Gamma-ray Burst Models:
General Requirements and Predictions

P. MÉSZÁROS
Pennsylvania State University, 525 Davey Laboratory,
University Park, PA 16803, USA

ABSTRACT
Whatever the ultimate energy source of gamma-ray bursts turns out to be, the resulting sequence of physical events is likely to lead to a fairly generic, almost unavoidable scenario: a relativistic fireball that dissipates its energy after it has become optically thin. This is expected both for cosmological and halo distances. Here we explore the observational motivation of this scenario, and the consequences of the resulting models for the photon production in different wavebands, the energetics and the time structure of classical gamma-ray bursters.

1. OBSERVATIONAL REQUIREMENTS
A main requirement of almost any model for gamma-ray burst sources (GRB), which has been long appreciated, is that the “working surface” must be expanding due to radiation pressure. This is expected either for an extended galactic halo ($D < \sim 10^{24}$ cm) or for a cosmological ($D \sim 10^{28}$ cm) spatial distribution (distances much smaller than 100 kpc are not favored by current observational limits on the isotropy of the location distribution, e.g. Fishman, 1994). For a characteristic observed fluence $F = 10^{-6} F_{-6}$ ergs cm$^{-2}$ the energy in a solid angle $\theta^2$ is

$$E = 10^{43} F_{-6} D_{24}^2 \theta^2 = 10^{51} F_{-6} D_{28}^2 \theta^2 \text{ ergs},$$  

(1)

so the luminosity is highly super-Eddington, $E/t_b \gg 10^{38} (M/M_\odot)$ ergs for the characteristic burst durations $t_b \gg 10^{-5}$ s and masses $M \sim M_\odot$ expected for most progenitors. Coupled with the fact that gamma-ray photons above $e^\pm$ pair threshold constitute most of the observed flux, this led to the concept of an expanding pair-photon fireball (Cavallo and Rees, 1978, Paczyński, 1986, Goodman, 1986). However, from the above information alone it is not possible to determine whether the expansion will be slow or fast. If the baryon load of the radiation-pressure ejected shells were large ($E/Mc^2 \ll 1$, the expansion would be subrelativistic, and the flow would remain optically thick, leading to a degradation of the gamma-rays (Paczyński, 1990).

A second element which must enter any successful GRB scenario is implied by the detection in many GRB of photons with energies $\epsilon_\gamma \gtrsim 1$ GeV. Pair formation sets in for

$$\epsilon_\gamma > 2(m_e c^2)^2 [E_t (1 - \cos \alpha)]^{-1} \simeq 4(m_e c^2)^2 \epsilon_t^{-1} \alpha^{-2}$$  

(2)

in the laboratory frame, where $\epsilon_t$ is the lab frame target photon energy and $\alpha$ is the relative angle of the two photons. However in the same frame, causality implies

*To appear in Proc. 17th Texas Conf. Relativistic Astrophysics, NY Acad.Sci., 1994
\( \alpha \lesssim \Gamma^{-1} \) where \( \Gamma \) is the bulk Lorentz factor. Therefore \( \Gamma^{-1} \lesssim \alpha \lesssim 2m_e c^2 / \sqrt{\epsilon \gamma}, \) or since \( \epsilon_t \sim 1 \) MeV is where much of the lab-frame GRB photons are,

\[
\epsilon_{\gamma, \text{MeV}} \lesssim 10^4 \epsilon_t^{-1} \text{MeV} \Gamma^2 \text{MeV}.
\]

This (e.g. Fenimore, Ho and Epstein, 1993, Harding and Baring, 1994) is sometimes referred to as the need for a “beaming” characterized by a factor \( \Gamma \). However, it must be stressed that this refers only to relative photon angles – the GRB could perfectly well be emitting isotropically. (The word “beaming” can be misleading, and is better reserved for actual channeling of the total emission into a restricted solid angle). In any case, one infers a highly relativistic expansion, \( \Gamma \gg 1 \), and this in turn implies that, somehow, the GRB deposits much of its radiation energy in a low density region where it significantly exceeds the baryon rest mass energy density. This “low baryon loading” is required by the observation of high energy photons \( \epsilon_{\gamma} > \sim 0.1 \) GeV.

