A UNIVERSAL CENTRAL ENGINE HYPOTHESIS FOR SHORT AND LONG GAMMA-RAY BURSTS

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ABSTRACT

It is noted that X-ray tails of short, hard γ-ray bursts (SHBs) are similar to X-ray flashes. We suggest a universal central engine hypothesis, as a way of accounting for this curiosity, in which SHBs differ from long γ-ray bursts in prompt emission because of the differences in the host star and attendant differences in the environment they present to the compact central engine (as opposed to differences in the central engine itself). Observational constraints and implications are discussed.

Key words: gamma rays: bursts

1. INTRODUCTION

Short γ-ray bursts (GRBs), originally defined to be GRBs lasting less than 2 s and predicted to be a separate class of phenomena (Kouveliotou et al. 1993), are now widely suspected of being two merging compact objects. This somehow distinguishes them in their duration and other properties from the core collapse of a massive star. In the former case, primary emission can in principle be detected even if it comes from less than 2 lt-s from the black hole (BH), which would probably be impossible for long bursts, where envelopes would obscure photon emission from these scales. The central engines of each, however, are likely to be similar: a BH of maximum angular momentum surrounded by an accretion disk of matter near nuclear densities.

A fundamental open question about short GRBs is why they are so short. Is it because the central engine (presumably a BH fed by an accretion disk) operates on a shorter timescale than those of long GRBs? Or they could represent two separate physical phases of a burst, the relative strengths of which depend on some parameters such as baryon content (Ruffini et al. 2001). Alternatively, it may be the timescale over which the γ-rays are visible to a given observer. For example, the prompt γ-rays could be scattered off slow baryons (Eichler & Manis 2007) and the short duration is a result of the baryons getting accelerated to a high enough Lorentz factor to exclude much further emission along our line of sight. What seems like a short burst to us would then appear to be a much longer burst to some other observer along a different line of sight. The hypothesis can account for the fact that short bursts tend to have harder spectra, lower luminosity, and a larger solid angle than long bursts. It also accounts for the inverse correlation between luminosity and spectral lag (Hakkila et al. 2008 and references therein) in a simple manner, assuming the acceleration is due to the primary radiation pressure.

In this Letter, we propose a universal central engine hypothesis for both short and long bursts. We suggest that the same compact, central engine can produce what seems to be a short, hard burst (SHB) to a viewer at large viewing angle, and a long burst to a viewer at a smaller viewing angle. The distinction between “central engine”—by which we mean the post-collapse compact object—and “progenitor” is emphasized. We keep the now common view that SHBs come from merging neutron stars (NSs) or other systems without a large envelope, whereas the long bursts typically come from progenitors with large, post-main-sequence envelopes.

That typical viewing angle should correlate with the progenitor and host environment is straightforward: a central engine sitting within a massive envelope is obscured by the envelope, and the fireball material within the envelope can be observed directly down the hole bored by the fireball in the envelope (Figure 1). Observers outside the opening angle θo established by this hole can see emission from the material only after it has nearly emerged from the envelope, and, from well outside the opening angle of the emerging material (including its 1/Γ emission cone), they detect kinematically softened emission that is nearly backward in the frame of the fireball. Such an observer cannot view matter while it is well within the confines of the envelope (R ≲ 10^{12} cm). When, on the other hand, there is no massive envelope obscuring the central engine, matter can be seen from within 10^{12} cm, and subsecond timescales become possible. The significance of the host/progenitor may then be the angles at which it allows the burst to be observed, and, therefore, the stage of the burst that is observable.

