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THE CASE FOR ANISOTROPIC AFTERGLOW EFFICIENCY WITHIN GAMMA-RAY BURST JETS

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ABSTRACT

Early X-ray afterglows recently detected by *Swift* frequently show a phase of very shallow flux decay lasting from $\sim10^{2.5}$ up to $\sim10^4$ s, followed by a steeper, more familiar decay. We suggest that the flat early part of the light curve may be a combination of (1) the decaying tail of the prompt emission and (2) the delayed onset of the afterglow emission observed from viewing angles slightly outside the edge of that part of the jet that generates prominent afterglow emission, as predicted previously. This would imply that a significant fraction of viewers get very little external shock energy along their line of sight and, therefore, see a very high γ-ray–to–kinetic energy ratio at early times. The early flat phase in the afterglow light curve implies, for standard afterglow theory, a very large γ-ray efficiency, typically $\gtrsim$90%, which is very difficult to extract from baryons by internal shocks.

Subject headings: gamma rays: bursts — gamma rays: theory — hydrodynamics — X-rays: general

Online material: color figures

1. INTRODUCTION

Although early models of fireballs (Goodman 1986) did not postulate baryons within, the existence of baryons in gamma-ray burst (GRB) fireballs was anticipated because the highly super-Eddington luminosities suggest that baryons are expelled. In fact, the baryonic component that is expected to accompany such an outflow would quench the γ-ray emission. This realization led to the popularization of a model for GRBs in which baryonic kinetic energy was reclaimed at large radii by internal shocks to be used for making high-energy particles (Levinson & Eichler 1993) and γ-rays (Mészáros & Rees 1994). This model postulated fewer baryons than expected from a priori estimates of the super-Eddington flux-driven mass outflow, but it did invoke baryons, or in any case matter, that survived annihilation in the compact regions closer to the central engine.

The above models should be contrasted with internal shocks models in which there are few baryons (Eichler 1994) where the role of the internal shocks, presumably near the photosphere, is simply to nonthermalize the spectrum of γ-rays that dominate the energy content. In particular, the reclamation of baryonic kinetic energy by internal shocks for the purposes of making the prompt γ-radiation of the GRB itself (Mészáros & Rees 1994) led to the prediction that there should be a blast wave in the circumburst medium that would generate afterglow. The discovery of afterglow appeared to provide enormous support to the internal shocks model of Mészáros & Rees (1994), who had predicted such an afterglow.

On the other hand, it has never been proven that the γ-rays and the ejecta are made by the same components of the outflow. More generally, the ratio of γ-ray to baryonic energy per solid angle may vary considerably within the outflow in a way that would have significant consequences both for observations and for theories of GRB origin. One consequence of GRB baryon anisotropy would be lines of sight that are more favored than others for GRB detection, while others might be more favorable for seeing early afterglow. In this Letter, we argue in favor of this hypothesis. In § 2 we present arguments in favor of baryon anisotropy. In § 3 we show that the combination of the decaying tail of the prompt emission and the flat early afterglow light curve from viewing angles slightly outside the edge of the region within the jet with prominent afterglow emission can produce the early flat decay phase of the X-ray afterglows recently observed by *Swift*. Our conclusions are discussed in § 4.

2. ARGUMENTS IN FAVOR OF BARYON ANISOTROPY WITHIN THE JET

Several arguments have been put forth that the baryon richness of a GRB fireball relative to the γ-ray intensity varies with the viewing angle for a given fireball. Levinson & Eichler (1993) argued theoretically that the anatomy of a GRB is likely to be Poynting flux or γ-rays emerging from horizon-threading magnetic field lines, while the baryons might flow out predominantly near the periphery of the above, along field lines that thread the interface of the inner accretion disk and the event horizon. On field lines that thread the accretion disk, which should also have a super-Eddington power output, there ought to be a "slow sheath" of baryons that, while being too baryon-rich to yield a detectable GRB, would yield a contribution to the afterglow and possibly a "dirty fireball." Several observations have also been interpreted in the context of a dichotomy between the baryon-poor flow lines and the baryon-rich ones. Scattering of γ-rays from baryon-poor regions off more slowly moving baryons could yield a weak spray of γ-rays at large angles. Such scattered emission would be a very small fraction ($\sim10^{-5}$) of the total and would thus be detectable only for very nearby GRBs. Nevertheless, they would be detectable over a much larger solid angle and would be manifested as soft GRBs (no photons well above 1 MeV), with smooth light curves from nearby sources. GRB 980425 was a good example of such a GRB and was interpreted in this light (Nakamura 1998; Eichler & Levinson 1999).

