GAMMA-RAY BURSTS: THE FIREBALL SHOCK MODEL AND ITS IMPLICATIONS

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ABSTRACT

Major advances and discoveries in the field of gamma-ray bursts are being made at an increasingly fast pace in the last two years. The successful discovery of X-ray, optical and radio afterglows, which were predicted by theory, has 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 non-thermal 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 0 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.

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1 Introduction

With the first discovery[1] of the afterglow of a Gamma-ray Burst (GRB) at X-ray and optical wavelengths in GRB 970228 in February 1998, a new and revolutionary phase has been entered in the investigation of these mysterious sources. The rapid successive detection of a number of other afterglows, extending in some cases to radio and microwave wavelengths as well, has made it possible to follow some of these sources over much longer time scales of many months, making the identification of counterparts and host galaxies possible (see the review by Norris in this volume). The study of afterglows has provided confirmation for much of the earlier work on the generic fireball shock model of GRB, in which the γ-ray emission arises at radii of $10^{13} - 10^{16}$ cm (Refs. 2-7). In particular, this model led to the prediction of the quantitative nature of the signatures of afterglows,[8,9] in advance of the observational studies[1,10] and, as it turned out, in substantial agreement with these.[11–14] The first measurement of a redshift[15] , in GRB 970508, provided confirmation of the hypothesis that these were at cosmological distances. More recently, significant interest was aroused by the report[16] of an afterglow for the burst GRB 971214 at a redshift $z = 3.4$, whose fluence corresponds to a γ-ray energy of $10^{53.5}(\Omega_\gamma/4\pi)$ erg, where $\Delta\Omega_\gamma$ is the solid angle into which the gamma-rays are beamed. Such energies were discussed[17] 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[18] in GRB970508, the absence of an optical afterglow and presence of strong soft X-ray absorption[19,20] in GRB 970828, the lack an an optical afterglow in the (radio-detected) afterglow[21] of GRB980329, and spectral fits to low energy portion of the X-ray afterglow.[22] The latter observations may be suggestive of "hypernova" models,[23,24] involving the collapse of a massive star or its merger with a compact companion. 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,[25] and the lack of structure associated with nearby galaxies indicated that their distance would be such that non-Euclidean and evolutionary effects may indeed be important. This was also indicated by studies of the counts of the number of bursts per unit fluence or peak flux (the brightness distribution),[25,26] as did evidence for time dilation in the bursts.[27] Fits to cosmological counts including curvature, luminosity function and evolution effects indicated that the latter could be important.[28] In particular, the evolution may be related to the star formation rate as a function of cosmological age.[29–31] The cosmological distances of some bursts have, since then[15,16] been directly measured. This, of course, poses significant constraints on the type of sources that may be able to produce this. The typical numbers required for the luminosity, total energy per bursts and event rate are

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

$$E \sim 10^{53}(\Omega/4\pi) \text{ erg} , \tag{2}$$

$$\mathcal{R} \sim 10^{-6}(\Omega/4\pi)^{-1} \text{ galaxy}^{-1}\text{yr}^{-1} , \tag{3}$$

where Ω is the solid angle into which the energy is channeled.

An early suggestion for a source of GRB at cosmological distances was the merger of NS-NS binaries (e.g.[32,33]) whose estimated numbers and merger rates are in fact quite close to the observed GRB rate.[34,35] A related possibility are BH-NS binary mergers,[34,38,42] which have only slightly different event rates. An alternative suggestion[36] 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 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.[32,33,37] One possible channel for converting some of this energy into electromagnetic form is given by the $\nu\bar{\nu} \to e^+e^-$ process.[39] A low baryon load condition (as 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.[40] 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.[36] Another suggestion for powering a fireball was that this might result from magnetic flaring activity[41] 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 $ct_{var} \lesssim 10^7$ cm, where t_{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 $\gamma\gamma \to e^\pm$ 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 ($\gamma\gamma \to e^\pm$ would lead, in a stationary or slowly expanding flow, to photons just below 0.511 MeV[43]). 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 , $^{-1}$ and the threshold for the pair production is effectively diminished. Thus, photons with energy

$$\epsilon_{\gamma,\mathrm{MeV}} \lesssim 10^4 \epsilon_{t,\mathrm{MeV}}^{-1} ,_2^2 . \tag{4}$$