A third requirement of a satisfactory GRB model is that it must account for the generally non-thermal appearance of the spectra, strongly suggesting an optically thin spectrum from power-law relativistic electrons. In principle a thermal electron distribution in a scattering-thick medium could produce a power law up to an energy \( \sim 3kT_e \), but in order to have the photon power law extend to GeV energies the “temperature” would have to be of the same order, and at these energies nonthermal distributions are more likely. The requirement is therefore very likely to be that the emitting plasma is optically thin and nonthermal. The comoving electron density is \( n_e' = L / 4\pi r^2 c^3 \eta \Gamma \), where primes denote comoving-frame (CF) quantities, and the scattering depth \( \tau_e \sim n_e' \sigma_T r / \Gamma \) must satisfy

\[
\tau_e \sim L \sigma_T / (4\pi r m_e c^3 \eta \Gamma^2) \sim 1 \ r_{12}^{-1} L_{51} \eta_2^{-3} \lesssim 1,
\]

requiring the observed radiation to be produced at radii \( r_{rad} \gtrsim 10^{12} r_{12} L_{51} \eta_2^{-3} \) cm (cosmological) or \( r_{rad} \gtrsim 10^7 r_7 L_{43} \eta_3^{-3} \) cm (halo).

An additional model requirement is that, for photons observed above pair threshold, the “compactness parameter” (or photon-photon optical depth) must be \( \tau_{\gamma\gamma} < 1 \) at the radius \( r_{rad} \). In the lab-frame (LF) we have \( \tau_{\gamma\gamma} \sim n_{\gamma}' \sigma_{T\gamma} r / \Gamma \), where the CF photon density in the frame moving with \( \Gamma \) is \( n_{\gamma}' = L / 4\pi r^2 c \epsilon_{\gamma} \), \( L / 4\pi r^2 c \epsilon_{\gamma} \Gamma \). Thus

\[
\tau_{\gamma\gamma} \sim L \sigma_{T\gamma} / (4\pi r c \epsilon_{\gamma} \Gamma^2) \lesssim 1
\]

for photons observed above the threshold for that \( \Gamma \). Otherwise, the above equation implies a cutoff of the photon spectrum above \( \epsilon_{\gamma} \). For the much smaller radii \( r_o \sim 10^6 r_6 \) cm expected as the initial size of the “primary” GRB event from a neutron star progenitor, the compactness parameter is large at MeV energies, which implies that the initial stages of an impulsive fireball (or for a continuous input, the lower portion of the wind) is an optically thick \( e^{+\gamma} \) flow, which eventually becomes thin at larger radii.

2. THE GENERIC GRB MODEL

The observational requirements discussed above provide very strong evidence for a relativistically expanding fireball scenario. This has some straightforward consequences. The bulk Lorentz factor initially grows linearly with the radius, \( \Gamma \propto r \), until the plasma becomes subrelativistic in its own rest frame. After this \( \Gamma \) saturates to the average value of the initial radiation to rest-mass ratio, \( \eta = E / Mc^2 = L / Mc^2 \),
The saturation radius $r_s \sim \eta r_o$ is usually much smaller than the radiation radii $r_{rad}$ required by the (optically thin spectrum) observations.

One problem faced by simple ($\lesssim 1992$) fireball models, caused by the saturation phenomenon, is that beyond the radius $r_s$ most of the initial energy has been converted to kinetic energy of the baryons, the radiation energy content decreasing adiabatically. This would raise enormously the initial energy required to explain the observed photon luminosity (Paczyński, 1990), and in addition it leads to photon energy degradation. Another major problem with simple fireball models (e.g. Paczyński, 1986, Shemi and Piran, 1990) is that the only radiation observed would be from the fireball photons that escape at the optical thinness radius, and these would have a quasi-thermal spectrum. In addition, if the initial event has a timescale comparable to a neutron star collapse dynamic time $r_o/c \sim 10^{-3}$ s, the observed time over which the fireball becomes thin is also comparable (Goodman, 1986). Both the spectrum and the timescale would be unacceptable.

