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Theories of Gamma-Ray Bursts

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CONTENTS

Abstract

The gamma ray burst phenomenon is reviewed from a theoretical point of view, with emphasis on the fireball shock scenario of the prompt emission and the longer wavelenght afterglow. Recent progress and issues are discussed, including spectral-temporal evolution, localizations, jets, spectral lines, environmental and cosmological aspects, as well as some prospects for future experiments in both electromagnetic and non-electromagnetic channels.

Keywords: Gamma-ray bursts - gamma-rays - high energy - cosmology - neutrinos

1 Introduction

Gamma-Ray Bursts (GRB) were first detected in the late 1960's by military satellites monitoring for compliance with the nuclear test ban treaty. This became public information only several years later, with the publication of the results from the Vela satellites (Klebesadel, et al. , 1973), which were quickly confirmed by data from the Soviet Konus satellites (Mazets, et al. , 1974). Their nature and origin remained thereafter a mystery for more than two decades, largely due to the fact that during this period they remained detectable only for tens of seconds, almost exclusively at gamma-ray energies (e.g. Hurley, 1992), with occasional reports at X-ray energies (e.g. Murakami et al. 1988, Yoshida et al. , 1989, Connors & Hueter 1998). Various satellites continued to accumulate data on hundreds of GRB over the years, attracting an increasing amount of attention and leading to a large variety of theoretical models (e.g. Ruderman 1975, Liang 1989).

A new era in GRB research opened in 1991 with the launch of the Compton Gamma-Ray Observatory (CGRO), whose ground-breaking results have been summarized in Fishman & Meegan 1995. The most significant results came from the all-sky survey by the Burst and Transient Experiment (BATSE) on CGRO, which recorded over 2700 bursts, complemented by data from the OSSE, Comptel and EGRET experiments. BATSE's earliest and most dramatic result was that it showed that GRB were essentially isotropically distributed in the sky, with no significant dipole or quadrupole moments, suggesting a cosmological distribution (Meegan et al. 1992). The spectra were non-thermal, the number of photons per unit photon energy varying typically as a power-law $N(\epsilon) \propto \epsilon^{-\alpha}$, where $\alpha \sim 1$ at low energies changes to $\alpha \sim 2-3$ above a photon energy $\epsilon_0 \sim 0.1-1$ MeV (Band et al. , 1993). This spectral power law dependence was found to extend in several bursts up to at least GeV energies (Schneid et al. 1995, Hurley et al. 1994). The gamma-ray light curves show a time dependence ranging from a smooth, fast-rise and quasi-exponential decay, through curves with several peaks, to variable curves with many peaks, and substructure sometimes down to milliseconds (Fig. 1). The durations at MeV energies range from 10^{-3} s to about 10^3 s , with a well-defined bimodal distribution for bursts longer or shorter than $t_b \sim 2$ s (Kouveliotou et al. 1993). There is also an anti-correlation between spectral hardness and duration, the short one being harder, e.g. (Fishman & Meegan 1995). The pulse distribution is complex, and the time histories of the emission as a function of energy can provide clues for the geometry or physics of the emitting regions (e.g. Fenimore, Ramirez-Ruiz & Wu 1999, Beloborodov, Stern & Svensson 1998). The results from BATSE sharpened the debate on whether the GRB were of a galactic or extragalactic origin, e.g. (Lamb 1995, Paczyński 1995), but the accumulating evidence increasingly swung the balance in favor of the cosmological interpretation.

A decisive watershed was reached in 1997, when the Italian-Dutch satellite Beppo-SAX succeeded in obtaining the first high resolution x-ray images (Costa et al. 1997) of the fading afterglow of a burst, GRB 970228, which had been expected on theoretical grounds. This discovery was promptly followed by an increasing list of other burst detections by Beppo-SAX, at the approximate rate of 10 per year. These X-ray detections, after a 4-6 hour delay needed for data processing, led to arc-minute accuracy positions, which finally made possible the optical detection and the follow-up of the GRB afterglows at longer wavelengths (e.g. van Paradijs et al. 1997, Frail et al. 1997). This paved the way for the measurement of redshift distances, the identification of candidate host galaxies, and the confirmation that they were at cosmological distances (Metzger et al. 1997, Kulkarni et al. 1999b, etc.). Over 40 GRB afterglows have been located as of late 2001 in X-rays and optical, and more than a dozen in radio (Frail et al. 1999, Weiler 2002). Some afterglows have been followed over time scales of many months to over a year, and in the majority of cases (over 30) they have also resulted in the identification of the likely host galaxy (Bloom, Kulkarni & Djorgovski 2001, Djorgovski 2001). A recent review of the observations and phenomenology of GRB afterglows is in van Paradijs, Kouveliotou & Wijers 2000.

2 Gamma-ray burst phenomenology: the fireball shock scenario

At cosmological distances the observed GRB fluxes imply energies of $\lesssim 10^{54}$ erg, if the emission is isotropic (see however §4.2), and from causality this must be liberated inside regions whose size is $\lesssim 100$ kilometers on time scales $\lesssim$ seconds.

Independently of the nature and details of the progenitor and the trigger, such an intense, localized and brief explosion implies the formation of an $e^{\pm},\gamma$ fireball (Cavallo & Rees 1978). In the context of a cosmological model, the fireball would be expected to expand relativistically (Paczyński 1986, Goodman 1986, Paczyński 1990). This hypothesis is natural, since most of the spectral energy is observed at $\gtrsim 0.5$ MeV, so the optical depth against $\gamma\gamma\rightarrow e^{\pm}$ is huge, and the expansion follows from the highly super-Eddington value of the luminosity. Since many bursts emit a large fraction of their luminosity at photon energies $\epsilon_\gamma \gg 1$ MeV, the flow must somehow be able to avoid the process $\gamma\gamma\rightarrow e^{\pm}$ degrading the observed photons to just below 0.511 MeV. A highly relativistic expansion is, in fact, strongly supported by the fact that it provides a natural explanation for the observed photons with $\epsilon_\gamma \gg 0.5$ MeV (Fenimore, Epstein & Ho 1993, Harding & Baring 1994). This is because in this case the relative angle at which the photons collide must be less than the inverse of the bulk Lorentz factor γ^{-1} and the effective threshold energy for pair production is correspondingly reduced. Roughly, the Lorentz factor must satisfy

$$\gamma \gtrsim 10^2(\epsilon_\gamma/10\mathrm{GeV})^{1/2}(\epsilon_t/\mathrm{MeV})^{1/2} \ , \tag{1}$$

in order for photons with $\epsilon_\gamma \gtrsim 10$ GeV to escape annihilation against target photons with $\epsilon_t \sim 1$ MeV. (A more detailed calculation is in Lithwick & Sari 2001).

From general considerations (Shemi & Piran 1990), a relativistic outflow arising from an initial energy E_o imparted to a mass $M_o << E_0/c^2$ starting out from a radius r_l leads to an expansion, as the gas converts its internal energy into bulk kinetic energy. Initially the bulk Lorentz $\gamma \simeq r/r_l \propto r$, while the comoving temperature drops $\propto r^{-1}$. Clearly, γ cannot increase beyond $\gamma_{max} \sim \eta \sim E_o/M_o c^2$, which occurs at a saturation $r_s \gtrsim r_l \eta$, beyond which the flow continues to coast with $\gamma \sim \eta \sim$ constant. The simplicity of the original fireball picture, however, led to some serious difficulties. Among these are that the expansion of the fireball should lead to a conversion of most of its internal energy into kinetic energy of the entrained baryons, rather than into photon luminosity, hence it would be energetically very inefficient. Furthermore, it would produce a quasi-thermal photon spectrum, instead of the observed power-law spectra; and the typical time scales over which these photons escape is comparable to that during which the flow makes a transition to optical thinness (milliseconds), which could not explain the many events lasting much longer than that.

This efficiency, timescale and spectrum problems can be solved with the *fireball shock* model, in its external (Rees & Mészáros 1992) and internal (Rees & Mészáros 1994) versions. This is based on the fact that shocks are likely to occur in such an outflow, and if these occur after the fireball has become optically thin, these shocks would reconvert the kinetic energy of the baryons into nonthermal particle and photon energy.

External shocks (Mészáros & Rees 1993a) will occur, unavoidably, in any outflow of total energy E_o in an external medium of average particle density n_o at a radius and on a timescale

$$\begin{aligned} r_{dec} \sim & \quad 10^{17} E_{53}^{1/3} n_o^{-1/3} \eta_2^{-2/3} \text{ cm} , \\ t_{dec} \sim & \quad r_{dec}/(c\gamma^2) \sim 3 \times 10^2 E_{53}^{1/3} n_o^{-1/3} \eta_2^{-8/3} \text{ s} , \end{aligned} \tag{2}$$

where (in the impulsive, or thin shell approximation) the lab-frame energy of the swept-up external matter ($\gamma^2 m_p c^2$ per proton) equals the initial energy E_o of the fireball, and $\eta = \gamma = 10^2 \eta_2$ is the final bulk Lorentz factor of the ejecta.

The external shock synchrotron spectra (Mészáros & Rees 1993a, Katz 1994b) and combined synchrotron-IC spectra (Mészáros , Laguna & Rees 1993, Mészáros , Rees & Papathanassiou 1994) reproduce in a general manner the observed gamma-ray spectral properties, as do the predicted spectral-temporal correlations (Sari, Narayan & Piran 1996, Panaitescu & Mészáros 1998b, Dermer, Böttcher & Chiang 1999, Böttcher & Dermer 2000; c.f. Liang et al. 1999). (However, internal shocks present an alternative for the brief burst of gamma-ray emission, motivated by variability issues, see below). External shocks also serve as the model of choice for the afterglow radiation (§3). The typical observer-frame dynamic time of the shock is $t_{dec} \sim r_{dec}/c\gamma^2 \sim$ 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 this is not widely favored for reproducing highly variable profiles. (Sari & Piran 1998; c.f. Dermer & Mitman 1999). They could, however, reproduce bursts with several peaks (Panaitescu & Mészáros 1998a) and may therefore be applicable to the class of long, smooth bursts.

