A MODEL FOR FAST RISING, SLOWLY DECAYING SUBPULSES IN γ-RAY BURSTS

DAVID EICHLER AND HADAR MANIS
Department of Physics, Ben-Gurion University, Beer-Sheva 84105, Israel; eichler@bgu.ac.il
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ABSTRACT
Gamma-ray bursts (GRBs) often feature subpulses that have a distinctively asymmetric profile—they rise quickly and decay much more slowly, while their spectrum softens slightly with observer time. It is suggested that these subpulses are caused by slow baryonic clouds embedded within a primary γ-ray beam, which scatter the γ-radiation into our line of sight as they accelerate. Good quantitative agreement is obtained with observed light curves and spectral evolution. The kinetic energy that the baryonic component of GRB jets receives from the primary γ-radiation is predicted to be about equal to the amount of γ-radiation that is scattered, consistent with observations of afterglow. Several other observational consequences are briefly discussed. The possibility is raised that the timescale of short GRBs is established by radiative acceleration and/or baryon injection rather than the timescale of the central engine.

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The nature of the central engine of GRBs remains unresolved by observations. It is not known what the primary form of energy output is or how the γ-radiation near the spectral peak is powered. Popular models invoke a baryonic outflow as the primary form of energy output, and synchrotron emission from electrons that are shock-accelerated in optically thin regions of the outflow (Meszaros & Rees 1994), presumably by internal shocks caused by the unsteadiness of the flow. Other models suggest that the primary output of the central engine is photons (e.g., Eichler 1994; Eichler & Levinson 2000; Rees & Mészáros 2005) or Poynting flux (e.g., Thompson 1994; Lyutikov & Blandford 2003). If the observed γ-radiation (and presumably a residue of pairs) is the primary form of released energy at the photosphere of the outflow, then the question is if and how the γ-radiation accelerates the baryonic outflow responsible for GRB afterglow.

In this Letter we propose that many γ-ray bursts are viewed at an angle that is slightly offset from the direction of the primary γ-ray beam, and that much of the primary radiation is, consequently, observed only after being scattered by slower baryons that have not yet reached their terminal Lorentz factor $Γ_ν$. The existence of slow baryons in the flow is not a strong assumption. They could enter the primary beam from the periphery due to the diffusion of slow neutrons from a surrounding wind (Eichler & Levinson 1999; Levinson & Eichler 2003) or possibly by turbulent excitation of transverse motion by Kelvin-Helmholtz instabilities at the side. Moreover, radiatively driven instabilities could bunch baryons within the outflow. Even in the internal shock model, slow material would be necessary to dissipate the energy of fast material, and the shocked material following their collision would still be slower than at the eventual terminal Lorentz factor. The main assumption made here is that the photons, although they may scatter off clouds of high optical depth, are not trapped within a large optical depth, and that they accelerate the clouds/bunches as they overtake them from the rear. We show that the observed temperature, as defined by the location of the emission peak, should then decrease approximately as $r^{-2/3}$, as reported by Ryde (2004). We also show that the observed time profile has a characteristic fast rise, slow decay typical of subpulses\(^1\) often seen in the prompt emission of GRBs. The decay is due largely to the acceleration of the scattering baryons by the radiation pressure of the primary photons, which causes the beam of scattered photons to narrow to below the offset angle.

It would not be surprising if matter were accelerated beyond the photosphere because the isotropic equivalent luminosity can be as high as $10^{53}$ Eddington luminosities or more. This would surely be a powerful accelerator of any material that did not already have a Lorentz factor of at least several hundred, even at distances of $10^{13}$–$10^{14}$ cm, where the photosphere is placed in many models. The acceleration of isolated baryons would be much faster than the hydrodynamical timescale. In the process of being accelerated, the baryonic scattering material would scatter as much radiative energy as the energy it received from the radiation pressure (see below). Thus, radiation scattered by accelerating baryons would represent as significant a part of the GRB energy budget as the baryons.\(^2\)