are able to escape, where $,_2$ is the bulk Lorentz factor in units of 10^2, and ϵ_t is the energy of the target photons.[44] Thus, simply from observations and general physical considerations, a relativistically expanding fireball is expected. However, the observed γ-ray spectrum observed 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.[2,3,6,7] 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.[4,5] This is a completely generic model, which is 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

$$r_{dec} \sim 10^{17} n_o^{1/3} E_{53}^{1/3} \eta_2^{-2/3} \text{ cm} , \tag{5}$$

where the lab-frame energy of the swept-up external matter (, $^2 m_p c^2$ per proton) equals the initial energy E_o of the fireball, and $\eta =$, $= 10^2 \eta_2$ is the final bulk Lorentz factor of the ejecta. The typical observer-frame dynamic time of the shock (assuming the cooling time is shorter than this) is $t_{dec} \sim r_{dec}/c$, $^2 \sim$ seconds, for typical parameters, and $t_b \sim t_{dec}$ would be the burst duration (the impulsive assumption requires that the initial energy input occur in a time shorter than t_{dyn}). Variability on timescales shorter than t_{dec} may occur on the cooling timescale or on the dynamic timescale for inhomogeneities in the external medium, but generally this is not ideal for reproducing highly variable profiles.[45] However, it can reproduce bursts with several peaks[46] and may therefore be applicable to the class of long, smooth bursts.

The same behavior , $\propto r$ with comoving temperature $\propto r^{-1}$, followed by saturation , $_{max} \sim \eta$ at the same radius $r/r_l \sim \eta$ occurs in a wind scenario, if one assumes that a lab-frame luminosity L_o and mass outflow $\dot{M}_o$ are injected at $r \sim r_l$ and continuously maintained over a time t_w; here $\eta = L_o/\dot{M}_o c^2$. In such wind model, internal shocks will occur at a radius[4]

$$r_{dis} \sim c t_{var} \eta^2 \sim 3 \times 10^{14} t_{var} \eta_2^2 \text{ cm}, \tag{6}$$

where shells of different energies $\Delta\eta \sim \eta$ initially separated by ct_v (where $t_v \le t_w$ is the timescale of typical variations in the energy at r_l) catch up with each other. In order for internal shocks to occur above the wind photosphere $r_{ph} \sim \dot{M}\sigma_T/(4\pi m_p c,\ ^2) = 1.2 \times 10^{12} L_{51} \eta_2^{-3}$ cm, but also at radii greater than the saturation radius (so that most of the energy does not come out in the photospheric quasi-thermal radiation component) one needs to have $3 \times 10^1 L_{51}^{1/5} t_{var}^{-1/5} \lesssim \eta 10^2 L_{51}^{1/4} t_{var}^{-1/4}$. This type of models have the advantage[4] that they allow an arbitrarily complicated light curve, the shortest variation timescale $t_{var} \gtrsim 10^{-3}$ s being limited only by the dynamic timescale at r_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.[45,47]

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.[48]) motivated the exploration of ways of increasing the possible total energy budget of GRB. The first explicit model to do this[17] involved converting a large fraction of the binding energy of a black hole and torus system ($\sim 10^{54}$ ergs) into a fireball outflow, 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 from a failed SN Ib). In the last year, a number of other possible energy sources have been considered as possible candidates for powering GRB.[49,50] A fact which is not widely realized[55] 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. An important point is that the overall energetics from these various progenitors do not differ by more than about one order of magnitude.

Two large reservoirs of energy are available in the generic merger or collapse scenario: the binding energy of the orbiting debris, and the spin energy of the black hole.[17] The first can provide up to 42% of the rest mass energy of the disk, for a maximally rotating black hole, while the second can provide up to 29% of the rest mass of the black hole itself. The $\nu\bar{\nu} \to e^+e^-$ 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 fireball of $\lesssim 10^{51}$ erg[56,50] , except perhaps in the "collapsar" or failed SN Ib case where estimates[50] indicate up to $10^{52.3}$ ergs for optimum parameters. If the fireball is collimated into a solid angle Ω_j then of course the apparent "isotropized" energy would be larger by a factor $(4\pi/\Omega_j)$, but unless Ω_j is $\lesssim 10^{-2} - 10^{-3}$ this may fail to satisfy the apparent isotropized energy of $10^{53.5}$ ergs implied by a redshift $z = 3.4$ for GRB 971214. An alternative way to tap the torus energy is through dissipation of magnetic fields generated by the differential rotation in the torus.[38,41,17,57] 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.[40,9] The above mechanisms tap the energy available in the debris torus or disk. However, 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[58] effect could then be even larger than that contained in the orbiting debris.[17,23] Collectively, any such MHD outflows have been referred to as Poynting jets.

