Short Gamma-Ray Bursts Viewed from Far Off-axis

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Abstract

The recent radio observations of a superluminal radio afterglow following gamma-ray burst (GRB) 170817A are interpreted in terms of a jet impacting a baryonic material, which is presumably the material caught at the front of the jet as the latter emerges from a denser ejected material. Assuming that we, the observers, are located at a viewing angle of ~0.2 radians from the emitting material (perhaps slightly more from jet axis), we suggest that the Lorentz factor of the jet is $\lesssim 20$ at the time of the prompt emission, and that, as suggested previously, it is accelerated to much higher values before finally decelerating during the afterglow phase. A less extreme example of a short GRB being observed off-axis may have been GRB 150101B. A feature of GRBs viewed from large offset angles is a large afterglow isotropic equivalent energy as compared to prompt emission, as predicted, and this is born out by the observations of these two GRB. It is also shown that the prompt emission of GRB 170817A, if seen way off-axis ($\theta \gg 1/\Gamma$), could not be made by internal shocks in the baryonic material that powers the afterglow.

Key words: gamma rays: general

1. Introduction

Mooley et al. (2018) have recently measured apparent superluminal motion in the radio afterglow emission of gamma-ray burst (GRB) 170817A, which was associated with a neutron star merger. The apparent motion is of order 4c around the time of radio maximum (circa day 150 after the prompt emission). From this the authors inferred that, at the epoch of this maximum, the Lorentz factor of the radio emitting region is about (or slightly greater than) 4 and that it is seen from an angle of about 0.25–0.35 radian, or about 14°–20°, from the jet axis. From the sharpness of the peak, they also inferred that the angular width of the jet itself cannot be much more than about 0.1 radian. Hence, if the jet is axisymmetric, the distance to the closest part of its perimeter cannot be less than about 0.15 radian from our line of sight, and is more likely offset by at least 0.175 or 0.2 radians. Mooley et al. (2018) also concluded that the energy in the blast that makes the afterglow has an isotropic equivalent energy $E_{\text{iso}} \approx 10^{52} E_{52}$ erg of about $10^{52}$ erg. If the asymptotic Lorentz factor $\Gamma \propto$ of the baryonic material that drives the blast is $10^{-2/3} \Gamma_{a,2.5}$, then its isotropic equivalent mass $m_{\text{iso}} \approx 10^{28.5} m_{28.5} \text{ g}$ is then $m_{\text{iso}} \approx 10^{28.5} E_{52}/\Gamma_{a,2.5} \text{ g}$.

The angular extent of the material that last interacted with (i.e., emitted or scattered) the prompt emission need not be the same as that of the material driving the late time afterglow. In particular, the former may be wider than the latter because the criterion for contributing to the prompt emission is determined by optical depth, which need not require much of the total mass, whereas the contribution to late-time afterglow depends on the angular distribution of ejected mass and momentum. Virtually all of the discussion below is qualified by this uncertainty. For the sake of concreteness, however, it is assumed below that the observer’s line of sight is 0.2 radians from the material that most contributes to the prompt emission, and the latter material is taken to be a pencil beam that is somewhat closer to our line of sight than the jet axis.

The relatively large viewing angle inferred for GRB 170817A was anticipated (e.g., Eichler 2017), if only because the accompanying gravitational wave signal selected it for unusually close proximity, while more distant GRBs are selected for small viewing angles, where relativistic beaming makes them bright enough to be detected. The observed initial rise in afterglow intensity with time, which has been recorded since the discovery, is consistent with an off-axis jet, whose forward shock becomes increasingly visible as it decelerates (e.g., Ioka & Nakamura 2018; Lazzati et al. 2018; Lyman et al. 2018; Resmi et al. 2018; Zhang & Sun 2017). However, the relatively sharp reversal from rising to declining afterglow in both the radio and X-ray (Alexander et al. 2018; Lamb et al. 2018; Margutti et al. 2018), together with the apparently superluminal motion in the radio, seems to clinch the case for a strongly relativistic off-axis jet over a quasi-spherical, mildly relativistic outflow.