The unified model proposed here should be contrasted to that of Yamazaki et al. (2004b; Toma et. al 2005a) which, somewhat presciently, was made before the operation of Swift (and the resulting localization of SHBs). They proposed that short bursts come from the same central engine as long bursts, and that they appear short when one emitting “minijet” of many comes close enough to the line of sight as to dominate over the contribution of all the others. Observers at large offset angle to the axis of the swarm of minijets see X-ray flashes (XRFs), but little or no hard emission. In the Yamazaki et al. picture, it would be hard to understand why SHBs typically come from different types of galaxies and, by inference, different types of progenitors (Toma et al. 2005b). It would also be hard to understand why SHBs are underluminous (or overly hard) in the context of the Amati relation. It is not clear that the hard part of the GRB would always precede the soft part. Finally, it would be hard to understand why the small-scale time structure and spectral lags...
in SHBs are qualitatively different from those in long GRBs.
In the unified model we propose here, on the other hand, the hard photons of the SHB are seen at large viewing angles, but can also observe an SHB of scattered γ-radiation as the scatterer accelerates through a Lorentz factor that is the reciprocal of the observer's viewing angle. Observer 3 sees an even weaker, softer XRT, and (also only if his line of sight is not obscured) an even shorter hard GRB.

Below, we summarize the observations that motivate the universal central engine hypothesis. We then show that a particular model for GRB subpulses can produce a viable model for SHBs and the X-ray tails (XRTs).

**Observational Motivations.** SHBs frequently display long XRTs that compare in duration to long XRFs. The discovery (e.g., Donaghy et al. 2006; Norris & Bonnell 2006; Gehrels et al. 2006) confirmed by *Swift* that short bursts have XRTs of much longer duration than the burst itself heightens the suspicion that the central engine continues to operate for longer than 2 s. Donaghy et al. report that most SHBs observed with *HETE II* (which has a lower photon energy threshold than *Swift*) have long, soft tails, whereas the fraction of *Swift* SHBs is somewhat less, about half. We may interpret this as XRTs being slightly softer than XRFs and/or as *Swift* being more sensitive than *HETE II* to the short, hard phase of SHBs. We argue below that these small spectral differences are expected, because the larger the viewing angle, the shorter and harder the emission of the short phase, when by hypothesis \( \Gamma \sim 1/\theta \), and the softer the tail emission when \( \Gamma \) has reached its terminal value.

Apart from possibly being slightly softer, these XRTs are quite similar to γ-ray-silent XRFs, which have been proposed to be “off axis” GRBs. This interpretation of XRFs has also been supported by their tendency to show depressed X-ray afterglow (relative to normal GRBs) until \( \sim 3 \times 10^4 \) s after the prompt emission (Sakamoto et al. 2008), after which the afterglow appears to be of about the same intensity as that of a classical GRB. This suggests that we are seeing a kinematically suppressed, under-blue-shifted signal that is predicted for an offset viewer.

There exists by now some evidence that SHBs are beamed into a small solid angle, similar to long GRBs. Fox et al. (2005) interpreted the steepening of the optical afterglow light curve of GRB 050709 and GRB 050724 in terms of a jet break, translating into a beaming factor \( f_b^{-1} \sim 50 \) (with \( f_b \) being the fraction of the 4π solid angle within which the GRB is emitted). Soderberg et al. (2006) found a beaming factor of \( \sim 130 \) for GRB 051221 A. Therefore, with the present data, the beaming angle of SHBs seems to be in a range of \( \sim 0.1–0.2 \) rad. The question is how this beam width compares to that of the XRT.

Below, we summarize the data on SHBs, note that the XRTs (unlike the hard emission) obey the Amati relation (Amati et al. 2002), describe a particular version of a universal central engine hypothesis, and attempt a rough estimate of the beam width of the XRTs of SHBs based on the supposition that they are basically XRFs. We have considered all the short bursts reported by *Swift* from its launch (2004 November) until 2008 March; this constitutes a sample of 28 bursts. As noted by Donaghy et al. (2006), prolonged soft emission in *HETE II* data is a rather reliable signature of SHBs, but, in the *Swift* data, there is large scatter in the luminosity of the XRTs relative to the γ-ray luminosity, and XRTs are not a reliable indicator for an SHB.

The XRTs are quite similar to γ-ray-silent XRFs detected by *HETE-II*, *BeppoSax*, and *Swift*. We made a spectral analysis of all the XRTs that could be detected by the WFC and did not find any evidence of a spectral break in the band 0.3–10 keV. We have therefore assumed a spectral peak at \( E_{\text{peak}} \sim 8 \) keV. The only burst that seems to have a higher energy break is 050724 (Campana et al. 2006), and we took \( E_{\text{peak}} \sim 20 \) keV for this burst. We see (Figure 2) that the XRTs obey the Amati correlation to within the uncertainties, whereas the prompt γ-ray emission is far removed from this correlation.

