Afterglows from Gamma-ray Bursts¹

P. Mészáros

Dpt. of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802

ABSTRACT

The successful discovery of X-ray, optical and radio afterglows of gamma-ray bursts has significantly helped our understanding of these sources, and made possible the identification of host galaxies at cosmological distances. The energy release inferred in these outbursts rivals that of supernovae, while its photon energy output may considerably exceed it. Current models envisage this to be the outcome of a cataclysmic stellar event leading to a relativistically expanding fireball, in which particles are accelerated at shocks and produce nonthermal radiation. The substantial agreement between observations and the theoretical predictions of the fireball shock model provide confirmation of the basic aspects of this scenario. The continued observations show a diversity of behavior, providing valuable constraints for more detailed models. Crucial questions being now addressed are the beaming at different energies and its implications for the energetics, the time structure of the afterglow, its dependence on the central engine or progenitor system behavior, and the role of the environment on the evolution of the afterglow.

1. Introduction

The first discovery of a GRB afterglow at X-ray wavelengths was made with the BeppoSAX satellite (Costa et al., 1997) in February 1997, followed by a long-term detection and follow-up at optical wavelengths (van Paradijs et al., 1997). This represents a major and long-awaited breakthrough in the investigation of these mysterious sources, and emphasizes the importance of high resolution X-ray imaging techniques, which were successfully used for other significant astronomical discoveries by Joachim Trümper and his colleagues with Rosat. The subsequent detection of other GRB afterglows followed in rapid succession, extending in some cases to radio and microwave wavelengths as well. This has made it possible to follow some of these sources over time scales of many months, making the identification of counterparts and host galaxies possible. The study of afterglows has provided strong confirmation for the generic fireball shock model of GRB, in which the $\gamma$-ray emission arises at radii of $10^{13} - 10^{16}$ cm (Rees & Mészáros, 1992, Mészáros & Rees, 1993, Rees & Mészáros, 1994, Paczyński & Xu, 1994, Katz, 1994, Sari).

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& Piran, 1995). In particular, this model led to the prediction of the quantitative nature of the signatures of afterglows (Mészáros & Rees, 1997a), in advance of the observational discoveries and in substantial agreement with these (Vietri, 1997a, Tavani, 1997, Waxman, 1997, Reichart, 1997, Wijers, Rees & Mészáros, 1997). The first measurement of a redshift (Metzger et al., 1997) in GRB 970508 provided confirmation of the hypothesis that bursts were at cosmological distances. More recently, significant interest was aroused by the report (Kulkarni et al., 1998) of a spectroscopic redshift measurement of $z = 3.4$ for the afterglow of the burst GRB 971214, whose fluence would then correspond to a $\gamma$-ray energy of $10^{53.5}(\Omega_{\gamma}/4\pi)$ ergs, where $\Delta\Omega_{\gamma}$ is the solid angle into which the gamma-rays are beamed. Such energies were discussed (Mészáros & Rees, 1997b) in the context of compact mergers, such as neutron star-neutron star (NS-NS) or black hole-neutron star (BH-NS) mergers, which can power a relativistic fireball resulting in the observed radiation. In some of the detected afterglows there is evidence for a relatively dense gaseous environments, as suggested, e.g. by evidence for dust (Reichart, 1998) in GRB970508, the absence of an optical afterglow and presence of strong soft X-ray absorption (Groot et al., 1997, Murakami et al., 1997) in GRB 970828, the lack of an optical afterglow in the (radio-detected) afterglow (Taylor et al., 1997) of GRB980329, and spectral fits to the low energy portion of the X-ray afterglow of several bursts (Owen et al., 1998). The latter observations may be suggestive of “hypernova” models (Paczyński, 1998, Fryer & Woosley, 1998), involving the collapse of a massive star or its merger with a compact companion, although it is probably too early to draw definite conclusions. While it is at present unclear which, if any, of these progenitors is responsible for GRB, or whether perhaps different progenitors represent different subclasses of GRB, there is general agreement that they all would be expected to lead to the generic fireball shock scenario mentioned above. Much of the current effort centers around trying to identify such progenitors more specifically, and trying to determine what effect, if any, they have on the observable fireball and afterglow characteristics.

2. The Fireball Shock Scenario

The isotropy of the angular distribution of GRB suggested already early on that GRB were outside our own galaxy (Fishman & Meegan, 1998), and the lack of structure associated with nearby galaxies indicated that their distance would be such that non-Euclidean and evolutionary effects may be important. This was also indicated by studies of the counts of the number of bursts per unit fluence or peak flux (Fishman & Meegan, 1998, Horack et al., 1996), as did evidence for time dilation in the bursts (Norris et al., 1995). Fits to cosmological counts including curvature, luminosity function and evolution effects indicated that the latter could be important (Reichart & Mészáros, 1997). In particular, the evolution may be related to the star formation rate as a function of cosmological age (Totani, 1997, Wijers et al., 1998, Krumholz et al., 1998). The cosmological distances of some bursts have, since then (Metzger et al., 1997, Kulkarni et al., 1998, Djorgovski et al., 1998) been directly measured. This, of course, poses significant constraints on the type of sources that may be able to produce this phenomenon. The typical
numbers characterizing the luminosity, duration, total energy per burst and event rate are

\[
L \sim 10^{52}(\Omega/4\pi) \text{ erg s}^{-1}, \quad (1)
\]

\[
t_w \sim 10 \text{ s}, \quad (2)
\]

\[
E \sim 10^{53}(\Omega/4\pi) \text{ erg}, \quad (3)
\]

\[
\mathcal{R} \sim 10^{-6}(\Omega/4\pi)^{-1} \text{ galaxy}^{-1}\text{yr}^{-1}, \quad (4)
\]

where \(\Omega\) is the solid angle into which the energy is channeled, and the durations \(t_w\) have a large spread \(10^{-3} \lesssim t_w \lesssim 10^3\) s. The luminosities and total energies are also likely to be affected by a significant spread, whose magnitude is harder to estimate. The beaming solid angle \(\Omega_j\) is also, thus far, very poorly constrained.

