QUASI-UNIVERSAL GAUSSIAN JETS: A UNIFIED PICTURE FOR GAMMA-RAY BURSTS AND X-RAY FLASHES

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ABSTRACT

An observed correlation $E_p \propto (E_{iso})^{1/2}$ extending from Gamma-ray Bursts (GRBs) to X-ray flashes (XRFs) poses problems both for a power-law universal jet model where the energy per solid angle decreases as the inverse square of the angle respect to the jet axis, and for a conical jet model with a uniform energy density within the jet beam and a sharp energy cut-off at the jet edge. Here we show that the current GRB-XRF prompt emission/afterglow data can be understood in terms of a picture in which the GRB-XRF jets are quasi-universal and structured, with a Gaussian-like or similar structure, i.e., one where the jet has a characteristic angle, with a mild variation of energy inside and a rapid (e.g. exponential) decrease of energy outside of it. A Monte Carlo simulation shows that the current data is compatible with such a quasi-universal Gaussian jet with a typical opening angle of $5.7^{+3.4}_{-2.1}$ degrees, and with a standard jet energy of about $\log(E_p/1\text{~erg}) = 51.1 \pm 0.3$. According to this model, the true-to-observed number ratio of the whole GRB-XRF population is about 14 with the current instrumental sensitivity.

Subject headings: Gamma ray bursts - X-rays - gamma rays

1. INTRODUCTION

The achromatic steepening in the afterglow lightcurves of some GRBs as well as energy budget arguments suggest that GRBs are produced by collimated jets (Rhoads 1999; Kulkarni et al. 1999; Harrison et al. 2001). This suggestion receives indirect support from the intriguing fact that a geometry-corrected jet energy appears to be standard (Frail et al. 2001; Panaitescu & Kumar 2001; Bloom, Frail & Kulkarni 2003; Berger, Kulkarni & Frail 2003). There are two straightforward interpretations of this fact. One is that different GRBs collimate the same total energy into different angular openings (ranging from 1 to 30 degrees) (Rhoads 1999; Frail et al. 2001). Another is that all GRBs have a universal jet shape with a varying energy per solid angle which is of the form $\propto \theta^{-2}$, where $\theta$ is the polar angle respect to the jet axis (Rossi, Lazzati & Rees 2002; Zhang & Mészáros 2002). In principle, an individual GRB could also have other jet structure, e.g. a Gaussian or even arbitrary function (Zhang & Mészáros 2002). When the jet parameters are allowed to have some dispersion around the mean values (which is demanded by the data), there is a “quasi-universal” jet structure, and a power-law jet structure is no longer a pre-requisite (Lloyd-Ronning, Dai & Zhang 2003).

Recently the so-called X-ray flashes (XRFs, Heise et al. 2003; Kippen et al. 2003) are identified and proposed as a natural extension of GRBs into a softer and fainter regime. Another intriguing empirical fact is that the GRB-XRF spectral break energy ($E_p$) in the cosmic rest frame appears to be correlated with the “isotropic-equivalent” energy (or luminosity) of the explosion (Amati et al. 2002; Sakamoto et al. 2003; Lamb, Donaghy & Graziani 2003; Lloyd et al. 2000) according to

$$E_p \sim 100\text{~keV} \left(\frac{E_{iso}}{10^{52}\text{~erg}}\right)^{1/2}. \hspace{1cm} (1)$$

Although the data sample in the XRF regime is currently very small (because the faintness of XRFs hinders the detection of their possible afterglows and the measurements of their redshifts), this intriguing result, if confirmed by further future data, strongly suggests that GRBs and XRFs are related events. A successful model should therefore be able to interpret both GRBs and XRFs within a unified framework. It is worth noticing that GRB 980425 has a very low $E_{iso}$ ($\sim 10^{48}$ ergs) but a relative large $E_p$ ($\sim 70$ keV), which is apparently inconsistent with eq.(1). Because it is atypical in other aspects as well, we do not interpret it within the current framework. Since there is no unified terminology, in this paper we call the combined population of GRBs and XRFs as GRB-XRF.

