Origin of Gamma Ray Bursters

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Major advances have been made in the field of gamma-ray bursts in the last two years. The successful discovery of X-ray, optical and radio afterglows has made possible the identification of host galaxies at cosmological distances. The energy release inferred in these outbursts place them among the most energetic and violent events in the Universe. They are thought to be the outcome of a cataclysmic stellar collapse or compact stellar merger, 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 standard fireball shock model provide confirmation of the basic aspects of this scenario. New issues being raised by the most recent observations concern the amount and the nature of the collimation of the outflow and its implications for the energetics, the production of prompt bright flashes at wavelengths much longer than gamma-rays, 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

Gamma-ray bursts (GRB) are brief pulses of gamma-rays which pierce, for a brief period of tens of seconds, an otherwise pitch-black gamma-ray sky. They are detected about once a day, and while they are on, they outshine everything else in the gamma-ray sky, including the Sun. In fact, they are the brightest explosions in the Universe. Until a few years ago, they left no trace at any other wavelengths besides gamma-rays, until in early 1997 the Italian-Dutch satellite Beppo-SAX succeeded in providing accurate X-ray measurements that allowed, after a delay of some hours to process the position. This made possible their follow-up with large ground-based optical and radio telescopes, which paved the way for the measurement of redshift distances, the identification of candidate host galaxies, and the confirmation that they were at cosmological distances, comparable to that of the most distant galaxies and quasars ever measured. Since even at those tremendous distances they appear so bright, their energy output needs to be stupendous. It is comparable to burning up the entire mass-energy of the Sun in a few tens of seconds, or to emit over that same period of time as much energy as our Milky Way does in a hundred years. The current interpretation of this radiation is that this large amount of energy, released in a very short time in a very small region, expands in highly relativistic outflow, which undergoes both internal shocks producing gamma-rays, and later develops a blast wave and reverse shock, as it is decelerated by interaction with the external

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medium. The remarkable thing about this model is that it successfully predicted the expected observational properties of the afterglows which such bursts leave at X-ray, optical and radio wavelengths, which can be observed over months. This fireball shock model and the blast wave model of the ensuing afterglow have become the leading paradigms for the current understanding of GRB.

GRBs were first discovered in 1974 by the Vela military satellites, monitoring for nuclear explosions in violation of the Nuclear Test Ban Treaty. When these mysterious gamma-ray flashes were first detected, which did not come from the Earth’s direction, the first suspicion (quickly abandoned) was that they might be the product of an advanced extraterrestrial civilization. Soon, however, it was realized that this was a new and extremely puzzling cosmic phenomenon. For the next 25 years, only these brief gamma-ray flashes were observed, which vanished too soon to get an accurate angular position and hence left no trace, or so it seemed. Gamma-rays are notoriously hard to focus, so no gamma-ray “images” exist to this day: they are just pin-points of gamma-ray light. This led to a huge interest and to numerous conferences and publications on the subject, as well as to a proliferation of theories. In one famous review article at the 1975 Texas Symposium on Relativistic Astrophysics, no fewer than 100 different possible theoretical models of GRB were listed, most of which could not be ruled out by the observations then available!

A major advance occurred in 1992 with the launch of the Compton Gamma-Ray Observatory, whose superb results are summarized in a review by Fishman & Meegan\textsuperscript{29}. The all-sky survey from the BATSE instrument showed that bursts were isotropically distributed, strongly suggesting a cosmological, or possibly an extended galactic halo distribution, with essentially zero dipole and quadrupole components. The spectra are non-thermal, typically fitted in the MeV range by broken power-laws whose energy per decade $\nu F_\nu$ peak is in the range 50-500 KeV\textsuperscript{3}, the power law sometimes extending to GeV energies\textsuperscript{45}. GRB appeared to leave no detectable traces at other wavelengths, except in some cases briefly in X-rays. The gamma-ray

![Fig. 1. Time Profile of a Typical Gamma Ray Burst. The y-axis is the photon count rate in the 0.05-0.5 MeV energy, the x-axis is the time in seconds after the trigger. Both before and after the burst, no gamma-rays are detectable from the direction of the burst (Fishman & Meegan, 1995).](image)

durations range from $10^{-3}$ s to about $10^{3}$ s, with a roughly bimodal distribution of long bursts of $t_b \gtrsim 2$ s and short bursts of $t_b \lesssim 2$ s\textsuperscript{55}, and substructure sometimes down to milliseconds. The gamma-ray light curves range from smooth, fast-rise and quasi-exponential decay (FREDs), through curves with several peaks, to highly variable
curves with many peaks\textsuperscript{29,56}. The pulse distribution is complex\textsuperscript{103,82}, and the time histories can provide clues for the geometry of the emitting regions\textsuperscript{27,28}.

At cosmological distances the observed GRB fluxes imply enormous energies, and from causality they must arise in a small volume in a very short time, so an $e^\pm - \gamma$ fireball must form\textsuperscript{88,39,131}, which would expand relativistically. The main difficulty with this was that a smoothly expanding fireball would convert most of its energy into kinetic energy of accelerated baryons (rather than photons), and would produce a quasi-thermal spectrum, while the typical timescales would not explain events much longer than milliseconds. This problem was solved with the introduction of the "fireball shock model"\textsuperscript{111,66}, based on the realization that shocks are likely to arise, at the latest when the fireball runs into an external medium, which would occur after the fireball is optically thin and would reconvert the kinetic energy into nonthermal radiation. The complicated light curves can be understood in terms of internal shocks\textsuperscript{112} in the outflow itself, before it runs into the external medium, caused by velocity variations in the outflow from the source.

