Romanian Reports in Phisics, Vol. 56, No. 2, P. 204-249, 2004

GAMMA-RAY BURSTS – A CRITICAL REVIEW

VALERIU TUDOSE[1] & PETER L. BIERMANN[2, 3]

[1]*Astronomical Institute of the Romanian Academy*
Str. Cutitul de Argint nr. 5, RO-75212, Bucharest, Romania
vtudose@aira.astro.ro

[2]*Max-Planck Institute for Radioastronomy*
Auf dem Huegel 69, D-53121, Bonn, Germany

[3]*Department of Physics & Astronomy, University of Bonn*
D-53121, Bonn, Germany
plbiermann@mpifr-bonn.mpg.de

(Received May 30, 2003)

Abstract. We present a short general introduction into the field of gamma-ray bursts (GRBs) research, summarizing the past and the present status. We give an ensemble view of the GRBs observations to date, both in the prompt emission phase as well as in the afterglow phase, and a brief primer into the theory, mainly in the framework of the fireball model.

Key words: gamma ray bursts

INTRODUCTION

The story of gamma-ray bursts (GRBs) began in the '60s, when the US Defense Department launched in space a series of spy satellites called Vela, whose purpose was to detect gamma-ray emission associated with possible clandestine nuclear tests performed by the Soviet Union. The instrumentation on board did record short bursts of gamma-rays in the keV-MeV energy range, lasting from 0.1 second up to 30 seconds. The soviet Konus military satellites made similar observations. Fortunately, the scientists realized that these are natural phenomena.

The first GRB event was observed on July 2, 1969, but the announcement of the discovery came several years later, in 1973, when Klebesadel, Strong and Olson (Klebesadel et al., 1973) published a report paper. The theoreticians became very interested in the new phenomenon and just within a couple of years, about 20 models had been proposed (Ruderman, 1975). Most of them involved supernovae, neutron stars, flare stars, antimatter effects, white holes, and so on. Now, there are more than one hundred GRBs models, and the number is increasing (Nemiroff, 1994). On the average, one new publication on GRBs enters the literature every day. The total amount of papers exceeds 5000 (at the end of 2002).

Basically, taking into account the distance scales only, the models can be divided in three groups (Rees, 2000): those in which the candidate objects are situated in the Galactic Disc (~ few hundred parsecs), in the halo (~ tens of kilo-parsecs; Brainerd, 1992; Podsiadlowski et al., 1995; Lamb, 1995), or at cosmological distances (~ giga-parsecs; Paczyñski, 1995). Until the 1990s, the consensus was that GRBs are local events related to the galactic old neutron stars population. There were even found observational proofs (i.e. cyclotron spectral lines, not confirmed by BATSE-CGRO; Mazets et al., 1980; Fenimore et al., 1988; Murakami et al., 1988; Palmer et al., 1994; Band et al., 1995; Band et al., 1996) to back up this idea. However, a revolution took place after the launch in 1991 of the Compton Gamma-Ray Observatory (CGRO) carrying on board the Burst and Transient Source Experiment (BATSE). BATSE observations of the isotropy of GRB locations (Meegan et al., 1992; Briggs et al., 1996) and the deficiency of faint GRBs (Meegan et al., 1992; Horack & Emslie, 1994), strongly suggested a cosmological origin. Subsequent redshift determinations (around 30 at the end of 2002; Bloom et al., 2001) confirmed the more and more popular belief that the majority of GRBs are at cosmological distances.

Accepting that GRBs are extragalactic distant sources, the equivalent isotropic energy implied is huge: $10^{51} – 10^{54}$ erg (Bloom et al., 2001; Frail et al., 2001; Panaitescu & Kumar, 2001b). Moreover, the rapid temporal variability on time scales of milliseconds suggests a compact object. It would have a very large optical depth via the electron-positron pair production mechanism $\gamma\gamma \rightarrow e^- e^+$. But the observed spectrum is non-thermal, extending far beyond 500 keV, so the source must be optically thin. The most natural and elegant solution (i.e. "non-exotic") to this problem is the relativistic motion of the emitting regions (Woltjer, 1966; Rees, 1967). If the source is moving toward us with an amazing, however reasonable, Lorentz factor of at least 100 (Fenimore et al., 1993; Woods & Loeb, 1995; Lithwick & Sari, 2001), then the whole picture starts to make sense.

According to the "accepted" model, the GRBs are produced when an ultra-relativistic energy flow is converted to radiation in an optically thin region (see Waxman, 2003 for the most recent review). The energy conversion seems to occur through internal processes, e.g. internal shocks (Narayan et al., 1992; Rees & Mészáros, 1994; Paczyñski & Xu, 1994). In this framework, an afterglow would be expected, that is emission from the external forward shock (Rees & Mészáros, 1992) when the "fireball" impacts the interstellar medium (ISM). And actually, such an observation was made for the first time on February 28, 1997, when the Italian-Dutch satellite BeppoSAX discovered an X-ray counterpart to GRB970228 (Costa et al., 1997). Optical (Groot et al., 1997) and radio transients (Frail et al., 1997) were also observed.

A huge step forward was made still in 1997, when spectroscopic observations of the afterglow of GRB970508 provided the first redshift determination (Metzger et al., 1997).

Due to the fact that broadband measurements (from radio to X-rays) are available, the physics behind the afterglow is better understood than the prompt gamma-ray emission. The standard afterglow model assumes a number of approximations (Mészáros, 2002): a) spherical outflow; b) homogeneous external medium; c) ultra-relativistic adiabatic expansion; d) an impulsive energy input and a uniform initial Lorentz factor of the ejecta; e) line of sight scaling relations assumed valid for the entire visible region; f) time-independent shock acceleration parameters (electron energy index, magnetic field to proton and electron to proton energy ratios); g) only the forward shock radiation is taken into account. Of course, these are rough simplifications, however the model can fit relatively well the observational data. Relaxations of the above approximations were followed in the last few years. Such an interesting possibility is that the fireballs are collimated (Piran, 1999; van Paradijs et al., 2000). The achromatic steepening of the light curves could be interpreted as a confirmation of this kind of jetted geometry. If so, there are very important implications, for instance, on the energy budget, events rate, etc. and many of them are going to be addressed in this review.

It should be stressed out that the fireball model, the standard model of GRBs, is not complete. Many problems are unsolved and many others are explained only qualitatively in this framework. Despite these drawbacks, the fireball model seems to be the best tool we have as our challenge to decipher the mystery of the GRBs. No doubt, there are few good alternative models, some of them quite successful in explaining particular features of GRBs phenomenon. An incomplete list of schemes and ideas includes (Mészáros, 2002) precessing jets from pulsars (Blackman et al., 1996); cannonballs from supernovae (Dar & De Rújula, 2000a; Dar & De Rújula, 2000b; Dado et al., 2002; Dado et al., 2003a; Dar, 2003); jet-disk symbiosis in a binary system (Falcke & Biermann, 1995; Falcke & Biermann, 1999; Pugliese et al., 1999); magnetar bubble collapse (Gnedin & Kiikov, 2000); neutron star collapse to a strange star (Cheng & Dai, 1996); collapse to a black hole caused by accretion (Vietri et al., 2000) or by capture of a primordial black hole (Derishev et al., 1999); supermassive black hole formation (Fuller & Shi, 1998); evaporating black holes (e.g. Halzen et al., 1991).

The progenitors of GRBs are not yet well identified. The current view is that GRBs arise in a very small fraction of stars that undergo a catastrophic energy release event toward the end of their evolution. There are quite few possibilities (Mészáros, 2001). The hypernovae are massive rotating stars whose core collapse is expected to lead to a black hole accreting from a debris torus resulting in a GRB, as well as the ejection of a supernova remnant shell of energy above that of usual supernovae (Paczyñski, 1998). The collapsars are massive stars, which in the course of merging with a compact companion (in its original formulation, the model implied a unique massive star; Woosley, 1993) undergo core collapse leading to a black hole, some of which result in a GRB, leaving a supernova-like remnant (Fryer et al., 1999). The magnetars are ultra-high magnetic field ($B > 10^{15}$ G), fast rotating neutron stars, essentially super pulsars resulting in a GRB. They would be created by the collapse of a massive rotating star leaving a supernova remnant (Usov, 1994; Thompson, 1994; Spruit, 1999; Wheeler et al., 2000; Ruderman et al., 2000). A supranova is a massive star whose initial core collapse would lead to a neutron star and an ejected supernova remnant; this precedes by days to weeks a second collapse of the neutron star into a black hole, which leads to a GRB (Vietri et al., 2000). Neutron star binary and neutron star-black hole binary mergers also lead to a black hole accreting from a debris torus, which would be expected to give rise to a GRB of comparable energy to those from massive stars; supernova remnants from the formation of the initial neutron star or black hole would have occurred and dissipated long time before the GRB (Paczyñski, 1986; Goodman, 1986; Eichler et al., 1989; Mészáros &

Rees, 1997a; Mészáros & Wijers, 1999). In all these cases, strong magnetic fields and $e^{\pm}$, γ from ν anti-ν annihilation are expected to drive a jet-like relativistic outflow that leads to the standard shock production of GRB and afterglows (Paczyñski, 1998; Fryer et al., 1999; Mészáros & Rees, 1997a). In the massive progenitor cases, this would occur after the jet funnels through the stellar envelope, probably leading to a highly collimated jet, whereas in the neutron star binary or neutron star-black hole binary mergers the lack of an envelope might lead to substantially less collimation.

