

Subject headings: gamma-ray bursts — hydrodynamics

1. INTRODUCTION

The origin of short GRBs has long been the subject of theoretical speculation. A long-standing prediction is that short GRBs might originate from NS+NS/BH mergers (e.g., Paczyński 1986; Eichler et al. 1989; Mészáros 2002, and references therein). In the widely favored scenario a NS+NS/BH system gives rise to a BH girded by a dense torus of gas from the disrupted NS companion. The BH accretes mass at rates up to many solar masses per second, releasing huge amounts of gravitational binding energy mostly in neutrinos, gravitational waves, and through magnetohydrodynamic processes.

Hydrodynamic simulations (Aloy, Janka, & Müller 2005) show that thermal energy deposition around post-merger BH-torus systems, e.g. by $\nu\bar{\nu}$ annihilation, can drive collimated, ultrarelativistic outflows with the high Lorentz factors, internal variability and internal shocks that are deemed necessary to explain GRBs with the fireball model (Piran 2004). Evidence for collimation (jet semi-opening angle $\theta_{\rm jet} \sim 8.6^{\rm o}$) was claimed for the short-GRB 050724 (Berger et al. 2005). This implies that only about 1% of all bursts point to Earth. Although more observations are needed to confirm the collimation of short GRBs, this first indication seems to agree with the hydrodynamic simulations of AJM05.

Only this year have a few short GRBs been localised. Their properties are recapped in Table 1. Two of these short GRBs are hosted by elliptical galaxies. This adds confidence to the idea that the progenitors of short GRBs are old systems. In addition, GRB 050509b is in the outskirts of its potential host, in agreement with expectations that coalescing compact binaries can travel large distances away from their birth sites during their long gravitational-wave driven inspiral. Moreover, a possible SN association has been ruled out for GRB 050509b (Hjorth et al. 2005; Castro-Tirado et al. 2005).

Three out of four short GRBs were detected at similar redshifts ($z \sim 0.2$), but their $E_{\gamma,\rm iso}$ span a factor of ~ 10. The observation of generically less energetic short GRBs at higher redshifts may be selected against.

In this paper we use the jet models of AJM05 to discuss theoretical predictions for the observable properties of short GRBs as a function of viewing angle (Sect. 2). In Sect. 3 we investigate the consequences of these models for the probability of observing short bursts with different apparent energies and Lorentz factors, including the selection effects due to cosmological redshift. A summary and conclusions follow in Sect. 4.

2. JETS FROM POST-MERGER BLACK HOLES

In the relativistic hydrodynamics simulations of AJM05 the formation of ultrarelativistic outflows from BH-torus systems is studied. The BH and torus masses and the deposition of thermal energy around the BH, are chosen as expected from NS+NS/BH merger models. For different assumptions about the environment density, the variable energy deposition rate, the geometry, and the time-dependence, we followed the acceleration, collimation, and propagation of the ultrarelativistic outflows for an evolution time of 0.5 seconds. Although these simulations are still far from taking into account all potentially relevant physics and do not self-consistently follow the viscosity-driven torus evolution and its neutrino emission, they nevertheless provide useful insight into the conditions and properties of mass outflows from post-merger BH-torus systems.

The fact that an ultrarelativistic jet is launched from a "naked" BH-torus system has important consequences for its properties. While in the case of collapsars as sources of long GRBs the ultrarelativistic outflow origi-