Another intriguing result of baryon anisotropy of the GRB fireball could be that the γ-ray emission itself—not just the baryonic content—could have a nontrivial angular profile. Here the details have not been worked out yet. It could be, for example, that most of the emission in the interior of the outflow is virgin Poynting flux and that the γ-rays themselves are generated preferentially at the periphery of the fireball where the Poynting flux is somehow tapped by interaction with the slower baryonic sheath. It is also not yet established under what conditions virgin Poynting flux creates afterglow. If a necessary

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condition for afterglow is that external protons can execute at least one gyroradius in the comoving frame within a proper hydrodynamic timescale, $\sim R/\Gamma c$, then the condition can be expressed (Eichler 2003) as $\Gamma \leq \Sigma^{1/3}$, where Σ is the electric potential energy drop, $e\beta BR$, across the ejecta in units of $m_p c^2$ and B is the magnetic field in the lab frame. This would typically imply that $\Gamma \lesssim 10^5$ for GRBs. However, there are still several additional considerations that could be relevant.

If the angular structure of the γ-ray–emitting region is more complicated than a solid cone, then the fraction (of solid angle over which γ-rays are detectable) that corresponds to off-beam viewing angles increases, thus making such lines of sight more probable. In this regard, the Amati et al. (2002) and Ghirlanda et al. (2004) relations, which correlate the spectral peak photon energy, $E_{\rm peak}$, and the apparent isotropic equivalent energy, $E_{\gamma,\,\rm iso}$, can both be explained as viewing angle effects (Eichler & Levinson 2004; Levinson & Eichler 2005). GRBs with $E_{\rm peak} \ll 1$ MeV are interpreted as viewed off-beam at angles $\theta > \Gamma^{-1}$ from the edge of the jet.[3] This lowers both the observed $E_{\gamma,\,\rm iso}$ and $E_{\rm peak}$ in a way that conforms to the Amati relation (Eichler & Levinson 2004). Furthermore, the value of the jet opening angle, as inferred from the observed break time in the afterglow and the observed $E_{\gamma,\,\rm iso}$, is then slightly overestimated relative to its true value, because the observed $E_{\gamma,\,\rm iso}$ is underestimated relative to its true value. When this slight overestimate is accounted for, the Ghirlanda relation becomes equivalent to the Amati relation (Levinson & Eichler 2005).

Additional evidence for baryon anisotropy comes from the 2004 December 27 giant flare from SGR 1806−20. The radio afterglow (Gaensler et al. 2005) that followed this event has been interpreted as being powered by a baryonic mass outflow of $\sim 10^{25}$ g (Gelfand et al. 2005) that is probably driven from the neutron star surface. This tentative conclusion is based on the fact that if the required mass had, instead, been dominated by swept-up matter from the surrounding medium, this would have required a highly contrived and unrealistic external density profile in order to explain the observed evolution of the source size, motion, and flux (Granot et al. 2006). Furthermore, this outflow should have been only mildly relativistic, with $\Gamma\beta \sim 1$, close to the escape velocity from the surface of the neutron star (Granot et al. 2006). On the other hand, such a large and mildly relativistic baryonic outflow would have (at least partly) obscured the prompt γ-rays from the flare had they been expelled in our direction. The data can be reconciled, however, by the assumption that the baryons are ejected in some directions and not others.

Eichler & Jontof-Hutter (2005) reconsidered the issue of blast efficiency, assuming that $E_{\rm peak}$ is determined mostly by the viewing angle effect. The blast efficiency was computed by previous authors based on the X-ray afterglow at 10 hr. The ratio of blast energy to apparent γ-ray energy for GRBs with known redshifts was found to be of order unity but with a great deal of scatter. This scatter, however, is considerably reduced when the ratio of "viewing-angle-corrected" γ-ray energy[4] ($\propto E_\gamma/E_{\rm peak}^{3/2}$) is compared with blast wave energy, and the characteristic value of the γ-ray–to–kinetic energy ratio seems to be $\sim$7. That is, nearly 90% of the energy goes into radiation (γ-rays), and only about 10%–15% goes into the blast wave.