In this Letter, we do not discuss the nature of the $E_p \propto (E_{iso})^{1/2}$ empirical law\textsuperscript{5}. Rather we conjecture that it is a universal law for the majority of GRB-XRFs, and evaluate its implications for various GRB-XRF jet models. We will show that a quasi-universal Gaussian-like structured jet model is compatible with the current prompt emission and afterglow data of GRBs and XRFs. This is consistent with earlier suggestions that GRBs would be seen as X-ray transients when viewed at large angles (e.g. Mészáros & Rees 1997; Woosley, Eastman & Schmidt 1999

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\textsuperscript{5}We note however that this information potentially contains important information to constrain the nature of the GRB fireball (whether or not it is magnetic-energy-dominated) and the location of the GRB prompt emission (whether internal or external). See Zhang & Mészáros (2002b) for more detailed discussions.
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2. CONSTRAINTS ON OTHER JET MODELS

A direct implication of the $E_p \propto (E_{\text{iso}})^{1/2}$ law is that it poses important constraints both on the specific "universal" structured jet model that assumes a power-law structure with index 2 (or $k = 2$ power-law model, Rossi et al. 2002; Zhang & Mészáros 2002a), and on the conventional "uniform" jet model (Rhoads 1999; Frail et al. 2001).\footnote{The discussions here are relevant when the prompt emission energy is roughly proportional to the kinetic energy, which is verified at least for GRBs since both geometry-corrected energy components are roughly standard.}

The constraint on the $k = 2$ power-law universal model was raised by Lamb et al. (2003). The argument is as follows: In the $k = 2$ model, we have $E_{\text{iso}} \propto \theta^{-2}$, where $\theta_0$ is the viewing angle (since $\epsilon(\theta) = \text{constant}$ in the structured jet model). This implies $E_p \propto \theta^{-1}$. Since the $E_p$ values range from $\gtrsim 300$ keV in GRBs all the way down to $\lesssim 3$ keV in XRFs, the viewing angles of XRFs need to be two orders of magnitude larger than those of the GRBs. Even if XRFs originate in standard jets viewed at the equator ($\theta_0 \sim 90^\circ$), all GRBs would have viewing angles less than $1^\circ$. The probability for a viewing angle $\theta_0$ is $P(\theta_0) d\theta_0 \propto \sin \theta_0 d\theta_0$, thus a $k = 2$ model greatly overpredicts the number of XRFs. This is in sharp contrast with the observations, which indicate that XRFs represent approximately 1/3 of the total GRB-XRF population (Lamb et al. 2003).

The above argument may be regarded as supporting a uniform jet model (Lamb et al., 2003), where the radiation is seen "on-beam". However, it does not address the afterglow data such as light-curve breaks, and leads to energetic and progenitor number inconsistencies. This is because in this model, even if XRFs correspond to isotropic events, GRBs have to still be jets with typical opening angles less than $1^\circ$. In the standard afterglow model, the bulk Lorentz factor evolves as $\Gamma(t) \simeq 6(E_{52}/n)^{1/8}(t/1 \text{ day})^{-1/8}(1 + z)^{3/8}$, where $E_{52}$ is the isotropic kinetic energy of the fireball, $n$ is the interstellar medium density, $t$ is the observer’s time, and $z$ is the redshift. Taking the standard view that the jet break time $t_j$ (around days) corresponds the epoch of $1/\Gamma(t) = \theta_j$ (Rhoads 1999), we get the constraint

$$\frac{E_{52}}{n} \simeq 8.5 \times 10^6 \left( \frac{t_j}{\text{1 day}} \right)^3 \left( \frac{\theta_j}{1^\circ} \right)^{-8} \left( \frac{1 + z}{2} \right)^{-3},$$

which requires an extremely large kinetic energy, or an extremely low medium density, or both. This is in sharp contrast with current afterglow analyses (Freedman & Waxman 2001; Panaitescu & Kumar 2001; Berger et al. 2003a). The price of accepting this picture would be to abandon the current afterglow theory completely, which has been well tested and proven adequate to deal with the bulk of the afterglow data. If, on the other hand, we take $E_{52} \sim 1$ as inferred from data (e.g. Berger et al. 2003a), this narrow-beam picture would imply that GRBs have a total energy of order $10^{59}$ ergs. It would also imply that the number of GRBs is similar to the number of SN Ib/c, whereas a sample of SN Ib/c reveals only $3\%$ have radio afterglows (Berger et al. 2003c).