The next major advance came in early 1997 when the Italian-Dutch satellite Beppo-SAX succeeded in providing accurate X-ray measurements which, after a delay of 4-6 hours for processing, led to positions\textsuperscript{17}, allowing follow-ups at optical and other wavelengths, e.g.\textsuperscript{141}. This paved the way for the measurement of redshift distances, the identification of candidate host galaxies, and the confirmation that they were indeed at cosmological distances\textsuperscript{78,23,57}. The detection of other GRB afterglows followed in rapid succession, sometimes extending to radio\textsuperscript{30,31} and over timescales of many months\textsuperscript{142}, and in a number of cases resulted in the identification of candidate host galaxies, e.g.\textsuperscript{122,11,84}, etc. The study of afterglows has provided strong confirmation for the generic fireball shock model of GRB. This model in fact led to a correct prediction\textsuperscript{70}, in advance of the observations, of the quantitative nature of afterglows at wavelengths longer than $\gamma$-rays, which were in substantial agreement with the data\textsuperscript{143,135,146,114,152}.

A major issue raised by the large redshifts, e.g.\textsuperscript{57,58}, is that the measured $\gamma$-ray fluences imply a total energy of order $10^{54}\left(\Omega_\gamma/4\pi\right)$ ergs, where $\Delta\Omega_\gamma$ is the solid angle into which the gamma-rays are beamed. A beamed jet would clearly alleviate the energy requirements, but it is only recently that tentative evidence has been reported for evidence of a jet\textsuperscript{58,33,16}. Whether a jet is present or not, such energies are possible\textsuperscript{71} in the context of compact mergers involving neutron star-neutron star (NS-NS ) or black hole-neutron star (BH-NS ) binaries, or in hypernova/collapsar models involving a massive stellar progenitor\textsuperscript{91,108}. In both cases, one is led to rely on MHD extraction of the spin energy of a disrupted torus and/or a central fast spinning BH, which can power a relativistic fireball resulting in the observed radiation.

While it is at present unclear whether there is a single or several classes of GRB progenitors, there is a general consensus that they would all lead to the generic fireball shock scenario mentioned above. Two recent trends in the observations are the increasing hints pointing at a massive progenitor, at least for those bursts where an afterglow is detected\textsuperscript{92}, and the possibility that, at least in some bursts, a peculiar supernova may be involved, e.g.\textsuperscript{150}. Much of the current effort is
dedicated to understanding the different possible progenitors more specifically, and trying to determine how this affects the details of the observable burst and afterglow. Some of these progenitors, clearly, could be amenable also to observation with the current generation of gravitational wave detectors, and the numerical simulations of the collapse or merger share many interesting aspects with calculations motivated by gravitational wave searches.

§2. Progenitors and Black Hole Systems

In the last few years it has become apparent that most plausible GRB progenitors would be expected to lead to a central black hole (BH) and a temporary debris torus around it. This includes both the currently popular massive progenitor systems, such as hypernova or collapsars (including failed supernova Ib [SNe Ib], single or binary Wolf-Rayet [WR] collapse, etc.\textsuperscript{155}, 91, 153, 71, 108), NS-NS or NS-BH mergers\textsuperscript{90}, 71, Helium core - black hole [He/BH] or white dwarf - black hole [WD-BH] mergers\textsuperscript{108, 155}, accretion-induced collapse\textsuperscript{144, 109}, etc.. An important point is that the overall energetics from these various progenitors do not differ by more than about one order of magnitude\textsuperscript{75}. Another possibility is massive black holes ($\sim 10^3 - 10^5 M_\odot$) in the halos of galaxies. Some related models involve a compact binary or a temporarily rotationally stabilized neutron star, perhaps with a superstrong field, e.g.\textsuperscript{139, 137, 144, 133}, which ultimately also should lead to a BH plus debris torus.

The two large reservoirs of energy available in these systems are the binding energy of the orbiting debris, and the spin energy of the black hole\textsuperscript{71}. 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. However, as in the related AGN case, the question is how to to extract this energy and how to deposit it at larger distances, where it produces optically thin radiation.

A classical energy extraction mechanisms is the $\nu\bar{\nu} \rightarrow e^+e^-$ process\textsuperscript{25}, which can tap the thermal energy of the torus produced by viscous dissipation. 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\textsuperscript{119, 34, 62}, except perhaps in the collapsar case where\textsuperscript{108} estimate $10^{52.3}$ 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 $\Omega_j$ is $\lesssim 10^{-3} - 10^{-4}$ this would fail to satisfy the apparent isotropized energy of $4 \times 10^{54}$ ergs deduced for GRB 990123\textsuperscript{58}.

A more efficient mechanism for extracting and transporting the energy from the vicinity of the BH may be through magnetic torques. Strong magnetic fields may be generated by the differential rotation in the torus\textsuperscript{90, 81, 71, 50}, in any of the above progenitors. In NS-NS mergers, even before the BH forms the shrinking binary may lead to winding up of the fields and dissipation in the last stages before the merger\textsuperscript{64, 143}. An even larger energy source is provided by the spin of the hole
itself, especially if formed from a coalescing compact binary, which is likelier to be rotating close to the maximal rate. Since the BH is more massive, it could contain more energy than the torus. The energy extractable in principle through MHD coupling to the rotation of the hole by the B-Z (Blandford & Znajek \(7\)) effect could then be even larger than that contained in the orbiting debris \(71\), \(91\). Collectively, any such MHD outflows have been referred to as Poynting jets.