An early suggestion for a GRB energy source at cosmological distances was the merger of NS-NS binaries (e.g. Paczyński, 1986, Goodman, 1986), whose estimated numbers and merger rates are close to the observed GRB detection rate (Narayan, Piran & Shemi, 1991, Phinney, 1991). A related possibility are BH-NS binary mergers (Narayan, Piran & Shemi, 1991, Paczyński, Meszáros & Rees, 1992), which have only slightly different event rates. An alternative suggestion (Woosley, 1993) was a “failed Supernova Ib”, resulting from the collapse of fast rotating massive star which fails to produce a core collapse SN. Both a compact merger, and a fast rotating stellar collapse were known, from numerical simulations, to lead to a fast rotating torus around a central, high density object which eventually would develop into a black hole. The binding energy liberated in both of these events is of order \(10^{54}\) ergs, a good fraction of which will be carried away in a short pulse of \(\nu\bar{\nu}\) and gravitational waves. If a small fraction of this emerges as electromagnetic energy, some of which is deposited in a region with sufficiently low baryon density, a relativistic fireball would form, whose radiation spectrum in the observer frame will peak in the MeV range (Paczynski, 1986, Goodman, 1986, Shemi & Piran, 1990). One possible channel for converting some of this energy into electromagnetic form is given by the \(\nu\bar{\nu} \rightarrow e^+e^-\) process (Eichler, et al., 1989). A low baryon load condition (required to make the fireball highly relativistic) can occur naturally in a binary merger since a centrifugal barrier develops along the orbital symmetry axis, which is relatively free of baryons and provides an escape route for the \(e^\pm, \gamma\) fireball (Meszáros & Rees, 1992). This would also imply a collimation of the relativistic fireball, which would enhance the apparent flux (relative to what it would be if it were isotropic) by factors which conservatively might be of order 10-100. The same processes were estimated to be able to produce a collimated relativistic fireball in the failed SN Ib model (Woosley, 1993). Another suggestion for powering a fireball was that this might result from magnetic flaring activity (Narayan, Paczyński & Piran, 1992) in the disrupted torus produced around the merged binary.

Irrespective of the details of the progenitor, the resulting fireball is expected to be initially highly optically thick. From causality considerations the initial dimensions must be of order \(ct_{\text{var}} \lesssim 10^7\) cm, where \(t_{\text{var}}\) is the variability timescale, and the luminosities must be much higher than a solar Eddington limit. Since most of the spectral energy is observed above 0.5 MeV, the
optical depth against $\gamma \gamma \rightarrow e^\pm$ is large, and an $e^\pm, \gamma$ fireball is expected. Due to the highly super-Eddington luminosity, this fireball must expand. Since in many bursts one observes a large fraction of the total energy at photon energies $\epsilon_\gamma \gtrsim 1$ GeV, somehow the flow must be able to avoid degrading these photons (since $\gamma \gamma \rightarrow e^\pm$ would lead, in a stationary or slowly expanding flow, to photons just below 0.511 MeV [Harding & Baring, 1994]). In order to avoid this, it seems inescapable that the flow must be expanding with a very high Lorentz factor, since in this case the relative angle at which the photons collide is less than $\Gamma^{-1}$ and the threshold for the pair production is effectively diminished. Thus, photons with energy

$$\epsilon_{\gamma,\text{MeV}} \lesssim 10^4 \epsilon_{\text{MeV}}^{-1} \Gamma_2^2 \ .$$

(5)

are able to escape, where $\Gamma_2$ is the bulk Lorentz factor in units of $10^2$, and $\epsilon_t$ is the energy of the target photons (Mészáros, 1995). Thus, simply from observations and general physical considerations, a relativistically expanding fireball is expected. However, the observed $\gamma$-ray spectrum is generally a broken power law, i.e., highly nonthermal. The optically thick $e^\pm, \gamma$ fireball cannot, by itself, produce such a spectrum (it would tend rather to produce a modified blackbody). In addition, the expansion would lead to a conversion of internal energy into kinetic energy of expansion, so even after the fireball becomes optically thin, it would be highly inefficient, most of the energy being in the kinetic energy of the associated protons, rather than in photons.

The most likely way to achieve a nonthermal spectrum in an energetically efficient manner is if the kinetic energy of the flow is re-converted into random energy via shocks, after the flow has become optically thin. This is a plausible scenario, in which two cases can be distinguished. In the first case (a) the expanding fireball runs into an external medium (the ISM, or a pre-ejected stellar wind [Rees & Mészáros, 1992, Mészáros & Rees, 1993, Katz, 1994, Sari & Piran, 1995]). The second possibility (b) is that (even before such external shocks occur) internal shocks develop in the relativistic wind itself, faster portions of the flow catching up with the slower portions [Rees & Mészáros, 1994, Paczyński & Xu, 1994]. In both of its versions, the fireball shock scenario is completely generic, independent of the specific nature of the progenitor, as long as it delivers the appropriate amount of energy ($\gtrsim 10^{52}$ erg) in a small enough region ($\lesssim 10^7$ cm). This model has been successful in explaining the major observational properties of the gamma-ray emission, and is the main paradigm used for interpreting the GRB observations.

