GAMMA-RAY BURSTS: MULTIWAVEBAND SPECTRAL PREDICTIONS FOR BLAST WAVE MODELS

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Abstract

In almost any scenario for ‘cosmological’ gamma-ray bursts (and in many models where they originate in our own Galaxy), the initial energy density is so large that the resulting relativistic plasma expands with \( v \sim c \) producing a blast wave ahead of it and a reverse shock moving into the ejecta, as it ploughs into the external medium. We evaluate the radiation expected from these shocks, for both cosmological and galactic bursts, for various assumptions about the strength of the magnetic field and the particle acceleration mechanisms in the shocks. The spectra are evaluated over the whole range from the IR to \( > \) GeV, and are compared with the variety of spectral behavior reported by BATSE, and with the X-ray and optical constraints. For bursts of duration \( \gtrsim 1 \) s acceptable \( \gamma \)-ray spectra and \( L_x/L_\gamma \) ratios are readily obtained for ‘cosmological’ models. Blast waves in galactic models can produce bursts of similar gamma-ray fluence and duration, but they violate the X-ray paucity constraint, except for the shorter bursts (\( \lesssim 1 \) s). We discuss the prospects for using O/UV and X-ray observations to discriminate among alternative models.

1. Introduction

Gamma-ray bursters (GRBs) emit most of their energy above \( \sim 0.5 \) MeV (e.g. Band, et al., 1993) and have not so far been convincingly detected at energies below a few KeV, despite intensive searches (e.g. Hartmann, 1993). Relatively large error boxes and the lack of good calibrations have provided only tentative upper limits from archival searches (e.g. Hudec, et al., 1992), while active optical monitoring has been carried out only sporadically and on a modest scale (e.g. Moskalenko, et al., 1992). Quasi-simultaneous X-ray emission has been detected in only a few objects (e.g. Murakami, et al., 1992, Boer, et al., 1992), and limits have been set on the X-ray to \( \gamma \)-ray luminosity ratio (X-ray paucity constraint) of \( \lesssim \) few \( 10^{-2} \), e.g. Laros, et al., 1984; Hurley, 1989). However, a new era of multiwaveband observing capability is expected to be ushered in with the launch in a few years of HETE (Ricker, 1992), which will carry broad-band gamma-ray, X-ray and UV detectors. This should improve the chances of finding counterparts and provide more accurate low frequency fluxes or upper limits.

If GRBs are at cosmological distances, the luminosity is so high that the dominant radiation mechanism would be highly relativistically outflowing plasma. Such a plasma is
bursts classed as “short/variable” (Kouveliotou, et al., 1993; Lamb, Graziani & Smith, 1993) come from the magnetosphere, and attribute the commoner “long/smooth” bursts to interaction of a relativistic outflow with external matter.

For relativistic blasts, the apparent diameter of the emitting region is larger by at least a factor $\Gamma$ (the bulk Lorentz factor) than in the corresponding nonrelativistic case. Consequently there is much less likelihood of strong suppression of the radiation down to optical frequencies due to self-absorption. For this reason, and also because the radiation mechanisms are more straightforward than in some alternative models (no ultra strong magnetic fields, etc.), any O-UV/ X-ray measurements or upper limits would have relatively straightforward implications for this promising class of models.

2. Shock Structure and Magnetic Fields

The relativistic ejecta may be either a radiation-pair fireball with some baryon loading, or could be predominantly Poynting flux if the initial event were strongly magnetically dominated. In either case, sweeping-up of the external medium will create a highly relativistic shock that can accelerate particles to relativistic energies; the reverse shock propagating back into the ejecta will also generally be strong and relativistic. Even if the magnetic fields already present in the ejecta or in the external medium are weak, they may be amplified up to equipartition values in the shocks (as seems to happen in supernova remnants and radio sources, probably because shock instabilities, e.g. Ryu and Vishniac, 1992, lead to turbulent field growth). The observable burst timescale $t_b$ is determined by the external density $n_o$ and the total burst energy $E_o$, if the initial energy deposition is impulsive (occurs on $\Delta t \ll t_b$); if $\Delta t$ is longer, it is determined by the energy release mechanism itself (Rees and Mészáros 1992).

The radiative efficiency of a GRB shock is a function of the bulk Lorentz factor, the magnetic field strength, the particle acceleration mechanism and the density of the external medium. Various combinations of these elements can lead to shocks with different spectra and radiation efficiencies (Mészáros and Rees, 1993, Katz, 1993). The minimum electron (random) Lorentz factor behind the blast wave is expected to be $\gamma_m = \kappa \Gamma$, where $\Gamma$ is the bulk Lorentz factor of the shock and $1 \leq \kappa \lesssim m_p/m_e$ (the latter occurring if energy is shared between electrons and protons in the shock). Diffusive shock acceleration is expected to produce a power law electron spectrum above $\gamma_m$, whose slope is typically -2 to -3 (e.g. Blandford and Eichler, 1987).