That short GRBs as a class are viewed from a larger viewing angle than long ones has been advocated for many years (e.g., Eichler et al. 2009). In this particular model, photons (or in any case a baryon-poor fireball) overtake baryonic matter in front of them, scattering off it and accelerating it. So accelerated, the baryonic matter eventually powers the afterglow. While a wider viewing angle is kinematically associated with lower Doppler factors and hence longer observed durations, in this particular model, photons seen near the peak of the burst are last scattered (or emitted and then never scattered) from an accelerating surface that is, at the time of the last scattering, moving at a Lorentz factor $\Gamma_0$ of at least $1/\theta$ relative to the observer’s line of sight. After the peak, the Lorentz factor is larger, causing the observer to see a “soft tail” (often called “extended emission”) of softening, dimming emission. This tail could also be due in part to a light echo off parts of the jet that are oriented further away from our line of sight. The short duration at larger viewing angle is attributed to the shorter acceleration time of the surface of last scattering when $\theta$ is large and $\Gamma_{\text{peak}}$, therefore, is small. The acceleration time (in the frame of the central engine) $d\ln(1-\beta)/dt$ is of order $\Gamma m_{\text{iso}} C^2/L_{53}$ (Eichler & Manis 2007), where $L_{53} = 10^{53} L_{53}$ erg s$^{-1}$ is the isotropic equivalent luminosity along the jet axis, which, for $m_{28.5}$, $E_{53}$ and $\Gamma_{a,2.5}$ all of order unity, is of order $10^{-3.5} \Gamma_3^3/L_{53}$ s. In observer time, this time interval is compressed by reduction in propagation distance by the factor $(1 - \beta \cos \theta)$, which, for GRB 170817A, is estimated below to be a factor of $(1 - \cos \theta) \approx 0.02$. Altogether, we might expect that within the first 0.1 s of...
observer time, the baryons are accelerated to a Lorentz factor of $\sim 25 L^{1/3}$. 

In anticipation of the announcement of the discovery of GRB 170817A, and in more detail just afterwards, it was noted (e.g., Eichler 2017) that this GRB, because it was so close, could be seen at even larger viewing angles, where it would appear softer and fainter than most GRB, yet where it would be within a broader and therefore more likely range of viewing angles for a random distribution of observers. As the spectral peak—at 180 keV $+\, -\, 60$ keV—was about 22 times softer than the spectral peak of GRB 090510 (which was taken as the benchmark spectral peak of an on-axis observer), it was conjectured in the above reference that the viewing angle was about $\sqrt{21}/\Gamma \sim 4.6/\Gamma$. This estimate follows from the fact that the observed photon energy $E''$ depends on the viewing angle $\theta$ to the direction of motion of the scatterer $\beta$ as $(1 - \beta)E/(1 - \beta \cos \theta) \sim E/[1 + (\theta \Gamma)^2] \sim E/22$, where $E$ is the energy seen by an on-axis observer given a monochromatic, monodirectional beam that overtakes the scatterer from behind. That is, $E$ is the photon energy in the observer frame prior to scattering.

Accordingly, the luminosity, which from a pencil beam scales as $[1/\Gamma(1 - \beta \cos \theta)]^4$ would scale as $(E''/E)^4$, which, in the case of GRB 0170817A, would be $\sim 22^{-4} \times 4 \times 10^{-6}$. Remarkably, this gives a reasonable estimate of the peak luminosity of GRB 170817A, which was of order $2.5 \times 10^{47}$ erg s$^{-1}$, relative to the peak luminosity of GRB 090510 ($L_{\text{iso}} \sim 1 \times 10^{53}$ erg s$^{-1}$), a short GRB that we have previously argued was seen on-axis (Eichler 2014, 2017), and sets the standard expectation for an on-axis observer.