OBSERVATIONS

2.1. Prompt emission. Burst rate

The GRB detection rate for the BATSE-CGRO detector was about one per day during its operation period 1991-2000. Assuming no source evolution, this would correspond to roughly speaking one event per million years per galaxy (Cohen & Piran, 1995). If the GRBs are beamed, the rate increases by a factor depending on the opening angle and could become even five orders of magnitude greater for highly collimated jets (Rhoads, 1997).

2.2. Prompt emission. Duration

The duration of GRBs ranges from about 5 ms to almost 1000 s (Paciesas et al., 1999). The duration is defined as the time T_{90} (T_{50}) needed to accumulate from 5% to 95% (from 25% to 75%) of the counts in the 50-300 keV band. The distribution of burst duration (Fig. 2.1) is bimodal (Kouveliotou et al., 1993; Lamb et al., 1993; Mao et al., 1994; Fishman et al., 1994; Meegan et al., 1996; Paciesas et al., 1999). However, there are even hints for trimodality (Horvath, 1998).

2.3. Prompt emission. Morphology

The time profiles of GRBs exhibit pulse-like shapes of a great diversity (Fig. 2.2). Fishman & Meegan (1995) made an attempt to roughly classify them in four classes: a) single pulse or spike events; b) smooth, either single or multiple, well-defined peaks; c) distinct, well-separated episodes of emission; d) very erratic, chaotic and spiky bursts.

The variability of the γ ray emission can reach a scale as low as ms (Walker et al., 2000). This is actually a very good test for the multitude of models.

2.4. Prompt emission. Spectrum

One of the key feature of a GRB is its non-thermal spectrum. Most of the energy is emitted in the few hundred keV ranges (Fig. 2.3). Most of the spectra can be fitted well by a smoothly broken power-law at a break energy H (Band et al., 1993; Piran, 1999):

$$N(\nu) = N_0 \begin{cases} (h\nu)^{\alpha} e^{-\frac{h\nu}{E_0}}, & h\nu < H \\ [(\alpha-\beta)E_0]^{\alpha-\beta}(h\nu)^{\beta} e^{\beta-\alpha}, & h\nu > H \end{cases} \qquad (2.1)$$

where $H \equiv (\alpha-\beta)\, E_0$ is sometimes called hardness, α is a low energy power law photon index, β is a high energy power law photon index. The characteristic energy (i.e. where νF_ν has a peak) is $E_p=[(\alpha+2)/(\alpha-\beta)]\, H$. Generally $\alpha \approx -1$, $\beta \approx -2$, $E_p \approx 300$ keV (Preece et al., 2000). It should be stressed out that eq.(2.1) is just a phenomenological function with no physical meaning whatsoever. Recently, Lloyd-Ronning & Ramirez-Ruiz (2002) found a dependence of $E_p\,(1+z)$ on the GRB variability at a confidence level of 5σ, for 159 bursts. A similar correlation E_p-luminosity emerged from the work of Amati et al. (2002) on a sample of 12 GRBs. These preliminary conclusions were further supported by Wei (2002). An analysis of the different E_p predictions in various GRB models was made by Zhang & Mészáros (2002b). Simulations of internal shocks and analyses of the resulting dispersion of the break energy were carried out by Asano & Kobayashi (2003).

Despite the tentative proposals (e.g. Kazanas et al., 2002; Schaefer, 2003), the fact is that none of the current GRB models can reproduce the narrow E_p distribution found by Preece et al. (2000), including the well-discussed internal shock and external shock models (Zhang et al., 2002). However, the growing population of X-ray flashes (XRFs; Heise et al., 2001; Kippen et al., 2001) may broaden the real E_p distribution. But the nature of XRFs is uncertain; they could be dirty fireballs (Dermer et al., 1999), jetted GRBs seen at large viewing angles (Woosley et al., 2002), photospheric emission from GRBs (Mészáros et al., 2002), emission from internal shocks with small variations of the Lorrentz factors (Mochkovitch et al., 2003), and so on.

In many cases, due to the lack of data, the spectrum is fitted only in particular energy range and a simpler power law is used :

$$N(E)dE \propto E^{-\alpha}dE \qquad (2.2)$$

with α a power law index.

The spectrum of GRBs varies with time. Hardness-intensity and hardness-fluence correlation were found in the data, mainly from BATSE detector (Ford et al., 1995; Liang & Kargatis, 1996; Crider et al., 1999; Ryde & Svensson, 2002). There are also hints that the pulses are narrower at higher energies through a power law like relation (Fenimore et al., 1995).

2.5. Prompt emission. Spectral lines

Before the BATSE era various satellites reported observations of absorption and emission lines in few GRBs (Mazets et al., 1980; Mazets et al., 1981; Murakami et al., 1988; Murakami et al., 1990; Fenimore et al., 1988). In spite of this, more recent data from BATSE detector failed to support previous findings (Palmer et al., 1994; Band et al., 1996). In other words, there is no clear observational evidence for the existence of spectral features (Band et al., 1997).

2.6. Prompt emission. Angular distribution

One important question, and a possible key in understanding the GRB phenomenon, was whether the sources are concentrated near the galactic plane or not (the distance is implicitly involved here). BATSE addressed this issue and its findings (Fig. 2.4) were rather unexpected : the spatial distribution of long GRBs is almost perfectly isotropic (Meegan et al., 1992; Meegan et al., 1996; Fishman et al., 1994; Briggs et al., 1996; Paciesas et al., 1999); however, some anisotropies on small angular scales might be present (Mészáros & Stocek, 2003). There is circumstantial evidence for anisotropy in the distribution of the short-lived GRBs (Magliocchetti et al., 2003).

It was also clear that the number of weak GRBs is below that expected from a homogeneous distribution of sources in an Euclidean space, case in which the slope should have had a value of -3/2 (Fig. 2.5). We will show this further on, following Mao & Paczyñski (1992). It is assumed that the Universe is flat, with the vacuum energy density Ω_Λ=0 and that the GRBs are standard candles and exhibit no cosmic evolution. Then, the luminosity distance d_L is (Weinberg, 1972; Peebles, 1993; Hogg, 1999; Peacock, 2001):

$$d_L(z) = \frac{2c}{H}\left(1 + z - \sqrt{1+z}\right) = (1+z)r \tag{2.3}$$

where r is the distance source-observer, c is the speed of light, H is the Hubble constant and z is the redshift.

The observed flux is :

$$F \propto \frac{L(z)}{4\pi d_L^2(z)} \tag{2.4}$$

where L is the luminosity in the comoving frame.

The comoving volume within the redshift z is given by :

$$V(z) = \frac{4\pi}{3} r^3 \tag{2.5}$$

Every detector has a threshold, say F_{min}, so the sources can only be seen out to a maximum redshift z_{max}. We have from eq. (2.4):

$$F_{\min} \propto \frac{L(z_{\max})}{4\pi d_L^2(z_{\max})} \tag{2.6}$$

Consequently, we have a maximum comoving volume $V_{\max}(z_{\max})$. Obviously:

$$\frac{V(z)}{V_{\max}(z_{\max})} = \left(\frac{r}{r_{\max}}\right)^3 \tag{2.7}$$

and

$$\frac{F}{F_{\min}} \propto \left(\frac{r}{r_{\max}}\right)^2 \tag{2.8}$$

From eqs. (2.7) and (2.8) we have :

$$\frac{V}{V_{\max}} \propto \left(\frac{F_{\min}}{F}\right)^{\frac{3}{2}} \tag{2.9}$$

The number of bursts per unit time within the volume V is then :

$$N \propto V \propto F^{-\frac{3}{2}} \tag{2.10}$$

We have qualitatively shown that in the case of an Euclidean space, under the above mentioned assumptions, the slope in the log N - log P diagram should have been -3/2. The observed distribution is inconsistent with any galactic disk model, while the galactic halo model can be accommodated only with some unnatural hypotheses. This was another hint for the cosmological origin of GRBs.