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Table 1
Observed short GRBs

GRB	z	Satellite	Band keV	$T_{\rm ob}^{(a)}$ ms	$T_{\rm i}^{(b)}$ ms	Fluence 10^{-8} erg cm^{-2}	$E_{\gamma,\rm iso}$ 10^{50} erg s^{-1}	$\langle L\rangle^{(c)}$ 10^{50} erg	$E_{\rm p}$ keV	$\eta^{(d)}$	$k^{(e)}$	Gal.	d$^{(f)}$ kpc	SFR $M_\odot yr^{-1}$	Ref.$^{(g)}$
050509b	0.225	Swift	15-150	40	33	0.95 ± 0.25	0.011	1.4	>150	1.5 ± 0.4	4.34	Ell	40	< 0.01	1,5
050709	0.16	Hete-II	30-400	70	60	29 ± 4	0.167	4.7	83^{+18}_{-12}	0.7 ± 0.2	1.71	SF	3	–	2,6
050724$^{(h)}$	0.257	Swift	15-350	250	200	11.3 ± 8.7	0.174	1.7	>350	1.71 ± 0.16	1.91	Ell	2.6	< 0.02	3,7
				3000	2387	63 ± 10	0.97	0.8	...						
050813	0.72?	Swift	15-350	32	19	12.4 ± 4.6	1.6	240	>350	1.19 ± 0.33	2.82	?	–	–	4,8

(a) Observed duration.
(b) Intrinsic duration (cosmologically corrected).
(c) Average luminosity (computed as $\langle L\rangle \equiv k\, E_{\gamma,\rm iso}/T_{\rm i}$).
(d) Photon index of the average GRB spectrum ($f(E) \propto E^{-\eta}$).
(e) Bolometric correction to rest-frame 20-2000 keV, following Bloom et al. (2001).
(f) Projected distance of GRB from host center.
(g) References: 1. Gehrels et al. (2005); 2. Boer et al. (2005); 3. Krimm et al. (2005); 4. Sato et al. (2005); 5. Bloom et al. (2005); 6. Price et al. (2005); 7. Berger et al. (2005); 8. Foley et al. (2005).
(h) This GRB shows a first short pulse, followed by a softer and longer event. We report the duration, fluence and $E_{\gamma,\rm iso}$ values for both the first short pulse and the total event.