2. Significance of Afterglow Observations

Most remarkably, however, the radio afterglow observations support the conclusion that in fact there was a more or less normal isotropic equivalent energy output for a short GRB, $E_{\text{iso}} \sim 10^{52}$ erg, beamed away from the observer.$^1$ One might suspect, therefore, that the prompt emission is viewed from the same angle as the radio emission, $\gtrsim 0.2$ radians. If the Lorentz factor $\Gamma$ of the scatterer (i.e., the surface of last interaction of the prompt $\gamma$-ray emission) obeys $\Gamma \lesssim 25$, then $\theta$ would indeed be $\gtrsim 4.5/\Gamma$, adequately accounting for the subluminous character of this particular short GRB.

GRB 170817A has much in common with GRB 150101B (Fong et al. 2016; Troja et al. 2018), also believed to have been viewed from a wide viewing angle, in that the afterglow fluence is much higher than that of the prompt emission. Both GRBs support the notion that most of the acceleration of the baryonic material that powers the afterglow took place after the prompt emission phase. This fits the picture (Eichler & Manis 2008; Eichler et al. 2009; Eichler 2017) that the prompt emission in our direction is aborted by the acceleration of the scattering material to values much greater than $1/\theta$. It connects the unusual brevity of GRB 150101B ($T_{\text{iso}}$ of only 18 ms) to the unusually high ratio of afterglow fluence to prompt fluence, as both correlate with large $\theta$.\footnote{This fact had been challenged earlier by advocates (Mooley et al. 2017) of a “choked GRB” interpretation of the low luminosity.}

Now Veres et al. (2018) have recently argued that in fact the spectral peak may be somewhat larger at peak luminosity, which would mean, in the context of Eichler (2017), that a smaller value $E/E''$ should be used, perhaps only 10 rather than 22, and that $\theta$ may be a small as $3/\Gamma$, giving a smaller reduction of apparent luminosity due to off-axis kinematic effects.\footnote{GRB 170817A is also unusually short, even among short GRB (Kaneko et al. 2015), if the spike, as defined by Kaneko et al. (2015) is taken to be the 100 ms peak, and the soft, extended emission is taken to be 2 ks.} However, given the uncertainties in the isotropic equivalent luminosity seen by an on-axis observer, this is not a serious concern. The principal uncertainty is that the vast majority of the kinetic energy that powers the afterglow may have entered the scatterer after the peak of the prompt emission, as discussed in Eichler (2017). This is supported by the wide range in the ratio $r$ of afterglow fluence $F_{\text{afterglow}}$ to prompt fluence $F_{\text{prompt}}$ over short GRB, ranging from $r \sim 10^3$ in the cases of highly off-axis viewing angles such as GRB 150101B (Fong et al. 2016; Troja et al. 2018) down to $r \sim 10^{-4}$ in the case of GRB 090510, which was probably viewed nearly face on. Additional uncertainty can arise from intrinsic scatter in $r$, apart from viewing angle considerations, especially because nearby GRB are more likely to be at the low end of this scatter, while distant ones are at the high end. Yet more uncertainty arises in the coverage factor of the scattering material ahead of the fireball.

In any case, there now seems to be agreement among theorists that GRB 170817A was observed way off-axis and that the prompt fluence was well below average for a short GRB, but that it was nevertheless accompanied by a long-term afterglow of average fluence. As such, it resembles the GRB 150101B, which had a low fluence (though average luminosity) and a huge $\sim 10^3$ afterglow to prompt fluence ratio. GRB 170817A is probably the even more extreme case, as it is viewed even further off-axis.

3. The Transparency Issue

Even within the framework of an off-axis kinematics picture, there remains the question of whether photons that are scattered off-axis (i.e., in the backward hemisphere in the frame of the scatterer) make any further interactions with not-yet-scattered ones, or more generally whether pairs are re-established by the interaction of photons with baryonic material.