External shocks will occur in an impulsive outflow of total energy $E_o$ in an external medium of average particle density $n_o$ at a radius

$$r_{\text{dec}} \sim 10^{17} n_o^{1/3} E_o^{1/3} \eta^{-2/3} \text{ cm} \ .$$

(6)

where the lab-frame energy of the swept-up external matter ($\Gamma^2 m_p c^2$ per proton) equals the initial energy $E_o$ of the fireball, and $\eta = \Gamma = 10^2 \eta_2$ is the final bulk Lorentz factor of the ejecta. The typical observer-frame dynamic time at the shock (assuming the cooling time is shorter than this) is $t_{\text{dec}} \sim r_{\text{dec}}/c \Gamma^2 \sim$ seconds, for typical parameters, and the observed burst duration would be $\sim t_{\text{dec}}$. The impulsive assumption requires that the initial energy input occur in a time
shorter than $t_{\text{dec}}$. Variability on timescales shorter than $t_{\text{dec}}$ may occur on the cooling timescale or on the dynamic timescale for inhomogeneities in the external medium, but generally external shocks are not ideal for reproducing highly variable profiles (Sari & Piran, 1998). However, they can reproduce bursts with several peaks (Panaitescu & Mészáros, 1998a) and may therefore be applicable to the class of long, smooth bursts, or bursts with a few smooth peaks.

In a wind scenario, the energy input occurs non-impulsively over a timescale $t_w$, and this can lead to internal shocks at smaller radii where $t_{\text{dec}} < t_w$. One expects a similar initial dynamic behavior as in the impulsive injection case, assuming that a lab-frame luminosity $L_\text{o}$ and mass outflow $\dot{M}_\text{o}$ are injected at $r \sim r_\text{l}$ and are continuously maintained over a time $t_w$. Initially $\Gamma \propto r$ (with comoving temperature $T \propto r^{-1}$), followed by saturation at the value $\Gamma_{\text{max}} \sim \eta$ which occurs at the radius $r_{\text{sat}} \sim r_\text{l} \eta$, where $\eta = L_\text{o}/\dot{M}_\text{o} c^2$. In such wind models, internal shocks will occur at a radius (Rees & Mészáros, 1994)

$$r_{\text{dis}} \sim c t_{\text{var}} \eta^2 \sim 3 \times 10^{14} t_{\text{var}} \eta^2 \text{ cm}, \quad (7)$$

where shells of different energies $\Delta \eta \sim \eta$ initially separated by $c t_{\text{var}}$ catch up with each other (with $t_{\text{var}} < t_w$). In order for internal shock radius $r_{\text{dis}}$ to occur above the wind photosphere radius

$$r_{\text{ph}} \sim \dot{M} \sigma_{\text{T}}/(4 \pi m_\text{p} c \Gamma^2) \sim 10^{14} L_{53} \eta_2^{-3} \text{ cm}, \quad (8)$$

but also at radii greater than the saturation radius $r_{\text{sat}} \sim r_\text{l} \eta$ (so that most of the energy does not come out in a photospheric quasi-thermal radiation component) one needs to have $7.5 \times 10^1 L_{53}^{1/5} t_{\text{var}}^{-1/5} \lesssim \eta \lesssim 3 \times 10^2 L_{53}^{1/4} t_{\text{var}}^{-1/4}$, where $L_{53} = E_{53}/t_w$. This type of models have the advantage (Rees & Mészáros, 1994) that they allow an arbitrarily complicated light curve, the shortest variation timescale $t_{\text{var}} \gtrsim 10^{-3} \text{ s}$ being limited only by the dynamic timescale at $r_\text{l}$, where the energy input may be expected to vary chaotically. Such internal shocks have been shown explicitly to reproduce (and indeed even be required by) some of the more complicated light curves (Sari & Piran, 1998, Panaitescu & Mészáros, 1998d; see however Dermer & Mitman, 1998).

3. Progenitors and Central Engines

Even before the measurement of a high redshift in a GRB afterglow, the difficulty in detecting the host galaxies of bright bursts(e.g. Schaefer, 1997) motivated the exploration of ways of increasing the possible total energy budget of GRB. The first explicit model to do this (Mészáros & Rees, 1997b), which was formulated before afterglows and their redshifts were discovered, involved converting a large fraction of the binding energy of a black hole and torus system ($\sim 10^{54} \text{ ergs}$) into a fireball through MHD torques which power a Poynting jet outflow. Such a system would naturally arise from a NS-NS or a BH-NS merger (and it may also arise naturally in a failed SN Ib or a “hypernova”). In the last year, a number of other possible energy sources have been considered as possible candidates for powering GRB (Fryer & Woosley, 1998, Popham, Woosley & Fryer, 1998). A fact which is not widely realized is that all plausible GRB progenitors suggested
so far (e.g. NS-NS or NS-BH mergers, Helium core - black hole [He/BH] or white dwarf - black hole [WD-BH] mergers, and the wide category labeled as hypernova or collapsars including failed supernova Ib [SNe Ib], single or binary Wolf-Rayet [WR] collapse, etc.) are expected to lead to a BH plus debris torus system, and they are all capable of producing relativistic outflows through the same mechanisms. An important point is that the overall energetics from these various progenitors do not differ by more than about one order of magnitude (Mészáros, Rees & Wijers, 1998b).

Two large reservoirs of energy are available in a generic merger or collapse scenario: the binding energy of the orbiting debris, and the spin energy of the black hole (Mészáros & Rees, 1997b, Paczyński, 1998).

The first mechanism, relying on the binding energy of the torus, can provide up to 42% of the rest mass energy of the disk, for a maximally rotating black hole. The $\nu\bar{\nu} \rightarrow e^+e^-$ process can tap the thermal energy of the torus produced by viscous dissipation. For this mechanism to be efficient, the neutrinos must escape before being advected into the hole; on the other hand, the efficiency of conversion into pairs (which scales with the square of the neutrino density) is low if the neutrino production is too gradual. Typical estimates suggest a neutrino powered fireball of $\lesssim 10^{51}$ erg (Ruffert, et al., 1997, Popham, Woosley & Fryer, 1998), except perhaps in the “collapsar” or failed SN Ib case where estimates (Popham, Woosley & Fryer, 1998) indicate up to $10^{52.3}$ ergs for optimum parameters. If the fireball is collimated into a solid angle $\Omega_j$ then of course the apparent “isotropized” energy would be larger by a factor $(4\pi/\Omega_j)$, but unless $\Omega_j \lesssim 10^{-2} - 10^{-3}$ this may fail to satisfy the apparent isotropized energy of $10^{53.5}$ ergs implied by a redshift $z = 3.4$ for GRB 971214 (a similar energy budget is implied by a possible photometric redshift $z \sim 5$ for GRB 980329, Fruchter, 1998). An alternative way to tap the torus energy is through dissipation of magnetic fields generated by the differential rotation in the torus (Paczyński, 1992, Narayan, Paczyński & Piran, 1992, Mészáros & Rees, 1997b, Katz, 1997). Even before the BH forms, a NS-NS merging system might lead to winding up of the fields and dissipation in the last stages before the merger (Mészáros & Rees, 1992, Vietri, 1997a).