The various progenitors 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.[60,59] 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[61] $M_d \sim 0.1 M_\odot$, and for a NS-BH, a He-BH, WD-BH merger or a binary WR collapse it may be estimated at[23,49] $M_d \sim 1 M_\odot$. 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 $1 M_\odot$ is just a rough estimate. The largest energy reservoir is therefore, 'prima facie', 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 failed SNe Ib (which is a slow rotator) it is $\sim 1.2 \times 10^{53}\epsilon(M_d/M_\odot)$ ergs, and for the (fast rotating) NS-NS merger it is $\sim 0.8 \times 10^{53}\epsilon(M_d/0.1M_\odot)$ ergs, where ϵ is the efficiency in converting gravitational into MHD jet energy. Conditions for the efficient escape of a high-, jet may, however, be less propitious if the "engine" is surrounded by an extensive envelope.

If the magnetic fields in the torus thread the BH, the rotational energy of the BH can be extracted via the Blandford & Znajek[58] (B-Z) mechanism.[17] The extractable energy is $\epsilon f(a) M_{bh} c^2$, where ϵ is the MHD efficiency factor and $a = Jc/GM^2$ is the rotation parameter, which equals 1 for a maximally rotating black hole. $f(a) = 1 - \sqrt{\frac{1}{2}[1 + \sqrt{1-a^2}]}$ 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 $0.29\epsilon M_{bh}c^2 \sim 5 \times 10^{53}\epsilon(M_{bh}/M_\odot)$ ergs. 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[61] of about $2.5M_\odot$, the NS-NS system can thus power a jet of up to $\sim 1.3 \times 10^{54}\epsilon(M_{bh}/2.5M_\odot)$ ergs. The scenarios less likely to produce a fast rotating BH are the NS-BH merger (where the rotation parameter could be limited to $a \le M_{ns}/M_{bh}$, 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). 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,[49] 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 $3M_\odot$ threaded by the magnetic field, the maximal energy carried out by the jet is then $\sim 1.6 \times 10^{54}\epsilon(M_{bh}/3M_\odot)$ ergs.

Thus in the accretion powered jet case the total energetics between the various models differs at most by a factor 20, whereas in the rotationally (B-Z) powered cases 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 γ-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.

There is also the apparent coincidence of GRB 980425 with the SN Ib/Ic 1998bw.[51] A simple but radical interpretation[52] 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.[53] If however the GRB 980425/1998bw association is real,[54] 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 likely 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.

4 The Afterglows of Gamma-Ray Bursts

Just as one can interpret supernova remnants without fully understanding the initiating explosion, one can also understand the dynamics of the afterglows of gamma ray bursts, despite the uncertainties recounted in the previous section. The simplest hypothesis is that the afterglow is due to a relativistic expanding blast wave. 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[8] preceded the observations of the first afterglow detected, GRB970228.[1]

The simplest spherical afterglow model has been remarkably successful at explaining the gross features of the GRB 970228, GRB 970508 and other afterglows.[14] This has led to the temptation to take the assumed sphericity for granted. For instance, the lack of a break in the light curve of GRB 970508 prompted the inference[16] that all afterglows are essentially isotropic, leading to the very large (isotropic) energy estimate of $10^{53.5}$ ergs in GRB 971214. The multi-wavelength data analysis has in fact advanced to the point where one can use observed light curves at different times and derive,[12,62] via parametric fitting, physical parameters of the burst and environment, such as the total energy E, the magnetic and electron-proton coupling parameters ϵ_B and ϵ_e and the external density n_o. However, what these fits constrain is only the energy per unit solid angle $\mathcal{E} = (E/\Omega_j)$.

In the simplest departure from a spherical model the blast wave energy may be channeled into a solid angle Ω_j. Then one might expect[63] a faster decay of , after it 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 afterglow downturn in the optical has been interpreted as further supporting the sphericity of the entire fireball. There are several important caveats, however. The first one is that the above argument assumes a simple, impulsive energy input (lasting $\lesssim$ than the observed γ-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 , $< \Omega_j^{-1/2} \lesssim$ few, could then be under a month,[9] especially if an initial radiative regime with , $\propto r^{-3}$ 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.[55] 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.[28] The transition to the , $< \Omega_j^{-1/2}$ regime occurring at , $\sim$ 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. Also, 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[65] rather than making for a faster decay.