The properties of the reverse shock depend on the nature of the fireball. In the case of a baryon-loaded fireball the sound speed in the ejecta may be low, and the reverse shock will be strong and at least mildly relativistic. If the fireball is magnetically dominated (almost completely unloaded, e.g. Narayan, Paczyński and Piran, 1992), it will have a large outward Lorentz factor even relative to the frame of the contact discontinuity. The reverse shock is then strong, the field in the shocked region providing most of the pressure that drives the blast wave. Particles (either entrained, or neutrals swept up from
the external medium), will be accelerated, rather as in the Crab’s wisps (e.g. Hoshino, et al., 1992).

3. Spectral Components

The radiative efficiency, and the spectrum, depend on the physical nature of the outflow material, the efficiency of field growth and particle acceleration behind the shocks, and the degree of mixing across the contact discontinuity. The energy bands at which the photons appear depend on the electron Lorentz factors $\gamma$ produced in the respective shocks. If an adequate magnetic field is present, either through shock amplification or (in the case of the reverse shock) because it is frozen into the ejecta, each shock contributes a synchrotron component, and a higher energy component due to IC scattering of the synchrotron photons by the same electrons (Mészáros, Laguna and Rees, 1993).

If both reverse shock and blast wave acceleration are efficient, a third additional IC component arises, due to upscattering of reverse synchrotron photons by blast wave electrons. (We neglect IC scattering in the reverse shock of any photons originating in the blast wave, which is a relatively weaker photon source, and also second-order IC, which is likely to occur in the Klein-Nishina regime).

If there is no frozen-in field, and only the blast wave leads to field growth, a two component spectrum arises. On the other hand, if the only strong field is associated with the reverse shock, a three component spectrum is expected: two from the reverse-shocked ejecta, plus a component due to IC scattering of this radiation by the high-energy electrons that are, in all cases, accelerated behind the ultrarelativistic blast wave. Finally, if substantial field growth occurs in both shocks (or the reverse shock is dominated by frozen-in fields and growth occurs in the blast wave), and acceleration is efficient in both, there will be five components altogether.

The energy slope of the synchrotron spectrum is $-(p - 1)/2$ above frequencies $\nu_m \sim 10^6 B \gamma_m^2$, where $-p$ is the electron power-law index above $\gamma_m$. We took $p$ to be around -3, giving a photon energy index about $-1$ above $\nu_m(\gamma_m)$. For a single value of $\gamma_m$, the photon energy spectrum below $\nu_m(\gamma_m)$ would be expected to have a slope $+1/3$. (Synchrotron self-absorption is included, but usually occurs below the UV range for the parameters of these models). The corresponding power per decade slopes below and above the break $\nu_m$ would be $4/3$ and 0, close to the observed “fiducial” values 1 and 0 deduced for those objects where a break is required (Schaefer, et al., 1993; but cf Band et al. 1993)). However, $\gamma_m$ may not be uniform throughout different regions of the shock, which could easily lead to a flattening of the slope below the break. We therefore assume, in accord with the data, a fiducial power per decade with slope 1 (energy slope 0) below the break. Thus the power per decade composite spectrum of GRBs, whether galactic or extragalactic, is made up of between two to five subcomponents with slopes roughly 1 (0) below (above) break energies determined by the comoving mean values of $B$, $\gamma_m$ (up to two synchrotron, up to three IC breaks and components).
The importance of each spectral component is found by estimating the corresponding radiative efficiency, based on the values of $\gamma_m$, $p$ and $u_B$, $u_r$ (the comoving magnetic and radiation density) in each shock. The efficiency of each radiation mechanism in a particular shock is $\alpha_j = t_j^{-1}/(t_j^{-1} + t_{ex}^{-1})$, where $t_i$ is the harmonic sum of the other competing radiative mechanisms and $t_{ex}$ is the expansion time in the comoving frame. The total available energy in each shock is a fraction of the kinetic energy of the ejected material ($\sim E_o$, the initial energy liberated). This is shared approximately equally between both shocks, since they are in pressure equilibrium, e.g. Rees and Mészáros, 1992. The total fluence is then determined by multiplying this fraction by the efficiency and by the total bolometric fluence potentially available, $S_b = E_o/(4\pi^2B^2)$ ergs cm$^{-2}$, where $\theta$ is the possible beaming angle and $D$ is the distance.