The second mechanism relies on tapping the spin energy of the black hole itself, and it can in principle extract up to 29% of the rest mass energy of the black hole. A hole formed from a coalescing compact binary is guaranteed to be rapidly spinning, and, being more massive, could contain more energy than the torus; the energy extractable in principle through MHD coupling to the rotation of the hole by the Blandford & Znajek, 1977 effect could then be even larger than that contained in the orbiting debris (Mészáros & Rees, 1997b, Paczyński, 1998). Collectively, any such MHD outflows have been referred to as Poynting jets.

The various progenitors (NS-NS, BH-NS, failed SNe, hypernovae and various collapsars) differ only slightly in the mass of the BH and that of the debris torus they produce, and they may differ more markedly in the amount of rotational energy contained in the BH. Strong magnetic fields, of order $10^{15}$ G, are needed needed to carry away the rotational or gravitational energy in a
time scale of tens of seconds (Usov, 1994, Thompson, 1994).

If the magnetic fields do not thread the BH, then a Poynting outflow can at most carry the gravitational binding energy of the torus. For a maximally rotating and for a non-rotating BH this is 0.42 and 0.06 of the torus rest mass, respectively. The torus or disk mass in a NS-NS merger is (Ruffert, et al., 1997) $M_d \sim 0.1M_\odot$, and for a NS-BH, a He-BH, WD-BH merger or a binary WR collapse it may be estimated at (Paczyński, 1998, Fryer & Woosley, 1998) $M_d \sim 1M_\odot$. In the HeWD-BH merger and WR collapse the mass of the disk is uncertain due to lack of calculations on continued accretion from the envelope, so $1M_\odot$ is just a rough estimate. The energy available is then

$$E_{\text{max},t} \sim \begin{cases} 8 \times 10^{53} \epsilon (M_d/M_\odot) \text{ ergs}, & \text{(fast rot.)}; \\ 1.2 \times 10^{53} \epsilon (M_d/M_\odot) \text{ ergs}, & \text{(slow rot.)}. \end{cases}$$

(9)

where $\epsilon$ is the efficiency for converting gravitational into MHD jet energy. The largest energy reservoir is therefore likely to be associated with NS-BH, HeWD-BH or binary WR collapse, which have larger disks and fast rotation, the maximum energy being $\sim 8 \times 10^{53} \epsilon (M_d/M_\odot)$ ergs; for the (fast rotating but smaller disk) NS-NS merger it is $\sim 8 \times 10^{52} \epsilon (M_d/0.1M_\odot)$ ergs; and for the failed SNe Ib (which is a slow rotator) it is $\sim 1.2 \times 10^{55} \epsilon (M_d/M_\odot)$ ergs. Conditions for the efficient escape of a high-$\Gamma$ jet may, however, be less propitious if the “engine” is surrounded by an extensive envelope, which is the case in the failed SNE Ib or hypernova models.

If the magnetic fields in the torus thread the BH, the spin energy of the BH can be extracted via the Blandford & Znajek, 1977 (B-Z) mechanism (Mészáros & Rees, 1997b). The extractable energy is

$$E \sim \epsilon f(a)M_{bh}c^2,$$

(10)

where $\epsilon$ is the MHD efficiency factor and $a = \frac{Jc}{GM^2}$ is the rotation parameter, which equals 1 for a maximally rotating black hole. The rotational parameter $f(a) = 1 - (1 + \sqrt{1 - a^2})/2$ is small unless $a$ is close to 1, where it sharply rises to its maximum value $f(1) = 0.29$, so the main requirement is a rapidly rotating black hole, $a \gtrsim 0.5$. For a maximally rotating BH, the extractable energy is therefore

$$E_{\text{max},bh} \sim 0.29 \epsilon M_{bh}c^2 \sim 5 \times 10^{53} \epsilon (M_{bh}/M_\odot) \text{ ergs}. \quad (11)$$

Rapid rotation is essentially guaranteed in a NS-NS merger, since the radius (especially for a soft equation of state) is close to that of a black hole and the final orbital spin period is close to the required maximal spin rotation period. Since the central BH will have a mass (Ruffert, et al., 1997, Ruffert & Janka, 1998) of about $2.5M_\odot$, the NS-NS system can thus power a jet of up to

$$E_{\text{max},bh} \sim 1.3 \times 10^{54} \epsilon (M_{bh}/2.5M_\odot) \text{ ergs}.$$

(12)

A maximal rotation rate may also be possible in a He-BH merger, depending on what fraction of the He core gets accreted along the rotation axis as opposed to along the equator (Fryer & Woosley, 1998), and the same should apply to the binary fast-rotating WR scenario, which probably does not differ much in its final details from the He-BH merger. For a fast rotating BH of $2.5 - 3M_\odot$
threaded by the magnetic field, the maximal energy carried out by the jet is then similar or somewhat larger than in equation (12). The scenarios less likely to produce a fast rotating BH are the NS-BH merger (where the rotation parameter could be limited to $a \leq \frac{M_{ns}}{M_{bh}}$, unless the BH is already fast-rotating) and the failed SNe Ib (where the last material to fall in would have maximum angular momentum, but the material that was initially close to the hole has less angular momentum). The electromagnetic energy extraction from the BH in these could be limited by the $f(a)$ factor, but a lower limit would be given by the energy available from the gravitational energy of the disk, in the second line of equation (3).