2.7. Afterglow. Discovery

The GRB field was revolutionized on February 28, 1997, when BeppoSAX satellite discovered the first afterglow, a X-ray counterpart to GRB970228 (Fig. 2.6; Costa et al., 1997).

In the meantime, GRB970228 had also become the first GRB for which an optical counterpart was found (Fig. 2.7; Groot et al., 1997). Subsequent deep images (Sahu et al., 1997; Fruchter et al., 1999) confirmed that the burst was hosted by a distant galaxy at a redshift of 0.695 (Djorgovski et al., 1999). For a review on optical afterglows see Pian (2001).

The first detection of a radio afterglow happened for GRB970508 (Fig. 2.8; Frail et al., 1997). Initially, the radio flux underwent strong variations that damped out after about one month. These variations were interpreted as interstellar scintillation in our galaxy (Goodman, 1997). In this framework, the dying of the fluctuations reflects the increase in the size of the radio emitter. From these data, Frail et al. (1997) estimated the source size at the time the fluctuations disappeared. The conclusion was that the source expands relativistically, with a velocity close to the speed of light. So far, there are only about six relatively well-studied radio afterglows (Weiler et al., 2002). For a short description of the importance of radio afterglows see Berger (2003).

GRB970508 also holds the distinction of being the first GBR for which simultaneous multi-wavelength afterglow observations were available, from X-ray to radio (Galama et al., 1998a).

2.8. Afterglow. Light curve and spectrum

The afterglow light curves, in any domain, can be well fitted by power-laws (or segments of power-laws). An example of light curves together with the best fits (not necessarily power-laws) is given for different GRBs in Fig. 2.9.

Due to the lack of data, an extensive instantaneous spectrum of a GRB afterglow is quite difficult to obtain. However, it should look, more or less, like the one built for the historical GRB970508 (Fig. 2.10): piecewise connected power-laws.

2.9. Afterglow. Spectral lines

For the first time, absorption lines of FeII and MgII were observed in the optical afterglow of GRB970508 (Fig. 2.11; Metzger et al., 1997).

There is evidence for X-ray emission lines features in the early X-ray afterglow of about 5 GRBs: GRB970508 (Piro et al., 1999), GRB970828 (Yoshida et al., 2001), GRB991216 (Piro et al., 2000), GRB000214 (Antonelli et al., 2000), GRB011211 (Reeves et al., 2002). The statistical evidence of these detections is at the ~3σ level, with the exception of GRB991216 where the significance is ~4σ. The presence of lines was also suggested for GRB001025A and GRB010220 (Watson et al., 2002) and in the case of GRB990705 a transient absorption feature was observed (Amati et al., 2000). With the exception of GRB011211, the features were interpreted as iron lines. For GRB011211, emission lines of lighter elements (Mg, Si, S, Ar, Ca) seem to be present in the spectrum. But this particular detection is very controversial (Borozdin & Trudolyubov, 2003; Rutledge & Sako, 2003). However, the lines can be alternatively interpreted as highly blueshifted hydrogen lines, in the framework of the cannonball model (Dar & De Rújula, 2001; Dado et al., 2003b).

The duration of the line emission is not completely clear. Most of the lines have been observed to be active for about 10 hours (comoving time). Some lines disappeared during the observations, some remained constant while the continuum faded, and in some cases the observations were too short for any conclusion.

X-ray emission features are very important because can provide another way to put constraints on the total energy in GRBs, and may reveal information on the degree of collimation and the density of the medium surrounding the burst (Ghisellini et al., 2002; Lazzati, 2002).

2.10. Afterglow. Host galaxy

Up to this moment (end of 2002), plausible or certain host galaxies have been found for almost all of the burst with optical, radio, or X-ray afterglows localized with arcsecond precision (Djorgovski et al., 2001; Bloom et al., 2002a; Hurley et al., 2003). The GRBs hosts are typically low mass, faint galaxies (with the median apparent magnitude R~25) with active star formation regions (Bloom et al., 2002a; Le Floc'h et al., 2003). The morphology of the galaxies is normal, except for some cases in which there is evidence for tidal disturbances (Chary et al., 2002; Djorgovski et al., 2002; Hjorth et al., 2002).

Within the host galaxies, the distribution of GRBs is offset from the center (Fig. 2.12) and follows the light distribution (which is roughly proportional to the density of star formation) closely (Bloom et al., 2002a).

Host galaxies of GRBs are essential in determining the redshifts for the bursts. Starting with the first redshift determination which demonstrated the cosmological nature of (most of the) GRBs (Metzger et al., 1997), there are now, at the end of 2002, over 30 redshift measurements (e.g. Bloom et al., 2001; Bloom, 2003a; Le Floc'h et al., 2003;).

The median value for z is ≈1, spanning the range from 0.25 to 4.5. The majority of redshifts so far are from the host galaxies spectroscopy, but an increasing number are based on the absorption lines in the spectra of the afterglows (in optical so far).

2.11. Afterglow. GRB/SN connection

There is evidence that the long duration GRBs might be connected to underlying supernovae (SNe) explosions. The discovery of the unusual SN 1998bw (Galama et al., 1998b) in a nearby galaxy, within the error box of an under-energetic GRB980425 (Pian et al., 2000) suggested the first hint. Another indication came from the observation of a red excess in the afterglow of GRB980326 (Fig. 2.13; Bloom et al., 1999). But, the lack of a measured redshift for this GRB and the possibility of other explanations (e.g. Panaitescu et al., 1998; Piro et al., 1999; Waxman & Draine, 2000; Esin & Blandford, 2000; Reichart, 2001) made the identification of the "bump" uncertain. Further attempts to identify similar bumps in the afterglows of GRBs with known redshifts returned non-conclusive results (Price et al., 2003).

The clearest evidence for a GRB-SN association is represented by the spectroscopy of GRB030329 (Stanek et al., 2003), which showed a spectrum very similar to the one obtained for SN 1998bw.

One of the best case for a SN underlying a GRB comes from the observations of GRB011121 (Bloom et al., 2002b; Garnavich et al., 2003). A bump was discerned in the optical afterglow light curve, and near-IR and radio observations indicated a wind-like environment for the GRB (Price et al., 2002a).

There are other circumstantial pieces of evidence for underlying SNe in

GRB970228 (Reichart, 1999; Galama et al., 2000), GRB020405 (Price et al., 2002b), GRB990712 (Bjornsson et al., 2001), GRB980703 (Holland et al., 2001), GRB970508 (Sokolov, 2001), GRB980910 (Thorsett & Hogg, 1999; Rigon et al., 2003), GRB970514 (Germany et al., 2000).

2.12. Afterglow. Polarization

High levels of linear polarization are usually a signature of synchrotron radiation. The direction of polarization is perpendicular to the magnetic field and the degree of polarization can be as high as 75% (Rybicki & Lightman, 1979).

Gruzinov & Waxman (1999) and Medvedev & Loeb (1999) considered the emission from spherical ejecta, which by symmetry should produce no polarization on average, except for some fluctuations of order a few percent. The polarization enters the game more naturally if the ejecta are jetted and the line of sight is within the jet but doesn't coincide with its axis. In this case, the polarization produced by synchrotron radiation won't vanish because the symmetry is broken (Gruzinov, 1999; Ghisellini & Lazzati, 1999; Sari, 1999).

Varying polarization at optical wavelengths was observed in GRB afterglows at the level of a few percent (e.g. Covino et al., 1999; Wijers et al., 1999; Rol et al., 2000), up to almost 10% for GRB020405 (Bersier et al., 2003). So far (January 2003), there are only 27 polarization measurements for 9 GRBs (Covino et al., 2003).

In addition to the intrinsic polarization, second order polarization (e.g. as a result of microlensing or interstellar scintillation) is possible to appear and should be taken into account (Bjornsson, 2003).