The various progenitors differ only slightly in the mass of the BH; they can differ more on the debris torus mass, can differ even more markedly in the amount of rotational energy contained in the BH. Strong magnetic fields, of order \(10^{15} \text{ G}\), are needed to carry away the rotational or gravitational energy in a time scale of tens of seconds \(139\), \(137\), which may be generated on such timescales by a convective dynamo mechanism, the conditions for which are satisfied in freshly collapsed neutron stars or neutron star tori \(24\), \(53\). 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 BH this is 42\%, and for a slow-rotating BH this is 6\% of the torus rest mass, multiplied by an additional efficiency factor \(\epsilon\) for converting MHD energy into radiation. The torus or disk mass in a NS-NS merger is \(121\) \(M_{d} \sim 10^{-1} - 10^{-2} M_{\odot}\), and for a NS-BH, a He-BH, WD-BH merger or a binary WR collapse it may be estimated at \(91\), \(34\) \(M_{d} \sim 1 M_{\odot}\). 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 \(1M_{\odot}\) is just a rough estimate. The maximum torus-based MHD energy extraction is then

\[
E_{\text{max},t} \sim 1 - 10 \times 10^{53}\epsilon(M_{d}/M_{\odot}) \text{ ergs} .
\] (2.1)

If the magnetic fields in the torus thread the BH, the spin energy of the BH can in principle be extracted via the \(7\) (B-Z) mechanism \((71)\). The extractable energy is

\[
E_{\text{max},bh} \sim (f(a)/0.29)\epsilon M_{bh} c^{2} \sim 5 \times 10^{53} f(a)\epsilon(M_{bh}/M_{\odot}) \text{ ergs}.
\] (2.2)

where \(f(a) = 1 - (\sqrt{1 - a^{2}}/2)^{1/2} \leq 0.29\) is the rotational efficiency factor, and \(a = Jc/GM^{2}\) is the rotation parameter, which equals 1 for a maximally rotating black hole. The \(f(a)\) rotational factor is is small unless \(a\) is close to 1, where it rises sharply to its maximum value \(f(1) = 0.29\), so the main requirement is a rapidly rotating black hole, \(a \geq 0.5\). For a massive progenitor it is then imperative that the collapsed rotate fast, and hence a system with a compact binary companion seems called for. A binary fast-rotating WR scenario might do this, which does not differ much in its final details from the He-BH merger, depending on what fraction of the He core gets accreted along the rotation axis as opposed to along the equator \(34\). For a fast rotating BH of \(2.5 - 3 M_{\odot}\) threaded by the magnetic field, the maximal energy carried out by the jet is then similar or somewhat larger than in the NS-NS case. Rapid rotation is also guaranteed in an NS-NS merger, since the radius is close to that of a black hole and the final orbital spin period is close to the required maximal spin rotation period. Some scenarios less likely to produce a fast rotating BH are the NS-BH merger (where the rotation parameter could be limited to \(a \leq M_{ns}/M_{bh}\)), unless the BH is already fast-rotating, and the (single) 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. Some examples are discussed in the accompanying article by Ruffert\cite{120). The main point that is worth stressing is that the total energetics differ between the various models at most by a factor 20 for a Poynting (MHD) jet powered by the torus binding energy, and by a factor of a few for Poynting jets powered by the BH spin energy, depending on the rotation parameter.

The major difference between the various models is expected to be in the location where the burst occurs relative to the host galaxy (see §7). They are also likely to differ substantially in the efficiency of producing a directly observable relativistic outflow, as well as in the amount of collimation of the jet they produce. The conditions for the efficient escape of a high-$\Gamma$ jet are less propitious if the “engine” is surrounded by an extensive envelope. In this case the jet has to “punch through” the envelope, and its ability to do so may be crucially dependent on the level of viscosity achieved in the debris torus (e.g.\cite{62}), higher viscosities leading to more powerful jets. The simulations, so far, are nonrelativistic and one can only infer that high enough viscosities can lead to jets capable of punching though a massive (several $M_\odot$) envelope. This is facilitated, of course, if the envelope is fast-rotating, as in this case there is a centrifugally induced column density minimum along the spin axis, which might be small enough to allow punch-through to occur. If they do, a very tightly collimated beam may arise. “Cleaner” environments, such as NS-BH or NS-NS merger, or rotational support loss/accretion induced collapse to BH would have much less material to be pushed out of the way by a jet. In these, however, there is no natural choke to collimate a jet, which might therefore be somewhat wider than in a massive progenitor case.

§3. The Generic Fireball Shock Scenario

No matter what the progenitor is, the ultimate result must almost unavoidably be an $e^\pm, \gamma$ fireball, which initially will be very optically thick. The initial dimensions must be of order $ct_{\var}\lesssim 10^7 \text{ cm}$, since variability timescales are $t_{\var}\gtrsim 10^{-3} \text{ s}$. Most of the spectral energy is observed above 0.5 MeV, hence the $\gamma\gamma \rightarrow e^\pm$ mean free path is very short. Due to the highly super-Eddington luminosity, this fireball must expand. Since many bursts show spectra extending above 1 GeV, the flow must be able to avoid degrading these via photon-photon interactions to energies below the threshold $m_e c^2 = 0.511 \text{ MeV}$\cite{41}. To avoid this, it seems inescapable that the flow must be expanding with a very high Lorentz factor $\Gamma$, since then the relative angle at which the photons collide is less than $\Gamma^{-1}$ and the threshold for the pair production is diminished. This condition is

$$\Gamma \gtrsim 10^2 [(\epsilon_\gamma/10\text{GeV})(\epsilon_t/\text{MeV})]^{1/2},$$

in order for photons $\epsilon_\gamma$ to escape annihilation against target photons of energy $\epsilon_t \sim 1 \text{ MeV}$\cite{63,41}. I.e., a relativistically expanding fireball is expected. From general considerations\cite{67}, an outflow arising from an initial energy $E_o$ imparted to a mass $M_o << E_o/c^2$ within a radius $r_l$ will lead to an expansion where initially the bulk
Lorentz $\Gamma \propto r$, while comoving temperature drops $\propto r^{-1}$. Since $\Gamma$ cannot increase beyond $\Gamma_{\text{max}} \sim \eta \sim E_o/M_o c^2$, which is achieved at a radius $r/r_1 \sim \eta$, beyond this radius the flow begins to coast, with $\Gamma \sim \eta \sim \text{constant}^{\text{90}}$. However, the observed $\gamma$-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, $^{\text{88}},^{\text{39}}$). 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$^{\text{111}}$. Two different types of shocks may arise in this scenario. In the first case (a) the expanding fireball runs into an external medium (the ISM, or a pre-ejected stellar wind$^{\text{111}},^{\text{66}},^{\text{48}},^{\text{123}}$). The second possibility (b) is that$^{\text{112}},^{\text{87}}$, even before external shocks occur, internal shocks develop in the relativistic wind itself, faster portions of the flow catching up with the slower portions. This is a completely generic model, which is independent of the specific nature of the progenitor, which 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