Thus in the case of a Poynting (MHD) jet powered by the binding energy of the torus, the total energetics between the various models differs at most by a factor 20, whereas for Poynting jets powered by the spin energy of the black hole they differ by at most a factor of a few, depending on the rotation parameter. For instance, even allowing for low total efficiency (say 30%), a NS-NS merger whose jet is powered by the torus binding energy would only require a modest beaming of the $\gamma$-rays by a factor $(4\pi/\Omega_j) \sim 20$, or no beaming if the jet is powered by the B-Z mechanism, to produce the equivalent of an isotropic energy of $10^{53.5}$ ergs. The beaming requirements of BH-NS and some of the other progenitor scenarios are even less constraining. Thus, even extreme redshifts $z \sim 5$ such as inferred by Fruchter, 1998 can be easily satisfied by secanrios leading to a BH plus torus system.

An interesting case is the apparent coincidence of GRB 980425 with the SN Ib/Ic 1998bw (Galama, et al., 1998). A simple but radical interpretation (Wang & Wheeler, 1998) is that all GRB may be associated with SNe Ib/Ic and differences arise only from different viewing angles relative to a very narrow jet. The difficulties with this are that it would require extreme collimations by factors $10^{-3} - 10^{-4}$, and that the statistical association of any subgroup of GRB with SNe Ib/Ic (or any other class of objects, for that matter) is so far not significant (Kippen, et al., 1998). If however the GRB 980425/1998bw association is real (Woosley, Eastman & Schmidt, 1998), then we may be in the presence of a new subclass of GRB with lower energy $E_\gamma \sim 10^{48}(\Omega_j/4\pi)$ erg, which is only rarely observable even though its comoving volume density could be substantial. In this, more extreme interpretation, the great majority of the observed GRB would have the energies $E_\gamma \sim 10^{54}(\Omega_j/4\pi)$ ergs as inferred from high redshift observations. Nonetheless, until further examples of such associations are discovered, one may not entirely discount the possibility of this being an extremely rare, low probability chance coincidence.

4. Afterglows: the Simple “Standard” Model

One can understand the dynamics of the afterglows of gamma-ray bursts in a fairly simple manner, without worrying about the uncertainties of the progenitor. This can be done through a relativistic generalization of the method used to understand supernova remnants without fully understanding the initiating explosion. The simplest hypothesis is that the afterglow is due to a relativistic expanding blast wave, which decelerates as time goes on (Meszáros & Rees, 1997a;
earlier simplified discussions were given by Katz, 1994b, Paczyński & Rhoads, 1993, Rees & Mészáros, 1992. The complex time structure of some bursts suggests that the central trigger may continue for up to 100 seconds. However, at much later times all memory of the initial time structure would be lost: essentially all that matters is how much energy and momentum has been injected; the injection can be regarded as instantaneous in the context of the much longer afterglow. Detailed calculations and predictions from such a model (Mészáros & Rees, 1997) preceded the observations of the first afterglow detected, GRB970228 (Costa et al, 1997, van Paradijs, et al., 1997).

The simplest spherical afterglow model consist of a three-pieced power law spectrum with two breaks. At low frequencies there is a steeply rising synchrotron self-absorbed spectrum up to a self-absorption break $\nu_a$, followed by a $+1/3$ energy index spectrum up to the synchrotron break $\nu_m$ corresponding to the minimum energy $\gamma_m$ of the power-law accelerated electrons, and then a $-\frac{p+1}{2}$ energy spectrum above this break, for electrons in the adiabatic regime (where $\gamma^{-p}$ is the electron energy distribution above $\gamma_m$). In addition, a third break is expected at energies where the electron cooling time becomes short compared to the expansion time, with a spectral slope $-\frac{p}{2}$ above that. With the inclusion of this third, “cooling” break $\nu_b$, first calculated in Mészáros, Rees & Wijers, 1998 and more explicitly detailed in Sari, Piran & Narayan, 1998, one has what has come to be called the simple “standard” model of a GRB afterglow. This implicitly assumes spherical symmetry (for a jet with opening angle $\theta_j$ this remains valid as long as $\Gamma \gtrsim \theta_j^{-1}$) and an impulsive energy input. As the remnant expands the spectrum simply moves to lower frequencies, so that in a given band the flux decays as a power law in time, whose index can change as breaks move through the observing band.

The simple standard model has been remarkably successful at explaining the gross features of the GRB 970228, GRB 970508 and other afterglows (Wijers, Rees & Mészáros, 1997, Tavani, 1997, Waxman, 1997, Reichart, 1997). The multi-wavelength data analysis has in fact advanced to the point where one can use observed light curves at different times to extrapolate in time to get spectral snapshots at a fixed time (Waxman, 1997, Wijers & Galama, 1998), allowing fits for the different physical parameters of the burst and environment, such as the total energy $E$, the magnetic and electron-proton coupling parameters $\epsilon_B$ and $\epsilon_e$ and the external density $n_o$. This has led to the temptation to take the assumed sphericity for granted. For instance, the lack of a break in the late light curve of GRB 970508 prompted the inference (Ramaprakash, A, et al., 1998) that all afterglows are essentially isotropic, leading to the very large (isotropic) energy estimate of $10^{53.5}$ ergs in GRB 971214. However, what these fits constrain is only the energy per unit solid angle $E = (E/\Omega_j)$. Furthermore, the assumption that a break should have been seen after months due to the fireball having become nonrelativistic, or $\Gamma$ having dropped below an inverse jet opening angle size, is based upon the simple impulsive energy input (a delta, or top hat function in initial energy and $\Gamma$, which are independent of angle). These are useful simplifications, but it is easy to see that departures from it are natural and would certainly not be surprising. Thus, as we emphasize below, there are so far no strong constraints on the possible anisotropy of the outflow
5. Realistic Afterglows Models

In the simplest departure from a spherical model the blast wave energy may be channeled into a solid angle $\Omega_j$. In this case one expects (Rhoads, 1997a, 1997b) a faster decay of $\Gamma$ after sideways expansion sets in, and a decrease in the brightness is expected after the edges of the jet become visible, when $\Gamma$ drops below $\Omega_j^{-1/2}$. A simple calculation using the usual scaling laws leads indeed to a steepening of the flux power law in time. The lack of such an observed downturn in the optical can, in a first approximation, be interpreted as an indication of the sphericity of the late stages of the fireball, and by extrapolation to the entire fireball including its early, gamma-ray emitting stages.