2.13. Afterglow. Reverse shock emission

During the first minutes of a GRB, two shocks determine the behavior of the fireball: a forward shock interacting with the ISM and a reverse shock going into the expanding ejecta (Sari & Piran, 1995). The emission from the reverse shock has a typical frequency lower by a factor γ^2 than in the case of the forward shock, therefore peaks in the UV-optical band (Mészáros & Rees, 1997b; Sari & Piran, 1999a; Sari & Piran, 1999b). Such an optical flash is difficult to detect and separate from other emission components (Kobayashi & Sari, 2000; Kobayashi, 2000).

Akerlof et al. (1999) Reported the detection of a bright optical emission simultaneous with GRB990123. This event was interpreted as an optical flash produced by the reverse shock (Mészáros & Rees, 1999; Sari & Piran, 1999c).

More recent, an apparent rebrightening in the R-band light curve of GRB021004 was observed. Kobayashi & Zhang (2003) showed that the fireball model with both the emissions from the forward and reverse shocks taken into account is able to interpret well the observation. However, other explanations are possible (e.g. Lazzati et al., 2002).

Wei (2003) explained the afterglow light curve of GRB021211 (before the break) as a contribution of the emission of the reverse and forward shock. This might be the third case so far of a detected reverse shock from a GRB.

Reverse shock emission data can be in principle used to estimate the initial Lorentz factor of GRBs (e.g. Zhang et al., 2003).

THEORY

3.1. The compactness problem

The observed spectra of GRBs contain a large fraction of high-energy γ ray photons. These photons (with energies ε_1) could interact with lower energy (say ε_2) photons and produce electron-positron pairs $\gamma\gamma \rightarrow e^- e^+$ if $(\varepsilon_1 \varepsilon_2)^{1/2}$ $m_e c^2$. Since many photons have energies $\varepsilon_1 >> 1$ MeV, the above condition is fulfilled. The average optical depth for the pair creation process is (Guilbert et al., 1983; Carigan & Katz, 1992; Piran & Shemi, 1993) :

$$\tau \propto \frac{FD^2 \sigma_T}{R^2 m_e c^2} \tag{3.1}$$

with σ_T the Thompson cross section.

For an observed fluence F in the range $[10^{-8}, 10^{-4}]$ erg/cm^2, a compact cosmological source (D~10^9 pc) of size R~10^9 cm (assuming variability at 100 ms time scale) would have an optical depth τ more than ten orders of magnitude higher than unity. This implies that the photons are thermalized, which is inconsistent with the observed non-thermal spectra.

The most natural solution to this so called "compactness problem" is relativistic motion (Paczyñski, 1986; Goodman, 1986; Krolik & Pier, 1991). In this case relativistic effects will reduce the optical depth by a factor of $\sim \gamma^6$, depending on the GRB spectrum (γ is the Lorentz factor of the source moving toward the observer). Now, for γ larger than about 100, τ becomes smaller than 1 (Fenimore et al., 1993; Woods & Loeb, 1995; Baring & Harding, 1997; Lithwick & Sari, 2001). Such high values of the Lorentz factor are achievable, however the situation becomes complicated if the ejecta contains baryons (more than roughly 10^{-5} M), because they could slow down the fireball (Paczyñski, 1990; Shemi & Piran, 1990).

3.2. Internal and external shocks

The general picture states that the GRBs occur when an ultra-relativistic energy flow (in the form of kinetic energy of relativistic particles or Poynting flux) is converted to radiation in an optically thin region. Different approaches were discussed in the literature: kinetic energy dominated flow (Mészáros & Rees, 1992; Narayan et al., 1992; Mészáros & Rees, 1993; Rees & Mészáros, 1994; Katz, 1994a), kinetic energy and Poynting flux flow (Thompson, 1994), Poynting flux dominated flow (Katz, 1997; Usov, 1994; Usov & Smolsky, 1996; Mészáros & Rees, 1997a). In all cases the energy flow has to be in form of kinetic energy at some point, this energy being converted to internal energy through shocks and then radiated away. There are two possibilities for the energy conversion: external shocks (Rees & Mészáros, 1992; Mészáros & Rees, 1993) and internal shocks (Narayan et al., 1992; Rees & Mészáros, 1994). The most popular mechanisms by which the internal energy produced by shocks is converted to radiation is synchrotron and inverse Compton. Synchrotron emission seems to be preferred in the literature (Rees & Mészáros, 1994; Katz, 1994b; Sari et al., 1996; Sari & Piran, 1997a), the inverse Compton mechanism (Mészáros et al., 1993) being made responsible for a higher energy component (Mészáros et al., 1994; Mészáros & Rees, 1994). But alternatives scenarios or variations of the synchrotron model have been proposed (Ghisellini, 2003), such as Comptonization of low energy photons by thermal or quasi-thermal particles (Liang et al., 1997; Ghisellini & Celotti, 1999), Compton drag (Lazzati et al., 2000; Ghisellini et al., 2000), jitter radiation (Medvedev, 2000), synchrotron emission from particles with an anisotropic pitch angle distribution (Lloyd & Petrosian, 2000; Lloyd-Ronning & Petrosian, 2002), thin/thick synchrotron emission from a stratified region (Granot et al., 2000), synchrotron self-Compton or inverse Compton off photospheric photons (Mészáros & Rees, 2000). Comparisons of a synchrotron hypothesis for the MeV radiation with the data have been made (Tavani, 1996; Preece et al., 2000; Eichler & Levinson, 2000; Mészáros & Rees, 2000; Medvedev, 2000; Panaitescu & Mészáros, 2000; Lloyd & Petrosian, 2000; Ghirlanda et al., 2002), but a clear conclusion cannot be advanced. Recently, Coburn & Boggs (2003) reported the discovery of linear polarization in the prompt gamma-ray emission from GRB 021206, an important indication for synchrotron emission from relativistic electrons in strong magnetic fields.

In the external shocks scenario, the relativistic material is running into the ambient medium (ISM or stellar wind emitted earlier by the progenitor). The observed variability is attributed to inhomogeneities in the surrounding medium (e.g. Dermer & Mitman, 1999; Dermer & Mitman, 2003), but highly variable GRBs profiles cannot be reproduced (Sari & Piran, 1997b; Panaitescu & Mészáros, 1998; see however Dermer & Mitman, 2003 for a different view).

In the internal shock scenario, the inner engine is assumed to emit an irregular flow consisting of many shells that travel with various Lorentz factors, the fast moving ones catching up with the slower ones. Observed variability of the GRBs light curves is well accounted for by numerical calculations (Kobayashi et al., 1999, Daigne & Mochkovitch, 2000; Spada et al., 2000; Nakar & Piran, 2002). A potential problem for internal shocks is the radiative efficiency. As a bolometric parameter it's estimated to be in the range 10-30 %, higher values being obtained if the shells have very different Lorentz factors (Spada et al., 2000; Beloborodov, 2000; Kobayashi & Sari, 2001). In the BATSE energy range, the efficiency is around 5 %, no matter which is the dominant emission process, synchrotron or inverse Compton (Kumar, 1999; Spada et al., 2000; Panaitescu & Mészáros, 2000; Guetta et al., 2001).

3.3. Relativistic inelastic collisions

Following Piran (1999), let's consider a mass m_1 with the Lorentz factor γ_1 that catches up a slower mass m_2 having a Lorentz factor $\gamma_2 < \gamma_1$. They collide and form a single mass m with Lorentz factor γ. The equations for the conservation of energy and momentum are:

$$m_1\gamma_1 + m_2\gamma_2 = \left(m_1 + m_2 + \frac{E}{c^2}\right)\gamma \tag{3.2}$$

$$m_1\sqrt{\gamma_1^2 - 1} + m_2\sqrt{\gamma_2^2 - 1} = \left(m_1 + m_2 + \frac{E}{c^2}\right)\sqrt{\gamma^2 - 1} \tag{3.3}$$

where E is the internal energy generated in the collision (in the rest frame of mass m).

We have from eqs. (3.2) and (3.3):

$$\gamma \approx \sqrt{\frac{m_1\gamma_1 + m_2\gamma_2}{\dfrac{m_1}{\gamma_1} + \dfrac{m_2}{\gamma_2}}} \tag{3.4}$$

which for m_1 m_2 becomes γ $(\gamma_1\gamma_2)^{1/2}$.