The idea that most GRBs are observed from an offset viewing angle is well motivated and has been amply discussed in the literature. One motivation is that very bright GRBs such as 990123 are much brighter than the detection threshold and could be viewed by observers that are offset by an angle of several times $1/Γ$, just from their kinematic broadening. Another is that the Amati (and Ghirlanda) correlations (Amati et al. 2002; Ghirlanda et al. 2004) can be explained as kinematically correlated softening of both the peak frequency and isotropic equivalent (jet) energy (Eichler & Levinson 2004, 2006). Scattered radiation from accelerating baryons can, at some cost to peak brightness, significantly enhance the solid angle over which a GRB could be detected, and, for sources with low $V/V_{\text{max}}$, thus enhance the maximum volume $V_{\text{max}} = \int r_{\text{max}}^2(θ, φ) dΩ/3$ over which a burst can be detected. A considerable fraction of all detected GRBs, or subclasses thereof, may then involve a component of scattered radiation. Many observers could detect such radiation while the baryons that scattered...
The received flux by a distant observer viewing angle $\theta_{\text{v}}$, as a function of observer time $t$ is given by (Rybicki & Lightman 1979)

$$dP_{\text{f}}/d\Omega = [\gamma(1 - \beta \cos \theta_{\text{v}})]^{-2}dP/d\Omega,$$

and the late time behavior when $1/T \ll \theta_{\text{v}}$ is, for constant $F$,

$$dP_{\text{f}}/d\Omega \propto (1 - \beta)^{3} \propto r^{-2}. $$

Note that for a powerful GRB with isotropic equivalent luminosity $L_{\text{iso}} = 10^{53}$ ergs s$^{-1}$, and baryons beginning from rest at radius $r = 10^{53} r_{\text{c}}$ cm, the acceleration time up to $\Gamma \leq (10^{5} L_{\text{iso}}/r_{\text{c}})^{1/3}$ is less than the hydrodynamical expansion time (Eichler 2004) for $r_{\text{c}}$, $L_{\text{iso}} \sim 1$. Thus, the model predicts a priori, given the relevant range of parameters for the central engine and host star envelope ($L_{\text{iso}} \sim 1, r_{\text{c}} \sim 1$), that the baryons naturally obtain a Lorentz factor of several hundred.

It is possible that the baryonic cloud is optically thick when injected into the primary beam. In this case, the back end is compressed by the radiation pressure, and a reverse shock is sent through the cloud (which could result in particle acceleration and a nonthermal component in the scattered radiation), and the average acceleration is reduced by the optical depth $\tau$. The scattered radiation emerges from the back end of the cloud, after only one or very few scatterings, so, in the frame of the cloud, the forward hemisphere is shaded. When the cloud accelerates beyond $\Gamma = 1/\theta_{\text{v}}$, the observer’s line of sight emerges from the shadow, and a sudden turn-on of the scattered radiation is seen. The turn on is just at the value of $\beta$ where the flux of scattered radiation detected by the observer is near maximum. Alternatively, the optical depth $\sigma_{\text{r}}[\int n(r)\int[1-\beta(r)]d\Omega r]$ of any given parcel of baryons also drops, due to the acceleration, much faster than the expansion. The photosphere can self-organize in the sense that a sudden drop in optical depth is then both the cause and effect of a sudden drop in $[1 - \beta]$.

Finally, the cloud may be optically thin. This would imply that much of the primary radiation escapes unscattered. This possibility seems to be allowed, at present, by observations: A GRB as bright as 990123, for example, although only occurring once per $10^{3}$ bursts, is $10^{3}$ times as bright as the typical GRB, and, having a high peak frequency, is a logical candidate for primary emission. The proposed model can thus accommodate a rather large range of initial optical depths, as long as the key assumption is maintained that the photons are not trapped within the baryons as they would be if everything were distributed smoothly.