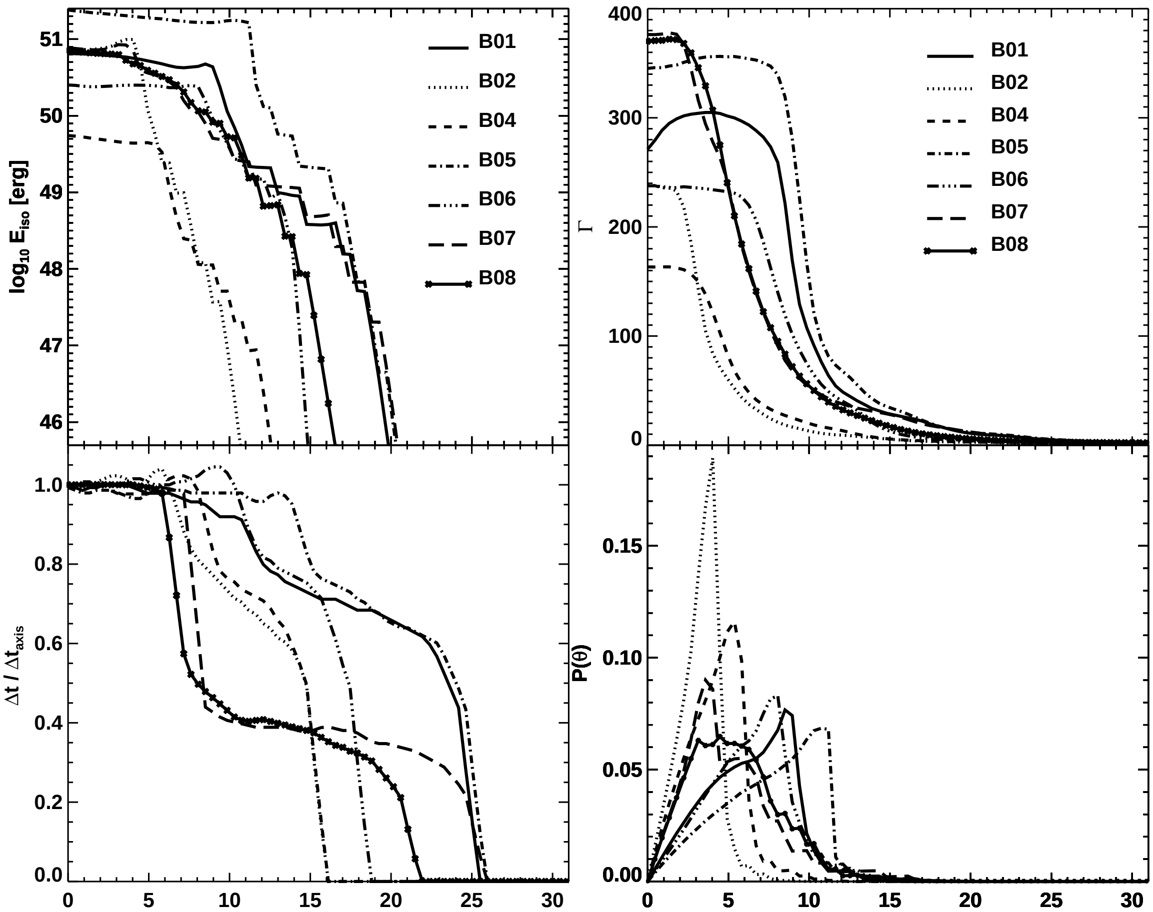

Fig. 1.— Properties of relativistic outflows from BH-torus systems as functions of viewing angle, determined by hydrodynamic simulations which show that collimated, ultrarelativistic outflow can be driven by sufficiently powerful deposition of thermal energy around the relic BH-torus systems of NS+NS/BH mergers. Models B01–B08 differ in the rate of energy deposition per unit of solid angle around the BH (AJM05). *Top left:* Total (internal plus kinetic) isotropic equivalent energy of ultrarelativistic, collimated ejecta with terminal Lorentz factors $\Gamma_\infty > 100$. This energy may be larger than the GRB energy by a factor depending on the conversion efficiency of outflow energy to γ-rays. *Top right:* Radially averaged Lorentz factor Γ at 0.5 seconds after the onset of energy deposition (AJM05). Note that the terminal value Γ_∞ can be higher by a factor of 2–3. *Bottom left:* Timescale of the observable GRB estimated from Eq. (1) relative to its on-axis duration. *Bottom right:* Relative probability of observing short GRBs from different viewing angles, estimated according to Eq. (2).

nates from BH-torus systems at the center of a massive star, the polar jets in NS+NS/BH mergers do not have to make their way through many solar masses of overlying stellar matter. Since the acceleration is not damped by swept-up matter, the jets very quickly reach Lorentz factors of a few. The acceleration is driven by the enormous radiation pressure of the pair-photon fireball produced by the energy release around the BH. Collimation of the baryon-poor jets is provided by the much denser torus walls which gird the evacuated polar regions of the BH. As the jets propagate into the extremely low-density environment, they continue to accelerate, reaching maximum Lorentz factors of a few 100 within the simulated evolution time.

As a consequence of the interaction with the torus matter at the jet basis and the subsequent free expansion, the collimated ultrarelativistic outflows possess flat core profiles with only little variation of specific properties. These cores are bounded at their lateral edges by very steep gradients, which are not smoothed by the prolonged entrainment of baryons as is the case for long GRB jets. Because of the rapid decrease of the isotropic-equivalent energy, for example, the probability of observing the lateral, lower Lorentz factor wings must be expected to be significantly reduced.