There are, however, several important caveats. The first one is that the above argument assumes a simple, impulsive energy input (lasting $\lesssim$ than the observed $\gamma$-ray pulse duration), characterized by a single energy and bulk Lorentz factor value. Estimates for the time needed to reach the non-relativistic regime, or $\Gamma < \Omega_j^{-1/2} \lesssim$ few, could then be under a month (Vietri, 1997a), especially if an initial radiative regime with $\Gamma \propto r^{-3}$ prevails. It is unclear whether, even when electron radiative time scales are shorter than the expansion time, such a regime applies, as it would require strong electron-proton coupling (Mesz` aros, Rees & Wijers, 1998).

Furthermore, even the simplest reasonable departures from a top-hat approximation (e.g. having more energy emitted with lower Lorentz factors at later times, which still do not exceed the gamma-ray pulse duration) would drastically extend the afterglow lifetime in the relativistic regime, by providing a late “energy refreshment” to the blast wave on time scales comparable to the afterglow time scale (Rees & Mesz` aros, 1998). The transition to the $\Gamma < \Omega_j^{-1/2}$ regime occurring at $\Gamma \sim$ few could then occur as late as six months to more than a year after the outburst, depending on details of the brief energy input. Even in a simple top-hat model, more detailed calculations show that the transition to the non-relativistic regime is very gradual ($\delta t/t \gtrsim 2$) in the light curve. A numerical computation of the sideways expansion effects also shows that its effects are not so drastic as inferred from simple scaling for the material along the line of sight. This is because even though the flux from the head-on part of the remnant decreases faster, this is more than compensated by the increased emission measure from sweeping up external matter over a larger angle, and by the fact that the extra radiation, which arises at larger angles, arrives later and re-fills the steeper light curve. The sideways expansion thus actually can slow down the flux decay (Panaitescu & Mesz` aros, 1998c) rather than making for a faster decay. Thus the conclusion is that we do not yet have significant evidence for whether the outflow is jet-like. The lack of a noticeable downturn in the light-curve is therefore, so far, compatible with either a spherical or a jet-like outflow.

The ratio $L_\gamma/L_{opt}$ (or $L_\gamma/L_x$) can be quite different from burst to burst. The fit of Wijers
& Galama, 1998 for GRB 970508 indicates an afterglow (X-ray energies or softer) energy per solid angle $E^{52} = 3.7$, while at $z = 0.835$ with $h_{70} = 1$ the corresponding $\gamma$-ray $E^{52,\gamma} = 0.63$. On the other hand for GRB 971214, at $z = 3.4$, the numbers are $E^{52} = 0.68$ and $E^{52,\gamma} = 20$. The $\gamma$-ray bursts themselves require ejecta with $\Gamma > 100$. The gamma-rays we receive come only from material whose motion is directed within one degree of our line of sight. They therefore provide no information about the ejecta in other directions: the outflow could be isotropic, or concentrated in a cone of angle (say) 20 degrees (provided that the line of sight lay inside the cone). At observer times of more than a week, the blast wave would be decelerated to a moderate Lorentz factor, irrespective of the initial value. The beaming and aberration effects are less extreme so we observe afterglow emission not just from material moving almost directly towards us, but from a wider range of angles.

The afterglow is thus a probe for the geometry of the ejecta — at late stages, if the outflow is beamed, we expect a spherically-symmetric assumption to be inadequate; the deviations from the predictions of such a model would then tell us about the ejection in directions away from our line of sight. It is quite possible, for instance, that there is relativistic outflow with lower $\Gamma$ (heavier loading of baryons) in other directions; this slower matter could even carry most of the energy (Wijers, Rees & Mészáros, 1997; Paczyński, 1998). This hypothesis is, in fact, supported to some degree by the fits of Wijers & Galama, 1998 mentioned above.

6. Environment Effects, Evolution and Diversity

One expects afterglows to show a significant amount of diversity. This is expected both because of a possible spread in the total energies (or energies per solid angle as seen by a given observer), a possible spread or changes in the injected bulk Lorentz factors, and also from the fact that GRB may be going off in very different environments.

The angular dependence of the outflow, and the radial dependence of the density of the external environment can have a marked effect on the time dependence of the observable afterglow quantities (Mészáros, Rees & Wijers, 1998). So do any changes of the bulk Lorentz factor and energy output during even a brief energy release episode (Rees & Mészáros, 1998). The afterglow light curves are also affected by the degree of coupling between electrons and protons in the outflow (Mészáros, Rees & Wijers, 1998; Panaitescu & Mészáros, 1998b). Diversity in the light curves of objects such as GRB 970508, e.g. sharp rises or humps followed by a renewed decay (Pedersen et al., 1998; Piro et al., 1998) is symptomatic of departures from the simple standard model. Detailed time-dependent model fits (Panaitescu, Mészáros & Rees, 1998) to the X-ray, optical and radio light curves of GRB 970228 and GRB 970508 show that, in order to explain the humps, a non-uniform injection or an anisotropic outflow is required. These fits indicate that the shock physics may be a function of the shock strength, and also indicate that dust absorption may be needed to simultaneously fit the X-ray and optical fluxes (the latter being affected more severely). The effects of beaming (outflow within a limited range of solid angles) can be significant
(Panaitescu & Mészáros, 1998c), but are coupled with other effects, and a careful analysis is needed to disentangle them.