A variant of the uniform jet model is to interpret GRBs as on-beam detections and XRFs as off-beam detections (Yamazaki, Ioka & Nakamura 2003a). This model may have the prospect of both interpreting the correct XRF-to-GRB ratio and preserving the standard afterglow model, but still requires GRB jets to have a large dispersion of opening angles. Furthermore, the XRFs’ afterglows in such a model should resemble those in the “orphan afterglows”, i.e., initially rising and peaking at a time $t_{pk}$ when $1/\Gamma = \theta_{j}$, where $\Gamma$ is the Lorentz factor within the uniform jet cone, and $\theta_{j}$ is the viewing angle (e.g. Granot et al. 2002). Since $\theta_{j} > \theta_{0}$ in this model, one should expect that $t_{pk}$ is typically larger than the typical $t_j$ in GRB afterglows. The recent afterglow observations for XRF 030723 indeed show an initial rising lightcurve (Huang et al. 2003, and references therein), but $t_{pk}$ is around 0.1 day, much smaller than the typical $t_j$ for GRBs, which is typically several days. In order to interpret the XRF as an off-beam GRB, the jet opening angle has to be anomalously small. The lightcurve, however, is consistent with the standard on-beam afterglow with the peak being due to crossing of the typical synchrotron frequency across the optical band (e.g. Kobayashi & Zhang 2003). Similarly, the optical afterglow data for XRF 020903 (Soderberg et al. 2003) indicate that the lightcurve already decays starting from 0.9 days, which is not consistent with an orphan afterglow lightcurve.

3. A QUASI-UNIVERSAL GAUSSIAN-LIKE STRUCTURED JET MODEL

Below we will argue that the current GRB-XRF prompt emission and afterglow data are compatible with a model in which the GRB-XRF jets have a quasi-universal structure, where the jet energy distribution is axially symmetric and Gaussian-like, i.e., a jet which still has a typical angle, with a mild variation of energy within this jet typical angle and a rapid (e.g. exponential) decrease of energy outside the typical angle (Zhang & Mészáros 2002a; Lloyd-Ronning et al. 2003). For analytical purposes, we approximate the angular distribution of the jet energy as

$$\epsilon(\theta) \sim \epsilon_\text{iso} \frac{1}{2\pi} \frac{1}{\theta_{pk}(1 + z)^{3/8}},$$

The initial Lorentz factor should also have an angular dependence, and we take it as a free function, since it is in principle independent and since it does not directly influence the GRB-XRF population study.\footnote{It, however, influences the rising time of the afterglow lightcurve. See below for further discussion.} The motivation for introducing a Gaussian-like jet are dual. First, it preserves a characteristic angle for the jet, $\theta_0$, which is more consistent with the jet structure generated in the numerical simulations for the collapsar model (Zhang, Woosley & MacFadyen 2003a; Zhang, Woosley & Heger 2003b). It also alleviates the divergence problem of a power-law model at small angles by introducing a smooth functional profile within the characteristic jet angle. Second, at larger angles (beyond $\theta_0$), the energy decrease is steeper than the power law model, so that in order to get an XRF whose $E_{\text{iso}}$ is $(10^4 - 10^5)$ times lower than the typical GRB $E_{\text{iso}}$, one only needs to have a viewing angle $\theta_{j} \sim (3 - 4)\theta_0$. This greatly reduces the predicted number of XRFs.
We perform a simple Monte Carlo simulation to verify this ansatz. Since it is unreasonable to expect that all GRB-XRFs are exactly the same, we allow some scatter of the model parameters. Such scatter is also needed (Lloyd-Ronning et al. 2003) to reproduce the observed $E_{iso} - \theta_0$ correlations from the afterglow data (Frail et al. 2001; Bloom et al. 2003), even for the $k = 2$ power-law jet model. We randomly generate 10000 bursts, each of which has a jet structure in the form of eq. (3). We define the total energy within the jet as $E_j = 2\pi \int_0^{\pi/2} (\theta) \sin \theta d\theta$. For small angles, this is $2\pi \theta_0^2$. The distributions of both $E_j$ and $\theta_0$ are lognormal. For each realization, we use the generated $E_j$ and $\theta_0$ to derive $\theta_0$ and to obtain the jet structure according to (eq.[3]). For each burst, we also generate a viewing angle with the probability $P(\theta_v) = \sin(\theta_v) d\theta_v$. The corresponding 4$\pi(\theta_v)$ is then assigned to be the $E_{iso}$ for that particular burst. The cosmic rest frame $E_p$ of that burst is generated via eq.(1) with a lognormal variation (with a standard deviation of 0.3), and the observed peak energy is $E_{p,obs} = E_p(1 + z)$. The redshift distribution of the bursts is assumed to trace the cosmic star-forming rate (Rowan-Robinson 1999). Standard cosmological parameters are adopted, i.e., $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. No redshift-evolution for the burst parameters are assumed. We then assign a redshift for each burst, and calculate the distance and the energy fluence for that burst. Finally we place a fluence truncation of $5 \times 10^{-8}$ erg cm$^{-2}$ to reflect the instrument sensitivity limit. This number matches the faintest HETE-2 XRF (Fig.1 of Lamb et al. 2003), and we regard it as reflecting HETE-2 sensitivity. (We have experimented with changing the fluence truncation limit. In general, the total number of the detectable GRB-XRFs increases with a deeper fluence truncation, and the fraction of XRFs from the whole population increases mildly.) The simulated bursts are plotted in the $E_p(\text{obs})$-fluence plane (Fig.1), together with the BeppoSAX and HETE-2 prompt emission data.