$$r_{\text{dec}} \sim (3E_o/(4\pi n_o m_p c^2 \eta^2))^{1/3} \sim 10^{17} E_{53}^{1/3} n_o^{-1/3} \eta_2^{-2/3} \text{ cm}, \quad (3.2)$$

and on a timescale $t_{\text{dec}} \sim r_{\text{dec}}/(c \Gamma^2) \sim 3 \times 10^2 E_{53}^{1/3} n_o^{-1/3} \eta_2^{-8/3}$ s, where $\eta = \Gamma = 10^2 \eta_2$ is the final bulk Lorentz factor of the ejecta. 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 this is not ideal for reproducing highly variable profiles$^{\text{125}}$. However, it can reproduce bursts with several peaks$^{\text{94}}$ and may therefore be applicable to the class of long, smooth bursts.

The same behavior $\Gamma \propto r$ with comoving temperature $\propto r^{-1}$, followed by saturation $\Gamma_{\text{max}} \sim \eta$ at the same radius $r/r_1 \sim \eta$ occurs in a wind scenario$^{\text{89}}$, if one assumes that a lab-frame luminosity $L_o$ and mass outflow $\dot{M}_o$ are injected at $r \sim r_1$ 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$^{\text{112}}$

$$r_{\text{dis}} \sim c t_{\text{var}} \eta^2 \sim 3 \times 10^{14} t_{\text{var}} \eta_2^2 \text{ cm}, \quad (3.3)$$

on a timescale $t_w \gg t_{\text{var}} \sim r_{\text{dis}}/(c \eta^2)$ s, where shells of different energies $\Delta \eta \sim \eta$ initially separated by $c t_v$ (where $t_v \leq t_w$ is the timescale of typical variations in the energy at $r_1$) catch up with each other. In order for internal shocks to occur above the wind photosphere $r_{\text{ph}} \sim \dot{M} \sigma_T/(4\pi m_p c \Gamma^2) = 1.2 \times 10^{14} L_{53} \eta_2^{-3}$ 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
$7.5 \times 10^1 L_{15}^{1/5} t_{\text{var}}^{-1/5} \lesssim 3 \times 10^2 L_{53}^{1/4} t_{\text{var}}^{-1/4}$. This type of models have the advantage that they allow an arbitrarily complicated light curve, the shortest variation timescale $t_{\text{var}} \gtrsim 10^{-3}$ 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 be required by) some of the more complicated light curves (see however).

A potentially valuable diagnostic tool for the central engine of GRB is the power density spectrum (PDS). An analysis of a sample of 228 BATSE burst light curves comes up with two interesting results, namely the logarithmic slope of the PDS between $10^{-2}$ and 2 Hz is approximately $-5/3$, and there is a cutoff of the average PDS above 2 Hz. While these experimental results need further verification by independent data analysis groups, the experience with radio and accreting pulsars, black hole binaries and QPO sources indicates that time series analyses can provide valuable constraints on physical source mechanisms, e.g.

Using a simple kinematical model for the shell ejection and collision and assuming the BATSE radiation to be due to synchrotron and/or IC scattered radiation, have calculated the light curves and PDS expected for a range of total burst energies and for a total mass ejected and bulk Lorentz factor distribution compatible with the internal shock scenario (Figure 2). The distance distribution also contributes to the observed PDS, and this is taken into account by using a distribution compatible with the observed logN-logP counts.

For optically thin winds, a slope approaching $-5/3$ requires a non-random Lorentz factor distribution, e.g. with an asymmetrical time modulation so as to produce a larger number of collisions at low frequencies. A cutoff at high frequencies ($\sim 2$ Hz) can be understood in terms of shocks which increasingly occur below the scattering photosphere of the outflow, or a deficit of energy in short pulses due to the modulation of the Lorentz factors favoring shocks arising further out.

An interesting development is that significant fraction of bursts appear to have low energy spectral slopes steeper than $1/3$ in energy. This has motivated consideration of a thermal or nonthermal comptonization mechanism. While an astrophysical model where this mechanism would arise naturally has been left largely unspecified, internal shocks which lead to pair formation could have a self-regulated low pair temperature favoring comptonization. There is also growing

![Figure 2. Average power density spectrum $P_f$ of simulated bursts from internal shocks, compared with the observed PDS (thick line) determined by 4). The average is done over 112 bursts with a square-sine modulated wind of random period between $t_w/4$ and $t_w$, with a power-law luminosity distribution and a constant comoving rate density evolution satisfying the observed logN-logP constraints (Spada, Panaitescu & Mészáros 1999).]
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Fig. 3. Luminosity per decade $xL_x$ vs. $x = h\nu/m_e c^2$ for two values of $\eta = L/\dot{M} c^2$ and marginal (left) or large (right) pair compactness. T: thermal photosphere, PHC: photospheric comptonized component; S: shock synchrotron; C: shock pair dominated comptonized component (Mészáros & Rees, 1999b).

evidence that the apparent clustering of the break energy of GRB spectra in the 50-500 keV range may not be due to observational selection\textsuperscript{101,14,21}. Models to explain this, e.g., through a Compton attenuation model\textsuperscript{15} require reprocessing by an external medium whose column density adjusts itself to a few g cm\textsuperscript{−2}. More recently a preferred break has been attributed to a blackbody peak at the comoving pair recombination temperature in the fireball photosphere\textsuperscript{26}. In this case a steep low energy spectral slope is provided by the Rayleigh-Jeans part of the photosphere, and the high energy power law spectra and GeV emission require a separate explanation. In order for such photospheres to occur at the pair recombination temperature in the accelerating regime requires an extremely low baryon load. For very large baryon loads, a related explanation has been invoked\textsuperscript{137}, considering scattering of photospheric photons off MHD turbulence in the coasting portion of the outflow, which upscatters the adiabatically cooled photons up to the observed break energy. These ideas have been synthesized\textsuperscript{77} to produce a generic scenario in which the presence of a photospheric component as well as shocks subject to pair breakdown can produce steep low energy spectra and preferred breaks.