The internal energy in the observer frame is:

$$E_{int} = \gamma E = m_1c^2(\gamma_1 - \gamma) + m_2c^2(\gamma_2 - \gamma) \tag{3.5}$$

The conversion efficiency of kinetic energy into internal energy is:

$$\varepsilon = 1 - \frac{(m_1 + m_2)\gamma}{m_1\gamma_1 + m_2\gamma_2} \tag{3.6}$$

For m_1 m_2 we obtain:

$$\varepsilon = 1 - \frac{2\sqrt{\gamma_1\gamma_2}}{\gamma_1 + \gamma_2} \tag{3.7}$$

It can be seen that for a high efficiency we need m_1 m_2 and $\gamma_1 >> \gamma_2$. This is a toy model for the case of internal shocks.

For an external shock, consider the mass m_2 at rest ($\gamma_2 = 1$). If we require that E $m_1/2$ and γ $\gamma_1/2$, then m_2 m_1/γ_1. That is, the external mass needed to convert half of the kinetic energy is smaller than the original mass by a factor of γ_1.

3.4. Synchrotron radiation from relativistic shocks

Consider a shock propagating into a medium. The particle number density is n_1 for the pre-shock region and n_2 for the post-shock region. e and γ are the internal energy density and the Lorentz factor of the shocked material respectively, relative to the rest frame of the material in the pre-shock region. For the ultra-relativistic case ($\gamma >> 1$), the jump conditions read (De Hoffmann & Teller, 1950; Blandford & McKee, 1976):

$$n_2 \approx 4\gamma n_1 \tag{3.8}$$

$$e \approx 4\gamma^2 n_1 m_p c^2 \tag{3.9}$$

where m_p is the proton mass and c is the speed of light in vacuum.

In a GRB, the situation is actually slightly more complicated than in the simple case above, because two shocks form. Therefore in order to avoid any confusion, we will define γ_{sh}, that is the Lorentz factor of the shock, measured relative to a rest frame in which the unshocked material is at rest.

To characterize the synchrotron emission two dimensionless parameters ε_B and ε_e are defined:

$$\varepsilon_B = \frac{U_B}{e} \tag{3.10}$$

where $U_B=B^2/8\pi$ is the magnetic field energy density.

$$\varepsilon_e = \frac{U_e}{e} \tag{3.11}$$

where U_e is the energy density that goes into random motion of the electrons.

Using the shock jump conditions eqs. (3.8) and (3.9), we obtain for the magnetic field the expression:

$$B = \gamma_{sh} c \sqrt{32\pi\varepsilon_B n_1 m_p} \tag{3.12}$$

It is assumed that the electrons are accelerated by the shock into a power-law distribution (Krymskii, 1977; Bell, 1978a; Bell, 1978b; Blandford & Ostriker, 1978; Axford et al., 1978):

$$N(\gamma_e)d\gamma_e = C\gamma_e^{-p}d\gamma_e\ , \qquad \gamma_{min} \le \gamma_e \le \gamma_{max} \tag{3.13}$$

where N is the number density of electrons, γ_e is the random electron Lorentz factor, C is a proportionality constant, p is a power-law index. The lower cutoff γ_{min} of this distribution is determined by the value of ε_e and gives:

$$\gamma_{\min} \approx \frac{p-2}{p-1}\frac{m_p}{m_e}\varepsilon_e\gamma_{sh} \tag{3.14}$$

The maximum Lorentz factor γ_{max} can be obtained through the equality between the acceleration time (t'_{acc}) and the synchrotron cooling time (t'_{syn}) in the comoving frame.

$$t'_{acc} \propto \frac{cR_L}{\varepsilon_B^2} \tag{3.15}$$

$$t'_{syn} = \frac{\gamma_e m_e c^2}{P_{syn}} \tag{3.16}$$

with R_L the Larmor radius, P_{syn} the power emitted due to synchrotron radiation in the local frame.

We have in the ultra-relativistic limit (Rybicki & Lightman, 1979; Longair, 1981):

$$P_{syn} = \frac{4}{3}\sigma_T c U_B \gamma_e^2 \tag{3.17}$$

where $\sigma_T = (8\pi q_e^4)/(3m_e^2c^4)$ is the Thompson cross section.

Finally, we get:

$$\gamma_{max} \propto \sqrt{\frac{24\pi\varepsilon_B^2 q_e \gamma_{sh}}{B\sigma_T}} \tag{3.18}$$

The characteristic energy of the synchrotron photon emitted by an electron with the Lorentz factor γ_e is (in the observer frame):

$$h\nu = \gamma_e^2\gamma_{sh}\frac{\hbar q_e B}{m_e c} \tag{3.19}$$

The integrated synchrotron spectrum can be described using a number of parameters: the power-law index of the electron distribution p, the total peak flux F_{max} and three characteristic frequencies ν_m, ν_c, ν_a (e.g. Sari & Piran, 1999a).

ν_m is the synchrotron frequency of the minimum electron energy $\nu_m \equiv \nu(\gamma_{min})$. In the observer frame it reads:

$$\nu_m = (1+z)^{-1}\varepsilon_e^2\varepsilon_B^{1/2}\gamma_{sh}^4 n_1^{1/2} \tag{3.20}$$

A critical Lorentz factor describing an electron that cools on a hydrodynamic time scale can be defined:

$$\gamma_c = \frac{3m_e c}{4\sigma_T U_B \gamma_{sh} t} \tag{3.21}$$

Correspondingly, a so-called cooling frequency can be written $\nu_c \equiv \nu(\gamma_c)$:

$$\nu_c = (1+z)\varepsilon_B^{-3/2}\gamma_{sh}^{-4} n_1^{-3/2} t^{-2} \tag{3.22}$$

Below a particular frequency ν_a, the synchrotron radiation is self-absorbed. Simply speaking there are two cases:

$$\nu_a = (1+z)^{-13/5}\varepsilon_B^{6/5}\gamma_{sh}^{28/5} n_1^{9/5} t^{8/5} \qquad \text{for} \quad \nu_c < \nu_m \tag{3.23}$$

$$\nu_a = (1+z)^{-8/5}\varepsilon_e^{-1}\varepsilon_B^{1/5}\gamma_{sh}^{8/5} n_1^{4/5} t^{3/5} \qquad \text{for} \quad \nu_c > \nu_m \tag{3.24}$$

The integrated synchrotron spectrum is split in two, relative to the way in which the electrons cool (Fig. 3.1). We discern a fast cooling regime for $\gamma_c < \gamma_{min}$ and a slow one for $\gamma_c > \gamma_{min}$ (Sari et al., 1998; Piran, 1999; Piran, 2000). In the first case the spectrum is (in the observer frame):

$$F_\nu \propto \begin{cases} \left(\nu\nu_c^{-1}\right)^{1/3}, & \nu_c > \nu \\ \left(\nu\nu_c^{-1}\right)^{-1/2}, & \nu_m > \nu > \nu_c \\ \left(\nu_m\nu_c^{-1}\right)^{-1/2}\left(\nu\nu_m^{-1}\right)^{-p/2}, & \nu > \nu_m \end{cases} \tag{3.25}$$

In the second case the spectrum becomes (still in the observer frame):

$$F_\nu \propto \begin{cases} \left(\nu\nu_m^{-1}\right)^{1/3}, & \nu_m > \nu \\ \left(\nu\nu_m^{-1}\right)^{-(p-1)/2}, & \nu_c > \nu > \nu_m \\ \left(\nu_c\nu_m^{-1}\right)^{-(p-1)/2}\left(\nu\nu_c^{-1}\right)^{-p/2}, & \nu > \nu_c \end{cases} \tag{3.26}$$

The evolution of the spectrum as a function of time depends on the hydrodynamics, that is on the variations of the Lorentz factor γ_{sh} with time and the pre-shock particle density n_1 with the distance from the center of the "explosion" (Sari et al., 1998; Piran, 1999; Granot et al., 2000; Hurley et al., 2003). Under adiabatic conditions, in a homogeneous environment we have:

$$\nu_m = (1+z)^{1/2} E^{1/2} \varepsilon_e^2 \varepsilon_B^{1/2} t^{-3/2} \tag{3.27}$$

$$\nu_c = (1+z)^{-1/2} E^{-1/2} \varepsilon_B^{-3/2} n_1^{-1} t^{-1/2} \tag{3.28}$$

$$\nu_a = (1+z)^{-1} E^{1/5} \varepsilon_e^{-1} \varepsilon_B^{1/5} n_1^{3/5} \tag{3.29}$$

An adiabatic evolution in circumstellar surroundings (Chevalier & Li, 1999) yields the frequencies:

$$\nu_m = (1+z)^{1/2} E^{1/2} \varepsilon_e^2 \varepsilon_B^{1/2} t^{-3/2} \tag{3.30}$$

$$\nu_c = (1+z)^{-3/2} E^{1/2} \varepsilon_B^{-3/2} A_*^{-2} t^{1/2} \tag{3.31}$$

$$\nu_a = (1+z)^{-2/5} E^{-2/5} \varepsilon_e^{-1} \varepsilon_B^{1/5} A_*^{6/5} t^{-3/5} \tag{3.32}$$

where $A_* = n_1 m_p r^2$, with r the distance from the center of the blast.