Figure 1 provides an overview of the results for the sample of "type-B" models discussed by AJM05. In these simulations the BH-torus system was assumed to be surrounded by a medium of extremely low density. The models differ in the adopted rate of thermal energy deposition per solid angle and in the prescribed time dependence. The parameters were chosen such that the $\nu\bar{\nu}$ annihilation as calculated from NS+NS/BH merger simulations, and in particular for the post-merger accretion of a BH (Ruffert & Janka 1999; Janka et al. 1999; Janka & Ruffert 2002; Setiawan et al. 2004) was qualitatively and quantitatively reproduced. Because of large variations of the torus masses expected from compact object mergers[4], AJM05 explored a wide range of energy deposition properties, approximately covering the range of predictions from merger simulations (cf. Table 1 in AJM05[5].

Model parameters account for the variation of the on-axis values of the *isotropic-equivalent kinetic plus internal energies* $E_{\rm iso}(\Gamma_\infty)$ of jet matter with estimated terminal Lorentz factors $\Gamma_\infty > 100$ (Fig. 1, top left). The models span a range of ~ 100 in $E_{\rm iso}$, from some 10^{49} erg to more than 10^{51} erg. Depending on the efficiency of energy conversion to γ-ray emission, the measurable γ-ray energy may be roughly a factor of 10 lower than $E_{\rm iso}(\Gamma_\infty)$ (e.g. Guetta, Spada, & Waxman 2001, and references therein). All models show a flat core and steep lateral wings in the radial average of Γ (Fig.1, top right), but Models B07 and B08 have a somewhat more shallow decline of $E_{\rm iso}$ because a gradual decrease of the energy deposition rate was assumed after an initial, burst-like phase. This caused a continuous decrease of the jet opening angle, thus softening the wings of the jet profile.

Energy release with $E_{\rm iso}(\Gamma_\infty) > 10^{48}$ erg is confined to semi-opening angles between about $8^{\rm o}$ and $18^{\rm o}$, corresponding to a collimation ("beaming") factor of the two polar jets of $f_\Omega = 1 - \cos\theta_{\rm jet}$ between 1% and 5%, where $\theta_{\rm jet}$ is the jet semi-opening angle. Variations of the predicted GRB duration are modest (~ 20–30% of the on-axis value, Fig. 1, lower left). The maximum duration of the GRB can be estimated as (AJM05, Eq. 15)

$$\Delta t_{\rm GRB}(\theta) \lesssim \left(R_\gamma - \frac{v_{\rm r}(\theta)}{v_{\rm f}(\theta)}(R_\gamma - t_{\rm ce}c) \right) c^{-1} \ , \quad (1)$$

where $v_{\rm f}$ and $v_{\rm r}$ are the velocities of the front and rear ends of the ultrarelativistic ejecta and R_γ is the radius at which the GRB is produced. Thus, burst duration not directly is associated with the on-time $t_{\rm ce}$ of the central engine [6], but takes into account the significant stretching an ultrarelativistic outflow experiences on its way to the radius where it becomes transparent (for details, see AJM05). This effect is not very relevant for long bursts where the engine at the center of a dying star releases energy over a timescale of many seconds, but can be the dominant effect determining the duration of short GRBs.

The relative probability of observing a short burst from a model of our set under different polar angles θ is shown in Fig. 1, lower right. We plotted there the quantity

$$P(\theta) \equiv \frac{\int_{\cos\theta}^{1} {\rm d}\cos\theta' \, E_{\rm iso}(\theta')}{\int_{-1}^{1} {\rm d}\cos\theta' \, E_{\rm iso}(\theta')} \ , \quad (2)$$

where for a rough estimate we assumed $f_{\rm det}(\theta) \propto E_{\rm iso}(\Gamma_\infty)$ for the detectability of a burst. The probability distribution confirms the steep lateral edges visible in the other quantities for Models B01–B06 and the slightly softer wings in Models B07 and B08, which correlate with a sharp drop of the average Lorentz factor. The probability $P(\theta)$ peaks at angles between $4^{\rm o}$ and $\sim 11^{\rm o}$, which is a somewhat smaller range than that associated with $E_{\rm iso}(\Gamma_\infty) > 10^{48}$ erg. Morever, $P(\theta)$ nicely demonstrates the widening of the lateral visibility of a GRB with increasing energy deposition per solid angle around the BH (cf. the sequence of Models B02, B04, B06, B01, and B05).