In Figure 1, we have plotted $F = (\sigma_{\text{r}}/m_{\text{e}}c^{2}) \left[ (1 - \beta \cos \theta_{\text{v}}) \times F\text{d}_{\text{source}} \right]$ as a function of $\beta$, the velocity of the scatterer in units of $c$. Here $F$ is to be taken at the instantaneous position of the scatterer. We have also assumed a plane parallel geometry, which is valid when the acceleration is rapid compared to the expansion time. Assuming constant $F$, we have then plotted in Figure 2 the observed light curve $dP/d\Omega$ as a function of $t$. Here we have assumed that the baryonic cloud is optically thin, so that its emission can be seen by the observer even when $\Gamma \ll 1/\theta$. It is seen that even in this case the characteristic time asymmetry that is the signature of GRB subpulses is nicely reproduced by the model as seen in Figure 2. In the case where the cloud is injected—or the radiation first transmitted to the observer—at finite $\beta$, the rise is even sharper relative to the decay, and the peak can be a true cusp (Fig. 3).

The late-time scaling behavior of the spectral location of the peak is easily calculated by noting that the initial peak photon frequency in the source frame $\nu_{\text{sp}}$ is seen in the scatterer frame as $\nu_{\text{sp}} = \nu_{\text{sp}}/\Gamma(1 + \beta)$ while the final peak frequency, as seen by the observer, is $\nu_{\text{f}} = \nu_{\text{f}}/\Gamma(1 + \beta)(1 - \beta \cos \theta_{\text{v}})$. This im-

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**Fig. 1.—The luminosity and time, both as measured by an observer viewing the GRB at an offset angle $\theta_{\text{v}} = 10$ degrees, are displayed as functions of $\beta$ of the scattering plasma. It is assumed that the plasma is optically thin. The normalization of $L$ and $r$, the distance of the plasma from the central engine, are arbitrary. [See the electronic edition of the Journal for a color version of this figure.]**

...it into the line of sight continue in a slightly different direction, and this separation between baryon direction and prompt $\gamma$-ray direction could be a reason for the delay of strong afterglow in many GRBs (Eichler & Granot 2006). We also note that at viewing angles $\theta_{\text{v}}$ that are large compared to the jet opening angle, many GRBs (Eichler & Granot 2006). We also note that at viewing angles $\theta_{\text{v}}$ that are large compared to the jet opening angle...
There are several free parameters in the model, including the viewing angle, the initial velocity, and radius at which the baryonic cloud is injected into the jet (or at which it becomes optically thin), the rate at which baryons are injected into the jet (e.g., suddenly or gradually), and the inevitable decline of the primary luminosity with time. Nevertheless, we believe that the fast rise, slow decay is a generic feature of both the observations and theoretical predictions. We find that the peculiar shape is insensitive to the viewing angle, the luminosity, and radius; these parameters basically rescale the x- and/or y-axis. The decline of the luminosity with time is expected and could be the reason the theoretical tails are slightly more prolonged than the ones actually observed (e.g., Fig. 3), but because the cloud moves almost as fast as the photons, the Langrangian derivative of the luminosity is considerably smaller than the Eulerian derivative, so this effect is likely to be small. By the same token, there could be a small component of the primary beam near the viewing angle, which could make the luminosity decline more gradually with time than if the primary beam is entirely within a narrow pencil shape.

In the case that the scatterer is optically thin, the model predicts correlation of polarization with intensity (Fig. 2). If the primary radiation is unpolarized, and the cloud is being accelerated through the Lorentz factor $\gamma = 1/\theta_{\nu}$, then the peak of the subpulse should correspond to $\Gamma \sim 1/\theta_{\nu}$. This corresponds to a $\pi/2$ scattering in the frame of the cloud and should correspond to maximum polarization.