**Interpretation.** That XRTs of SHBs are consistent with the Amati relation is what is expected if both the short hard emission and the XRT are attributed to the offset viewing of what might be observable as a classic long GRB from a different direction. The X-rays are photons beamed backward in the frame of the classical fireball. They are reduced in frequency as the first power of the Doppler factor, and, in time-integrated fluence, by the square of the Doppler factor, when the beam is wider.
than the angular separation $\theta_V$ of the observer’s line of sight from the beam (Eichler & Levinson 2004). This gives the Amati correlation. When, on the other hand, $\theta_V$ is comparable to or larger than $\theta_o$, the apparent luminosity decreases as a steeper power of peak frequency (Yamazaki et al. 2002, 2004a; Eichler & Levinson 2004). The hard photons, on the other hand, are scattered into the line of sight by baryonic material that has not yet been accelerated beyond a Lorentz factor of $1/\theta_V$ (but soon will be). As such, the primary luminosity, as seen by observers in the beam, is diluted by the scattering, because the $1/\Gamma$ cone at low $\Gamma$ is much wider than it will end up when a maximum Lorentz factor is reached. Whereas the scattering reduces only modestly the individual photon energies to observers within $1/\Gamma$ of the axis of the scatterer’s motion—$[\cos \theta_V \geq \beta] - E'/E$ being at least $1/\Gamma^2 (1 - \beta^2) (1 + \beta) > 1/2$—it greatly dilutes the fluence by spreading it over a much wider solid angle. So the fluence is greatly below what the Amati relation would predict for viewers that are within $1/\Gamma_o$ of the primary beam when it is finally at its terminal Lorentz factor $\Gamma_o$. The observer at a wide angle (from the direction of the low $\Gamma$ scatterer) sees a much shorter hard pulse than the viewer at a smaller offset angle (Eichler & Manis 2007), as shown in Figure 3, because the acceleration time as measured by the observer is proportional to $\Gamma$. In these figures, we plot the light curve of the scattered emission from a single accelerating cloud with a pointlike geometry as seen by viewers at two different viewing angles. (We stress that this is not the same as predicting a light curve from the burst, which has a finite solid angle and time interval in which scatterers can be injected. The data superimposed in the same graph are merely for reference.) Other factors could contribute to the duration, such as the intensity of radiation pressure that causes the acceleration.

Assuming a Lorentz factor for the blast of $\Gamma(t) \simeq 100(t/100 \text{ s})^{3/8}$ (Sari et al. 1998), we estimate the Lorentz factor of the blast wave after $3 \times 10^3$ s, the typical recovery time for XRFs (Sakamoto et al. 2008), to be $\Gamma(10^3.5 \text{ s}) \sim (10^{11/16}) \sim 5$. Attributing the afterglow recovery to the decrease of the blast’s Lorentz factor down to $1/\theta_V$, one estimates that XRFs are typically observed at an offset angle of $\theta_V \sim 0.2 \sim 10^2$ from the blast. In fact, a complete recovery requires that $\Gamma$ decline to comfortably below $1/\theta_V$, so $\theta_V$, defined to be the angular distance to the edge of the jet, is defined to be less than 0.2. Writing $\theta_V$ as $10^{-1} \theta_{-1}$, the typical spectral peak of the XRTs $E_{\text{peak}}$ as $30 E_{30,30}$ keV, and the expected spectral peak measured by the head-on (ho) observer as $E_{\text{ho}} \sim 1 \text{ MeV}$, we estimate the Lorentz factor of the fireball that emits the prompt emission to be given by $0.03 E_{30,30}/E_{\text{ho}} = 1/\Gamma^2 (1 + \beta)(1 - \beta \cos \theta) \sim (\theta_V \Gamma)^{-2}$, or

$$\theta_V \Gamma \sim 6 \left[E_{30,30}/E_{\text{ho}}\right]^{1/2}.$$  \hspace{1cm} (1)