Consider a baryonic shell impacted from behind by an ultrarelativistic jet: the jet is assumed to be mostly or all photons that peak at several MeV. In the case of GRB 090510, the spectral peak of the photospheric emission $E_p$ was at $E_p \approx 4$ MeV. A photon observed at earth of energy $E''$ had an energy $E'$ in the scatterer frame of $E' = E''(1 - \beta \cos \theta)$, whereas the photons in the not-yet-scattered jet have an energy $E_j' = E/\Gamma(1 + \beta)$. The criterion for pair production from massless photons is satisfied when the center-of-mass energy $E_{CM}$ exceeds $2mc^2$, i.e., when the the square of the four momentum $[p_{\mu}]^2 \geq 4m^2c^4$. Noting that $p_{\mu}p_{\mu}' = 0$ for massless photons, and that $p_{\mu}p_{\mu}' = E'_0E_{j'}(1 - \cos \theta)$, it follows that this criterion is $2E''E(1 - \cos \theta) = 2E'/E_j' \gtrsim 2mc^2$. For $\Gamma \gtrsim (1 + \beta)$, photons fall below the threshold for pair production with their post-scattered selves even for $\cos \theta = -1$ and even if the scattering is elastic.

\footnote{They also assume that the ratio of prompt emission on and off-axis varies as $(E/E'')^2$, which is inappropriate for an observer who sees the jet as a pencil beam. They also equate the afterglow energy with the on-axis prompt emission, which is also without justification. Each of these unjustified assumptions leads to an overestimate of $E/E''$.}
Compton recoil of the scatterer further relaxes the constraint on $\Gamma$. The Compton scattering in the scatterer frame leaves the photon of initial energy $E'_i = c' m_e c^2 = \mathcal{E}_e c^2 / \Gamma (1 + \beta)$ with a final energy of

$$E'_o = \frac{\epsilon'_o m_e c^2}{[(1 + \epsilon'_o) (1 - \cos \theta')]} = \frac{E}{\Gamma [1 + \beta][1 + \epsilon'_o (1 - \cos \theta')]}$$

(1)

The threshold for pair production by backscattered photons with prescattered photons is thus given by

$$\epsilon'_o (1 - \cos \theta') = \epsilon'_o (1 - \cos \theta') / [\Gamma (1 + \beta)]^2 [1 + \epsilon'_o (1 - \cos \theta')] \geq 2$$

(2)

As the quantity $\epsilon'_o$ is unlikely to be much more than 0.5, the minimum $\Gamma$ necessary to avoid pair production is reduced to $\epsilon / 2 (1 + \beta)$.

For $\Gamma = 20$, the jet may thus contain photon energies of up to 40 MeV (in the frame of the central engine) without pair producing with the back-scattered photons.

The possibility exists that the photons that emerge from the central engine with a fully Comptonized tail, which would include photons that exceed the threshold energy $E^* \sim 40$ MeV in energy, whose fraction would be proportional to the Boltzmann factor $e^{-E^* / \Gamma}$. Although the likelihoods of strong synchrotron cooling and of a last Compton scattering off of the walls of the material that shape the jet each make this assumption questionable, I consider the possibility for completeness. We are concerned with the question of whether or not the photons at the spectral peak $E_p = \epsilon'_o m_e c^2 = 2 \mathcal{E}_p$ escape, and it can be shown that for $L_{53} \sim 1$, transparency requires $\exp[-E^* / T] \lesssim e^{-25}$, i.e., that $\epsilon^* \gtrsim 12.5 \epsilon_p$. As

$$\epsilon^* (1 - \cos \theta') / [\Gamma (1 + \beta)]^2 \geq \epsilon^* (1 - \cos \theta') / [\Gamma (1 + \beta)]^2 [1 + \epsilon'_o (1 - \cos \theta')] \geq 2$$

(3)

it follows that

$$\epsilon^* \gtrsim [2 / (1 - \cos \theta')] [\Gamma (1 + \beta)]^2 / \epsilon_p \geq [\Gamma (1 + \beta)]^2 / \epsilon_p$$

(4)

and that the transparency condition, even in the presence of a Comptonized tail, is satisfied when $[\Gamma (1 + \beta)]^2 / \epsilon_p \gtrsim 12.5$. Assuming that $1 + \beta \approx 2$,

$$[\Gamma / \epsilon_p] \gtrsim 3.1$$

(5)

So for the range of $6 \lesssim \epsilon_p \lesssim 8$ suggested by the hardest sGRB, $\Gamma$ exceeding 10 to 14 suffices for transparency even if the jet photons have a Comptonized spectrum.