§4. The Simple Standard Afterglow Model

The dynamics of GRB and their afterglows can be understood in a fairly simple manner, independently of any uncertainties about the progenitor systems, using a generalization of the method used to model supernova remnants. The simplest hypothesis is that the afterglow is due to a relativistic expanding blast wave, which decelerates as time goes on\textsuperscript{70}. The complex time structure of some bursts suggests that the central trigger may continue for up to 100 seconds, the $\gamma$-rays possibly being due to internal shocks. 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. As pointed in the original fireball shock paper\textsuperscript{111}, the external shock bolometric luminosity builds up as $L \propto t^2$ and decays as $L \propto t^{-(1+q)}$. At the deceleration radius (3.2) the fireball energy and the bulk Lorentz factor decrease by a factor $\sim 2$ over a timescale $t_{\text{dec}} \sim r_{\text{dec}}/(c\Gamma^2)$, and thereafter the bulk Lorentz factor decreases as a power law in radius. This is

$$\Gamma \propto r^{-g} \propto t^{-g/(1+2g)} , \quad r \propto t^{1/(1+2g)} , \quad (4.1)$$

with $g$ is 3 for the radiative, 3/2 for the adiabatic regime (in which $\rho r^3 \Gamma$ $\sim$ constant or $\rho r^3 \Gamma^2$ $\sim$ constant).

The most obvious radiation mechanism is synchrotron, whose peak frequency in the observer frame is $\nu_m \propto \Gamma B' \gamma^2$, and both the comoving field $B'$ and electron Lorentz factor $\gamma$ are expected to be proportional to $\Gamma$\textsuperscript{66}. As $\Gamma$ decreases, so will $\nu_m$, and the radiation will move to longer wavelengths. Looking at the implications of this for the forward blast wave,\textsuperscript{86, 49} discussed the possibility of detecting at late times a radio or optical afterglow of the GRB. A more detailed treatment of the fireball dynamics indicates that approximately equal amounts of energy are radiated by the forward blast wave, moving with $\sim \Gamma$ into the surrounding medium, and by a reverse shock propagating with $\Gamma_r - 1 \sim 1$ back into the ejecta\textsuperscript{66}. The electrons are shocked to much higher energies in the forward shock than in the reverse shock, producing a two-step synchrotron spectrum which during the deceleration time $t_{\text{dec}}$ peaks in the optical (reverse) and in the $\gamma/X$ (forward)\textsuperscript{68, 69}. Detailed calculations and predictions of the time evolution of such a forward and reverse shock afterglow model (70) preceded the observations of the first afterglow GRB970228 (17, 141)), which was detected in $\gamma$-rays, X-rays and several optical bands, and was followed up for a number of months.

![Fig. 4. The observed light curves of the afterglow of GRB 970228 at various wavelengths, compared\textsuperscript{152} to the simple blast wave model predictions of\textsuperscript{70}.

The simplest spherical afterglow model concentrates on the properties of the forward blast wave only. The flux at a given frequency and the synchrotron peak frequency decay at a rate\textsuperscript{70, 76}:

$$F_\nu \propto t^{[3-2g(1-2g)]/(1+2g)} , \quad \nu_m \propto t^{-4g/(1+2g)} , \quad (4.2)$$
where $g$ is the exponent of $\Gamma$ (equ. [4.1]) and $\beta$ is the photon spectral energy slope. The decay rate of the forward shock $F_\nu$ in equ.(4.2) is typically slower than that of the reverse shock $^{70}$, and the reason why the "simplest" model was stripped down to its forward shock component only is that, for the first two years 1997-1998, afterglows were followed in more detail only after the several hours needed by Beppo-SAX to acquire accurate positions, by which time both reverse external shock and internal shock components are expected to have become unobservable. This simple standard model has been remarkably successful at explaining the gross features and light curves of GRB 970228, GRB 970508 (after 2 days; for early rise, see §5) e.g. $^{152,135,146,114}$ (see Figure 4).

This standard afterglow model produces at any given time a three-segment 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 $-(p-1)/2$ energy spectrum above this break, for electrons in the adiabatic regime (where $\gamma^{-p}$ is the electron energy distribution above $\gamma_m$). A fourth segment and a third break is expected at energies where the electron cooling time becomes short compared to the expansion time, with a spectral slope $-p/2$ above that. With this third "cooling" break $\nu_b$, first calculated in $^{74}$ and more explicitly detailed in $^{126}$, one has what has come to be called the simple "standard" model of GRB afterglows. One of the predictions of this model$^{70}$ is that the relation between the temporal decay index $\alpha$, for $g = 3/2$ in $\Gamma \propto r^{-g}$, is related to the photon spectral energy index $\beta$ through

$$F_\nu \propto t^{\alpha} \nu^{\beta}, \text{ with } \alpha = (3/2)\beta. \quad (4.3)$$

This relationship appears to be valid in many (although not all) cases, especially after the first few days, and is compatible with an electron spectral index $p \sim 2.2 - 2.5$ which is typical of shock acceleration, e.g. $^{146,126,151}$, etc. As the remnant expands the photon spectrum moves to lower frequencies, and the flux in a given band decays as a power law in time, whose index can change as breaks move through it. For the simple standard model, snapshot overall spectra have been deduced by extrapolating spectra at different wavebands and times using assumed simple time dependences $^{147,151}$. These can be used to derive rough fits for the different physical parameters of the burst and environment, e.g. the total energy $E$, the magnetic and electron-proton coupling parameters $\varepsilon_B$ and $\varepsilon_e$ and the external density $n_o$ (see Figure 5).