For $\Gamma \sim 10^2$, and $E_{30,30}, E_{\text{ho}}$ both $\sim 1$, this gives $\theta_V \sim 6 \times 10^{-2} \left[E_{30,30}/E_{\text{ho}}\right]^{1/2}$, which is consistent with the estimate of $\theta_V$ from the afterglow recovery time. Assuming that the jet itself has an opening angle of order $10^{-1}$ rad, this gives an opening angle for an XRF of about 0.1–0.2 rad, in reasonable agreement with the estimate from the flat phase of the afterglow. That the offset $\theta_o$ is comparable to the opening angle of the fireball jet $\theta_o$ suggests that for $E_{30} \ll 1$ the luminosity of the XRF should drop below that predicted by the Amati relation.

Short bursts, inasmuch as they are believed to be merging compact objects (NS–NS or NS–BH), are expected to be closely connected to gravitational wave signals (Eichler et al. 1989), and potential candidates, if close enough, for detection by LIGO. As these events could be of marginal statistical significance, it would be good to verify them independently with detections of high-energy emission that is believed to be associated with mergers. A wide angle X-ray camera in addition to a Swift-type detector that triggers on hard $\gamma$-ray emission could possibly increase our ability to corroborate LIGO signals as well as learn more about merger events. However, the large variation in X-ray to $\gamma$-ray fluence suggests that we should be cautious about making simple generalizations regarding the relative characteristics of the XRT and the $\gamma$-ray beams. Given our estimates of 0.1–0.2 rad for both the soft and hard beams, we could attribute the large variation in hard/soft emission ratio to the fact that the opening angles of the XRTs and hard $\gamma$-ray emissions are comparable, and that one can be observed...
near the ragged edge of the other. In our model, moreover, the fraction of hard γ-rays scattered into our line of sight can be highly variable from one burst to the next. Furthermore, the directions of the prompt γ-radiation and the accelerating baryons need not be the same (e.g., Eichler & Granot 2006, and references therein), so the respective locations of the observer’s line of sight to each of them are a somewhat free parameter. This affects the Lorentz factor of the scatterer that contributes to our line of sight, and hence the extent of solid angle dilution of the photon intensity. XRTs should therefore be considered as an important complement to (but not necessarily better than) SHBs in corroborating LIGO signals.

Summary. We have suggested that short, hard GRBs may have the same central engine as that of long GRBs, though having a different size host envelope, and that their duration is determined by the acceleration time of a relativistic scatterer that scatters them into our line of sight. A very rough estimate of the opening angle of XRTs, based on their hypothesized similarity to XRFs, is 0.1–0.2 rad, which is comparable to estimates of the opening angles for the hard emission. It is thus difficult to say which would be better for corroborating nearby compact mergers following LIGO triggers. Further information on the relative detectabilities of XRTs and the corresponding short hard γ-emission could be obtained by a wide field X-ray camera and γ-ray detectors working together. In six of 12 cases with known redshifts, the XRT would exceed $10^{-10}$ erg cm$^{-2}$ s$^{-1}$ had the burst been within 300 Mpc, the distance of GW detectability if the SHBs come from NS–NS mergers (e.g., Guetta & Stella 2008), so that LIGO might in such cases act as the primary trigger, which would have the valuable property of being free of any electromagnetic spectral bias.