The ratio L_γ/L_{opt} (or L_γ/L_x) can be quite different from burst to burst. The fit of Wijers & Galama[62] for GRB 970508 indicates an afterglow (X-ray energies or softer) energy per solid angle $\mathcal{E}_{52} = 3.7$, while at $z = 0.835$ with $h_{70} = 1$

the corresponding γ-ray $\mathcal{E}_{52\gamma} = 0.63$. On the other hand for GRB 971214, at $z = 3.4$, the numbers are $\mathcal{E}_{52} = 0.68$ and $\mathcal{E}_{52\gamma} = 20$. The bursts themselves require ejecta with , > 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 , (heavier loading of baryons) in other directions; this slower matter could even carry most of the energy.[14,23] This hypothesis is, in fact, supported to some degree by the fits of Wijers & Galama[62] mentioned above.

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), 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.[55] So do any changes of the bulk Lorentz factor and energy output during even a brief energy release episode.[64] The afterglow light curves are also affected by the degree of coupling between electrons and protons in the outflow.[55,66] Detailed model fits[67] to the X-ray, optical and radio light curves of GRB 970228 and GRB 970508 show 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,[65] but are coupled with other effects, and a careful analysis is needed to disentangle them. Finally, both the outflowing ejecta[68] and the external medium[69,70] are expected to provide discernible atomic edge and line features 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.

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.[22] On the other hand, for a number of bursts there are strong constraints from the lack of a detectable, even faint, host galaxy.[71] 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[73]), leading to a burst presumably in a less dense environment. The fits of Wijers & Galama[62] to the observational data on GRB 970508 and GRB 971214 in fact suggest external densities in the range of $n_o = 0.04$–$0.4\ \mathrm{cm}^{-1}$, which would be more typical of a tenuous interstellar medium. 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[72]) would give a burst much closer to the birth site. BH-NS mergers would also occur in timescales $\lesssim 10^7$ years, and would be expected to give bursts well inside the host galaxy.[73]

5 Conclusions

The simple blast wave model seems able to accommodate the present data on afterglows remarkably well. However, the constraints on the angle-integrated γ-ray energy are not strong, and beaming effects remain uncertain. A relatively brief (1-100 s), probably modulated energy input appears likely, although in some progenitor scenarios there may be delayed effects. We need to be open minded about 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.[74] Some caution is needed in interpreting this, since selection effects could lead to a bias against detecting HE emission in dim bursts.[10]

Much 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 formidable challenge to theorists and to computational techniques. However, they do not appear insurmountable, and the prospects for significant progress in the near future are realistic.

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References

[1] Costa, E., et al., 1997, Nature, 387, 783

[2] Rees, M.J. & Mészáros, P., 1992, MNRAS, 258, P41

[3] Mészáros, P. & Rees, M.J., 1993, ApJ, 405, 278

[4] Rees, M.J. & Mészáros, P., 1994, ApJ, 430, L93.

[5] Paczyński, B. & Xu, G., 1994, ApJ, 427, 708

[6] Katz, J., 1994, ApJ, 422, 248

[7] Sari, R. & Piran, T., 1995, ApJ, 455, L143

[8] Mészáros, P & Rees, M.J., 1997a, ApJ, 476, 232

[9] Vietri, M., 1997a, ApJ, 478, L9

[10] Norris, J, 1998, these proceedings

[11] Tavani, M., 1997, ApJ, 483, L87

[12] Waxman, E., 1997, ApJ(Letters)

[13] Reichart, D., 1997, ApJ, in press

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

[15] Metzger, M et al., 1997, Nature, 387, 878

[16] Kulkarni, S., et al., 1998, Nature, 393, 35

[17] Mészáros, P & Rees, M.J., 1997b, ApJ, 482, L29

[18] Reichart, D., 1998, ApJ, 495, L99

[19] Groot, P. et al., 1997; in *Gamma-Ray Bursts*, Meegan, C., Preece, R. & Koshut, T., eds., 1997 (AIP: New York), p. 557

[20] Murakami, T. et al., 1997, in Gamma-Ray Bursts, Meegan, C., Preece, R. & Koshut, T., eds., 1997 (AIP: New York), p. 435