Taking the simple case of a uniform ambient medium, ν_c decreases more slowly with time than ν_m (Fig. 3.1). A transition fast cooling-slow cooling takes place at a given time t_t, when $\nu_c = \nu_m$. Considering an observed frequency ν, two critical times, t_c and t_m can be defined, when the frequencies ν_c and ν_m cross the frequency ν (Piran, 1999):

$$t_c = \begin{cases} \varepsilon_B^{-3} E^{-1} n_1^{-2} \nu^{-2} \quad , & \text{adiabatic regime} \\ \varepsilon_B^{-21/4} E^{-2} n_1^{-13/4} \nu^{-7/2} \gamma^2 \quad , & \text{radiative regime} \end{cases} \tag{3.33}$$

$$t_m = \begin{cases} \varepsilon_B^{1/3} \varepsilon_e^{4/3} E^{1/3} \nu^{-2/3} \quad , & \text{adiabatic regime} \\ \varepsilon_B^{7/24} \varepsilon_e^{7/6} E^{1/3} n_1^{-1/24} \nu^{-7/12} \gamma^{-1/3} \quad , & \text{radiative regime} \end{cases} \tag{3.34}$$

where γ is the initial Lorentz factor.

The critical frequency $\nu_0 = \nu_c(t_t) = \nu_m(t_t)$ is:

$$\nu_0 = \begin{cases} \varepsilon_B^{-5/2} \varepsilon_e^{-1} E^{-1} n_1^{-3/2} \quad , & \text{adiabatic regime} \\ \varepsilon_B^{-19/10} \varepsilon_e^{-2/5} E^{-4/5} n_1^{-11/10} \gamma^{4/5} \quad , & \text{radiative regime} \end{cases} \tag{3.35}$$

The high frequency light curve (i.e. $\nu > \nu_0$; $t_t > t_m > t_c$) and the low frequency light curve (i.e. $\nu < \nu_0$; $t_t < t_m < t_c$) are represented in Fig. 3.2.

More detailed calculations of the synchrotron emission were carried out by Gruzinov & Waxman (1999), Granot et al. (1999a), Granot et al. (1999b), Granot et al. (2000), Granot & Sari (2002).

3.5. Inverse Compton (IC) radiation

IC emission might be an important component of the radiation from a GRB (afterglow). Multiple IC scattering of order higher than 2 of the same photon are suppressed by the Klein-Nishina effect (Heitler, 1954) and therefore are unimportant (Panaitescu & Kumar, 2000). The importance of IC depends on the Comptonization parameter Y (Rybicki & Lightman, 1979). We have (Sari et al., 1996; Sari & Esin, 2001):

$$Y = \frac{L_{IC}}{L_{syn}} = \frac{U_{rad}}{U_B} = \frac{U_{syn}}{U_B} = \frac{\eta U_e}{U_B(1+Y)} = \frac{\eta \varepsilon_e}{\varepsilon_B(1+Y)} \tag{3.36}$$

where L_{IC} is the IC luminosity, L_{syn} is the synchrotron luminosity, U_{rad} is the energy density in soft radiation (i.e. synchrotron), U_{syn} is the energy density of synchrotron radiation, η is the fraction of the electron energy that was radiated via synchrotron and IC emission.

Solving the above equation, the solution is:

$$Y = \begin{cases} \dfrac{\eta\varepsilon_e}{\varepsilon_B}, & \dfrac{\eta\varepsilon_e}{\varepsilon_B} << 1 \\ \left(\dfrac{\eta\varepsilon_e}{\varepsilon_B}\right)^{1/2}, & \dfrac{\eta\varepsilon_e}{\varepsilon_B} >> 1 \end{cases} \tag{3.37}$$

with $\eta = (\gamma_c/\gamma_m)^{2-p}$ (γ_m is the Lorentz factor corresponding to the synchrotron frequency ν_m) for slow cooling and $\eta=1$ for fast cooling (Sari & Esin, 2001).

Afterglow observations showed that in many GRBs $\varepsilon_e > \varepsilon_B$ (e.g. Wijers & Galama, 1999; Granot et al., 1999b; Panaitescu & Kumar, 2002), so Y>1, therefore at least in the early phases, the IC emission should be taken into account (especially for the reverse shock).

Typical IC photons would have the energy, in the observer frame (assuming synchrotron self-Compton conditions):

$$h\nu = \gamma_e^4 \gamma_{sh} \frac{\hbar q_e B}{m_e c} \tag{3.38}$$

3.6. Dynamics of the blast wave

We consider the case of a slowing down relativistic shell through repeated inelastic collisions between the shell itself and the external mass. The total energy (kinetic and internal) of the burst is (Panaitescu et al., 1998):

$$E = (\gamma - 1)(M_0 + m)c^2 + (1 - \varepsilon)\gamma U \tag{3.39}$$

where γ is the Lorentz factor of the shell, M_0 is the rest mass of the shell, m is the swept-up mass, ε is the radiative efficiency (i.e. the fraction of the post-shock generated internal energy that is radiated away), U is the internal energy.

The radiated energy is (Blandford & McKee, 1976):

$$dE_{rad} = \varepsilon\gamma(\gamma - 1)c^2 dm \tag{3.40}$$

The internal energy reads (Huang et al., 1999):

$$U = (\gamma - 1)mc^2 \tag{3.41}$$

Since dE = $-dE_{rad}$ we finally have (Huang et al., 1999; Huang et al., 2000a):

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_0 + \varepsilon m + 2(1 - \varepsilon)\gamma m} \tag{3.42}$$

In the radiative case (ε=1), the above equation has the solution (Blandford & McKee, 1976):

$$\frac{(\gamma - 1)(\gamma_0 + 1)}{(\gamma + 1)(\gamma_0 - 1)} = \left(\frac{m_0 + M_0}{m + M_0}\right)^2 \tag{3.43}$$

where γ_0 and m_0 are initial values of γ and m, usually assumed to be given by $\gamma_0 \sim \eta/2$, $m_0 \sim M_0/\eta$, with $\eta \equiv E_0/(M_0c^2)$; E_0 is the initial total energy (Waxman, 1997).

For the ultra-relativistic case, in a uniform ambient medium, we obtain $\gamma \propto r^{-3}$, r being the radius of the blast wave. In the non-relativistic limit, $\beta \propto r^{-3}$, consistent with the expansion of a supernova remnant (Spitzer, 1968).

In the adiabatic case (ε=0), the solution is (Huang et al., 1999):

$$(\gamma - 1)M_0c^2 + (\gamma^2 - 1)mc^2 \equiv E_{ini} \tag{3.44}$$

where E_{ini} is the initial value of E. In the ultra-relativistic limit, we get for a uniform surrounding medium $\gamma \propto r^{-3/2}$, while for the non-relativistic limit, $\beta \propto r^{-3/2}$, consistent with the Sedov solution (Sedov, 1969).

3.7. Jets in GRBs. Terminology

The jets are present in many astrophysical phenomena, such as young stellar objects, microquasars, blazars, active galactic nuclei, and the list could continue (e.g. Mirabel & Rodriguez, 1999; Ghisellini & Celotti, 2002). In this context, the speculation that jets may appear in GRBs also was quite natural (Paczyñski, 1993).

The notion jet has two different meanings: geometrical and relativistic (Piran, 2000; Hurley et al., 2003). In the first case we are dealing with a relativistic flow of matter intrinsically collimated into an angle θ. In the other case, a reference to a relativistic effect is made: the radiation from a source that radiates (isotropically in the comoving frame) and moves with a Lorentz factor γ toward the observer, is beamed into an angle γ^{-1} around the direction of motion (Rybicki & Lightman, 1979).

The angular size of a causally connected region is γ^{-1}, therefore as long as $\gamma^{-1} < \theta$ the equations describing the dynamics of a spherical ejecta still holds locally. But, once γ^{-1} θ, a change is expected in the dynamics: sideways expansion (with the Lorentz factor decreasing exponentially with radius), assumed to take place (in the comoving frame) with the speed of light c (Sari et al., 1999), the sound speed c_s $3^{-1/2}c$ (Rhoads, 1997; Rhoads, 1999), or close to the sound speed (Huang et al., 2000a).