There are, however, at least two ways in which a relativistic fireball can produce a longer ($10^{-1} - 10^{3}$ s) duration, nonthermal $\gamma$-ray burst with reasonable energy and spectrum. One of them results from the fact that the baryons entrained in the ejecta will eventually have to run into an external medium, and there they will reconvert their kinetic energy into radiation (e.g. Mészáros, Laguna and Rees, 1993; Rees and Mészáros, 1992; Katz, 1994). The external medium may either be a pre-ejected wind from the progenitor, or the interstellar medium. If its density is $n_o$ cm$^{-3}$, deceleration occurs at a radius

$$r_{dec} \sim 10^{17}(E_{51}/n_0)^{1/3}(\theta \eta_2)^{-2/3} \text{ cm} \quad (6)$$

and the time-delayed LF duration of the burst is

$$t_{dec} \sim r_{dec}/c \Gamma^2 \sim 5 \times 10^2(E_{51}/n_0)^{1/3} \theta^{-2/3} \eta_2^{-8/3} \text{ s}. \quad (7)$$

Here the total (initial) energy $E \sim 10^{51}E_{51}$ in a solid angle $\theta^2$ is assumed to be released during an intrinsic time shorter than $t_{dec}$ (otherwise, the intrinsic timescale $t_w$ would be the observed duration). The total photon energy produced in the deceleration, for very modest subequipartition magnetic fields which ensure high radiative efficiency, is the entire baryon kinetic energy, comparable to the initial burst radiative energy. The large radius $r_{rad} \sim r_{dec}$ ensures optical thinness, and the strong deceleration and reverse shocks ensure ideal conditions for relativistic particle acceleration leading to synchrotron and inverse Compton (IC) nonthermal radiation.

In addition, shocks may also arise internally in the ejecta itself, before any deceleration by the external medium occurs. Such internal shocks could arise for various reasons. For instance, the energy or matter input may be time-variable, so that higher $\Gamma$ shells overtake lower $\Gamma$ shells (e.g Paczyński and Xu, 1994, Rees and Mészáros, 1994). If the energy or matter input at the base of the wind occurs during an intrinsic time $t_w$, but is modulated on some timescale $t_v$ (shorter than $t_w$) with $\Delta \Gamma \sim \Delta \eta \sim \eta$ around an average final Lorentz factor $\Gamma \sim \eta$, an overtaking collision (internal dissipation shock) occurs at

$$r_{dis} \sim c t_v \eta^2 \sim 3 \times 10^{14} t_v \eta_2^2 \text{ cm}. \quad (8)$$

This occurs beyond the wind Thomson photosphere

$$r_{ph} \sim \dot{M} \sigma_T/4\pi m_p c^2 \eta^2 \sim 10^{12} L_{51} \eta_2^{-3} \text{ cm} \quad (9)$$
(larger than the saturation radius) for \(0.3(L_{51}/t_{v})^{1/5} \lesssim \eta_2 \lesssim 10^2(L_{51}/t_{v})^{1/4}\). Also, in general \(r_{\text{dis}} < r_{\text{dec}}\). For the magnetic fields turbulently generated in the shocks, or for a young pulsar wind, the radiative efficiency of the internal shocks is sufficient to radiate an appreciable fraction of the wind bulk kinetic energy. Other mechanisms for randomizing the wind energy might be the dissipation of Alfvén turbulence beyond the photosphere (Thompson, 1994; see also Duncan and Thompson, 1992) or the conversion of Poynting flux into photons after the charge density becomes insufficient to sustain the frozen-in magnetic field of a young pulsar type wind (Usov, 1994, 1992). Convective Rayleigh-Taylor instabilities may also arise and become nonlinear beyond the saturation radius (Waxmann and Piran, 1994). Below the photosphere this would become pressure that reaccelerates the flow, while above the photosphere it would be expected to result in freely coasting shells of different \(\eta\) as discussed above.

3. SOME OBSERVATIONAL CONSEQUENCES

What are some of the predictions of the dissipative relativistic fireball scenario?

One consequence of models based on this scenario is that emission is expected at energies other than in gamma-rays. A simultaneous burst of the same duration and low but significant fluence is predicted at X-ray and optical energies (Mészáros and Rees, 1993b). Breaks in the photon power-law spectrum are also predicted (Mészáros et al., 1994), in qualitative agreement with \(\gamma\)-ray spectra (Band et al., 1994), and detailed comparison of such calculations with observations could provide useful insights into the source physics. For a typical MeV fluence \(F_{\gamma} \sim 10^{-6}\) ergs cm\(^{-2}\) the optical and X-ray fluences predicted for cosmological models are compatible with the few detected X-ray flashes as well as the lack of widespread X-ray identifications (X-ray paucity), and with the lack (so far) of optical detections. Typically, however, they are above the expected HETE threshold (Ricker et al., 1994) of \(\sim 10^{-10}\) ergs cm\(^{-2}\). As an example, for some cosmological models in the optical U-band, \(m_U \sim 11 - 2.5 \log(F_u/10^{-9}\text{ergs cm}^{-2}) + 2.5 \log(t_{b}/s)\) (Mészáros et al., 1994). Other satellite or ground-based observations triggered by BATSE via systems such as BACODYNE could, for appropriate sensitivities and pointing times less than the burst duration, also detect the GRB at other wavelengths. Previous attempts at simultaneous optical detection (e.g. Vanderspek et al., 1994, Krimm et al., 1994) did not yet have the sensitivity needed for a meaningful comparison, while most other searches were not simultaneous.