It is easy to see that any parcel of energy $dE_b$ that emerges as scattered radiation by relativistic baryons is about equal to the kinetic energy $dE_b$ that is imparted to baryons as a result of its scattering: In the instantaneous rest frame of the baryon, in the limit of elastic Thomson scattering, the scattered radiation has, on average, zero momentum, $dp_b' = 0$, and all its original energy $dE_b'$, while the scatterer has gotten all the momentum, $dp_b'' = dE_b'/c$, and essentially none of the energy, $dE_b' \sim 0$. In the source frame, the ratio of energy in scattered photons $dE_b = \Gamma dE_b' + \beta cd p_b'$ to the energy they impart to the scatterer $dE_b = \Gamma \beta cd p_b'$ is $dE_b/dE_b = \beta^{-1}$, so that in the limit $\beta \sim 1$, the energy that ultimately remains in the scattered radiation is nearly equal to the kinetic energy that it imparted to the scatterer. Allowing for the possibility of only partial coverage, then in fact a significant fraction of the primary radiation remains unscattered, in which case the energy in prompt emission should consistently exceed the energy inferred from afterglow data. This is consistent with the results of Eichler & Jontof-Hutter (2005), which indicate that the prompt emission, corrected for viewing angle, is typically 3–15 times larger than the estimated kinetic energy (Lloyd-Romming & Zhang 2004) inferred from the X-ray afterglow after 10 hr.

Scattering by slow ($\Gamma \sim 1/\theta_{\nu} \ll 1/\theta_{\nu}$) baryons, in contrast to the viewing angle effect when $\Gamma \geq 1/(\theta_{\nu} - \theta_{\nu})$, widens the observable photon beam relative to the baryon beam without significantly altering the observed spectrum. It thus introduces one-sided scatter into the Frail, Amati, and Ghirlanda, etc., correlations in that it lowers the observed fluence (and ultimately the inferred $E_{iso}$) without altering the inferred (via afterglow breaks) opening angle of the jet or observed spectral peak. At a given spectral peak, therefore, there should always be outliers that appear underluminous in the context of these correlations, or overly hard spectra for a given $E_{iso}$. This is consistent with observations (e.g., Butler et al. 2007).

The angular profile of the time-integrated scattered radiation has, during the acceleration phase of the scatterer, a “universal” structure and a systematic correlation between fluence and observed duration: For any given source, the amount of energy $E(\theta_{\nu})$ that fills a cone of opening angle $\theta_{\nu}$ is proportional to $\theta_{\nu}^{-1/2}$.

3 The peak frequency at the peak of the light curve is half the intrinsic peak frequency of the source, independent of $\theta_{\nu}$.
proportional to $1/\sin \theta_v$ when the observer is well outside the cone (or annulus) of primary emission $\theta_v$. This follows from the fact that the amount of energy scattered by a scatterer at energy $\Gamma mc^2$ is proportional to $\Gamma$, while the observer at viewing angle $\theta_v$ does not see any scattered radiation after the scatterer has accelerated much beyond $\Gamma \approx 1/\sin \theta_v$. Because the emission cone’s solid angle $\Delta \Omega$, at the observed peak of the subpulse goes as $1 - \cos \theta_v$, the observer sees a fluence $F = E/\Delta \Omega \cdot d^2$ (where $d$ is the luminosity distance) that scales as $F \propto 1/\sin \theta_v (1 - \cos \theta_v) \approx 2/\theta_v^2$, and this would induce some scatter in the prompt radiative output as inferred from the Frail anticorrelation between isotropic equivalent energy and apparent opening angle (the latter being inferred from afterglow breaks).

Specifically, GRB subpulses observed at very large $\theta_v (\gg 1/\Gamma_v)$ would appear less energetic, although their spectra might be especially atypical, between fluence and peak frequency.