Internal shocks (Rees & Mészáros 1994) address another problem, posed by some of the rapidly variable γ-ray light curves, which for total durations of tens to hundreds of seconds are, sometimes, endowed with variability down to milliseconds or less (Fishman & Meegan 1995). One ingredient in solving this problem is to postulate a "central engine" (Fenimore et al. 1993) which ejects energy at a variable rate. This could be, e.g. magnetic flares in a transient accretion disk around a central compact object resulting from the disruption of a merging compact binary (Narayan, Paczyński & Piran 1992). By itself, such a variable central engine is however not enough to explain the variable light curves, since a relativistic outflow is inevitable, and even if intermittent, this outflow will be on average optically thick to Compton scattering out to very large radii, leading to a smoothing-out of the light curve. This difficulty, however, is solved with the introduction of the internal shock model (Rees & Mészáros 1994), in which the time-varying outflow from the central engine leads to successive shells ejected with different Lorentz factors. Multiple shocks form as faster shells overtake slower ones, and the crucial point is that for a range of plausible parameters, this occurs above the Compton photosphere. These shocks are called internal because they arise from the flow interacting with itself, rather than with the external environment.

One can model the central engine outflow as a wind of duration t_w, whose average dynamics is similar to that of the impulsive outflows described previously, with an average lab-frame luminosity $L_o = E_o/t_w$ and average mass outflow $\dot{M}_o$, and mean saturation Lorentz factor $\gamma \sim \eta = L_o/\dot{M}_o c^2$. Significant variations of order $\Delta\gamma \sim \gamma \sim \eta$ occurring over timescales $t_{var} \ll t_w$ will lead then to internal shocks (Rees & Mészáros 1994) at radii r_{dis} above the photosphere r_{phot},

$$\begin{aligned} r_{dis} \sim & \quad c t_{var} \eta^2 \sim 3 \times 10^{14} t_{var} \eta_2^2 \text{ cm}, \\ r_{phot} \sim & \quad \dot{M} \sigma_T / (4\pi m_p c \eta^2) \sim 10^{11} L_{50} \eta_2^{-3} \text{ cm}. \end{aligned} \tag{3}$$

The above assumes the photosphere to be above the saturation radius $r_s \simeq r_o \eta$, so that most of the energy comes out in the shocks, rather than in the photospheric quasi-thermal component (such photospheric effects are discussed in Mészáros & Rees 2000b). For shocks above the photosphere, large observable γ-ray variations are possible on timescales $t_{var} \gtrsim t_{var,min} \sim 10^{-3}(M_c/M_\odot)^{3/2}$, for an outflow originating from a central object of mass M_c at radii $\gtrsim r_o \sim c t_{var,min}/2\pi$. The internal shock model was specifically designed to allow an arbitrarily complicated light curve (Rees & Mészáros 1994) on timescales down to ms, the optically thin shocks producing the required non-thermal spectrum. Numerical calculations (Kobayashi, Piran & Sari 1999, Daigne & Mochkovitch 2000, Spada, Panaitescu & Mészáros 2000) confirm that the light curves can indeed be as complicated as observed by BATSE in extreme cases. (By contrast, in external shocks the variations are expected to be smoothed out by relativistic time delays, e.g. Sari & Piran 1998, at most a few peaks being possible, e.g. Panaitescu & Mészáros 1998a. An alternative view invoking large variability from blobs in external shocks is discussed by Dermer & Mitman 1999). The observed power density spectra of GRB light curves (Beloborodov, Stern & Svensson 2000) provide an additional constraint on the dynamics of the shell ejection by the central engine and the efficiency of internal shocks (Spada, Panaitescu & Mészáros 2000, Guetta, Spada & Waxman 2001).

When internal shocks occur, these are generally expected to be followed (Mészáros & Rees 1994, Mészáros & Rees 1997a) by an external shock, a sequential combination sometimes referred to as the internal-external shock scenario (Piran & Sari 1998). The GRB external shocks, similarly to what is observed in supernova remnants, consist of a forward shock or blast wave moving into the external medium ahead of the ejecta, and a reverse shock moving back into the ejecta as the latter is decelerated by the inertia the external medium. The internal shocks would consist of forward and reverse shocks of a more symmetrical nature. As in interplanetary shocks studied with spacecraft probes, the internal and external shocks in GRB are tenuous, and expected to be collisionless, i.e. mediated by chaotic electric and magnetic fields. The minimum random Lorentz factor of protons going through the shocks should be comparable to the relative bulk Lorentz factor, while that of the electrons may exceed this by a factor of up to the ratio of the proton to the electron mass. The energy of the particles can be further boosted by diffusive shock acceleration (Blandford & Eichler 1987) as they scatter repeatedly across the shock interface, acquiring a power law distribution $N(\gamma_e) \propto \gamma_e^{-p}$, where $p \sim 2-3$. In the presence of turbulent magnetic fields built up behind the shocks, the electrons produce a synchrotron power-law radiation spectrum (Mészáros & Rees 1993a, Rees & Mészáros 1994) similar to that observed (Band et al. , 1993), while the inverse Compton (IC) scattering of these synchrotron photons extends the spectrum into the GeV range (Mészáros , Rees & Papathanassiou 1994). Comparisons of a synchrotron hypothesis for the MeV radiation with data have been made by, e.g. Tavani 1996, Preece et al. 2000, Eichler & Levinson 2000, Mészáros & Rees 2000b, Medvedev 2000, Panaitescu & Mészáros 2000, Lloyd & Petrosian 2001a. The effects of pair production and inverse Compton on the prompt spectra are discussed in §4.4.

It is worth stressing that the fireball shock scenario, whether internal or external, is fairly generic: it is largely independent of the details of the progenitor. Although it is somewhat geometry dependent, the central engine generally lies enshrouded and out of view inside the optically thick outflow. Even after the latter becomes optically thin, the progenitor's remnant emission should be practically undetectable, compared to the emission of the fireball shock which is its main manifestation (see, however, §7).

3 Blast Wave Model of GRB afterglows

The external shock becomes important when the inertia of the swept up external matter leads to an appreciable slowing down of the ejecta. As the fireball continues to plow ahead, it sweeps up an increasing amount of external matter, made up of interstellar gas plus possibly gas which was previously ejected by the progenitor star. As the external shock builds up, for high radiative efficiency its bolometric luminosity rises approximately as $L \propto t^2$. This follows from equating in the contact discontinuity frame the kinetic flux $L/4\pi r^2$ to the external ram pressure $\rho_{ext}\gamma^2$ during the initial phase while $\gamma \sim$ constant, $r \propto t$ (Rees & Mészáros 1992; see also Sari 1998). After peaking, or plateauing in the thick shell limit, as the Lorentz factor decreases one expects a gradual dimming $L \propto t^{-1+q}$ (from energy conservation $L \propto E/t$ under adiabatic conditions, q takes into account radiative effects or bolometric corrections). At the deceleration radius (2) the fireball energy and the bulk Lorentz factor decrease by a factor ~ 2 over a timescale $t_{dec} \sim r_{dec}/(c\gamma^2)$, and thereafter the bulk Lorentz factor decreases as a power law in radius,

$$\gamma \propto r^{-g} \propto t^{-g/(1+2g)} \ , \ r \propto t^{1/(1+2g)}, \tag{4}$$

with $g = (3, 3/2)$ for the radiative (adiabatic) regime, in which $\rho r^3\gamma \sim$ constant ($\rho r^3\gamma^2 \sim$ constant). At late times, a similarity solution (Blandford & McKee 1976a, Blandford & McKee 1976b) solution with $g = 7/2$ may be reached. The spectrum of radiation is likely to be due to synchrotron radiation, whose peak frequency in the observer frame is $\nu_m \propto \gamma B' \gamma_e^2$, and both the comoving field B' and the minimum electron Lorentz factor $\gamma_{e,min}$ are likely to be proportional to γ (Mészáros & Rees 1993a). This implies that as γ decreases, so will ν_m, and the radiation will move to longer wavelengths. Consequences of this are the expectation that the burst would leave a radio remnant (Paczyński & Rhoads 1993) after some weeks, and before that an optical (Katz 1994b) transient.

The first self-consistent afterglow calculations (Mészáros & Rees 1997a) took into account both the dynamical evolution and its interplay with the relativistic particle acceleration and a specific relativistically beamed radiation mechanism resulted in quantitative predictions for the entire spectral evolution, going through the X-ray, optical and radio range. For a spherical fireball advancing into an approximately smooth external environment, the bulk Lorentz factor decreases as in inverse power of the time (asymptotically $t^{-3/8}$ in the adiabatic limit), and the accelerated electron minimum random Lorentz factor and the turbulent magnetic field also decrease as inverse power laws in time. The synchrotron peak energy corresponding to the time-dependent minimum Lorentz factor and magnetic field then move to softer energies as $t^{-3/2}$. These can be generalized in a straightforward manner when in the radiative regime, or in presence of density gradients, etc.. The radio spectrum is initially expected to be self-absorbed, and becomes optically thin after a few days. For times beyond about one hour the dominant radiation is from the forward shock, for which the flux at a given frequency and the synchrotron peak frequency decay as (Mészáros & Rees 1997a)

$$F_\nu \propto t^{-(3/2)\beta} \quad , \quad \nu_m \propto t^{-3/2} \ , \tag{5}$$

as long as the expansion is relativistic. This is referred to as the "standard" (adiabatic) model, where $g = 3/2$ in equ. [4] and β is the photon spectral energy slope ($F_\nu \propto \nu^{-\beta}$). The transition to the non-relativistic regime has been discussed, e.g. by Wijers, Rees & Mészáros 1997, Dai & Lu 1999, Livio & Waxman 2000. More generally (Mészáros & Rees 1999) the relativistic forward shock flux and frequency peak are given by $F_\nu \propto t^{[3-2g(1+2\beta)]/(1+2g)}$ and $\nu_m \propto t^{-4g/(1+2g)}$. (A reverse shock component is also expected (Mészáros & Rees 1993b, Mészáros & Rees 1997a), with high initial optical brightness but much faster decay rate than the forward shock, see §4.3). It is remarkable, however, that the simple "standard" model where reverse shock effects are ignored is a good approximation for modeling observations starting a few hours after the trigger, as during 1997-1998.

The predictions of the fireball shock afterglow model (Mészáros & Rees 1997a) were made in advance of the first X-ray detections by Beppo-SAX (Costa et al. 1997) allowing subsequent follow-ups (van Paradijs et al. 1997, Metzger et al. 1997, Frail et al. 1999) over different wavelengths, which showed a good agreement with the standard model, e.g. (Vietri 1997a, Wijers, Rees & Mészáros 1997, Tavani 1997, Waxman 1997a, Reichart 1997) (Fig. 2). The comparison of increasingly sophisticated versions of this theoretical model (e.g. Sari, Piran & Narayan 1998, Wijers & Galama 1999, Piran 1999, Dermer, Böttcher & Chiang 2000, Granot, Piran & Sari 2000a) against an increasingly detailed array of observations (e.g. as summarized in van Paradijs, Kouveliotou & Wijers 2000) has provided confirmation of this generic fireball shock model of GRB afterglows.