Spectral signatures, such as atomic edges and lines, may be expected both from the outflowing ejecta (Mészáros & Rees, 1998a) and from the external medium (Perna & Loeb, 1998, Mészáros & Rees, 1998b) in the X-ray and optical spectrum of afterglows. These may be used as diagnostics for the outflow Lorentz factor, or as alternative measures of the GRB redshift. An interesting prediction (Mészáros & Rees, 1998b; see also Ghisellini, et al., 1998, Böttcher, et al., 1998) is that the presence of a measurable Fe K-α emission line could be a diagnostic of a hypernova, since in this case one can expect a massive envelope at a radius comparable to a light-day where τT ∼ 1, capable of reprocessing the X-ray continuum by recombination and fluorescence.

The location of the afterglow relative to the host galaxy center can provide clues both for the nature of the progenitor and for the external density encountered by the fireball. A hypernova model would be expected to occur inside a galaxy, in fact inside a high density (n_o > 10^3 – 10^5). Some bursts are definitely inside the projected image of the host galaxy, and some also show evidence for a dense medium at least in front of the afterglow (Owen, et al., 1998). On the other hand, for a number of bursts there are strong constraints from the lack of a detectable, even faint, host galaxy (Schaefer, 1998). In NS-NS mergers one would expect a BH plus debris torus system and roughly the same total energy as in a hypernova model, but the mean distance traveled from birth is of order several Kpc (Bloom, Sigurdsson & Pols, 1998), leading to a burst presumably in a less dense environment. The fits of Wijers & Galama, 1998 to the observational data on GRB 970508 and GRB 971214 in fact suggest external densities in the range of n_o = 0.04–0.4 cm^{-1}, which would be more typical of a tenuous interstellar medium (however, Reichart & Lamb, 1998 report a fit for GRB 980329 with n_o ∼ 10^4 cm^{-3}). These could arise within the volume of the galaxy, but on average one would expect as many GRB inside as outside. This is based on an estimate mean NS-NS merger time of 10^8 years; other estimated merger times (e.g. 10^7 years, van den Heuvel, 1992) would give a burst much closer to the birth site. BH-NS mergers would also occur in timescales ≲ 10^7 years, and would be expected to give bursts well inside the host galaxy (Bloom, Sigurdsson & Pols, 1998).

7. Conclusions

The simple blast wave model has proved quite robust in providing a consistent overall interpretation of the major features of gamma-ray bursts and their afterglows at various frequencies. However, the constraints on the angle-integrated energy, especially in γ-rays, are not strong, and beaming effects remain uncertain. Some of the observed light curve humps are likely to be indicative of either non-uniform injection episodes or anisotropic outflows. A relatively brief (1-100 s), probably modulated energy input appears the likeliest interpretation for most bursts, although in some progenitor scenarios there may be delayed effects. This can provide an explanation both for highly variable γ-ray light curves and late glitches in the afterglow decays.
One needs to be mindful of the possibility of there being more subclasses of classical GRB than just short ones and long ones. For instance, GRB with no high energy pulses (NHE) appear to have a different (but still isotropic) spatial distribution than those with high energy (HE) pulses (Pendleton, et al., 1996). Some caution is needed in interpreting this, since selection effects could lead to a bias against detecting HE emission in dim bursts (Norris, 1998). A connection to peculiar supernova events, or the formation of a temporarily rotationally stabilized strong-field pulsar are also possibilities which cannot be ruled out.

Significant progress has been made in understanding how gamma-rays can arise in fireballs produced by brief events depositing a large amount of energy in a small volume, and in deriving the generic properties of the long wavelength afterglows that follow from this. There still remain a number of mysteries, especially concerning the identity of their progenitors, the nature of the triggering mechanism, the transport of the energy and the time scales involved. Nevertheless, even if we do not yet understand the intrinsic gamma-ray burst central engine, they may be the most powerful beacons for probing the high redshift (z > 5) universe. Even if their total energy is reduced by beaming to a “modest” $\sim 10^{52} - 10^{52.5}$ ergs in photons, they are the most extreme phenomena that we know about in high energy astrophysics. The modeling of the burst mechanism itself will continue to be a major challenge to theorists and to computational techniques. However, there is every prospect for continued and vigorous developments both in the observational analyses and in the theoretical understanding of these fascinating objects.