One interesting prediction of the universal central engine hypothesis is that, while much of the X-ray flux comes before the location and slewing of the Swift X-ray telescope, much of the flux also can come out on a short timescale, the so-called “spike,” depending on whether the source has a soft primary component. This appears to be consistent with HETE-II observations of short bursts (Donaghy et al. 2006; Figures 2–5, 13, Table 7). An important distinction should be made between the short rise of soft emission and the longer tail. The “spike” (i.e., rise and peak) consists either of (1) photons that were soft at the primary source, and lost only about half their (observer frame) energy during the scattering, or (2) primary radiation that was softened by reprocessing at the scatterer, while the tail consists of photons that may well have been hard at the source and were drastically softened in the observer’s frame by making a near 180° rear end collision with the scatterer. The former should have a rise time that is nearly energy independent, as it is established by the acceleration time of the scatterer to 1/θ, while the latter have a much longer decay time at low energy because the collision-softened photons populate the low-energy bins at large τ (Eichler & Manis 2007). Thus, the relative shapes of the light curves in different energy bins, which reflect the relative contributions of these two classes of photons to the XRT, can be very sensitive to the primary spectrum, which, in turn, can be sensitive to the type of progenitor/host. For example, if the prompt, soft photons have a component of thermal emission from the back side of the scatterer that has been heated by a Compton recoil, we expect this component to have the same time profile as the hard γ-rays. Such a component could be more important for SHB environments, where the scatterer is closer to the central engine and sees a stronger radiation field. Moreover, at a lower Lorentz factor, its back end sees a harder radiation field, so the Compton recoil heats more efficiently. This and several other matters beyond the scope of this Letter bear further investigation.

A serious quantitative model of a SHB light curve within the context of the ideas sketched here should take into account the following: (1) the scatterer may in fact be a swarm of individual clumps running into each other and accelerating uniformly only as a group. Figure 3 should therefore be taken, at best, as a rough envelope that characterizes the general trend of the light curve. The individual subpulses may be scattered photons from scatterers that are accelerating (as well as decelerating) on a somewhat faster timescale, and therefore have smaller positive (as well as negative) spectral lags. (2) The distribution of scatterers as a function of angular separation from the observer’s line of sight is unknown but there are probably more at larger angles. The observed light curve is the sum over the individual contributions from the members of the swarm. (3) While the scatterer is at a modest Lorentz factor, backscattered photons may be intercepted by pair-producing collisions with primary photons. This can lower the X-ray luminosity near and just after the peak, when, for viewers at large angle, the Lorentz factor is still modest. (Eventually, as the Lorentz factor picks up, the primary photons in the frame of the scatterer are not energetic enough for pair production.) Thus, while primary, soft photons may escape immediately, the nearly 180° backscattered hard photons escape only after the overall Lorentz factor of the scatterers is high enough.

The universal central engine hypothesis also predicts that, occasionally, we are close to the axis of a GRB that originates from a SHB-type host. In such a case, the GRB would appear long in duration, but of the “short” variety in other ways. Indeed, there are such bursts (e.g., 060614) that confound a simple two-class classification scheme (Donaghy et al. 2006; Gehrels et al. 2006).

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REFERENCES

Amati, L., et al. 2002, A&A, 390, 81
Campana, S., et al. 2006, A&A, 454, 113
Donaghy, T. Q., et al. 2006, arXiv:0605570
Eichler, D., & Granot, J. 2006, ApJ, 641, L5
Eichler, D., & Levinson, A. 2004, ApJ, 614, L13
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126
Eichler, D., & Manis, H. 2007, ApJ, 669, L65
Fox, D. B., et al. 2005, Nature, 437, 845
Gehrels, N., et al. 2006, Nature, 444, 1044
Guetta, D., & Stella, L. 2008, A&A, in press
Hakkila, J., et al. 2008, ApJ, 677, L81
Kouveliotou, C., et al. 1993, ApJ, 413, L101
Norris, J. P., & Bonnell, J. T. 2006, ApJ, 643, 266
Ruffini, M., et al. 2001, ApJ, 555, L113
Sakamoto, T., et al. 2008, ApJ, 679, 570
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Soderberg, A., et al. 2006, ApJ, 650, 261
Toma, K., Yamazaki, R., & Nakamura, T. 2005a, ApJ, 620, 835
Toma, K., Yamazaki, R., & Nakamura, T. 2005b, ApJ, 635, 481
Yamazaki, R., Ioka, K., & Nakamura, T. 2002, ApJ, 571, L31
Yamazaki, R., Ioka, K., & Nakamura, T. 2004a, ApJ, 606, L33
Yamazaki, R., Ioka, K., & Nakamura, T. 2004b, ApJ, 607, L103