We can check the model for the particular case of GRB 170817A by deriving the square of the center of mass energy from $E_{CM}^2 = [p_\gamma - p']^2 = 2 E_{\gamma} E (1 - \cos \theta)$ directly from the observed $E'' \equiv c'' m_e c^2$. It exceeds the pair production threshold $4 (m_e c^2)^2$ if $0.02 c'' \epsilon \gtrsim 2$. Thus, if photons from the GRB are observed at $E'' \sim 1$, as claimed by Veres et al. (2018), then $\epsilon = 100$ as claimed by Veres et al. (2018), then $\epsilon^* = 100$, and $\epsilon^* / \epsilon_p = 12.5$, which just barely satisfies the transparency requirement for $\epsilon_p = 8$.

Now consider the alternative model in which the baryons that power the afterglow are already mixed with the on-axis photons (e.g., photons resulting from internal shocks) at the time of the prompt emission. In this case the afterglow itself constrains the baryon environment through which those photons must escape. The density of baryons, if they power afterglow with about the same luminosity as the prompt emission that would be seen by an on-axis observer, is estimated using the condition that they must contain more energy than the prompt emission (as seen by an on-axis observer):

$$U = L_{iso} / [4 \pi c R^2] = \Gamma n m_e c^2$$

(6)

and

$$\tau = n' \sigma_T R / \Gamma = n \sigma_T R / \Gamma^2$$

$$= [L_{iso} / 4 \pi c R m_e c^3 \Gamma^{-1}] = 2.2 \cdot 10^8 L_{iso,53} R_{12}^{-1} \Gamma^{-1}$$

(7)

so that $\tau \lesssim 1$ implies $\Gamma \gtrsim 600 L_{iso,53} R_{12}^{-1} \Gamma^{-1}$. In other words, if the observed gamma rays had needed to escape from within the baryons that power the afterglow, then they could do so only if the latter had a Lorentz factor of several hundred, and this would be too ultrarelativistic to give significant amounts of off-axis radiation. This lower limit on $\Gamma$ is well known in the GRB literature.

We thus derive an important result: there cannot be much off-axis emission from within the material that powers the long-term afterglow. It would be too opaque to emit far off axis. Photons generated from within the jet by internal shocks would be dragged away from the observer’s line of sight by the motion and opacity of the baryonic fluid. The off-axis viewing hypothesis for GR 170817A works only if the photons impact the baryons from without and scatter off of its surface. We interpret this to mean that the baryons are probably from the recombination and are plowed up by the jet from behind.

In any case, any trace pairs that formed would be pinned against the scatterer by the radiation pressure of the jet and essentially become part of the scattering material. Thus, we do not consider their opacity.

4. Conclusions and Further Discussion

The surprisingly transparent nature of GRBs, given their high compactness, is perhaps the central mystery of GRBs. Two completely different explanations have been attempted. One is that huge Lorentz factors dilate both comoving time and distance scales of the fireball (Rees & Meszaros 1992), the effect of which is to lower the density of the outgoing material as well as its true compactness required to account for rapid variability. The other (Levinson & Eichler 1993) invokes a baryon-free corridor—probably connected to an event horizon—that the photons are either produced inside of or scattered into. If they are scattered by swept-up material at the leading edge nearly opposite to the direction of the scatterer’s motion (i.e., back toward the central engine that the scatterer is presumed to be receding from), then they are observed at “large” viewing angles” (i.e., at least several times $1 / \Gamma$) relative to the motion of the scatterer.