A snapshot spectrum of the standard model at any given time consists of a three-segment power law with two breaks. At low frequencies there is a steeply rising synchrotron self-absorbed spectrum up to a self-absorption break ν_a, followed by a $+1/3$ energy index spectrum up to the synchrotron break ν_m corresponding to the minimum energy γ_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 γ_e^{-p} is the electron energy distribution above γ_m). A fourth segment is expected at energies above where the electron cooling time becomes short compared to the expansion time, with a spectral slope $-p/2$ above that, with a corresponding "cooling" break ν_b (Mészáros , Rees & Wijers 1998, Sari, Piran & Narayan 1998). The observations (e.g. van Paradijs, Kouveliotou & Wijers 2000) are compatible with an electron spectral index $p \sim 2.2-2.5$ (Gallant et al. 1999), which is typical of shock acceleration, e.g. Waxman 1997a, Sari, Piran & Narayan 1998, Wijers & Galama 1999, 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. Snapshot spectra have been deduced by extrapolating measurements at different wavelengths and times, and assuming spherical symmetry and using the model time dependences (Waxman 1997b, Wijers & Galama 1999), fits were obtained for the different physical parameters of the burst and environment, e.g. the total energy E, the magnetic and electron-proton coupling parameters ϵ_B and ϵ_e and the external density n_o (see right panel of Figure 3). These lead to typical values $n_o \sim 10^{-2} - 10$ cm^{-3}, $\epsilon_B \sim 10^{-2}$, $\epsilon_e \sim 0.1 - 0.5$ and $E \sim 10^{52} - 10^{54}$ ergs (if spherical; but see §4.2).

4 Standard Model Developments and Issues

The standard afterglow model is based on the following approximations: a) spherical outflow; b) a homogeneous external medium $n \sim n_o$; c) highly relativistic expansion in the adiabatic approximation; d) an impulsive energy input E_o and a single $\gamma_o = \eta = E_o/M_o c^2$; e) line of sight scaling relations assumed valid for the entire visible hemisphere; f) time-independent shock acceleration parameters p, ε_B, ε_e (electron energy index, magnetic to proton and electron to proton energy ratios); g) only the forward shock radiation is included. The significant success of this model in explaining many of the observations in the first years after GRB

970228 indicates that these approximations are robust, at least in a broad sense and over a range of timescales. However, they are clearly simplifications, and are expected to be appropriate only within certain limits.

4.1 Density, Angle and Time-dependent Injection

Departures from the simplest standard model occur, e.g. if the external medium is inhomogeneous. For instance, for $n \propto r^{-d}$, the energy conservation condition is $\gamma^2 r^{3-d} \sim$ constant, which changes significantly the temporal decay rates (Mészáros , Rees & Wijers 1998). Such a power law dependence is expected if the external medium is a wind, say from an evolved progenitor star, and light curve to some bursts fit better with such a hypothesis (Chevalier & Li 2000), whereas in many objects a homogeneous medium seems a better fit (Frail et al. 2001, Panaitescu & Kumar 2001b) (for a critical discussion see Li & Chevalier 2001). Another obvious non-standard effect is departures from a simple impulsive injection approximation (i.e. an injection which is not a delta or a top hat function with a single value for E_o and γ_o in time). 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 (refreshed shocks). 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 (Rees & Mészáros 1998, Kumar & Piran 2000, Dai & Lu 2000, Sari & Mészáros 2000).

These examples lead to non-standard decay rates

$$\gamma \propto r^{-g} \propto \begin{cases} r^{-(3-d)/2} & ; n \propto r^{-d}; \\ r^{-(3-d)/(1+s)} & ; E(>\gamma) \propto \gamma^{1-s} \ , \ n \propto r^{-d} \ . \end{cases} \tag{6}$$

An additional complication occurs if the outflow has a transverse (θ- dependent) gradient in its properties such as energy per solid angle or Lorentz factor, e.g. as some power law $\theta^{-j},\ \theta^{-k}$ (Mészáros , Rees & Wijers 1998). Expressions for the temporal decay index $\alpha(\beta, s, d, j, k, ..)$ in $F_\nu \propto t^\alpha$ are given by (Mészáros , Rees & Wijers 1998, Sari & Mészáros 2000), which now depend also on s, d, j, k, etc. (and not just on β as in the standard relation of equ.(5). The result is that the decay can be flatter (or steeper, depending on s, d, etc) than the simple standard $\alpha = (3/2)\beta$,

$$F_\nu \propto t^\alpha \nu^\beta \quad \text{, with} \quad \alpha = \alpha(\beta, d, s, j, k, \cdots) \ . \tag{7}$$

Thus, a diversity of behaviors is not unexpected. What is more remarkable is that, in many cases, the simple standard relation (5) 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 (Pedersen et al. 1998, Piro et al. 1998a). Detailed time-dependent model fits (Panaitescu, Mészáros & Rees 1998) to the X-ray, optical and radio light curves of GRB 970228 and GRB 970508 indicate that, in order to explain the humps, a *non-uniform* injection is required. Other ways to get a lightcurve bump after $\sim$ days is through microlensing (Garnavich, Loeb & Stanek 2000), late injection (Zhang & Mészáros 2001a), or inverse Compton effects (Zhang & Mészáros 2001b, Harrison et al. 2001).

4.2 Jets and limb-brightening effects

The spherical assumption is valid even when considering a relativistic outflow collimated within some jet of solid angle $\Omega_j < 4\pi$, provided the observer line of sight is inside this angle, and $\gamma \gtrsim \Omega_j^{-1/2}$ (Mészáros , Laguna & Rees 1993), so the light-cone is inside the jet boundary (causally disconnected) and the observer is unaware of what is outside the jet. As deceleration proceeds and the Lorentz factor drops below this value (in $\sim$ days), a change is expected in the dynamics and the light curves (Rhoads 1997, Rhoads 1999). The first effect after $\gamma < \Omega_j^{-1/2}$ is that, whereas before the effective transverse emitting area increased as $(r_\parallel/\gamma)^2 \propto t^2\gamma^2$, thereafter it grows more slowly as $r_\parallel \Omega_j^{-1/2} \propto t^2\gamma^4$, i.e. one expects a faster decay by $\gamma^2 \propto t^{-3/4}$ (Mészáros & Rees 1999), which in fact is the magnitude of the break seen, e.g. in GRB 990123 (Kulkarni et al. 1999, Fruchter A et al. 1999, Castro-Tirado et al. 1999). Soon after this sideways expansion of the jet would lead to an even steeper decay, $\propto t^{-p}$ (Rhoads 1997, Panaitescu & Mészáros 1998d), possibly complicated by jet anisotropy (Dai & Gou 2001). Variable optical linear polarization can also be expected (Sari 1999, Ghisellini & Lazzati 1999). An example of the lightcurve break and a snapshot fit is shown in Fig. 3. Numerical simulations of jet development (e.g. Granot et al. 2000b) are complicated due to the need for both high dimensionality and relativistic effects, and comparison between such models and phenomenological fits (Frail et al. 2001, Panaitescu & Kumar 2001a, Panaitescu & Kumar 2001b) still requires caution.

If the burst energy were emitted isotropically, the energy requirements spread over many orders of magnitude, $E_{\gamma,iso} \sim 10^{51} - 10^{54}$ erg (Kulkarni et al. 1999b). However, taking into account the evidence for jets (Panaitescu & Kumar 2001a, Panaitescu & Kumar 2001b, Frail et al. 2001) the inferred spread in the total γ-ray energy is reduced to one order of magnitude, around a much less demanding mean value of $E_{\gamma,tot} \sim 8 \times 10^{50}$ erg. This is not significantly larger than the kinetic energies in core-collapse supernovae, although it differs from the latter by being concentrated in the gamma-ray range, and by being substantially more collimated than supernovae (see, however, Höfflich, Wheeler & Wang 1999). Radiative inefficiencies and the additional energy which must be associated with the proton and magnetic field components increase this value, but it would still be well within the theoretical energetics $\lesssim 10^{53.5} - 10^{54}$ erg achievable in *either* NS-NS, NS-BH mergers (Mészáros & Rees 1997b) or in hypernova/collapsar models (Paczyński 1998, Popham, Woosley & Fryer 1999) using MHD extraction of the spin energy of a disrupted torus and/or a central fast spinning BH. It is worth stressing that the presence of jets does not invalidate the usefulness of snapshot spectral fits, since these constrain only the *energy per solid angle* (Mészáros , Rees & Wijers 1999).

An interesting property, which arises even in spherical outflows, is that the effective emitting region seen by the observer resembles a ring (Waxman 1997b, Goodman 1997, Panaitescu & Mészáros 1998b, Sari 1998, Granot, Piran & Sari 1999a). This effect is thought to be implicated in giving rise to the radio diffractive scintillation pattern seen in several afterglows, since this requires the emitting source to be of small dimensions (the ring width), e.g. in GRB 970508 (Waxman, Kulkarni & Frail 1998). This provided an important observational check, giving a direct confirmation of the relativistic source expansion and a direct determination of the (expected) source size (Waxman, Frail & Kulkarni 1998, Katz, Piran & Sari 1998).

4.3 Prompt Flashes and Reverse Shocks

A remarkable discovery was the observation (Akerlof et al. 1999) of a prompt and extremely bright ($m_v \sim 9$) optical flash in the burst GRB 990123, 15 seconds after the GRB started (and while it was still going on). A prompt multi-wavelength flash, contemporaneous with the γ-ray emission and reaching such optical magnitude levels is an expected consequence of the reverse component of external shocks (Mészáros & Rees 1993b). The prompt optical flash of 990123 is generally interpreted (Sari & Piran 1999, Mészáros & Rees 1999) as the radiation from a reverse (external) shock, although a prompt optical flash could be expected either from an internal shock or from the reverse external shock (Mészáros & Rees 1997a). The decay rate of the optical flux from reverse shocks is much faster (and that of internal shocks is faster still) than that of forward shocks, so the emission of the latter dominate after tens of minutes. Such bright prompt flashes, however, appear to be rare, since they have not so far been detected from other bursts, either using upgraded versions of the original ROTSE camera (Kehoe et al. 2001) or other similar systems (Park et al. 2001, Boer 2001). This is further discussed by Soderberg & Ramirez-Ruiz 2001.