The simplest afterglow model is based on the following assumptions: a) A single value of $E_o$ and $\Gamma_o = \eta$ is used, b) the external medium $n_{ext}$ is homogeneous, c) the accelerated electron spectral index $p$, the magnetic field and electron to proton equipartition ratios $\varepsilon_B$ and $\varepsilon_e$ do not change in time, d) the expansion is relativistic and the dynamics are given by $\Gamma \propto r^{-3/2}$ (adiabatic), d) the outflow is spherical, e) the observed radiation is characterized by the scaling relations along the line of sight. These assumptions, even if correct over some range, clearly would break down after some time. Estimates for the time needed to reach the non-relativistic expansion regime are typically $\lesssim$ month(s) ($^{143}$), or less if there is an initial radiative
regime $\Gamma \propto r^{-3}$. However, even when electron radiative times are shorter than the expansion time, it is unclear whether a regime $\Gamma \propto r^{-3}$ should occur, since it would require strong electron-proton coupling\(^{74}\). As far as sphericity, the standard model can be straightforwardly generalized to the case where the energy is assumed to be channeled initially into a solid angle $\Omega_j < 4\pi^{67}\). In this case\(^{117},^{118}\) a change occurs after $\Gamma$ drops below $\Omega_j^{-1/2}$, after which the side of the jet becomes observable, and soon thereafter one expects a faster decay of $\Gamma$ if the jet starts to expands sideways, leading to a decrease in the brightness. A calculation based on the sideways expansion, using the usual scaling laws for a single central line of sight\(^{118}\) leads then to a steepening of the light curve. Until recently, no evidence for a steepening could be found in afterglows over several months. E.g., in GRB 971214\(^{110}\), a snapshot standard model fit and the lack of a break in the late light curve could be, in principle, interpreted as evidence for lack of a jet, leading to an (isotropic) energy estimate of $10^{53.5}$ ergs. While such large energy outputs are possible in either NS-NS, NS-BH mergers\(^{71}\) or in hypernova/collapsar models\(^{91},^{108}\) using MHD extraction of the spin energy of a disrupted torus and/or a central fast spinning BH, it is worth stressing that what these snapshot fits constrain is only the energy per solid angle\(^{75}\). Also, the expectation of a break after some weeks or months (e.g., due to $\Gamma$ dropping either below a few, or below $\Omega_j^{-1/2}$) is based upon the simple impulsive (angle-independent delta or top-hat function) energy input approximation. The latter is useful, but departures from it would be natural, and certainly not surprising. In fact, as discussed below, tentative evidence for beaming in one oject has recently been reported\(^{58},^{33},^{16}\), but it is difficulty to ascertain, and could be masked by a number of commonly expected effects.

**§5. More Realistic (“Post-standard”) Afterglow Models**

Despite the success of the simple standard model, realistically one could expect any of several fairly natural departures from this to occur. One of these is that the emitting region, as seen by the observer, should resemble a ring\(^{147},^{95},^{124}\). This effect may, in fact, be important in giving rise to the radio scintillation pattern seen in several afterglows, since this requires the emitting source to be of small dimensions, which is aided if the emission is ring-like, e.g. in the example of GRB 970508\(^{148}\).
Another likely complication is that the afterglows should show a diversity in their decay rates, not only due to different $\beta$ but also from the possibility of a non-standard relation between the temporal decay index $\alpha$ and the spectral energy index $\beta$, different from equ. (4-3).

The most obvious departure from the simplest standard model occurs if the external medium is inhomogeneous: for instance, for $n_{\text{ext}} \propto r^{-d}$, the energy conservation condition is $\Gamma^2 r^{3-d} \sim \text{constant}$, which changes significantly the temporal decay rates\(^7\). Such a power law dependence is expected if the external medium is a wind, say from an evolved progenitor star as implied in the hypernova scenario (such winds are generally used to fit supernova remnant models). Another obvious non-standard effect, which is reasonable to expect, is departures from a simple impulsive injection approximation (i.e. from a delta or top hat function with a single value for $E_o$ and $\Gamma_o$). An example is if the mass and energy injected during the burst duration $t_w$ (say tens of seconds) obeys $M(>\Gamma) \propto \Gamma^{-s}$, $E(>\Gamma) \propto \Gamma^{1-s}$, i.e. more energy emitted with lower Lorentz factors at later times (but still shorter than the gamma-ray pulse duration). This would drastically change the temporal decay rate and extend the afterglow lifetime in the relativistic regime, providing a late “energy refreshment” to the blast wave on time scales comparable to the afterglow time scale\(^1\). These two cases lead to a decay rate

$$\Gamma \propto r^{-g} \propto \begin{cases} r^{-(3-d)/2} & ; n_{\text{ext}} \propto r^{-d}; \\ r^{-3/(2+s)} & ; E(>\Gamma) \propto \Gamma^{1-s}. \end{cases} \quad (5.1)$$

Expressions for the temporal decay index $\alpha(\beta, s, d)$ in $F_\nu \propto t^\alpha$ are given by\(^7,1\), which now depend also on $s$ and/or $d$ (and not just on $\beta$ as in the simple standard relation of equ.(4-3). The result is that the decay can be flatter (or steeper, depending on $s$ and $d$) than the simple standard $\alpha = (3/2)\beta$. A third non-standard effect, which is entirely natural, occurs when the energy and/or the bulk Lorentz factor injected are some function of the angle. A simple case is $E_o \propto \theta^{-j}$, $\Gamma_o \propto \theta^{-k}$ within a range of angles; this leads to the outflow at different angles shocking at different radii and its radiation arriving at the observed at different delayed times, and it has a marked effect on the time dependence of the afterglow\(^7\), with $\alpha = \alpha(\beta, j, k)$ flatter or steeper than the standard value, depending on $j, k$. Thus in general, a temporal decay index which is a function of more than one parameter

$$F_\nu \propto t^\alpha \nu^\beta , \quad \text{with } \alpha = \alpha(\beta, d, s, j, k, \cdots) , \quad (5.2)$$

is not surprising; what is more remarkable is that, in many cases, the simple standard relation (4-3) is sufficient to describe the gross overall behavior at late times.