4. O/UV, X, and $\gamma$ Fluences

The predicted spectrum may in principle show up to five breaks. In most cases, however, the net spectra are dominated by not more than three distinguishable components, the break energies depending on the density, magnetic field, etc. If the main break is outside all three observational bands or windows considered, the fluence in the $u$, $x$ windows relates to that in the $\gamma$ window as $S_u/S_\gamma = (E_u/E_\gamma)^\alpha$, $S_x/S_\gamma = (E_x/E_\gamma)^\alpha$, where $(E_u, E_x, E_\gamma) \sim (5 \text{ eV}, 10^3 \text{ eV}, 5 \times 10^5 \text{ eV})$ are the appropriate energies of the bands. The fiducial value of $\alpha$ is 1 for a high-energy break and 0 for a low-energy break. In general, especially if two or three breaks dominate the total spectrum, these spectral breaks come between or within the bands, and the ratios are more complicated.

We have performed calculations for a range of $E_o$, $D$ and $\theta$ corresponding to both extragalactic and galactic models, for various assumptions about the magnetic field generation and frozen-in component, as well as about the electron acceleration parameters and the strength of the shock $\eta = E_o/M_o c^2$ for matter-dominated shocks or $\Gamma$ for magnetic dominated shocks. In the cosmological cases we took $D = 10^{28}$ cm and in the galactic cases $D = 1$ kpc. A modest variation of $\eta$ by one order of magnitude results in a range of burst durations $0.1 \text{ s} \lesssim t_b \lesssim 10^3 \text{ s}$, while the burst diversity is easily explained by variability in the density of the external medium encountered and/or cooling timescale substructure induced by magnetic inhomogeneities in the shocks caused by instabilities or turbulence. We report here some results for typical parameter values; further details will be discussed elsewhere.

If turbulent field growth leads to equipartition fields in both the reverse shock and the blast wave, the models show at most three dominant spectral components. For cosmological models with $E_o = 10^{51}$ ergs, $D = 10^{28}$ cm and $\theta = 10^{-1}$, with $\eta = 10^3$ and external density $n_o = 1 \text{ cm}^{-3}$, the burst lasts $5 \text{ s}$, and for equipartition fields one gets fluences of $\log S_{u,x,\gamma} \sim (-5.9, -4.9, -4.7), (-9.3, -6.8, -6.7)$ in ergs cm$^{-2}$, for $\kappa = 1$, $10^3$. Similar models at galactic disk distances with $E_o = 10^{39}$ ergs, $D = 1$ kpc and $\theta = 10^{-1}$, $\eta = 10^2$ and $n_o = 1 \text{ cm}^{-3}$ give bursts that last $5 \text{ s}$ with fluences $\log S_{u,x,\gamma} \sim (-6.5, -6.5, -6.5), (-5.0, -3.9, -3.9)$ for $\kappa = 1$, $10^3$. 


If field amplification is negligible in either shock, but frozen-in magnetic fields are radiatively dominant in the ejecta, there are three spectral components with fluences generally lower than in the shock turbulent growth case. At cosmological distances, $E_o = 10^{51}$, $D_{28} = 1$, $\theta = 10^{-1}$, $\eta = 10^3$, $t_b = 5$ s, we find $\log S_{u,x,\gamma} \sim (-10.5, -10.5, -10.5), (-7.6, -7.6, -6.2)$ for $\kappa = 1$, $10^3$. In the galactic case, the radiative efficiency is much lower, so larger explosion energies are required, e.g. $E_o = 10^{43}$ ergs, $\theta = 10^{-1}$, $\eta = 10^2$, $t_b = 5$ s, giving $\log S_{u,x,\gamma} \sim (-7.8, -7.8, -7.8), (-4.8, -4.8, -4.8)$ for $\kappa = 1$, $10^3$. The frozen-in cosmological (full line) and galactic (long dashed line) cases for $\kappa = 10^3$ are shown in Fig. 1.

Another possibility is that the fireball is so magnetically dominated that it does not contain enough electrons to be accelerated by the reverse shock, or it is matter dominated but the reverse shock is inefficient. Then, unless mixing across the contact discontinuity occurs, the ejecta just act as a ‘piston’. Two spectral components can then arise if turbulent field growth and acceleration occurs in the blast wave. For the cosmological parameters above ($t_b = 5$ s), the fluences are $\log S_{u,x,\gamma} \sim (-7.3, -4.9, -4.7), (-18.3, -15.8, -13.2)$ for $\kappa = 1$, $10^3$, while for galactic parameters ($E_o = 10^{39}$, $\theta = 10^{-1}$, $\eta = 3 \times 10^4$) one expects $\log S_{u,x,\gamma} \sim (-6.5, -6.5, -6.5), (-6.4, -3.9, -3.9)$ for $\kappa = 1$, $10^3$. Two ‘piston model’ spectra are shown in Fig. 1 for the cosmological case ($\eta = 10^3$, $\kappa = 40$, $\xi = 10^{-3}$, $t_b = 5$ s, dot-dashed line) and for the galactic case ($E_o = 10^{39}$ ergs, $\eta = 10^2$, $\kappa = 10^2$, $\lambda = 1$, $t_b = 0.2$ s, short dashed line).