4.4 Radiation Processes, Efficiences and Pairs

Pair-production due to $\gamma\gamma$ interactions among intra-shock photons satisfying $\epsilon_1\epsilon_2 \gtrsim m_e c^2$ can be important when the compactness parameter $\ell \sim n_\pm \sigma_T \Delta R_{com} > 1$, where ΔR_{com} is the comoving shock width and $n_\pm \propto L_\gamma$. This can affect the spectrum of external shocks (Mészáros , Rees & Papathanassiou 1994, Baring 2000, Lithwick & Sari 2001) above GeV energies. An external shock occurring beyond a preceding internal shock (Mészáros & Rees 1994) is a possible model for the EGRET GeV observations (e.g. Hurley et al. 1994) of 1-20 GeV photons in several GRBs. Internal shocks, occurring at smaller radii (equation [3]) than external shocks (equation [2]) will have larger compactness parameters, and pair formation can be more important (Rees & Mészáros 1994, Papathanassiou & Mészáros 1996, Pilla & Loeb 1998). For close-in shocks and high luminosities, pair-breakdown could lead to a self-regulating moderate pair optical thickness and subrelativistic pair temperature leading to a comptonized spectrum (Ghisellini & Celotti 1999). Comptonization in a generic context has also been advocated by, e.g., Crider et al 1997, Liang et al. 1999.

Low energy γ-ray spectral indices which appear steeper than predicted by a synchrotron mechanism has been reported by, e.g. Preece et al. 2000. Possible explanations include a fireball photospheric component, photospheric bulk and pair-breakdown comptonization (Mészáros & Rees 2000b and references therein). Other possibilities are synchrotron self-absorption in the X-ray (Granot, Piran & Sari 1999b) or in the optical range upscattered to X-rays (Panaitescu & Mészáros 2000), low-pitch angle scattering (Medvedev 2000), or time-dependent acceleration and radiation (Lloyd-Ronning & Petrosian 2001b), where the latter also point out that low-pitch angle acceleration of electrons in a strong magnetic field may be preferred and can explain high energy indices steeper than predicted by an isotropic electron distribution.

A related problem is that of the radiative efficiency. For internal shocks, this is estimated to be moderate in the bolometric sense (10-30%), higher values being obtained if the shells have widely differing Lorentz factors (Spada, Panaitescu & Mészáros 2000, Beloborodov 2000, Kobayashi & Sari 2001). The total efficiency is substantially affected by inverse Compton losses (Papathanassiou & Mészáros 1996, Pilla & Loeb 1998, Ghisellini, Celotti & Lazzati 2000). The efficiency for emitting in the BATSE range is typically low $\sim 2-5\%$, both when the MeV break is due to synchrotron (Kumar 1999, Spada, Panaitescu & Mészáros 2000, Guetta, Spada & Waxman 2001) and when it is due to inverse Compton (Panaitescu & Mészáros 2000). This inefficiency is less of a concern when a jet is present (e.g. with typical values $\theta_{jet} \sim 3$ degrees and required total energies $E_0 \sim 10^{50}-10^{51}$ erg, e.g. Frail et al. 2001, Panaitescu & Kumar 2001a).

Pair formation can also arise when γ-rays back-scattered by the external medium interact with the original γ-rays (Dermer & Böttcher 2000). This may lead to a cascade and acceleration of the pairs (Thompson & Madau 2000, Madau & Thompson 2000, Madau, Blandford & Rees 2000). For a model where γ-rays are produced in internal shocks, analytical estimates (Mészáros , Ramirez-Ruiz & Rees 2001) indicate that even for modest external densities a pair cloud forms ahead of the fireball ejecta, which can accelerate to Lorentz factors $\gamma_\pm \lesssim 30-50$. These pairs produce a radio signal when they are swept-up by the ejecta, and when the pair-enriched ejecta is in turn decelerated by the external medium, its radiative efficiency is increased. The afterglow reverse shock shares the same energy among a larger number of leptons so that its spectrum is softened towards the IR (Mészáros , Ramirez-Ruiz & Rees 2001; see also Beloborodov 2001), compared of the optical/UV flash expected in the absence of pairs; this may contribute to the rarity of prompt optical detections.

Inverse Compton scattering (IC) can be an important energy loss mechanism in external shocks (Mészáros , Laguna & Rees 1993) and is the likeliest mechanism for producing GeV radiation (Mészáros , Rees & Papathanassiou 1994, Mészáros & Rees 1994). Its effects on afterglows were considered by (Waxman 1997b), and observational manifestations in afterglows were investigated more carefully by Panaitescu & Kumar 2000 and Sari & Esin 2001. This mechanism may be responsible for X-ray bumps after days in some afterglow light curves (Zhang & Mészáros 2001b, Harrison et al. 2001), alternative possibilities being microlensing (Garnavich, Loeb & Stanek 2000) or late injection (Zhang & Mészáros 2001a).

4.5 Shock Physics

The non-thermal spectrum in the fireball shock model is based on assuming that Fermi acceleration (e.g. Blandford & Eichler 1987) accelerates electrons to highly relativistic energies following a power law $N(\gamma_e) \propto \gamma_e^{-p}$, with $p \sim 2 - 2.5$ (Gallant et al. 1999). To get reasonable efficiencies, the accelerated electron to total energy ratio $\epsilon_e \lesssim 1$ must not be far below unity (Mészáros & Rees 1993a, Kumar 2000), while the magnetic to total energy ratio $\epsilon_b < 1$ depends on whether the synchrotron or the IC peak represents the observed MeV break (Papathanassiou & Mészáros 1996). The radiative efficiency and the electron power law minimum Lorentz factor also depends on the fraction $\zeta < 1$ of swept-up electrons injected into the acceleration process (Bykov & Mészáros 1996, Daigne & Mochkovitch 2000). While many afterglow snapshot or multi-epoch fits can be done with time-independent values of the shock parameters $\epsilon_b,\ \epsilon_e,\ p$ (e.g. Wijers & Galama 1999), in some cases the fits indicate that the shock physics may be a function of the shock strength. For instance p, $\epsilon_b,\ \epsilon_e$ or the electron injection fraction ζ may change in time (Panaitescu, Mészáros & Rees 1998, Panaitescu & Kumar 2001a). While these are, in a sense, time-averaged shock properties, specifically time-dependent effects would be expected to affect the electron energy distribution and photon spectral slopes, leading to time-integrated observed spectra which could differ from those in the simple time-averaged picture (Medvedev 2000, Lloyd & Petrosian 2001a). The back-reaction of protons accelerated in the same shocks (§8) and magnetic fields may also be important, as in supernova remnants (e.g. Ellison, Berezhko & Baring 2000). Turbulence may be important for the electron-proton energy exchange (Bykov & Mészáros 1996, Schlickeiser & Dermer 2000), while reactions leading to neutrons and viceversa (Rachen & Mészáros 1998) can influence the escaping proton spectrum.

4.6 Other Effects

Two potentially interesting developments are the possibility of a relationship between the differential time lags for the arrival of the GRB pulses at different energies and the luminosity (Norris, Marani & Bonnell 2000), and between the degree of variability or spikyness of the gamma-ray light curve and the luminosity (Fenimore & Ramirez-Ruiz 2001, Reichart et al. 2000). Attempts at modeling the spectral lags have relied on observer-angle dependences of the Doppler boost (Nakamura 2000, Salmonson 2001b). In these correlations the isotropic equivalent luminosity was used, in the absence of jet signatures, and they must be considered tentative for now. However, if confirmed, they could be invaluable for independently estimating GRB redshifts.

5 Some Alternative Models

While space limitations preclude a comprehensive review of many alternative models, a partial list includes precessing jets from pulsars (Blackman, Yi & Field 1996; c.f. Fargion 1999); jets (Cen 1997) or cannonballs from supernovae (Dado, Dar & de Rújula 2001); magnetar bubble collapse (Gnedin & Kiikov 2000); neutron star collapse to a strange star (Cheng & Dai 1996), or collapse to a black hole caused by accretion (Vietri et al. 2000) or by capture of a primordial black hole (Derishev, Kocharovsky & Kocharovsky 1999c); supermassive black hole formation (Fuller & Shi 1998), and evaporating black holes (Halzen, Zas, McGibbon & Weekes 1991, Belyanin, Kocharovsky & Kocharovsky 1996, Cline & Hong 1996).

6 Progenitors

The currently most widely held view is that GRBs arise in a very small fraction of stars ($\sim 10^{-6}$, or somewhat larger depending on beaming) which undergo a catastrophic energy release event toward the end of their evolution. One class of candidates involves massive stars whose core collapses (Woosley 1993, Paczyński 1998, Fryer, Woosley, Hartmann 1999), probably in the course of merging with a companion, often referred to as hypernovae or collapsars. Another class of candidates consists of neutron star (NS) binaries or neutron star-black hole (BH) binaries (Paczyński 1986, Goodman 1986, Eichler, et al. 1989, Mészáros & Rees 1997b), which lose orbital angular momentum by gravitational wave radiation and undergo a merger. Both of these progenitor types are expected to have as an end result the formation of a few solar mass black hole, surrounded by a temporary debris torus whose accretion can provide a sudden release of gravitational energy, with similar total energies, sufficient to power a burst. An important point is that the overall energetics from these various progenitors do not differ by more than about one order of magnitude (Mészáros , Rees & Wijers 1999). The duration of the burst in this model is related to the fall-back time of matter to form an accretion torus around the BH (Fryer, Woosley, Hartmann 1999, Popham, Woosley &

Fryer 1999) or the accretion time of the torus (Narayan, Piran & Kumar 2001). Other possible alternatives include, e.g. the tidal disruption of compact stars by $10^5 - 10^6 M_\odot$ black holes (Blandford, Ostriker & Mészáros 2001), and the formation from a stellar collapse of a fast-rotating ultra-high magnetic field neutron star (Usov 1994, Thompson 1994, Spruit 1999, Wheeler, et al. 2000, Ruderman 2000).

Two large reservoirs of energy are available in such BH systems: the binding energy of the orbiting debris (Woosley 1993) and the spin energy of the black hole (Mészáros & Rees 1997b). 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 question is how to extract this energy.