Strong evidence for departures from the simple standard model is provided by, e.g., sharp rises or humps in the light curves followed by a renewed decay, as in GRB 970508 (\(^1\)). Detailed time-dependent model fits\(^9\) 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 (e.g. the electron index $p$, injection fraction $\zeta$ and/or $\epsilon_b$, $\epsilon_e$ change in time), and also
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indicate that dust absorption is needed to simultaneously fit the X-ray and optical fluxes. The effects of beaming (outflow within a limited range of solid angles) can be significant [97], but are coupled with other effects, and a careful analysis is needed to disentangle them.

One consequence of “post-standard” decay laws (e.g. from density inhomogeneities, non-uniform injection or anisotropic outflow) is that the transition to a steeper jet regime \( \Gamma < \theta^{-1}_j \) few can occur as late as six months to a year after the outburst, depending on details of the energy input. This transition is made more difficult to detect by the fact that, as numerical integration over angles of the ring-like emission [96] show, the transition is very gradual and the effects of sideways expansion effects are not so drastic as inferred [118] from the scaling laws along the central 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, arising at larger angles, arrives later and re-fills the steeper light curve. The inference (e.g. [110], [118]) that GRB 970508 and a few other bursts were isotropic due to the lack of an observable break is predicated entirely on the validity of the \textit{simplest standard} fireball assumption. Since these assumptions are drastic simplifications, and physically plausible generalizations lead to different conclusions, one can interpret the results of [110], [118] as arguments indicating that \textit{post-standard} features are, in fact, necessary in some objects.

§ 6. \textbf{Prompt multi-wavelength flashes, reverse shocks and jets}

Prompt optical, X-ray and GeV flashes from reverse and forward shocks, as well as from internal shocks, have been calculated in theoretical fireball shock models for a number of years [68], [69], [93], [70], [127], as have been jets (e.g. [64], [67], [69], and in more detail [117], [99], [97], [118]). Thus, while in recent years they were not explicitly part of the “simple standard” model, they are not strictly “post”-standard either, since they generally use the “standard” assumptions, and they have a long history. However, observational evidence for these effects were largely lacking, until the detection of a prompt (within 22 s) optical flash from GRB 990123 with ROTSE by [2], together with X-ray, optical and radio follow-ups citekul99,gal99,fru99,and99,cas99,hjo99. GRB 990123 is so far unique not only for its prompt optical detection, but also by the fact that if it were emitting isotropically, based on its redshift \( z = 1.6^{58}, 1 \) its energy would be the largest of any GRB so far, \( 4 \times 10^{54} \) ergs. It is, however, also the first (tentative) case in which there is evidence for jet-like emission [58], [33], [16]. An additional, uncommon feature is that a radio afterglow appeared after only one day, only to disappear the next [36], [58].

The prompt optical light curve of GRB 990123 decays initially as \( \propto t^{-2.5} \) to \( \propto t^{-1.6} \), much steeper than the typical \( \propto t^{-1.1} \) of previous optical afterglows detected after several hours. However, after about 10 minutes its decay rate moderates, and appears to join smoothly onto a slower decay rate \( \propto t^{-1.1} \) measured with large telescopes [36], [58], [33], [16] after hours and days. The prompt optical flash peaked at 9-th magnitude after 55 s [2], and in fact a 9-th magnitude prompt flash with a steeper
decay rate had been predicted more than two years ago\textsuperscript{70}, from the synchrotron radiation of the reverse shock in GRB afterglows at cosmological redshifts (see also \textsuperscript{127}). An optical flash contemporaneous with the $\gamma$-ray burst, coming from the reverse shock and with fluence corresponding to that magnitude, had also been predicted earlier\textsuperscript{68, 69}. An origin of the optical prompt flash in internal shocks\textsuperscript{70, 76} cannot be ruled out yet, but is less likely since the optical light curve and the $\gamma$-rays appear not to correlate well\textsuperscript{128, 36} (but the early optical light curve has only three points). The subsequent slower decay agrees with the predictions for the forward component of the external shock\textsuperscript{70, 128, 76}.

The evidence for a jet is possibly the most exciting, although must still be considered tentative. It is based on an apparent steepening of the light curve after about three days\textsuperscript{58, 33, 16}. This is harder to establish than the decay of the two previous earlier portions of the light curve, since by this time the flux has decreased to a level where the detector noise and the light of the host galaxy become important. However, after correcting for this, the r-band data appears to steepen significantly. (In the K-band, where the noise level is higher, a steepening is not obvious, but the issue should be settled with further Space Telescope observations). If real, this steepening is probably due to the transition between early relativistic expansion, when the light-cone is narrower than the jet opening, and the late expansion, when the light-cone has become wider than the jet, leading to a drop in the effective flux\textsuperscript{117, 58, 76, 118}.

A rough estimate leads to a jet opening angle of 3-5 degrees, which would reduce the total energy requirements to about $4 \times 10^{52}$ ergs. This is about two order of magnitude less than the binding energy of a few solar rest masses, which, even allowing for substantial inefficiencies, is compatible with currently favored scenarios (e.g.\textsuperscript{108, 62}) based on a stellar collapse or a compact binary merger.

§7. Location and Environmental Effects

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 a high density environment $n_0 > 10^3 - 10^5$ cm$^{-3}$. Most of the detected and well identified afterglows are inside the projected image of the host galaxy\textsuperscript{9}, and some also show evidence for a dense medium at least in front of the afterglow (\textsuperscript{85}). For a number of bursts there are constraints from the lack of a detectable, even faint, host galaxy\textsuperscript{130}, but at least for Beppo-SAX bursts (which is sensitive only to long bursts $t_b \gtrsim 20$ s) the success rate in finding candidate hosts is high.