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REFERENCES

Blandford, R.D. & Znajek, R.L., 1977, MNRAS, 179, 433
Bloom, J., Sigurdsson, S. & Pols, O., 1998, MNRAS in press [astro-ph/9805222]
Böttcher, M, et al., 1998, astro-ph/9809156
Costa, E., et al., 1997, Nature, 387, 783
Dermer, C & Mitman, K, 1998, astro-ph/9809411
Djorgovski, S.G. et al., 1998, astro-ph/9808188
Eichler, D., Livio, M., Piran, T. and Schramm, D.N., 1989, Nature, 340, 126
Fishman, G. & Meegan, C., 1995, Ann.Rev Astr.Ap.,33, 415
Fruchter, A, astro-ph/9810224
Fryer, C & Woosley, S, 1998, ApJ(Lett) subm (astro-ph/9804167)
Galama, T. et al., 1998, Nature, in press (astro-ph/9806177)
Ghisellini, G, et al., 1998, astro-ph/9808156
Goodman, J., 1986, ApJ.(Lett.), 1986, 308, L47
Groot, P. et al., 1997; in Gamma-Ray Bursts, Meegan, C., Preece, R. & Koshut, T., eds., 1997 (AIP: New York), p. 557
Harding, A.K. and Baring, M.G., 1994, in Gamma-ray Bursts, ed. G. Fishman, et al., p. 520 (AIP 307, NY)
Horack, J. M., Mallozzi, R. S., & Korshut, T. M. 1996, ApJ, 466, 21
Katz, J., 1994, ApJ, 422, 248
Katz, J., 1994b, ApJ, 432, L107
Katz, J.I., 1997, ApJ, 490, 633
Kippen, R.M. et al., 1998, ApJ subm (astro-ph/9806364)
Krumholz, M, Thorsett, S & Harrison, F, 1998, preprint (astro-ph/9807117)
Kulkarni, S., et al., 1998, Nature, 393, 35
Mészáros , P., 1995, 17th Texas Symp. Relativistic Astrophysics, H. Böhringer et al, N.Y. Acad. Sci., 440
Mészáros , P & Rees, M.J., 1992, ApJ, 397, 570
Mészáros , P & Rees, MJ, 1992b, MNRAS, 257, 29P
Mészáros , P. & Rees, M.J., 1993, ApJ, 405, 278
Mészáros , P & Rees, M.J., 1997a, ApJ, 476, 232
Mészáros , P & Rees, M.J., 1997b, ApJ, 482, L29
Mészáros , P & Rees, M.J., 1998a, ApJ(Letters) 502, L105
Mészáros , P & Rees, M.J., 1998b, MNRAS, 299, L10 (astro-ph/9806183)
Mészáros , P, Rees, M.J. & Wijers, R, 1998, Ap.J., 499, 301 (astro-ph/9709273)
Mészáros , P, Rees, M.J. & Wijers, R, 1998b, New Astron, in press (astro-ph/9808106)
Metzger, M et al., 1997, Nature, 387, 878
Murakami, T. et al., 1997, in Gamma-Ray Bursts, Meegan, C., Preece, R. & Koshut, T., eds., 1997 (AIP: New York), p. 435
Narayan, R., Piran, T. & Shemi, A, 1991, Ap.J.(Lett.), 379, L17
Narayan, R., Paczyński, B. & Piran, T., 1992, Ap.J., 395, L83
Norris, J, 1998, private communication
Norris, J. P., et al. 1995, ApJ, 439, 542
Owen, A., et al. 1998, Astron.&Astrophys. in press [astro-ph/9809356],
Paczyński, B. & Rhoads, J, 1993, Ap.J., 418, L5
Paczyński, B. & Xu, G., 1994, ApJ, 427, 708
Paczyński, B., 1986, Ap.J.(Lett.), 308, L43
Paczyński, B., 1991, Acta. Astron., 41, 257
Paczyński, B., 1998, ApJ, 494, L45
Panaitescu, A & Mészáros, P, 1998a, ApJ, 492, 683
Panaitescu, A. & Mészáros, P., 1998b, ApJ, 501, 772
Panaitescu, A. & Mészáros, P., 1998c, ApJ, subm. [astro-ph/9806016]
Panaitescu, A. & Mészáros, P., 1998d, ApJ, subm [astro-ph/9810258]
Panaitescu, A, Mészáros, P & Rees, MJ, 1998, ApJ, 503, 314
ApJ 496 (1998) 311
Pendleton, G, et al., 1996, ApJ, 464, 606
Perna, R. & Loeb, A., 1998, ApJ(Letters), 503, L135
Phinney, E.S., 1991, Ap.J.(Lett.), 380, L17
Piro, L, et al., 1998, A & A, 331, L41
Popham, R., Woosley, S & Fryer, C., 1998, ApJ subm [astro-ph/9807028]
Ramprakash, A.N. et al., 1998, Nature, 393, 38
Rees, M.J. & Mészáros, P., 1992, MNRAS, 258, P41
Rees, M.J. & Mészáros, P., 1994, ApJ, 430, L93
Rees, M.J. & Mészáros, P., 1998, ApJ, Letters, 496, L1
Reichart, D. & Mészáros, P, 1997, ApJ, 483, 597
Reichart, D., 1997, ApJ, in press
Reichart, D., 1998, ApJ, 495, L99
Reichart, D. & Lamb, D.Q., 1998, talk at the Rome Conference on GRB in the Afterglow Era.
Rhoads, J, 1997a, Ap.J., 487, L1
Rhoads, J, 1997b, preprint

Ruffert, M., Janka, H.-T., Takahashi, K., Schaefer, G., 1997, A&A, 319, 122

Ruffert, M. & Janka, H.-T., 1998, A&A subm [astro-ph/9804132]

Sari, R. & Piran, T., 1995, ApJ, 455, L143

Sari, R & Piran, T, 1998, ApJ, 485, 270

Sari, R., Piran, T & Narayan, R, 1998, ApJ, 497, L17 [astro-ph/9712005]

Schaefer, B.E. et al, 1997, ApJ, 489, 693

Schaefer, B.E., 1998, ApJ in press [astro-ph/9810424]

Shemi, A. and Piran, T., 1990, Ap.J.(Lett.), 365, L55

Tavani, M., 1997, ApJ, 483, L87

Taylor, G.B., et al., 1997, Nature, 389, 263

Thompson, C., 1994, MNRAS, 270, 480

Totani, T, 1997, ApJ, 486, L71

Usov, V.V., 1994, MNRAS, 267, 1035

van den Heuvel, E., in X-ray Binaries and Recycled Pulsars (ed. E.P.J.van den Heuvel and S.A.Rappaport), Kluwer Ac. Pub., 1992, pp 233-256.

van Paradijs, J, et al., 1997, Nature,386, 686

Vietri, M., 1997a, ApJ, 478, L9

Wang, L. & Wheeler, J.C., 1998, ApJ subm [astro-ph/9806212]

Waxman, E., 1997, ApJ(Letters)

Wijers, R.A.M.J. & Galama, T., 1998, ApJ, subm [astro-ph/9805341]

Wijers, R, Bloom, J, Bagla, J & Natarajan, P, 1998, MNRAS, 294, L17

Wijers, R.A.M.J., Rees, M.J. & Mészáros , P., 1997, MNRAS, 288, L51

Woosley, S., 1993, Ap.J., 405, 273

Woosley, S., Eastman, R. & Schmidt, B., 1998, ApJ, subm [astro-ph/9806299]

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