One energy extraction mechanisms is the $\nu\bar{\nu} \to e^+e^-$ process (Eichler, et al. 1989), 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. Estimates suggest a fireball of $\lesssim 10^{51}$ erg (Ruffert et al. 1997, Fryer & Woosley 1998, MacFadyen & Woosley 1999), or in the collapsar case (Popham, Woosley & Fryer 1999) possibly $10^{52.3}$ ergs (c.f. higher estimates in the NS-NS case by (Salmonson, Wilson & Matthews 2001a)). If the fireball is collimated into a solid angle Ω_j then of course the apparent "isotropized" energy would be larger by a factor $(4\pi/\Omega_j)$. Using the recent total energy estimates (corrected for jet collimation) $E_{\gamma,tot} \sim 10^{51}$ erg deduced from jet data by Frail et al. 2001 and Panaitescu & Kumar 2001b, neutrino annihilation would appear to be a likelier possibility than it did before these analyses. An alternative, and more efficient mechanism for tapping the energy of the torus may be through dissipation of magnetic fields generated by the differential rotation in the torus (Paczyński 1991, Narayan, Paczyński & Piran 1992, Mészáros & Rees 1997b, Katz 1997). Even before the BH forms, a NS-NS merging system might lead to winding up of the fields and dissipation in the last stages before the merger (Mészáros & Rees 1992, Vietri 1997a).

The black hole itself, being more massive than the disk, could represent an even larger source of energy, especially if formed from a coalescing compact binary, since then it is guaranteed to be rapidly spinning. The energy extractable in principle through MHD coupling to the rotation of the hole by the B-Z (Blandford & Znajek 1977) mechanism could then be even larger than that contained in the orbiting debris (Mészáros & Rees 1997b, Paczyński 1998). (Less conventional and more specific related BH energization of jets is discussed e.g. by van Putten 2000, Li 2000, Ruffini et al. 2001). Collectively, such MHD outflows have been referred to as Poynting jets.

The various stellar progenitors differ slightly in the mass of the BH and somewhat more in that of the debris torus, but they can differ markedly in the amount of rotational energy contained in the BH. Strong magnetic fields, of order 10^{15} G, are needed to carry away the rotational or gravitational energy in a time scale of tens of seconds (Usov 1994, Thompson 1994), 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 (Duncan & Thompson 1992, Kluzniak & Ruderman 1998). If the magnetic fields do not thread the BH, a Poynting outflow can at most carry the gravitational binding energy of the torus.

This is

$$E_t \simeq \epsilon_m q 0.42 M_d c^2 \lesssim 8 \times 10^{53} \epsilon_m q (M_d/M_\odot) \text{ ergs} , \quad (8)$$

where $\epsilon_m \lesssim 0.3$ is the efficiency in converting gravitational into MHD jet energy, q is in the range $[1, 1/7]$ for [fast,slow] rotating BHs, and the mass M_d of the torus or disk in a NS-NS merger is (Ruffert & Janka 1998) $\sim 10^{-1} - 10^{-2} M_\odot$, while in NS-BH, He-BH, WD-BH mergers or a binary WR collapse it may be (Paczyński 1998, Fryer & Woosley 1998) $\sim 1 M_\odot$.

If the magnetic fields in the torus thread the BH, the spin energy of the BH which can be extracted e.g. through the B-Z or related mechanisms is (Mészáros & Rees 1997b, Mészáros , Rees & Wijers 1999)

$$E_{bh} \simeq \epsilon_m f(a) M_{bh} c^2 \lesssim 5 \times 10^{53} \epsilon_m (M_{bh}/M_\odot) \text{ ergs}, \quad (9)$$

where $f(a) = 1 - ([1 + \sqrt{1 - a^2}]/2)^{1/2} \leq 0.29$ is the rotational efficiency factor, $a = Jc/GM^2$ = rotation parameter ($a = 1$ for a maximally rotating BH). The rotational factor is small unless a is close to 1, so the main requirement is a rapidly rotating black hole, $a \gtrsim 0.5$. Rapid rotation is guaranteed in a NS-NS merger, since (especially for a soft equation of state) 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. The central BH mass (Ruffert et al. 1997, Ruffert & Janka 1998) is $\sim 2.5 M_\odot$, so a NS-NS merger could power a jet of up to $E_{NS-NS} \lesssim 1.3 \times 10^{54} \epsilon_m$ ergs. A maximal rotation rate may also be possible in a He-BH merger, depending on what fraction of the He core gets accreted along the rotation axis as opposed to along the equator (Fryer & Woosley 1998). For a rotating He star, recent calculations (Lee, Brown & Wijers 2001) indicate that a BH rotaion parameter $a = 0.7 - 0.9$ is achievable. A similar end result may apply to the binary fast-rotating WR scenario, which probably does not differ much in its final details from the He-BH merger. For a fast rotating BH of $2.5 - 3M_\odot$ threaded by the magnetic field, the maximal energy carried out by the jet is then similar or somewhat larger than in the NS-NS case. The scenarios less likely to produce a fast rotating BH are the NS-BH merger (where the rotation parameter could be limited to $a \leq M_{ns}/M_{bh}$, 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). Recent calculations of collapsar central BH mass/rotation rates and disk masses have been discussed by Fryer & Kalogera 2001, MacFadyen, Woosley & Heger 2001, Fryer, Woosley, Hartmann 1999, Janka et al. 1999, Zhang & Fryer 2001. The magnetic interaction between a rotating hole and disk is further discussed in (van Putten & Ostriker 2001).

The total jet energetics differ between the various BH formation scenarios at most by a factor 20 for Poynting jets powered by the torus binding energy, and at most by factors of a few for Poynting jets powered by the BH spin energy, depending on the rotation parameter. For instance, allowing for a total efficiency of 50%, a NS-NS merger whose jet is powered by the torus binding energy would require a beaming of the γ-rays by a factor $(4\pi/\Omega_j) \sim 100$, or beaming by a factor ~ 10 if the jet is powered by the B-Z mechanism, to produce the equivalent of an isotropic energy of 4×10^{54} ergs. These beaming factors are compatible with the values derived from observations (Frail et al. 2001) (albeit so far available for long bursts only).

In all cases including solar mass BHs and magnetar central objects an $e^{\pm}, \gamma$ fireball would be expected to arise from the heating and dissipation associated with the transient accretion event, in addition to MHD stresses. Even if the latter are not dominant, values in excess of 10^{15} Gauss can provide the driving stresses leading to highly relativistic $\gamma_j \gg 1$ expansion. The fireball would also be likely to involve some fraction of baryons, and uncertainties in this "baryon pollution" (Paczyński 1990) remain difficult to dispel until 3D MHD calculations capable of addressing baryon entrainment become available. In spherical symmetry, general considerations give insights into the development of the Lorentz factor in a shock wave as it propagates down the density gradient of a stellar envelope (Sari, Waxman & Shvarts 2000, Tan, Matzner & McKee 2001). The expectation that the fireball is likely to be substantially collimated is prevalent especially if the progenitor is a massive star, due to the constraint provided by an extended, fast-rotating envelope, which provides a natural fireball escape route along the rotation axis. The development of a jet and its Lorentz factor in a collapsar is discussed analytically in Mészáros & Rees 2001 and numerically in, e.g. Aloy et al. 2000 and Zhang, Woosley & MacFadyen 2001 (see Fig. 4) while the case of a magnetar jet is discussed by Wheeler, et al. 2000. In the case of NS-NS or BH-NS mergers a weaker degree of collimation would be expected, due to the lack of an extended envelope (unless magnetic or hydrodynamic self-collimation occurs, e.g. Levinson & Eichler 2000).

An interesting question is whether the long bursts arise from a different parent population as the short bursts. A current hypothesis is that while massive stars (e.g. via the collapsar scenario) appear implicated in long bursts, NS-NS mergers might possibly lead to short bursts (Katz & Canel 1996, Popham, Woosley & Fryer 1999), as also discussed in the next §. (c.f. van Putten & Ostriker 2001 for an alternative view in which both long and short bursts originate in collapsars).

7 Cosmological Setting, Galactic Hosts and Environment

For the long GRB afterglows localized so far, a host galaxy has been found in most cases ($\gtrsim 80\%$ out of over 30 optically identified, Bloom, Kulkarni & Djorgovski 2001). The GRB hosts are typically low mass, sub-L_* galaxies, with the blue colors and atomic lines indicative of active star formation (Fruchter 2000, Bloom, Kulkarni & Djorgovski 2001, Frail et al. 2001; see also Schaefer 2000). Many of them are obscured, far-infrared luminous galaxies, some of which appear tidally disturbed (Chary, Becklin & Armus 2001). The redshifts of the hosts, with one exception, are in the range $0.43 \lesssim z \lesssim 4.5$, i.e., comparable to that of the most distant objects detected in the Universe. The observed number of bursts per unit photon flux can be fitted by cosmological distribution models, with a somewhat better fit if one assumes that the burst rate scales proportionally to the observed star-formation rate as a function of redshift (Wijers et al. 1998, Totani 1999, Blain & Natarajan 2000, Böttcher & Dermer 2000, Stern, Tikhomirova & Svensson 2001). The spread in the inferred isotropic-equivalent luminosities extends over three orders of magnitude, i.e. far from standard candles for the purposes of testing cosmological models (Mao & Mo 1998). However, this spread in luminosities is considerably reduced to less than one order of magnitude (Panaitescu & Kumar 2001a, Frail et al. 2001, Panaitescu & Kumar 2001b, Piran et al. 2001) if allowance is made for jet-like collimation. The sample of bursts for which this is possible is still too small ($\lesssim 10$) to do cosmology with them.

The bursts for which the intrinsic brightness is known from their measured redshifts would, in principle, be detectable out to much larger redshifts $z \lesssim 15-20$ with present detectors (Lamb & Reichart 2000). Within the first minutes to hours after the burst, the afterglow optical light is expected to be in the range

$m_v \sim 10 - 15$, far brighter than quasars, albeit for a short time. Thus, promptly localized GRB could serve as beacons which, shining through the pregalactic gas, provide information about much earlier epochs in the history of the Universe. The presence of iron or other x-ray lines provides an additional tool for measuring GRB distances, which may be valuable for investigating the small but puzzling fraction of bursts which have been detected only in X-rays but not optically, perhaps due to a high dust content in the host galaxy.