The model can be also compared to the afterglow light curve break data (Bloom et al. 2003). In a structured jet, if the jet structure is steep enough (e.g. for the power law jets), the viewing angle defines the jet break time (Rossi et al. 2002; Zhang & Mészáros 2002a; Kumar & Granot 2003; Granot & Kumar 2003; Panaitescu & Kumar 2003; Wei & Jin 2003; Salmonson 2003). For a Gaussian jet, although the viewing angle defines the jet break time for $\theta_v > \theta_0$, the jet structure is only mild within the typical angle $\theta_0$, so that for $\theta_v < \theta_0$, it is $\theta_0$ rather than $\theta_v$ which defines the jet break time (Kumar & Granot 2003). In our simulation, we assign a jet break angle $\theta_j = \max(\theta_0, \theta_v)$ for each burst*. The $\Gamma$-flux-terminated bursts are plotted in the $E_{iso} - \theta_j$ plane (Fig.2), with the afterglow data.

Figures 1 and 2 show our simulation results. The parameters adopted are log($E_j/1$ erg) = 51.1 $\pm$ 0.3 and log($\theta_0/1$ rad) = $-1.0 \pm 0.2$, where the error is the standard deviation of the lognormal distribution. This corresponds to a quasi-standard explosion energy of $E_j = 1.3^{+1.2}_{-0.5} \times 10^{51}$ ergs, and a quasi-standard jet configuration with the typical opening angle of $\theta_0 = 5.7^{+3.4}_{-2.1}$ degrees. This is in excellent agreement with collapsar simulations (Zhang et al. 2003a). Figure 1 shows that this model is compatible with the prompt emission data collected by BeppoSAX and HETE-2. Defining XRFs as those events with $E_p(\text{obs}) < 25$ keV (Soderberg et al. 2003), the simulated number of XRFs is roughly 1/3 of the whole GRB-XRF population within the fluence-truncated observed sample, as in the observations. Figure 2 shows that the same set of parameters is compatible with the jet angle data within the framework of the standard afterglow model.

Among 10000 simulated bursts, 702 GRB-XRFs survive the fluence-selection effect. Since this takes viewing angle effects into account, the simulation suggests that the true-to-observed number ratio for the entire combined GRB-XRF population is about 14 (or 21 for GRB plus X-ray-rich bursts, or 42 for GRBs alone). The ratio should decrease for higher sensitivities. This number is much smaller than the beaming correction factor ($\sim 500$) in the uniform jet model for the GRB population (Frail et al. 2001; van Putten & Regimbau 2001), suggesting that the number of GRB-XRF progenitors required is smaller than previously thought.