Low-energy GRBs such as GRB 980425 might thus lie well off the Frail relation because they are observed at large viewing angles. In the case of large viewing angle, the observed duration $\Delta t_{\text{peak}}$ of the subpulse peak scales as $\Gamma_{\text{peak}} \sim 1/\sin \theta_v$, because, although the observed time lapse is compressed as $\Delta t_{\text{peak}}/\Delta t_{\text{peak, source}} \propto 1/\Gamma_{\text{peak}}$, the acceleration time in the source frame goes as $-[d \ln (1 - \beta)/d t_{\text{source}}]^{-1} \propto \Gamma_{\text{peak}}$. The peak flux $E_v (\theta_v)/\Delta \Omega d^2$ is proportional to $1/\Delta \Omega d^2 = 1/2\pi (1 - \cos \theta_v) d^2$, and, given that $d^2_{\text{max}} \propto 1/\Delta \Omega$, the maximum volume of detectability $V_{\text{max}} = d^3_{\text{max}} \Delta \Omega$ scales as $1/(1 - \cos \theta_v)^{3/2}$.

Thus, bursts observed at large angle due to scattering by baryons at an early stage of acceleration have an inferred radiative output that is only $[(1 - \cos \theta_v)/(1 - \cos \theta_v)]^{3/2}$ times of that of a typical GRB and, from this viewing angle, would be detected only $[(1 - \cos \theta_v)/(1 - \cos \theta_v)]^{3/2}$ times as frequently.

To summarize, we propose that at least part of the baryons in GRBs are frequently bunched, either because they are injected in bunches, or because radiatively driven instabilities bunch them. The primary radiation that scatters off them is seen by an offset observer as fast rise, slow decay subpulses, of the sort typically seen in GRBs. The peak frequency as seen by the observer decays roughly as $t^{-2/3}$, in agreement with the data analysis of Ryde (2004). Because this softening is kinematic, the power spectrum of rapid variations originating in the source, if they survive time-of-flight dispersion due to the finite size of the scattering region, should, even in the limit of zero scatterer size, be softened in the same way as the spectral peak. This could provide a future confirmation of the model. Another possible observational consequence of the model (cleanest if the scatterers are optically thin) is that the polarization should correlate positively with the received flux in the subpulse.

In constructing the simplest mathematical model for scattering by primary $\gamma$-rays by slow material, we have assumed that the scatterer is pointlike in solid angle and that the radiation is radially combed. In reality, any given observer may see a superposition of radiation from a finite range of directions, including primary emission beamed directly at him. Moreover, the finite angular spread $\Delta \theta$ of the primary photons, which may not be negligible if and when $\Gamma$ approaches $1/\Delta \theta$, is determined by the collimation profile imposed by the host star. These considerations undoubtedly vary from burst to burst and can, along with other variable factors, provide the rich diversity of individual light curves and spectra found among GRBs.

We might even conjecture that the difference between short and long GRBs lies not so much in the lifetime or energy of the central engine, but rather in the acceleration time of baryons in the path of the fireball and/or the duration of baryon injection into the primary beam. Differences in the apparent acceleration time would likely accompany the differences in the corresponding host stars (e.g., a white dwarf or neutron star merger that collapsed into a black hole would accelerate baryons much closer to the central engine), and could also be due at least in part to differences in the observer’s viewing angle. This interpretation of short GRBs would be consistent with the view that they are typically observed from a much larger viewing angle off the jet axis than long GRBs and appear to have lower energy than long GRBs. It must be kept in mind, however, that this model for short GRBs would be constrained by any millisecond variability observed. It would also be worth looking for “breakout flashes” at large viewing angle, which could occur when a GRB fireball is just breaking through the uppermost layer of its post–main-sequence host star. The baryons in the way of the GRB fireball just as it is breaking out would be accelerated on a timescale much shorter than the hydrodynamical timescale, so the observed duration would be short. The short term (millisecond) variability, however, would be washed out by the scattering, and this would distinguish it from other short GRBs. Standard short GRBs, by the same token, may simply be breakout flashes from merged white dwarfs or neutron stars.

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