Accurate localizations and host galaxies have, so far, been restricted to the class of "long" bursts (γ-ray durations $t_b \sim 10 - 10^3$ s), because BeppoSAX is mostly sensitive to bursts longer than about 5-10 s. (One exception is a recent short burst localization, which led to optical upper limits $R > 22.3$ and $I > 21.2$ about 20 hours after the trigger Gorosabel et al. 2001. For the long bursts, the fading x-ray and optical afterglow emission is predominantly localized within the optical image of the host galaxy. In most cases it is offset from the center, but in a few cases (out of a total of about twenty) it is near the center of the galaxy (Bloom, Kulkarni & Djorgovski 2001). This is in disagreement with current simple calculations of NS-NS mergers which suggest (Bloom, Sigurdsson & Pols 1999; also Narayan, Paczyński & Piran 1992) that high spatial velocities would take these binaries, in more than half of the cases, outside of the confines of the host galaxy before they merge and produce a burst. These calculations, however, are uncertain, since they are sensitive to a number of poorly known parameters (e.g distribution of initial separations, etc). On the other hand, theoretical estimates (Fryer, Woosley, Hartmann 1999) suggest that NS-NS and NS-BH mergers will lead to shorter bursts ($\lesssim 5s$), beyond the capabilities of Beppo-SAX but expected to be detectable with the recently launched HETE-2 spacecraft (HETE hompage).

More effectively, short as well as long bursts should be detected at the rate of 200-300 per year with the *Swift* multi-wavelength GRB afterglow mission (Swift hompage) currently under construction and scheduled for launch in 2003. Swift will be equipped with γ-ray, x-ray and optical detectors for on-board follow-up, and will capable to slew within 30-70 seconds its arc-second resolution X-ray camera onto GRBs acquired with their large field-of-view gamma-ray monitor, relaying to the ground the burst coordinates within less than a minute from the burst trigger. This will permit much more detailed studies of the burst environment, the host galaxy, and the intergalactic medium.

Hydrogen Lyman α absorption from intervening newly formed galaxies would be detectable as the GRB optical/UV continuum light shines through them (Loeb & Barkana 2001, Lamb & Reichart 2000). While the starlight currently detected is thought to come mostly from later, already metal-enriched generations of star formation, GRB arising from the earliest generation of stars may be detectable; and if this occurs before galaxies have gravitationally assembled, it would provide a glimpse into the pregalactic phase of the Universe. At a given observed wavelength and a given observed time delay, the observed brightness of a burst afterglow decreases more slowly at higher redshifts, since the afterglow is observed at an earlier source time and at a higher frequency where it is brighter (Ciardi & Loeb 2000, Lamb & Reichart 2000). The high redshift afterglows shining through their host or intervening galaxies would be expected to provide valuable information in the near IR, while in the far IR and sub-mm they would provide invaluable information about the dust content in high redshift environments (Venemans & Blain 2001). Dust affects the colors of the light curves and contains information about the metallicity as a function of redshift (Reichart 2001). Bursts which are highly dust-obscured in the optical would generally be detectable in γ-rays and X-rays, and quantitative information about the dust content may be obtained through the detection of a hump accompanied by a spectral softening in the keV X-ray light curve (Mészáros & Gruzinov 2000), caused by small-angle forward scattering on the dust grains, accompanied by a late brightening in the near-IR.

Most of the host galaxies of the long bursts detected so far show signs of active star formation, implying the presence of young, massive stars forming out of dense gaseous clouds. The diffuse gas around a GRB is expected to produce time-variable O/UV atomic absorption lines in the first minutes to hours after a burst (Perna & Loeb 1998). There is also independent evidence from the observation of 0.5-2 keV absorption in the x-ray afterglow spectra, attributed to metals in a high column density of gas in front of the burst (Galama & Wijers 2001). This appears to be higher than expected from optical extiction measures, which may be due to dust destruction by UV photons (Waxman & Draine 2000, Esin & Blandford 2000, Fruchter, Krolik & Rhoads 2001).

It is interesting that, at least in a few bursts so far, there appears to be evidence for an approximately coincident supernova explosion. There is good spatial-temporal coincidence for one burst, GRB 980425, associated with the unusually bright SN Ib/Ic 1998bw (Galama et al. 1998, Bloom et al. 1998, van Paradijs 1999). At a measured redshift of 0.0085 the association would imply an abnormally faint GRB luminosity ($\sim 10^{47}$ ergs), although it can be argued that the jet appears fainter due to being seen by chance almost close to its edge (e.g. Höflich, Wheeler & Wang 1999). For SN 1998bw, a mildly relativistic and quasi-spherical shock break-out is also a good model (Waxman & Loeb 1999, Tan, Matzner & McKee 2001). In at least three other localized long GRB, there is circumstantial evidence for a supernova remnant in the form of a bump and reddening in the GRB afterglow optical light curve after several weeks (Lazzati et al. 2001b, Galama et al. 2000, Reichart 1999, Bloom et al. 1999). Alternative explanations based on dust sublimation and scattering have been proposed by Esin & Blandford 2000 and Waxman & Draine 2000. The hypothesis of a generic association of GRB and supernovae ("hypernovae") has been discussed by Paczyński 1998 (see also Woosley 1993) and by Wheeler, et al. 2000, while multiple sub-jets are discussed by (Nakamura 2000).

X-ray atomic edges and resonance absorption lines are expected to be detectable from the gas in the immediate environment of the GRB, and in particular from the remnants of a massive progenitor stellar system (Mészáros & Rees 1998b, Weth et al. 2000, Böttcher & Fryer 2001). Observations with the *Chandra* ACIS X-ray spectrographic camera has provided evidence, at a moderate $\gtrsim 4\sigma$ confidence level, for iron K-α line and edge features in at least one burst (GRB 991216, Piro et al. 2000), and there are at least four other detections at the $\sim 3\sigma$ level with Beppo-SAX and ASCA (e.g. Amati et al. 2000, Yoshida et al. 1999, van Paradijs, Kouveliotou & Wijers 2000). The observed frequency of the iron lines appear displaced from the laboratory frequency by the right amount expected from the measured optical redshift, when available, indicating that the material producing the lines is expanding at $v/c \lesssim 0.1$ (Piro et al. 2000). The presence of iron line features would again strongly suggest a massive stellar progenitor, but the details remain model dependent.

One possible interpretation of the iron emission lines ascribes the approximate one day delay between the burst and the Fe line peak to light-travel time effects, a specific example postulating an Fe-enriched supernova remnant situated outside the burst region, which is illuminated by X-rays from the afterglow leading to Fe recombination line emission (Fig. 5). This would require about $10^{-1} - 1\ M_\odot$ of Fe in the shell from, e.g., a supernova (SN) explosion by the progenitor occurring weeks before the burst, which might be due from the accretion-induced collapse of the NS remnant left behind by the SN (Piro et al. 2000, Vietri et al. 2000). A similar interpretation is made (Lazzati et al. 2001c) in the one reported Beppo-SAX case which appears as prompt ($\lesssim 40$ s) Fe absorption feature (Amati et al. 2000). A delay of weeks is required to allow SNR shell to travel out to a light-day distance and for the Ni in the explosion to decay to Fe. If the lines are ascribed to Ni or Co (Lazzati, Perna & Ghisellini 2001a) the shell velocity must match the difference to the Fe line energies. In either case some fine-tuning appears necessary.

A less demanding Fe line model is possible if the GRB, after its usual initial outburst, continues to eject a progressively weaker jet for a few days, at a rate which does not violate the observed light-curve (Rees & Mészáros 2000). This jet may be fed, e.g. through continued fall-back at low on the BH, or through spin-down if the central object is a magnetar. A decaying jet with a luminosity $L \sim 10^{47}$ erg/s at one day impinging on the outer layers near $\sim 10^{13}$ cm of the progenitor envelope leads to Fe recombination line emission at the observed rate, requiring only solar abundances or a total of $\sim 10^{-5} M_\odot$ of Fe (Fig. 5). However, the most plausible model may be one based upon the the after-effects of the cocoon of waste heat pumped into the lower envelope as the relativistic jet makes its way through the progenitor envelope (Mészáros & Rees 2001). This bubble (Figure 6) of waste heat, after the jet has emerged and produced the burst, rises slowly by buoyancy and emerges through the outer envelope on timescales of a day after the burst. Its structure is likely to be highly inhomogeneous, resulting in non-thermal X-rays produced by synchrotron in the low density medium between much denser photo-ionized filaments which can produce the observed Fe line luminosity through recombination, requiring a modest $\sim 10^{-5} M_\odot$ of Fe which can be easily supplied from the core of the star as the jet develops. In this type of nearby ($\lesssim 10^{13}$ cm) line production models, the Fe line energies could be more naturally mimicked by down-scattering of Ni or Co lines (McLaughlin, Wijers, Brown & Bethe 2001).

The simple picture of an origin in star-forming regions, at least for the long ($t_b \gtrsim 5$ s) bursts, is complicated by the fact that the observed optical absorption is less than expected for the corresponding x-ray absorption. Also, standard afterglow model fits indicate an ambient gas density generally lower than that expected in star-forming clouds (Galama & Wijers 2001, Panaitescu & Kumar 2001b). These contradictions may possibly be reconcilable, e.g. through dust sublimation by x-ray/UV radiation (Waxman & Draine 2000, Esin & Blandford 2000, Fruchter, Krolik & Rhoads 2001) or the blowing out of a cavity by a progenitor wind (Wijers 2000).

While it is unclear whether there is one or more classes of GRB progenitors, e.g. corresponding to short and long bursts, there is a general consensus that they would all lead to the generic fireball shock scenario. Much of the current effort is dedicated to understanding the different progenitor scenarios, and trying to determine how the progenitor and the burst environment can affect the observable burst and afterglow characteristics.

8 Cosmic Rays, Neutrinos, GeV-TeV Photons and Gravity Waves

There are several other, as yet unconfirmed, but potentially interesting observing channels for GRBs, relating to the baryonic component of the outflow, the shock physics and the progenitor collapse dynamics.