A 90% γ-ray efficiency raises serious problems for the internal shocks model, in which the γ-ray energy is powered by whatever fraction of the baryonic kinetic energy can be radiated away by the internal shocks. In particular, it requires the internal shocks to consistently radiate away nearly 90% of the total energy within the observed photon energy range and consistently leave the same small fraction. It is hard to see how internal shocks, which are by nature erratic, could perform so efficiently and so consistently. Moreover, even if internal shocks could consistently convert more than 90% of the kinetic energy into internal energy, they would still need to put more than 90% of the internal energy into electrons (and therefore <10% into ions) that could radiate this energy within the dynamical (i.e., expansion) time.

The idea that many GRBs are viewed slightly off the main intensity peak, by an offset angle θ, was used (Eichler 2005) to interpret delayed onset of X-ray afterglow that was reported by Piro et al. (2005). The delay is simply the time needed for the flow to decelerate to $\Gamma < 1/\theta$, i.e., for the afterglow beam to encompass our line of sight. This would predict, under the assumption that the afterglow-generating blast wave and the γ-ray beam coincide, that the lower $E_{\rm peak}$, the longer it will take for the afterglow to assume its full on-beam value (Granot et al. 2002; Granot 2005). However, the outliers to the ϵ_b-$E_{\rm peak}$ correlation found by Eichler & Jontof-Hutter (2005) suggest that this correlation could be contaminated by many GRBs that are bright, spectrally hard, and have extensively delayed afterglow onset.

Very recently, Nousek et al. (2005) arrived at a similar conclusion using early X-ray afterglow data taken by *Swift*. The X-ray afterglows frequently show an intermediate phase ($t_1 < t < t_2$) of very flat flux decay at early times ($t_1 \sim 10^{2.5}$ s and $t_2 \sim 10^4$ s) that is deficient relative to expectations from a uniform adiabatic blast wave. Among this subset of GRBs, it typically takes the X-ray afterglow a few hours to attain the values inferred from *BeppoSAX* data. They note that for $t \ll t_2$, the γ-ray efficiency, ϵ_γ, is typically much higher than previously inferred (Panaitescu & Kumar 2001; Lloyd-Ronning & Zhang 2004), yet at $t \gtrsim t_2$, the distribution in these efficiencies converges to the narrow range of values inferred previously.[5]

3. DELAYED AFTERGLOW ONSET AND FLAT EARLY LIGHT CURVES

The explanation favored by Nousek et al. (2005) for the early flat part of the *Swift* X-ray afterglow light curves is energy injection into the afterglow shock (see also Zhang et al. 2005, Panaitescu et al. 2006, and Granot & Kumar 2006). Here we suggest an alternative explanation for this early flat phase, namely, the flat early afterglow light curve for viewing angles slightly outside the (rather sharp) edge of the jet (i.e., outside the regions where the energy per solid angle in the external shock is large enough to produce bright afterglow emission).

For such "off-beam" lines of sight, the afterglow flux initially rises, at early times, as the beaming of the radiation away from the line of sight gradually decreases with time, then rounds off as the afterglow beaming cone expands enough to include the line of sight, and finally gradually joins the decaying "on-beam" light curve (seen by observers within the jet). For a point source, the fluxes seen by off-beam and on-beam observers are related by

$$F_\nu(\theta,\ t) \approx a^3 F_{\nu/a}(0, at) = a^{3+\beta_{\rm X}-\alpha_{\rm X}} F_\nu(0, t) \qquad (1)$$

[3] In this case, the observed photons are directed backward in the comoving frame of the emitting plasma.

[4] The form of this correction assumes that the Ghirlanda relation is due to viewing angle effects so that the factor $E_{\rm peak}^{3/2}$ is taken to be a measure of the Doppler factor that corresponds to the viewing offset angle.

[5] Actually, the better terminology is the blast efficiency, $\epsilon_b = 1 - \epsilon_\gamma$. In this class of bursts, $\epsilon_\gamma \sim 90\%$, and the blast efficiencies $\epsilon_b \sim 10\%$ have greater relative scatter due to their smaller values.