A qualitative difference between the two accounts of GRBs is that one—using baryonic kinetic energy as the primary source of energy—puts the energy in baryons, which only later manage to generate photons via shocks, whereas the other—a fireball that is nearly baryon free—has the energy flowing into baryons from an essentially non-baryonic fireball and predicts that the baryons that eventually power the afterglow will be accelerated by the push of a non-baryonic fireball from which the prompt emission originates.
The baryon-poor fireball scenario thus lends itself to a scenario in which the length of prompt GRB emission may depend on the timescale over which the observer is within the $1/\Gamma$ cone of emission, which in turn depends on the viewing angle of the observer. In fact, the dichotomy between short and long GRB and their different progenitors may be that the range of viable viewing angles depends strongly on the progenitor—i.e., merging neutron stars (short GRB) allow viewing from a wider range of angles than collapsars within giant envelopes (long GRB).

It should also be recalled that the combination of acceleration and viewing angle, with few free parameters, has considerable predictive power and, unlike the alternative models, quantitatively explains the Amati relation for long GRB (Eichler & Levinson 2004, Eichler & Levinson 2006), the flat phase of afterglows (Eichler 2005; Eichler & Jontof-Hutter 2005), spectral hard-to-soft evolution (Eichler & Manis 2007, Eichler & Manis 2008), and the differences between short and hard GRB (Eichler et al. 2009; Eichler 2017). In particular, to accommodate the Amati relation extending down to several KeV and $E_{\text{iso}} \sim 10^{48}$ erg s, i.e., almost six orders of magnitude in isotropic equivalent energy, the viewing offset must be as large as $30/\Gamma$ for the softest sources.

Afterglow observations of GRB 170817A provide an unprecedented arena for testing the hypothesis that the above features of GRB are due explainable by viewing angle kinematics, because the viewing angle relative to the jet axis is probably larger than that for any other GRB to date, and because the large viewing angle is verifiable in several different ways (gravitational wave polarization, radio afterglow, etc.). In an off-axis viewing scenario, photons coming from the jet that end up in our direction must be traveling nearly backward in the frame of the jet material, and here we have carefully considered the question of whether they could get out through the stream of outwardly propagating photons from the central source without pair producing. We find that there is no reason they should not, unless their energy is much higher than those detected in the NaI detectors of the GBM.

Using the above considerations, the following scenario for prompt emission can be suggested based on Figure 6 of Goldstein et al.: the GRB begins with $100 \lesssim E_p \lesssim 500$ KeV, with $\Gamma \lesssim 20$ and, by the end, where the spectrum peaks at only $10-20$ KeV, it has been accelerated to $\Gamma \gtrsim 20$. Attributing the softening to acceleration alone would not account quantitatively for the brightness of the soft tail. The soft tail could be due to a light echo off parts of the baryonic shell whose orientation is further from the line of sight. A detailed account of the light curve, though beyond the scope of this Letter, is important.

A viewing offset of $10^\circ$ or $15^\circ$ is not consistent with any and all models. We find, for example, that a viewing offset of 0.2 radians is incompatible with the prompt emission being powered by the same pool of kinetic energy that powers the long-term afterglow (e.g., internal shocks tapping about half of this kinetic energy for prompt emission and leaving the other half for powering the afterglow); then, in order to power the afterglow, the accompanying electrons would be optically thick to the prompt photons unless their Lorentz factor was above several hundred. But such a high Lorentz factor would give negligible emission at a viewing angle of at least 0.2 radians. The once-popular internal shock model for prompt emission is thus challenged unless the opening angle for the observed prompt emission is higher than that of the afterglow core (e.g., as in a structured jet or shock breakout model), in which case the direction of the motion of the shocked material can be nearly along our line of sight.

If the baryonic material that powers the afterglow also powers the prompt emission, then we expect the opening angle of each to be more or less the same. On the other hand, if the material merely reflects the prompt emission, then there is no reason to expect that the latter need scale with the mass of the baryonic material, and the profile of the prompt emission could in fact be wider than the core of the afterglow.

Future gravitational wave signals from neutron star mergers may be viewed at even larger angles from the rotational axis. In this case, the prompt emission would be even softer and dimmer than for GRB 170817A. Here, wide-angle X-ray cameras would be the more suitable means of detecting an accompanying electromagnetic signal (Eichler & Guetta 2010).

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