5. Discussion

The detection of bursts (or even improved upper limits) in other wavebands would aid greatly in discriminating among various models. Moreover the present indications that there are two classes of classical gamma-ray bursts (Kouveliotou, et al., 1993, Lamb, Graziani and Smith, 1993) would be greatly strengthened if these classes turned out to be distinctively different at lower frequencies. The results summarised here relate to models where the gamma-rays result from braking of relativistic ejecta by an external medium. We originally applied these models to “cosmological” bursts; however, a similar mechanism, with scaled-down parameters, may also be relevant to one class of “galactic” bursts (Begelman, Mészáros and Rees, 1993). The fluences depend on $\eta$, $n_o$, $E_o$, $D$ and $\theta$, and on the magnetic field (though not in a simple manner), and the ratios of the fluences in the three bands also depend in a complicated manner on the various parameters. The numbers discussed above, however, give an idea of some of the consequences of various physical assumptions. In most of the cases producing a detectable $\gamma$-ray emission, a significant O/UV and X-ray emission is also predicted.

Matter dominated (loaded) models are radiatively efficient if strong fields build up behind both shocks, but lead to X-ray to $\gamma$-ray ratios in excess of the usually invoked X-ray paucity requirement $L_x/L_{\gamma} \lesssim 0.03$. This X-ray constraint is better satisfied by loaded models involving frozen-in magnetic fields in the ejecta, which initially were close to equipartition, and where the reverse shock is radiative (with or without a third component from blast wave IC). These models can give $L_x/L_{\gamma} \lesssim 0.03$ at cosmological distances (full
lines, Fig. 1), but not at galactic disk distances, where all three fluences in the O/UV, X-ray and γ-ray bands are comparable (long-dashed line, Fig. 1).

Magnetically dominated (unloaded) models, or loaded models with an inefficient reverse shock, can give ratios $L_x/L_\gamma \approx 0.03$ in the “piston” case, where only the blast wave radiates, but these models are less satisfactory in some other respects. For cosmological distances, $\kappa = 4 \times 10^1$ satisfies the X-ray paucity criterion above (dot-dashed line, Fig. 1), but the fluences are several orders of magnitude lower than in previous models. For galactic disk distances, $\kappa = 10^3$ fits the X-ray paucity spectrum as written above (short dashed line, Fig. 1), but the duration is $t_b \sim 0.2$ s, unless an extra free parameter is introduced for the initial energy deposition timescale. On the other hand, if the blast wave does not radiate (no turbulent field growth) but local acceleration or mixing causes the reverse shock to be an efficient radiator, the cosmological case satisfies the X-ray paucity constraint, but the galactic case does not.

It may be possible to distinguish between the models above which satisfy the X-ray paucity constraint, if positive measurements become available of the O/UV fluences. Even if future observations brought about modifications of this constraint in some cases, predictions can be made about the expected ratio of fluence at various wavelengths. The O/UV fluences in the (loaded or unloaded) frozen-in cosmological reverse shock case are predicted to be higher, comparable in energy to the X-ray fluence, or $\sim 1.5 - 2$ orders of magnitude below the γ-ray fluence. On the other hand the unloaded magnetic piston or the matter-dominated piston models predict an O/UV fluence which is $\sim 1.5$ orders of magnitude below the X-ray fluence, or $\sim 3.5 - 4.$ orders of magnitude below the γ-ray fluence.

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Fig. 1.- Power per decade spectra for bursts with $n_o = 1 \text{ cm}^{-3}$, $\theta = 10^{-1}$. 1) Solid line: cosmological, frozen-in field, $E_o = 10^{51}$ ergs, $\eta = 10^{4}$, $\kappa = 10^{3}$, $\xi = 1$, $t_b = 5$ s. 2) Dot-dashes: cosmological, ‘piston’, $E_o = 10^{51}$ ergs, $\eta = 10^{3}$, $\kappa = 40$, $\xi = 10^{-3}$, $t_b = 5$ s. 3) Short Dashes: galactic, ‘piston’, $E_o = 10^{39}$ ergs, $\eta = 10^{2}$, $\kappa = 10^{3}$, $\lambda = 1$, $t_b = 0.2$ s. 4) Long Dashes: galactic, frozen-in field, $E_o = 10^{43}$ ergs, $\eta = 10^{2}$, $\kappa = 10^{3}$, $\xi = 1$, $t_b = 5$ s. The first three satisfy the X-ray paucity constraint, but in 3) only for $t_b \lesssim 1$ s, while 4) overproduces X-rays.