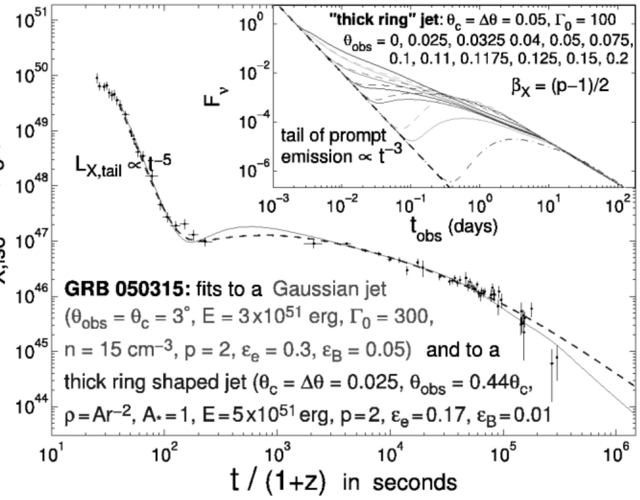

FIG. 1.—Tentative fit to the X-ray light curve of GRB 050315 (from Nousek et al. 2005), with (1) a Gaussian jet (*solid line*, using model 1 of Granot & Kumar 2003) and (2) a ring-shaped jet, uniform within $\theta_c < \theta < \theta_c + \Delta\theta$ (*dashed line*, following the model described in Granot 2005). The initial fast decay is attributed to the tail of the prompt emission and modeled as a power law proportional to t^{-5}. The inset shows afterglow light curves for a ring-shaped jet (Granot 2005), for different viewing angles $\theta_{\rm obs}$ from the jet symmetry axis. [*See the electronic edition of the Journal for a color version of this figure.*]

(Granot et al. 2002), where θ is the angle between the source's velocity and the direction to the observer in the lab frame, t is the observed time, $a = (1-\beta)/(1-\beta\cos\theta) \approx (1+\Gamma^2\theta^2)^{-1}$ is the ratio of the off-beam (at θ) and on-beam ($\theta = 0$) Doppler factors, and the last equality is valid when $F_\nu(0,t) \propto t^{-\alpha_X}\nu^{-\beta_X}$. Thus, the off-beam flux is suppressed relative to the on-beam flux by a factor $\eta = a^{3+\beta_X-\alpha_X}$. At early times, when $\Gamma\theta \gg 1$, we have $a \approx (\Gamma\theta)^{-2}$ and $\Gamma \propto t^{-(3-k)/2}$, where $\rho_{\rm ext} \propto R^{-k}$, so that $a \propto t^{3-k}$, $\eta \propto t^{(3-k)(3+\beta_X-\alpha_X)}$ and $F_\nu(\theta,t) \propto \eta(t)t^{-\alpha_X} \propto t^{(3-k)(3+\beta_X)-(4-k)\alpha_X}$. The point-source limit is valid when the angle θ from the closest point along the edge of the jet is larger than the typical angular extent of the jet, $\theta_{\rm jet}$. However, more often the opposite is true, i.e., $\theta < \theta_{\rm jet}$ (or $\Gamma_0^{-1} \ll \theta \ll \theta_{\rm jet}$, where Γ_0 is the initial Lorentz factor of the jet), in which case the dependence of η on a decreases by one power (Eichler & Levinson 2004; Levinson & Eichler 2005) to $\eta = a^{2+\beta_X-\alpha_X}$. This implies $\eta \propto t^{(3-k)(2+\beta_X-\alpha_X)}$ and $F_\nu(\theta,t) \propto \eta(t)t^{-\alpha_X} \propto t^{(3-k)(2+\beta_X)-(4-k)\alpha_X}$ at very early times.

Figure 1 shows two tentative fits to the X-ray light curve of GRB 050315, which is perhaps the best monitored X-ray light curve showing a pronounced early flat phase (Nousek et al. 2005). The first fit (*solid line*) is for a Gaussian jet, calculated using model 1 of Granot & Kumar (2003). The second fit (*dashed line*) is for a jet with a cross section in the shape of a thick ring, calculated using the model developed in Granot (2005). The latter model was also used in the *inset* of Figure 1, which shows the light curves for different viewing angles. In all cases the early fast decay is attributed to the tail emission of the prompt GRB (Kumar & Panaitescu 2000) and is modeled by a steep power law. As derived analytically in the previous paragraph, the light curves for off-beam viewing angles (with respect to a sharp-edged–emitting region) show a rather sharp rise in the flux at very early times. However, in most cases, the steep early rise of the afterglow emission is hidden below the steeply decaying tail of the prompt GRB emission. Figure 1 demonstrates that the combination of the decaying tail emission of the prompt GRB and the gently rising or rounding off afterglow emission from slightly off-beam viewing angles can produce a flat early phase in the afterglow light curves, similar to those seen by *Swift* in the X-rays (Nousek et al. 2005). In some cases we expect to even see a gentle rise at very early times. As can be seen from Figure 1, different combinations of jet structure and viewing angle can generally fit the same observed X-ray light curve.