3. OBSERVABILITY OF SHORT GRBS

From our set of jet models we can make predictions for the observable short-GRB distributions versus redshift z, fluence, $E_{\gamma,\rm iso}$, and Lorentz factor Γ, and discuss these in view of the observed bursts of Table 1. For this analysis we assume that our models have equal probability and are representative of the intrinsic variability of the short GRB source population at all redshifts. This crucial assumption can certainly be questioned, but can currently hardly be replaced by better and meaningful alternatives because of the still large uncertainties on to the link between NS+NS/BH binary parameters and GRB properties (a more detailed discussion of this will be given in Aloy at al., in preparation).

[4] The mass of the remnant torus varies with the masses and spins of the binary components and with their mass ratio; it is also sensitive to as yet uncertain properties of dense NS matter and depends on general relativity effects that are included only in a subset of the current NS+NS/BH merger simulations.

[5] A lower limit to the energy deposition rate needed to drive a relativistic outflow is set by the fact that the ram pressure of polar mass inflow to the BH must be overcome (see AJM05 for details; Model B03 in that paper did not reach the energy deposition threshold.)

[6] This is the timescale over which the energy release is sufficiently powerful to drive an ultrarelativistic outflow as required for GRBs.

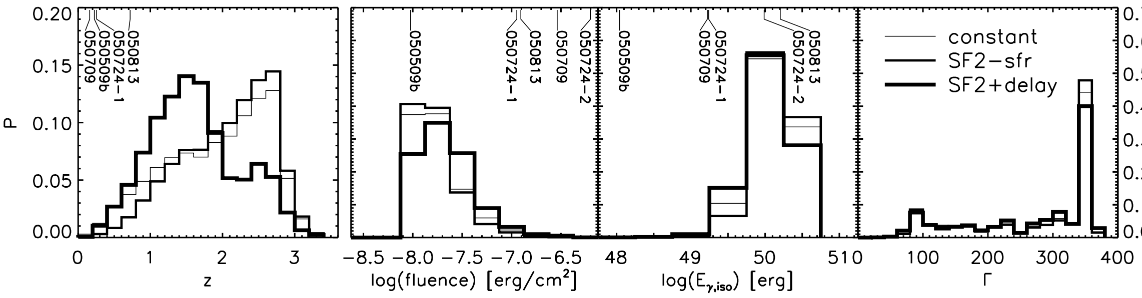

Fig. 2.— Normalized probability distributions of short GRBs as functions of redshift z, fluence, apparent energy $E_{\gamma,\mathrm{iso}}$, and Lorentz factor Γ. The theoretical predictions are based on the results for the sample of jet models shown in Fig. 1, adopting a lower fluence cut-off of $10^{-8}\,\mathrm{erg\,cm^{-2}}$ for the burst detectability. Note that the terminal Lorentz factors Γ_∞ will be higher. The lines correspond to three cases of different assumed comoving short GRB rate density as function of z (see text for details). The locations of the observed short GRBs listed in Table 1 are indicated.

In order to test the sensitivity of our analysis to a variation of the comoving short GRB rate density as function of redshift, $R_{\mathrm{GRB}}(z)$, we consider three cases, namely a GRB rate which (i) is constant with comoving volume, (ii) follows the star formation rate SF2-sfr in Fig. 5 of Guetta & Piran (2005), or (iii) varies according to the binary neutron star merger rate, case SF2+delay in Fig. 5 of Guetta & Piran (2005).