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\textsuperscript{12}, leading to a burst presumably in a less dense environment. The fits\textsuperscript{151} to the observational data on GRB 970508 and GRB 971214 in fact suggest external densities in the range of $n_0 = 0.04-0.4$ cm$^{-3}$, which would be more typical of a tenuous interstellar medium. These could be within the volume of the galaxy, but for NS-NS on average one would expect as many GRB inside as outside. This is based on an estimate of the mean NS-NS merger time of $10^8$
years; other estimated merger times (e.g. $10^7$ years, $140$) 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 (12); see however 34). In at least one “snapshot” standard afterglow spectral fit for GRB 980329$^{116}$ the deduced external density is $n_0 \sim 10^3$ cm$^{-3}$. In some of the other detected afterglows there is other evidence for a relatively dense gaseous environments, as suggested, e.g. by evidence for dust$^{115}$ in GRB970508, the absence of an optical afterglow and presence of strong soft X-ray absorption$^{40,79}$ in GRB 970828, the lack an an optical afterglow in the (radio-detected) afterglow (136) of GRB980329, and spectral fits to the low energy portion of the X-ray afterglow of several bursts$^{85}$. The latter observations may be suggestive of hypernova models$^{91,34}$, involving the collapse of a massive star or its merger with a compact companion.

One important caveat is that all afterglows found so far are based on Beppo-SAX positions, which is sensitive only to long bursts $t_b > \sim 20$ s$^{46}$. This is significant, since it appears likely that NS-NS mergers lead$^{62}$ to short bursts with $t_b \lesssim 10$ s. To make sure that a population of short GRB afterglows is not being missed will probably need to await results from HETE$^{42}$ and from the planned Swift$^{134}$ mission, which is designed to accurately locate 300 GRB/yr.

An interesting case is the apparent coincidence of GRB 980425 with the unusual SN Ib/Ic 1998bw$^{35}$, which may represent a new class of SN$^{47,10}$. If true, this could imply that some or perhaps all GRB could be associated with SN Ib/Ic$^{145}$, differing only in their viewing angles relative to a very narrow jet. Alternatively, the GRB could be (e.g. $154$) a new subclass of GRB with lower energy $E_\gamma \sim 10^{48}(\Omega_j/4\pi)$ erg, only rarely observable, while 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. The difficulties are that it would require extreme collimations by factors $10^{-3} - 10^{-4}$, and the statistical association is so far not significant$^{51}$. However, two more GRB light curves may have been affected by an anomalous SNR (see, e.g. the review of $150$).

The environment in which a GRB occurs should also influence the nature of the afterglows in other ways. The blast wave and reverse shock that give rise to the X-rays, optical, etc occur over timescales proportional to $t_{\text{dec}} \propto n_{\text{ext}}^{-1/3}$ (equ.[3-2]) which is longer in lower density environments, so for the same energy the flux is lower, roughly $F_\nu \propto E_\nu n_{\text{ext}}^{1/2}$, contributing also to make afterglows in the intergalactic medium harder to detect. However, in addition to affecting broad-band fluxes, one may also expect specific spectral signatures from the external medium imprinted in the X-ray and optical continuum, such as atomic edges and lines$^{6,104,73}$. These may be used both to diagnose the chemical abundances and the ionization state (or local separation from the burst), as well as serving as potential alternative redshift indicators. (In addition, the outflowing ejecta itself may also contribute blue-shifted edge and line features, especially if metal-rich blobs or filaments are entrained in the flow from the disrupted progenitor debris$^{72}$, which could serve as diagnostic for the progenitor composition and outflow Lorentz factor). To distinguish between progenitors (§2), an interesting prediction$^{73}$; see also$^{37,13}$) is that the presence of a measurable Fe K-α X-ray emission line could be a diagnostic of a hypernova, since
in this case one may expect a massive envelope at a radius comparable to a light-
day where \( \tau_T \lesssim 1 \), capable of reprocessing the X-ray continuum by recombination
and fluorescence. Detailed radiative transfer calculations have been performed to
simulate the time-dependent X/UV line spectra of massive progenitor (hypernova)
remnants\(^{149}\), see Figure 6. Two groups\(^{107},\, 156\) have in fact recently reported the
possible detection of Fe emission lines in GRB 970508 and GRB 970828.

§8. Conclusions

Gamma Ray bursts provide perhaps the most direct method for studying strong
gravity phenomena near black holes, and with over 4,000 bursts detected, they would
represent the most abundant supply of high quality photon data on black holes. The
fireball shock model of gamma-ray bursts has proved quite robust in providing a
consistent overall interpretation of the major features of these objects at various
frequencies and over timescales ranging from the short initial burst to afterglows ex-
tending over many months. The standard internal shock scenario is able to reproduce
the properties of the \( \gamma \)-ray light curves, while external shocks involving a forward
blast wave and a reverse shock are successful in reproducing the afterglows observed
in X-rays, optical and radio. The “simple standard model” of afterglows, involving
four spectral slopes and three breaks is quite useful in understanding the ‘snapshot’
multiwavelength spectra of most afterglows. However, the effects associated with
a jet-like outflow and the possible differential beaming at various energies requires
further investigations, both theoretical and observational. Caution is required in
interpreting the observations on the basis of the simple standard model. For instance, more detailed numerical models, as opposed to the more common analytical scaling law models, show that the contributions of radiation from different angles and the gradual transition between different dynamical and radiative regimes lead to a considerable rounding-off of the spectral shoulders and light-curve slope changes. Time-dependent multiwavelength fits of some bursts also indicate that the parameters characterizing the shock physics change with time, and a non-standard relation between the spectral and temporal decay slope observed in several objects, e.g. GRB 990123, may provide evidence for “post-standard” effects in such bursts.

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, the time scales involved, and the nature and effects of beaming. However, even if we do not yet understand the details of the gamma-ray burst central engine, it is clear that these phenomena are among the most powerful transients in the Universe, and they could serve as powerful beacons for probing the high redshift ($z > 5$) universe. The modeling of the burst mechanism itself, as well as the resulting outflows and radiation, will continue to be a formidable challenge to theorists and to computational techniques. Nonetheless, the collective theoretical and observational understanding is vigorously advancing, and with dedicated new and planned observational missions under way, further significant progress may be expected in the near future.

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