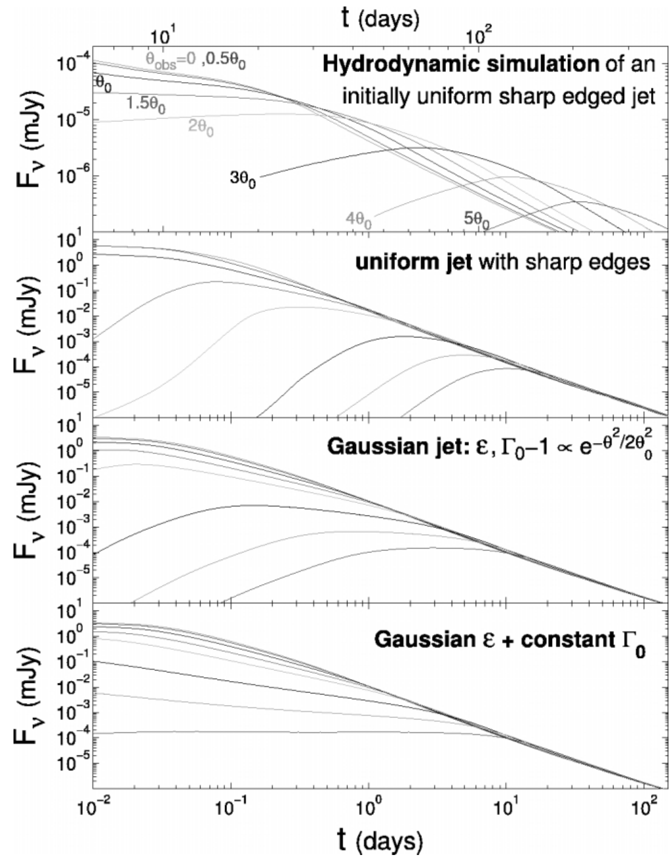

FIG. 2.—Light curves for different jet structures, dynamics, and viewing angles. The top panel is from an initially uniform jet with sharp edges whose evolution is calculated using a hydrodynamic simulation (taken from Fig. 2 of Granot et al. 2002). The remaining three panels are taken from Fig. 5 of Granot et al. (2005), where a simplified jet dynamics with no lateral expansion is used. The second panel is for a uniform jet with sharp edges. The two bottom panels are for a Gaussian jet, in energy per solid angle, and either a Gaussian or a uniform initial Lorentz factor. The viewing angles are $\theta_{\rm obs}/\theta_0 = 0$, 0.5, 1, 1.5, 2, 3, 4, and 5, where θ_0 is the (initial) half-opening angle for the uniform jet (*two top panels*) and the core angle for the Gaussian jet (*two bottom panels*). [*See the electronic edition of the Journal for a color version of this figure.*]

Figure 2 demonstrates the dependence of the early rise in the afterglow light curves, for off-beam viewing angles, on the jet structure and dynamics. The three bottom panels are taken from Granot et al. (2005) and are calculated using model 1 of Granot & Kumar (2003). The second panel shows afterglow light curves from a uniform jet with sharp edges for different viewing angles $\theta_{\rm obs}$ from the jet symmetry axis. The light curves are similar to those for a wide ring jet (Fig. 1) for similar off-beam viewing angles. The two bottom panels in Figure 2 are for a Gaussian jet, and they show that the smoother the edges of the jet (both in terms of energy per solid angle and in terms of the initial Lorentz factor Γ_0), the shallower the initial rise in the flux for off-beam viewing angles.