As a consequence, an achromatic break will appear in the light curve (when $\gamma^{1} < \theta$ there is a balance between the dimming of the surface brightness of the jet and an increasing in the observed emitting area; as soon as $\gamma^{-1} = \theta$ and later on when $\gamma^{-1} > \theta$, the emitting area, limited by the size of the cone, stays constant).

3.8. Jets in GRBs. Consequences of the jet hypothesis

Writing the observed specific flux in a general form $F_\nu \propto t^\alpha \nu^\beta$, the isotropic energy (i.e. the same amount of energy in all directions) in the comoving frame is (Weinberg, 1972; Peebles, 1993; Hogg, 1999; Berger et al., 2003):

$$E_{iso} = 4\pi d_L^2 f (1+z)^{\alpha-\beta-1} \tag{3.45}$$

where f is the observed fluence. The resulting energies for GRBs are huge, ranging from 10^{51} up to 10^{54} erg. But if the energy is emitted in some solid angle (a jet), the situation is different. Let's say we have an angular distribution of energy dE/dΩ'.

In the isotropic case we can write:

$$E_{iso} = 4\pi \frac{dE}{d\Omega'} \tag{3.46}$$

Assuming a conical collimated flow, with the half-opening angle θ_j, we have:

$$E_{\mathrm{jet}} = \Omega \frac{dE}{d\Omega'} \tag{3.47}$$

and in spherical coordinates, $d\Omega = \sin\theta \, d\theta \, d\phi$ and represents the solid angle of the jet.

From the above equations, we can infer a simple relation between the energies in the presence of a jet and in the isotropic case:

$$E_{\mathrm{jet}} = E_{\mathrm{iso}} \frac{\Omega}{4\pi} \tag{3.48}$$

It is obvious, that in the case of jetted ejecta, the "true" energy (E_{jet}) is few orders of magnitude lower than under the isotropic assumption.

We have further on:

$$\Omega = 2 \int_0^{\theta_j} \int_0^{2\pi} \sin\theta \, d\theta \, d\phi \tag{3.49}$$

The factor 2 is coming from the fact that there are actually two jets oriented in opposite directions.

The result is:

$$\Omega = 2\pi(1 - \cos\theta_j) \tag{3.50}$$

and since $\cos\theta_j$ $1-\theta_j^2/2$, we get:

$$\Omega \approx 2\pi\theta_j^2 \tag{3.51}$$

Hence (Rhoads, 1997; Frail et al., 2001):

$$E_{\mathrm{jet}} \approx E_{\mathrm{iso}} \frac{\theta_j^2}{2} \tag{3.52}$$

An important parameter in the study of GRBs is the event rate. Present estimations give a value between one and 10 bursts per galaxy at every million years (Piran, 1999; Schmidt, 1999; Schmidt, 2001). But, if the emission is collimated, then the true event rate is higher by a factor $4\pi/\Omega$ (Rhoads, 1997).

3.9. Jets in GRBs. The jet break

The achromatic break in the power-law decay of the afterglow emission is interpreted as a signature of a jet (Rhoads, 1999; Sari et al., 1999). As mentioned before, this break is an edge effect combined with the lateral expansion of the collimated flow (Rhoads, 1999; Panaitescu & Mészáros, 1999; Mészáros & Rees, 1999; Moderski et al., 2000). However, other mechanisms can produce steep declines in the afterglow light curves: a sudden drop in the external density (Kumar & Panaitescu, 2000b), a transition from relativistic to non-relativistic regime (Wang et al., 2000), a break in the power-law distribution of radiating electrons (Li & Chevalier, 2001).

The break time, for adiabatic evolution in constant density medium, is given by (Rhoads, 1999; Sari et al., 1999; Panaitescu & Kumar, 2001b; Panaitescu & Kumar, 2002):

$$t_j \approx (1+z) E^{1/3} n_1^{-1/3} \theta_j^2 \tag{3.53}$$

where E is the jet energy, n_1 is the external medium density, θ_j is the half opening angle.

The synchrotron spectrum and the light curve are different in the case of jetted emission (Sari et al., 1999). The break frequencies evolve as $\nu_m \propto t^{-2}$, $\nu_c \propto t^0$, $\nu_a \propto t^{-1/5}$. We have for collimated ejecta:

$$F_\nu \propto \begin{cases} \nu^2 t^0 \quad , & \nu < \nu_a \\ \nu^{1/3} t^{-1/3} \quad , & \nu_a < \nu < \nu_m \\ \nu^{-(p-1)/2} t^{-p} \quad , & \nu_m < \nu < \nu_c \\ \nu^{-p/2} t^{-p} \quad , & \nu > \nu_c \end{cases} \tag{3.54}$$

3.10. Jets in GRBs. Observational evidence

There are about a dozen well observed afterglows with known redshifts for which a break was observed in the light curve and allowed the calculation of the jet opening angle (Huang et al., 2000b; Panaitescu & Kumar, 2001b; Frail et al., 2001; Panaitescu & Kumar, 2002; Berger et al., 2003).

Panaitescu & Kumar (2001a, 2001b, 2002) modeling the broad-band emission of up to ten well studied afterglows found that the jet kinetic energies after the GRB phase are within one decade around 5×10^{50} erg, while the energy released in gamma-rays (even after correcting for collimation) has a larger dynamical range, more than one order of magnitude; the half opening angles range from 2° to 20°, most of them being narrower than 10°.

On the other hand, Frail et al. (2001) using 17 GRBs afterglows with known redshifts found that the gamma-ray energy release (corrected for jetted emission) is tightly clustered around 5×10^{50} erg (Fig. 3.3). They also confirmed the "predisposition" of half opening angles for small values, with a concentration near 4°. A more recent analysis was performed by Bloom et al. (2003b), with compatible results.

Berger et al. (2003) analysing a sample of 41 X-ray GRBs afterglows reported a strong clustering (with a dispersion of only a factor of 2) of the corrected X-ray luminosities suggesting a narrow distribution of the blast wave kinetic energy in the afterglow phase (Fig. 3.4).

It seems that the GRBs produce a similar amount of energy and the broad range of fluence and luminosity observed appears to be the result of a wide variation of opening angles. However, Postnov et al. (2001), Rossi et al. (2002) and Zhang & Mészáros (2002a) pointed out that another interpretation is possible: instead of a variety of jets with different opening angles, a standard jet can be invoked, with energy density per unit solid angle falling away from the axis as some function (e.g. a power-law); this way, the differences in the apparent opening angle come from variations in the orientation of the observer relative to the axis of the jet.

3.11. Jets in GRBs. Structured jets

Most GRBs jet models consider an outflow that is uniform within some finite, well defined opening angle around its symmetry axis, and where the Lorentz factor and energy density drop sharply beyond this opening angle (Rhoads, 1997; Rhoads, 1999; Panaitescu & Mészáros, 1999; Sari et al., 1999; Kumar & Panaitescu, 2000a; Moderski et al., 2000; Granot et al., 2002). Such a uniform jet is referred to as a "top hat jet" or "uniform jet". The possibility that GRBs jets can display an angular structure, where the kinetic energy per unit solid angle and the Lorentz factor vary as a power-law with respect to the jet axis, was proposed by Mészáros et al. (1998). This kind of outflow is referred to as "structured jet" or "anisotropic jets".

While the evolution of top hat jets and their light curves have been widely investigated, much less work has been done on structured jets (Postnov et al., 2001; Dai & Gou, 2001; Rossi et al., 2002; Zhang & Mészáros, 2002a; Ramirez-Ruiz & Lloyd-Ronning, 2002; Wei & Jin, 2003; Granot & Kumar, 2002; Panaitescu & Kumar, 2003; Granot et al., 2003; Kumar & Granot, 2003; Perna et al., 2003).

CONCLUSIONS

What is the source of a GRB (i.e. the progenitor)? Is there a connection between GRBs and SNe? Are we dealing with spherical or/and collimated “explosions”? Can the GRBs be made responsible for certain components of the cosmic rays population? What is the microphysics at work in a GRBs (e.g. with respect to the acceleration mechanisms, radiation processes)? How important is the magnetic field and what is its structure (tangled, large scale)?