A much delayed (days to weeks) radio outburst at the mJy level could also become observable when the ejecta has expanded sufficiently for the radio opacity to become negligible (Paczynski and Rhoades, 1993).

Simultaneous (and delayed) GeV emission is also a fairly straightforward consequence of this scenario, for electron power-law indices not too steep and moderate shock magnetic field strengths (which can be inferred from MeV spectra). A sustained or delayed GeV emission (as observed, e.g. by Hurley et al., 1994) can be understood in terms of a wind with internal dissipation and an external deceleration shock (Mészáros and Rees, 1994). The wind, with an \(\eta \approx 10^2\) and duration \(t_{w}\) produces via internal shocks an MeV burst extending up to \(\lesssim\) few GeV, and also produces a longer event \((t \sim t_{\text{dec}}, \text{which may be up to hours, see eq[7]})\) as the wind is decelerated in the external medium. At these \(\eta\) the external burst is below BATSE threshold at MeV, but is prominent at GeV and due to the low compactness it extends easily above 30 GeV. An alternative possibility for delayed GeV bursts is discussed by Katz, 1994.
4. DISCUSSION AND PROSPECTS

A dissipative relativistic fireball scenario is motivated (and practically required) by the key observations discussed in §1. It is to a large degree generic, and is expected whether the “ultimate source” is, e.g., a young high-field pulsar, a failed supernova Ib, a neutron star binary merger, a halo neutron star quake, or comets crashing into magnetospheres. The basic assumption common to all such sources is that they deliver the required energy in a small initial volume \( r_0 \lesssim 10^6 - 10^7 \) cm in a short time. Whatever the ultimate source is, it should in any case remain hidden behind an opaque \( e^\pm, \gamma \) veil, and the subsequent evolution of the fireball (during which the object manifests itself observationally) is independent of the birth details. This may be phrased as a GRB “No-Hair” theorem: the only thing that characterizes observationally a GRB is the initial energy, the initial volume and (possibly) the initial energy deposition timescale. Knowing the exact nature of the primary GRB source would, of course, greatly help in estimating expected rates per galaxy per year and details of the spatial distribution. However, this should be (to a good first approximation) irrelevant for understanding the physics of the observable intrinsic GRB properties.

A fireball model is, in principle, expected also if GRB arise in the galactic halo. In this case the nature, the rate of events and the spatial distribution might be understood (see, e.g. Podsiadlowski, Rees and Ruderman, 1995; Colgate and Leonard, 1994; Wasserman and Salpeter, 1994) if one makes some new assumptions about the source physics. In a cosmological setting, on the other hand, there are plausible astrophysical sources with relatively uncomplicated physics that could supply the observed rate and distribution (e.g. Eichler, et al., 1989, Narayan, Paczyński and Piran, 1992, Mészáros and Rees, 1992, Woosley, 1993). The dissipative fireball scenario described above explains then in a straightforward manner (Mészáros and Rees, 1993a, Mészáros, Laguna and Rees, 1993) the GRB energies, the typical overall durations and the non-thermal spectra. What is not specifiable in detail in such a model is how the energy gets deposited in a low density region to provide a high \( \Gamma \), which is puzzling either for halo or cosmological sources. However, the conclusion that this does occur seems unavoidable, since the observations demand such conditions (see §1).

Several other questions can be addressed within the context of such models. One of them is the difference in spectral and temporal properties of halo and cosmological models. The former have smaller total energy and lower magnetic field strengths in the wind or at the shocks. If the minimum particle energies accelerated in the shocks were very high this could still yield halo GRB spectra which satisfy the X-ray paucity and have acceptable MeV breaks, but the time-delayed durations are all less than a second (Mészáros and Rees, 1993b). This may be helped if the durations are explained with a (so far unspecifiable) internal time \( t_w \), but they would still tend to overproduce X-rays. In cosmological models, on the other hand, either the calculated dynamic time \( t_{\text{dec}} \) or an internal time \( t_w \) can give acceptable spectra. Details of the spectrum at several wavelengths, if observed simultaneously, could provide discriminants between these cases.