Based on these prescriptions, we produced random observed GRB distributions by Monte Carlo sampling, using GRB energies and Lorentz factors as functions of viewing angle θ from our models (Fig. 1). We estimated the apparent GRB energy, $E_{\gamma,\mathrm{iso}}(\theta)$, by reducing the isotropic equivalent kinetic plus internal energy of the outflow, $E_{\mathrm{iso}}(\theta)$, by a factor of 10 to account for the limited efficiency of energy conversion to γ-rays. The number of events $\mathrm{d}N(x_1, x_2)$ in a parameter interval $x_1 < x < x_2$ was calculated according to

$$N(x_1, x_2) = \int_{x_1}^{x_2} \mathrm{d}x \int_0^{\infty} \frac{\mathrm{d}V}{\mathrm{d}z}\,\frac{\epsilon_{\mathrm{det}}}{1+z}\,\frac{\mathrm{d}R_{\mathrm{GRB}}}{\mathrm{d}x}\,\mathrm{d}z\ , \quad (3)$$

where $\mathrm{d}V/\mathrm{d}z = 4\pi D_{\mathrm{L}}^2(z) c [H_0(1+z)^2(\Omega_{\mathrm{M}}(1+z)^3 + \Omega_{\mathrm{B}}(1+z)^2 + \Omega_\Lambda)^{1/2}]^{-1}$ is the comoving volume element, $(1+z)^{-1}$ accounts for cosmological time dilation, and ϵ_{det} is the detection efficiency parameter, which we simply approximate by a step function, cutting off detections with fluence below $10^{-8}\,\mathrm{erg\,cm^{-2}}$. The fluence at the detector was computed from the intrinsic source energy output $E_{\gamma,\mathrm{iso}}$ and the luminosity distance $D_{\mathrm{L}}(z)$. The cosmological parameters used in our study are $H_0 = 72\,\mathrm{km\,s^{-1}Mpc^{-1}}$, $\Omega_{\mathrm{M}} = 0.24$, $\Omega_{\mathrm{B}} = 0.04$, and $\Omega_\Lambda = 0.72$. The results of this analysis are displayed in Fig. 2, which shows the normalized probability distributions versus redshift, fluence, $E_{\gamma,\mathrm{iso}}$, and Γ. We point out that the Lorentz factors are based on those shown in Fig. 1 and therefore must be expected to be smaller by a factor of 2–3 than the terminal values Γ_∞.

4. DISCUSSION AND CONCLUSIONS

According to Fig. 2, we expect that short-GRB observations should be gradually depleted at $z \gtrsim 1.5$ for case (iii) or rapidly beyond $z\ \sim 2.6$ for cases (i) and (ii). The latter two cases show very similar results for all parameters, because the distributions are dominated by sources at $z \gtrsim 1$, where the star formation rate SF2-sfr becomes essentially constant. Smaller differences for $z \lesssim 1$ are caused by the decay of the latter in this region. In case (iii) roughly 20% of all bursts are seen at $z < 1$. We estimate measurable fluences below $\sim 10^{-7}\,\mathrm{erg\,s^{-1}}$ for the large majority of our simulated short GRBs. Three of the four observed GRBs in Table 1 are therefore near the bright end.

The distribution of $E_{\gamma,\mathrm{iso}}$ is strongly peaked at $\sim 10^{50}\,\mathrm{erg}$, with wings extending in both directions over roughly an order of magnitude. GRB 050509b was certainly an exceptionally weak event, which most probably was *not* an off-axis observation, but requires either events with lower energy output than for any of the jet models in our sample, or an efficiency of energy conversion to γ-rays lower than assumed here. The probability distribution of the Lorentz factor reflects the discreteness of our sample of models, because the redshift has no influence on Γ and because the jet wings are extremely steep and the off-axis visibility much reduced (see Fig. 1). Therefore, the high-energy Model B05 with a relatively wide jet clearly sticks out in the Γ-distribution. A continuous set of models would broaden this peak, but hardly add much to the very low "underwood" of events extending to low values of Γ. We hypothesize that this clear bias towards observing high-Γ events may be connected with the lack of short, soft GRBs in the duration-hardness diagram.

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