Kumar & Granot (2003) have performed a numerical hydrodynamical modeling of the evolution of a Gaussian-jet, which reveals a substantial energy redistribution in the jet structure during its evolution. The resultant lightcurves (their Fig.5a) are consistent with most of the jet break data. For $\theta_v < \theta_0$, the lightcurves are similar to those of a uniform jet model which is consistent with the data. For $\theta_v > \theta_0$, a jet break is visible around the time of $\Gamma(\theta_v) \sim \theta_v^{-1}$. In their calculations, the structure of $\Gamma(\theta_v)$ is also taken as a Gaussian, so that when $\theta_v > \theta_0$, the lightcurves become analogous to those of orphan afterglows characterized by a late rising. However, if the initial Lorentz factor at large viewing angles is high, i.e., $\Gamma_0(\theta_v) \gg \theta_v^{-1}$, the rising segment of the lightcurve would be shifted to earlier times, followed by a decaying lightcurve (Zhang & Mészáros 2002b). For $\theta_v \gg \theta_0$, a lightcurve bump may be expected for $\theta_v \gg \theta_0$ when the jet axis becomes visible (J. Granot, 2003, personal communication), since the main power at the jet axis is initially not in the relativistic light cone. However, the energy redistribution effect (e.g. Fig.1 of Kumar & Granot 2003) may smear the bump to be less significant. In any case, XRFs in the current model only imply $\theta_v$ to be at most 4$\theta_0$. Observationally, light curve breaks are currently well monitored mainly for those bursts whose break time is typically days, which corresponds to small jet angles (i.e. $\theta_v \ll \theta_0$). The afterglow data for the recent XRF 030723 (Huang et al. 2003 and references therein), on the other hand, shows a lightcurve re-brightening after 10 days. For an initial Gaussian jet (in the prompt phase), the jet structure would evolve during the afterglow phase because of a pole-to-equator energy flow. For a large viewing angle corresponding to an XRF, the late-time afterglow energy in the viewing direction could be much larger than the energy in the prompt phase. This is consistent with the recent radio afterglow observation for XRF 020903 (Soderberg et al. 2003). We therefore conclude that the model discussed

*The result does not differ too much from the present simulation if we assumed that $\theta_0$ is exclusively the agent which defines the jet break (e.g. Lloyd-Ronning et al. 2003). The reason is that the probability for small viewing angles (which make the difference) is small.
4. DISCUSSION

We have argued that in order to incorporate both the prompt emission and afterglow data for GRBs and XRFs within a unified theoretical framework, both the simple $k = 2$ power-law universal jet model and the on-beam uniform jet model encounter difficulties. With a Monte Carlo simulation, we show that the current data are compatible with a quasi-universal Gaussian-like structured jet model.

Other possible models may still interpret the data. First, a uniform jet also produces an equivalent isotropic energy outside the jet cone due to the off-beam Doppler effect. So an off-beam model for XRFs (Yama et al. 2003a) does not over-generate XRFs. However, the decline of the isotropic energy at larger viewing angles is even steeper than exponential (e.g., Yama et al. 2003b). So one can only generate XRFs at even steeper than exponential (e.g., Yama et al. 2003b). The lack of such signatures in most of the afterglow lightcurves poses constraints on the parameters for such two-component structured jet models. Third, we do not exclude the possibility that a $k = 2$ power law structure extends only up to a certain angle, above which the jet energy has a much steeper decline (Zhang & Mészáros 2002a). However, the current Gaussian model is the simplest among these, and can accommodate the widest range of prompt emission and afterglow data for the majority of GRBs and XRFs. More detailed Monte Carlo simulations for this as well as other models and their comparison to a wider set of detailed prompt emission and afterglow data will be presented elsewhere (Dai & Zhang 2003, in preparation, see also Liang, Wu & Dai 2003).

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FIG. 1.—The $E_{\text{pk}}(\text{obs})$-fluence diagram of the simulated GRB-XRFs (small dots) as compared with the HETE-2 and BeppoSAX data (heavy dots with error bars, data from Lamb et al. 2003).
Fig. 2.— The $E_{\text{iso}} - \theta_j$ diagram of the simulated GRB-XRFs (small dots) as compared with the afterglow jet break data (heavy dots with error bars, data from Bloom et al. 2003).