Among these, cosmic rays are perhaps most directly implicated in the fireball shock mechanism, thought to accelerate the electrons responsible for the non-thermal γ-rays in GRB. The same shocks should also accelerate protons, based on experience from interplanetary shocks. Both the internal and the external reverse shocks are mildly relativistic, and are expected to lead to relativistic proton energy spectra of the form $dN_p/d\epsilon_p \propto \gamma_p^{-2}$ (Blandford & Eichler 1987; see also Kirk et al. 2000 and Lloyd-Ronning & Petrosian 2001b). The maximum proton energies achievable in GRB shocks are $E_p \sim 10^{20}$ eV (Waxman 1995, Vietri 1995, Dermer & Humi 2001), comparable to the highest energies measured with large cosmic ray ground arrays (e.g. Hayashida et al. 1999). The condition for this is that the acceleration time up to that energy is shorter than the radiation or adiabatic loss time as well as the escape time from the acceleration region. The resulting constraints on the magnetic field and the bulk Lorentz factor (Waxman 1995) are close to those required to obtain efficient gamma-ray emission at ~ 1 MeV. If the accelerated electrons which produce the γ-rays and the protons carry a similar fraction of the total energy (a conservative assumption, based on interplanetary collisionless shock acceleration measurements), the GRB cosmic ray energy production rate at 10^{20} eV throughout the universe is of order 10^{44} erg/Mpc^3/yr, comparable to the observationally required rate from γ-ray observations and from the observed diffuse cosmic ray flux (Waxman 1995; c.f. Stecker 2000a). These numbers depend on uncertainties in the burst total energy and beaming fraction, as well as on the poorly constrained burst rate evolution with redshift. The highest energy protons would need to have arrived from within less than about 50-100 Mpc, to avoid interaction with the microwave background, and reasonable intergalactic magnetic field strengths can ensure time dispersions in excess of a few hundred years, needed to achieve compatibility with the estimated burst rate of $\sim 10^{-6}$ /galaxy/year, as well as with arrival from clustered sources (Bahcall & Waxman 2000). The unknown strength and correlation length of the field could lead to anisotropies constraining both GRB models and competing AGN or other discrete source origin models, an issue which will be addressed by future large area ground cosmic ray arrays such as, e.g., Auger and HiRes.

Any stellar origin mechanism (whether collapsar, neutron star merger, etc) would lead to a very large ($\sim M_{\odot}c^2$) luminosity in thermal neutrinos and antineutrinos with energies $\sim$ few MeV, as in core-collapse supernova. However, at MeV energies the neutrino detection cross section is $\sim 10^{-44}$ cm^2, and as shown by the low count rates in the supernova SN 1987a detection from $\sim$ 50 Kpc, even larger detectors at these energies (super-Kamiokande, Sudbury, etc) would be insensitive to sources such as GRB with typical distances $\gtrsim$ 100 Mpc.

A mechanism leading to higher (GeV) energy neutrinos in GRB is inelastic nuclear collisions. Proton-proton collisions at internal shock radii $\sim 10^{14}$ cm could lead to $\sim$ GeV neutrinos in the observer frame through charged pion decay (Paczyński & Xu 1994), with low efficiency due to the low densities at these large radii and small relative velocities between protons. However, proton-neutron inelastic collisions are expected, even in the absence of shocks, at much lower radii, due to the decoupling of neutrons and protons in the fireball or jet (Derishev, Kocharovsky & Kocharovsky 1999a). Provided the fireball has a substantial neutron/proton ratio, as expected in most GRB progenitors, the collisions become inelastic and their rate peaks at when the nuclear scattering time becomes comparable to the expansion time. This occurs when the n and p fluids decouple, their relative drift velocity becoming comparable to c, which is easier due to the lack of charge of the neutrons. Inelastic n, p collisions then lead to charged pions and GeV muon and electron neutrinos (Bahcall & Mészáros 2000). The early decoupling and saturation of the n also leads to a somewhat higher final p Lorentz factor (Derishev, Kocharovsky & Kocharovsky 1999a, Bahcall & Mészáros 2000, Fuller, Pruet & Kevork 2000, Pruet, Kevork & Fuller 2001), implying a possible relation between the n/p ratio and the observable fireball dynamics, relevant for the progenitor question and burst timescales. Inelastic p, n collisions leading to neutrinos can also occur in fireball outflows with transverse inhomogeneities in the bulk Lorentz factor, where the n can drift sideways into regions of different bulk velocity flow, or in situations where internal shocks involving n and p occur close to the saturation radius or below the photon photosphere (Mészáros & Rees 2000a). The typical n, p neutrino energies are in the 5-10 GeV range, which could be detectable in coincidence with observed GRBs for a sufficiently close photo-tube spacing in future km^3 detectors such as ICECUBE (Halzen 2000).

In addition, neutrinos with energies $\gtrsim$ PeV can be produced in p, γ photo-pion interactions involving highly relativistic protons accelerated in the fireball internal or external shocks. A high collision rate is ensured here by the large density of photons in the fireball shocks. The most obvious case is the interaction between MeV photons produced by radiation from electrons accelerated in internal shocks (see Fig. 5), and relativistic protons accelerated by the same shocks (Waxman & Bahcall 1997), leading to charged pions, muons and neutrinos. This p, γ reaction peaks at the energy threshold for the photo-meson Δ resonance in the fluid frame moving with γ, or

$$\epsilon_p \epsilon_\gamma \gtrsim 0.2 \mathrm{GeV}^2 \gamma^2 \ . \tag{10}$$

For observed 1 MeV photons this implies $\gtrsim 10^{16}$ eV protons, and neutrinos with $\sim 5\%$ of that energy, $\epsilon_\nu \gtrsim 10^{14}$ eV in the observer frame. Above this threshold, the fraction of the proton energy lost to pions is $\sim 20\%$ for typical fireball parameters, and the typical spectrum of neutrino energy per decade is flat, $\epsilon_\nu^2 \Phi_\nu \sim$ constant. Synchrotron and adiabatic losses limit the muon lifetimes (Rachen & Mészáros 1998), leading to a suppression of the neutrino flux above $\epsilon_\nu \sim 10^{16}$ eV. In external shocks (Fig. 5), another copious source of targets are the O/UV photons in the afterglow reverse shock (e.g. as deduced from the GRB 990123 prompt flash of Akerlof et al. 1999). In this case the resonance condition implies higher energy protons, leading to neutrinos of $10^{17} - 10^{19}$ eV (Waxman & Bahcall 1999a, Vietri 1998). These neutrino fluxes are expected to be detectable above the atmospheric neutrino background with the planned cubic kilometer ICECUBE detector (Halzen 2000, Alvarez-Muniz, Halzen & Hooper 2000). Useful limits to their total contribution to the diffuse ultra-high energy neutrino flux can be derived from observed cosmic ray and diffuse gamma-ray fluxes (Waxman & Bahcall 1999b, Bahcall & Waxman 2001, Mannheim 2001). While the p, γ interactions leading to $\gtrsim 100$ TeV energy neutrinos provide a direct probe of the internal shock acceleration process, as well as of the MeV photon density associated with them, the $\gtrsim 10$ PeV neutrinos would probe the reverse external shocks, as well as the photon energies and energy density there.

The most intense neutrino signals, however, may be due to p, γ interactions occurring *inside* collapsars while the jet is still burrowing its way out of the star

(Mészáros & Waxman 2001), before it has had a chance to break through (or not) the stellar envelope to produce a GRB outside of it. While still inside the star, the buried jet produces thermal X-rays at ~ 1 keV which interact with $\gtrsim 10^5$ GeV protons which could be accelerated in internal shocks occurring well inside the jet/stellar envelope terminal shock, producing $\sim$ few TeV neutrinos for tens of seconds, which penetrate the envelope (Figure 7). This energy is close to the maximum sensitivity for detection, and the number of neutrinos is also larger for the same total energy output. The rare bright, nearby or high γ collapsars could occur at the rate of ~ 10/year, including both γ-ray bright GRBs (where the jet broke through the envelope) and γ-ray dark events where the jet is choked (failed to break through), and both such γ-bright and dark events could have a TeV neutrino fluence of ~ 10/neutrinos/burst, detectable by ICECUBE in individual bursts.

GeV to TeV photon production is another consequence of the photo-pion and inelastic collisions responsible for the ultra-high energy neutrinos (Waxman & Bahcall 1997, Böttcher & Dermer 1998, Derishev, Kocharovsky & Kocharovsky 1999a, Bahcall & Mészáros 2000). This is in addition to the GeV emission from electron inverse Compton in internal (Papathanassiou & Mészáros 1996) and external shocks Mészáros , Rees & Papathanassiou 1994, Derishev, Kocharovsky & Kocharovsky 2001 and afterglows (Zhang & Mészáros 2001b). In these models, due to the high photon densities implied by GRB models, $\gamma\gamma$ absorption within the GRB emission region must be taken into account (see also Baring 2000, Lithwick & Sari 2001). A tentative $\gtrsim 0.1$ TeV detection of an individual GRB has been reported with the water Cherenkov detector Milagrito (Atkins et al. 2000), and better sensitivity is expected from its larger version MILAGRO as well as from atmospheric Cherenkov telescopes under construction such as VERITAS, HESS, MAGIC and CANGAROO-III (Weekes 2000). GRB detections in the TeV range are expected only for rare nearby events, since at this energy the mean free path against $\gamma\gamma$ absorption on the diffuse IR photon background is $\sim$ few hundred Mpc (Coppi & Aharonian 1997, Stecker 2000b). The mean free path is much larger at GeV energies, and based on the handful of GRB reported in this range with EGRET (Schneid et al. 1995), several hundred should be detectable with large area space-based detectors such as GLAST (Gehrels & Michelson 2000, Zhang & Mészáros 2001b), in coincidence with the neutrino pulses and the usual MeV γ-ray event. Their detection would provide important constraints on the emission mechanism and the progenitors of GRBs.

GRB are also expected to be sources of gravitational waves. A time-integrated luminosity of the order of a solar rest mass ($\sim 10^{54}$ erg) is predicted from merging NS-NS and NS-BH models (Narayan, Paczyński & Piran 1992, Kochanek & Piran 1993, Ruffert & Janka 1998, Oohara & Nakamura 1999), while the luminosity from collapsar models is more model-dependent, but expected to be lower (Fryer, Woosley, Heger 2001, Dimmelmeier, Font & Mueller 2001; c.f. van Putten 2001). The rates of gravitational wave events (Finn, Mohanty & Romano 2000) detectable by the Laser Interferometric Gravitational Wave Observatory (LIGO, currently under construction) from compact binary mergers, in coincidence with GRBs, has been estimated at a few/year for the initial LIGO, and up to 10-15/year after the upgrades planned 2-4 years after first operations. The observation of such gravitational waves is greatly facilitated by coincident detections in other channels, either electromagnetic or neutrinos. Detection of gravity wave pulses fitting the templates for compact binary mergers (or collapsars), in coincidence with positive GRB localizations, would have a great impact on our understanding of GRB progenitor systems.

In conclusion, major advances have been made in the understanding of GRB since their discovery almost 30 years ago. However many questions remain, while new ones arise in the wake of the increasingly sophisticated and extensive observations. These questions will be addressed with new space missions and ground experiments dedicated to GRB studies which will come on-line in the near future. Based on past experience the chances are high that these will bring not only answers but also new surprises and challenges.