Another question that may be addressed in these models is the reported bimodal duration distribution (Kouveliotou, et al., 1993 and these proceedings). One possibility is that the durations are given by the deceleration time (7) and bursts occur in two main types of external environment. One may speculate, e.g., that the progenitor’s random spatial velocity causes a fraction of the bursts to occur in the galactic halo, while others occur in the disk. The density contrast would be at least \( 10^{-3} \) and the duration difference at least a factor \( \Delta n_o^{-1/3} \sim 10 \). Alternatively, there
may be a fraction of bursts for which deceleration occurs in a pre-ejected denser wind, while in others the latter is unimportant compared to the ISM.

**Acknowledgements:** I am grateful to Martin Rees for many discussions and insights into these problems. The research is partially supported through NASA NAGW-1522 and NAG5-2362.

**References**

Band, D., *et al.*, 1993, Ap.J., 413, 281
Cavallo, G. and Rees, M.J., 1978, M.N.R.A.S., 183, 359
Colgate, S.A. and Leonard, P.J.T., 1994, in *Gamma-ray Bursts*, ed. G. Fishman, *et al.*, p. 518 (AIP 307, NY)
Duncan, R.C. and Thompson, C., 1992, Ap.J.(Letters), 392, L9
Eichler, D., Livio, M., Piran, T. and Schramm, D., 1989, Nature, 340, 126
Fenimore, E.E., Epstein, R.I. and Ho, C., 1993, Astr.Ap.Suppl, 97, 59.
Fishman, G., these proceedings
Goodman, J., 1986, Ap.J., 308, L47
Harding, A.K. and Baring, M.G., 1994, in *Gamma-ray Bursts*, ed. G. Fishman, *et al.*, p. 520 (AIP 307, NY)
Hurley, K., *et al.*, 1994, Nature, 372,652
Katz, J.I., 1994, Ap.J., 422, 248
Katz, J.I., 1994, Ap.J.(Lett.), 432, L27
Kouveliotou, C., *et al.*, 1993, Ap.J., 413, L101
Mészáros, P. and Rees, M.J., 1992, Ap.J., 397, 570
Mészáros, P. and Rees, M.J., 1993a, Ap.J., 405, 278
Mészáros, P. and Rees, M.J., 1993b, Ap.J. (Letters), 418, L59.
Mészáros, P., Laguna, P. and Rees, M.J., 1993, Ap.J., 415, 181.
Mészáros, P. and Rees, M.J., 1994, M.N.R.A.S., 269, L41
Mészáros, P., Rees, M.J. and Papathanassiou, H., 1994, Ap.J., 430, L93
Narayan, R., Paczynski, B. and Piran, T., 1992, Ap.J.(Letters), 395, L83
Paczyński, B., 1986, Ap.J.(Lett.), 308, L43
Paczyński, B., 1990, Ap.J., 363, 218.
Paczyński, B. and Rhoads, 1993, Ap.J., 418, L5
Paczyński, B. and Xu, G., 1994, Ap.J., 427, 708
Podsiadlowski, P., Rees, M.J. and Ruderman, M., 1995, M.N.R.A.S., in press
Ricker, G., *et al.*, 1992, in *Gamma-ray Bursts*, C. Ho, R. Epstein and E. Fenimore, eds. (Cambridge U.P.), p. 288
Rees, M.J. and Mészáros, P., 1992, M.N.R.A.S., 258, 41P
Rees, M.J. and Mészáros, P., 1994, Ap.J.(Letters), 430, L93-L96
Shemi, A. and Piran, T., 1990, Ap.J.(Lett.), 365, L55
Thompson, C., 1994, M.N.R.A.S., 270, 480
Usov, V.V., 1992, Nature, 357, 472
Usov, V.V., 1994, M.N.R.A.S., 267, 1035
Wasserman, I. and Salpeter, E.E., 1994, Ap.J., 433, 670
Waxmann, E. and Piran, T., 1994, Ap.J., 433, L85
Woosley, S., 1993, Ap.J., 405, 273