[21] Taylor, G.B., et al., 1997, Nature, 389, 263

[22] Owen, A., et al, 1998, Astron.&Astrophys. in press (astro-ph/9809356),

[23] Paczyński, B., 1998, ApJ, 494, L45

[24] Fryer, C., & Woosley, S., 1998, subm to Ap.J.(Lett.), (astro-ph/9804167)

[25] Fishman, G. & Meegan, C., 1995, Ann.Rev Astr.Ap.,33, 415

[26] Horack, J. M., Mallozzi, R. S., & Korshut, T. M. 1996, ApJ, 466, 21

[27] Norris, J. P., et al. 1995, ApJ, 439, 542

[28] Reichart, D.E. & Mészáros, P, 1997, ApJ, 483, 597

[29] Totani, T, 1997, ApJ, 486, L71

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

[31] Krumholz, M, Thorsett, S & Harrison, F, 1998, preprint (astro-ph/9807117)

[32] Pacziński, B., 1986, Ap.J.(Lett.), 308, L43

[33] Goodman, J., 1986, Ap.J.(Lett.), 1986, 308, L47

[34] Narayan, R., Piran, T. & Shemi, A, 1991, Ap.J.(Lett.), 379, L17

[35] Phinney, E.S., 1991, Ap.J.(Lett.), 380, L17

[36] Woosley, S., 1993, Ap.J., 405, 273

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

[38] Pacziński, B., 1991, Acta. Astron., 41, 257

[39] Eichler, D., Livio, M., Piran, T. and Schramm, D.N., 1989, Nature, 340, 126

[40] Mészáros, P & Rees, M.J., 1992, ApJ, 397, 570

[41] Narayan, R., Paczynski, B. & Piran, T., 1992, Ap.J., 395, L83

[42] Mészáros, P & Rees, MJ, 1992b, MNRAS, 257, 29P

[43] Harding, A.K. and Baring, M.G., 1994, in *Gamma-ray Bursts*, ed. G. Fishman, *et al.*, p. 520 (AIP 307, NY)

[44] Mészáros, P., 1995, 17th Texas Symp. Relativistic Astrophysics, H. Böhringer et al, N.Y. Acad. Sci., 440

[45] Sari, R & Piran, T, 1998, ApJ, 485, 270

[46] Panaitescu, A & Mészáros, P, 1998a, ApJ, 492, 683

[47] Panaitescu, A. & Mészáros, P., 1998d, ApJ, subm (astro-ph/9810258)

[48] Schaefer, B.E. et al, 1997, ApJ, 489, 693

[49] Fryer, C & Woosley, S, 198, ApJ(Lett) subm (astro-ph/9804167

[50] Popham, R., Woosley, S & Fryer, C., 1998, ApJ subm (astro-ph/9807028)

[51] Galama, T. et al., 1998, Nature, in press (astro-ph/9806175)

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

[53] Kippen, R.M. et al., 1998, ApJ subm (astro-ph/9806364)

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

[55] Mészáros, P, Rees, M.J. & Wijers, R, 1998, New Astron, in press (astro-ph/9808106)

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

[57] Katz, J.I., 1997, ApJ, 490, 633

[58] Blandford, R.D. & Znajek, R.L., 1977, MNRAS, 179, 433

[59] Thompson, C., 1994, MNRAS, 270, 480

[60] Usov, V.V., 1994, MNRAS, 267, 1035

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

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

[63] Rhoads, J, 1997, preprint

[64] Rees, M.J. & Mészáros, P., 1998, ApJ, Letters, 496, L1

[65] Panaitescu, A. & Mészáros, P., 1998c, ApJ, subm. (astro-ph/9806016)

[66] Panaitescu, A. & Mészáros, P., 1998b, ApJ, 501, 772

[67] Panaitescu, A, Mészáros, P & Rees, MJ, 1998, ApJ, 503, 314

[68] Mészáros, P & Rees, M.J., 1998a, ApJ(Letters) 502, L105

[69] Perna, R. & Loeb, A., 1998, ApJ(Letters), 503, L135

[70] Mészáros, P & Rees, M.J., 1998b, MNRAS in press (astro-ph/9806183)

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

[72] 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.

[73] Bloom, J., Sigurdsson, S. & Pols, O., 1998, MNRAS in press (astro-ph/9805222)

[74] Pendleton, G, et al., 1996, Ap[J, 464, 606