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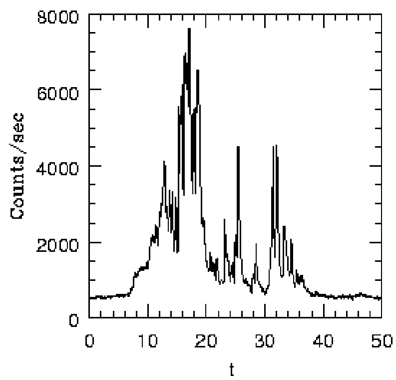

Figure 1: Typical GRB lightcurve observed with BATSE, showing photon count rate (0.05-0.5 MeV) versus time (s). No γ-rays are detected either before or after the burst trigger (Fishman & Meegan 1995).

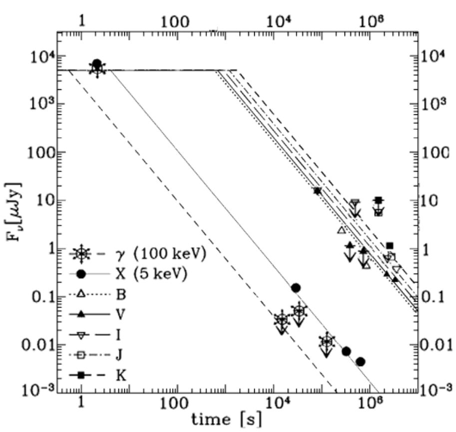

Figure 2: Comparison (Wijers, Rees & Mészáros 1997) of the observed light curves of the afterglow of GRB 970228 at various wavelengths with the simple blast wave model predictions (Mészáros & Rees 1997a).

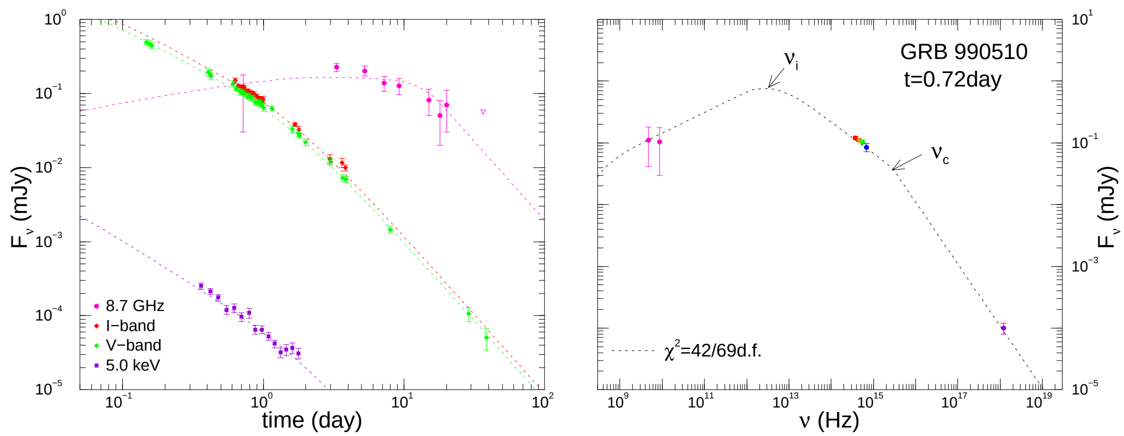

Figure 3: Model light curves at various energies (left panel) and snapshot spectral fit at 0.72 days (right panel) for GRB 990510, compared against the data (Panaitescu & Kumar 2001a). The model shown has $\chi^2 = 42$ for 69 df, and parameters: $E_0 = 3.0 \times 10^{50}$ erg, $\theta_{jet} = 2.7\,\mathrm{deg}$, $n_o = 0.14\ \mathrm{cm}^{-3}$, $\epsilon_e = 0.046$, $\epsilon_B = 8.6 \times 10^{-4}$, $p = 2.01$. The steepening of the optical decay is due to the the effect of a jet.

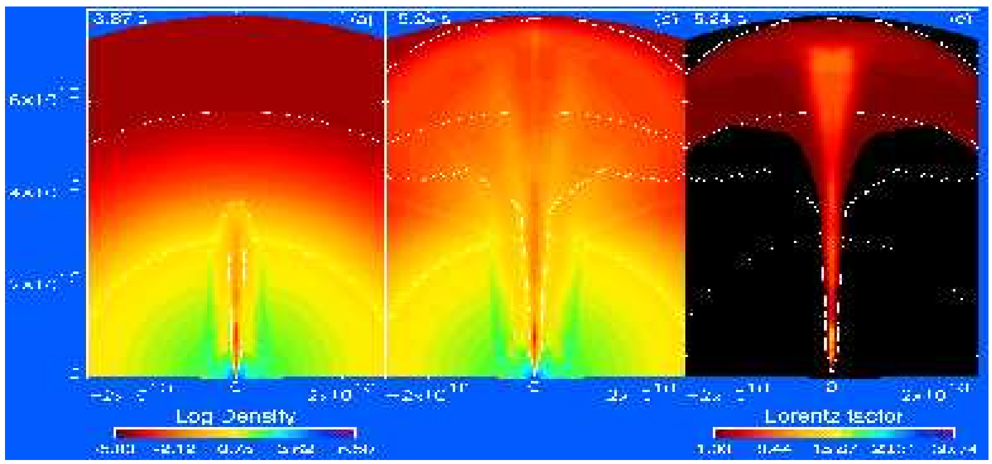

Figure 4: Jet development in a $14M_{\odot}$ collapsar (Aloy et al. 2000) after substantial envelope mass loss. Contours of the logarithm of density after 3.87 s and 5.24 s (left two panels), and of the Lorentz factor (right panel) after 5.24 s. X and Y axis measure distance in centimeters. Dashed and solid arcs mark the stellar surface and the outer edge of the exponential atmosphere.

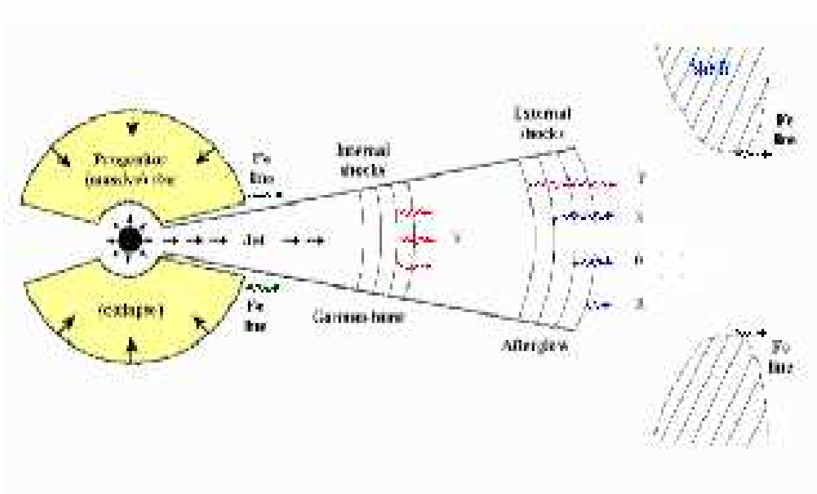

Figure 5: Schematic GRB from internal shocks and afterglow from external shock, arising from a relativistic jet emerging from a massive progenitor collapse (similar jets could arise from other progenitors). Internal shocks produce γ-rays and PeV neutrinos, external shocks produce γ-rays, X-rays, optical, radio and EeV neutrinos. Fe X-ray lines may arise from X-ray illumination of a pre-ejected supernova remnant (Piro et al. 2000) or from continued X-ray irradiation of the outer stellar envelope (Rees & Mészáros 2000) (c.f. also Fig. 6).

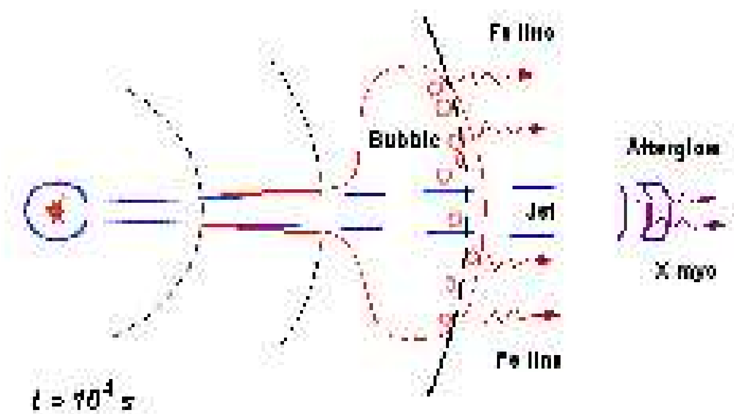

Figure 6: Schematic GRB afterglow from a jet emerging from a massive progenitor, followed hours later by emergence of a bubble of waste heat producing additional non-thermal X-ray and reprocessed Fe Kα recombination from dense filaments in the bubble and envelope (Mészáros & Rees 2001).

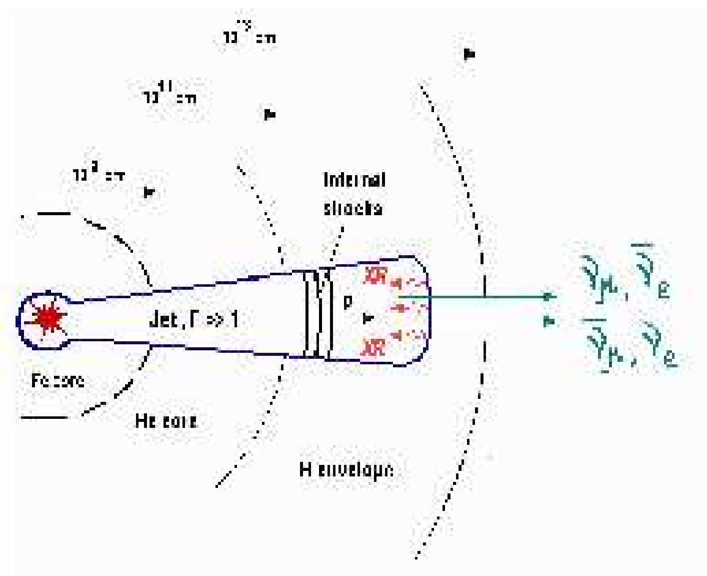

Figure 7: Sketch of TeV neutrino production by photomeson interactions in internal shocks before a relativistic jet has broken through the progenitor envelope (Mészáros & Waxman 2001). Neutrinos would be expected whether the jet is choked off (γ-dark) or emerges to make a GRB.