The top panel in Figure 2 shows the afterglow light curves for an initially uniform sharp-edged jet whose dynamics were calculated using a hydrodynamic simulation (Granot et al. 2001). The initial conditions were a cone of half-opening angle θ_0 taken out of the spherical self-similar solution of Blandford & McKee

(1976). The light curves for off-beam viewing angles, and especially for $1 \lesssim \theta_{obs}/\theta_0 \lesssim 2$, are much flatter at early times compared to those calculated using semianalytic models for the jet dynamics, since the shocked external medium at the sides of the jet has a significantly smaller Lorentz factor than that near the head of the jet, and therefore its emission is not so strongly beamed away from off-beam lines of sight. Thus, we conclude that very flat (either a very shallow rise or a very shallow decay) early afterglow light curves are expected for a realistic jet structure and dynamics. Combined with the rapidly decaying tail of the prompt GRB emission, this can nicely reproduce the observed early flat parts of the X-ray afterglow light curve observed by *Swift*.

4. DISCUSSION

We have shown that the early flat phase in the X-ray afterglow light curves observed by *Swift* is broadly consistent with earlier predictions that afterglow onset might appear delayed to an "offset viewer"—an observer who is outside of the directed beam of baryons. Many authors (e.g., Panaitescu & Mészáros 1998; Panaitescu et al. 1999; Moderski et al. 2000; Granot et al. 2001; Dalal et al. 2002; Dado et al. 2002) have previously noted that offset viewing would suppress early afterglow and presumably prompt γ-rays as well. Granot et al. (2002) predicted that this would be the case for orphan afterglows, and Granot et al. (2005) argued that this is expected for X-ray flashes (and nicely agrees with their pre-*Swift* optical and X-ray early afterglows), assuming that the softening or nonappearance of prompt γ-rays in these instances is due to offset viewing (relative to both the regions of prominent γ-ray and afterglow emission, which were assumed to coincide). Eichler & Levinson (2004) and Eichler & Jontof-Hutter (2005) predicted that this could also be the case for "normal" γ-ray bursts with a bright prompt emission if the viewer is in the direct beam of the gamma rays but not of the baryons. Delays of several minutes in some afterglows whose onsets were serendipitously caught by the wide field camera of *BeppoSAX* (Piro et al. 2005) led Eichler (2005) to conjecture that the prompt emission was seen along an afterglow-inefficient line of sight and that, if caught during the first several hours, an even larger fraction of afterglow onsets would appear delayed. This now seems to be the case in our view. We have argued here that the stage of flat decay, often seen within the first few hours of afterglow, can be attributed to the delayed onset discussed in these earlier papers.

For off-beam viewing angles that are offset from the prominent early afterglow emission but *not* from the prompt γ-ray beam, we expect greater scatter in the early afterglow *relative* flux (i.e., relative to the prompt flux, whose tail is identified with the early rapid decay phase of the X-ray light curve), which is affected by such an offset, than in the less affected late afterglow relative flux. This indeed appears to be the case judging from Figures 1 and 2 of Nousek et al. (2005), where the scatter in X-ray afterglow relative flux is significantly smaller at late times than in the flat decay phase; i.e., the flatness seems to be due to diminished early afterglow rather than to enhanced late afterglow, and the former is diminished by a factor that varies significantly among different GRBs. This is hard to explain with late-time energy infusion, which would be expected, rather, to increase the amount of scatter at late times relative to early ones. For viewing angles that are offset from *both* the region of prominent γ-ray emission and the region prominent early afterglow, one might expect a correlation between α_2 and the spectral peak photon energy, E_{peak}, or isotropic equivalent energy in γ-rays, $E_{\gamma, iso}$. Tables 1 and 2 of Nousek et al. (2005) show no obvious apparent correlation between α_2 and $E_{\gamma, iso}$. The lack of such a correlation would suggest, under the offset viewing interpretation, that among the GRBs with a flat intermediate decay phase, *the regions of prominent afterglow emission and of prominent γ-ray emission do not coincide*, as we have suggested in this work. Furthermore, some of the GRBs recorded by *Swift*, such as GRB 050315, have a rather large $E_{\gamma, iso}$ *as well as* long stages of very flat decay, and could be interpreted as being due to lines of sight along which the early afterglow emission was intrinsically weak relative to the prompt γ-rays. Such a weak afterglow emission can easily be attributed to a paucity of baryons relative to γ-rays in the outflow along our line of sight.

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