These are just few questions that remain unanswered for the moment. The last years witnessed a real boom in deciphering the complex GRB phenomenon and the efforts towards a better understanding seem to become more concentrated, day by day. Much hope and excitement are channeled on the account of the future dedicated space missions, such as SWIFT, scheduled for launch at the end of 2003. Nevertheless, the GRBs have still many secrets to reveal and perhaps some surprises are just around the corner. Along with the answers, other questions emerge. It is the nature…

Acknowledgements. V.T. was partially supported by a Socrates-Erasmus Scholarship, by the AUGER grant to P.L.B. and by the MPIfR.

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FIGURES CAPTION

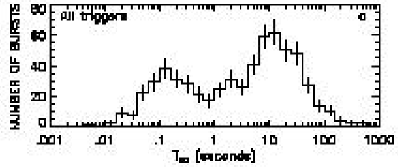
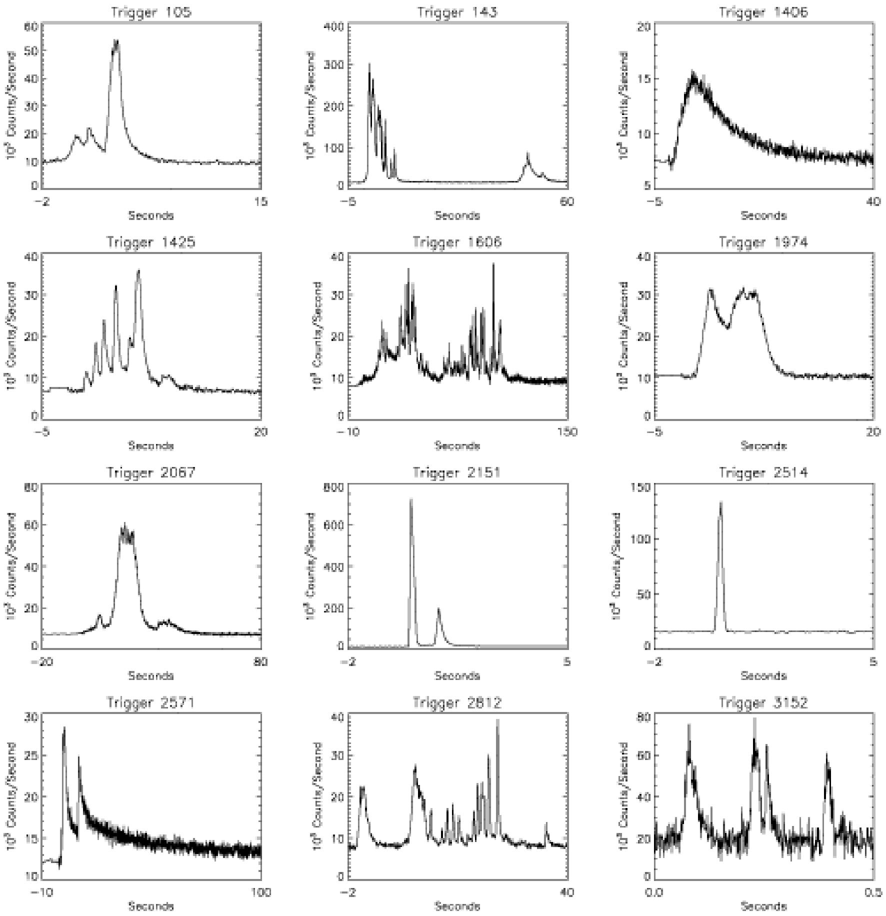


Fig. 2.1.- The duration distribution of GRBs from the forth BATSE catalog. From Paciesas et al., 1999.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Trigger 143
Trigger 1406
Trigger 1425
Trigger 1606
Trigger 1974
Trigger 2067
Trigger 2151
Trigger 2514
Trigger 2571
Trigger 2812
Trigger 3152
10^3 Counts/Second
Seconds
0
10
20
30
40
50
60
100
200
300
400
600
800
150
5
15
25
80
-2
-5
-10
-20
0.0
0.5

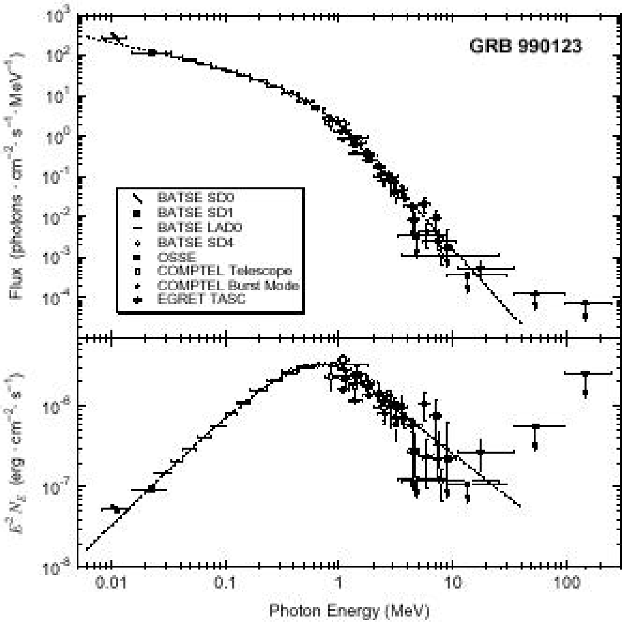


Fig. 2.3. The spectrum of GRB990123. From Briggs et al., 1999.

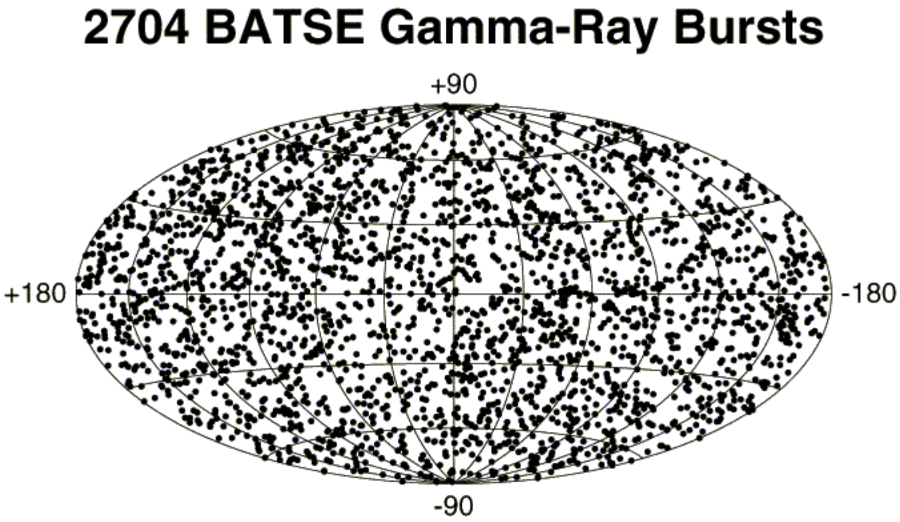


Fig. 2.4. The distribution of 2704 GRBs as seen by BATSE-CGRO. Credit BATSE team.

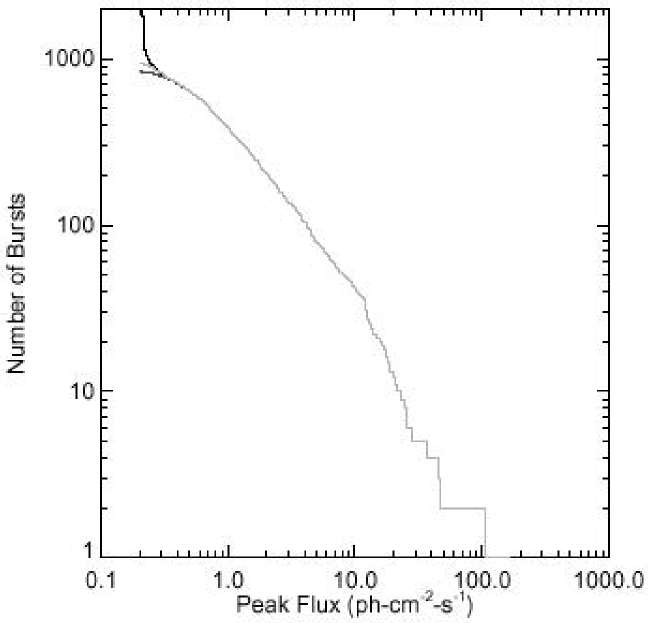


Fig. 2.5. 4BATSE catalog log N - log P distributions for 50-300 keV energy range and 1024 ms triggering time scale. From Paciesas et al., 1999.

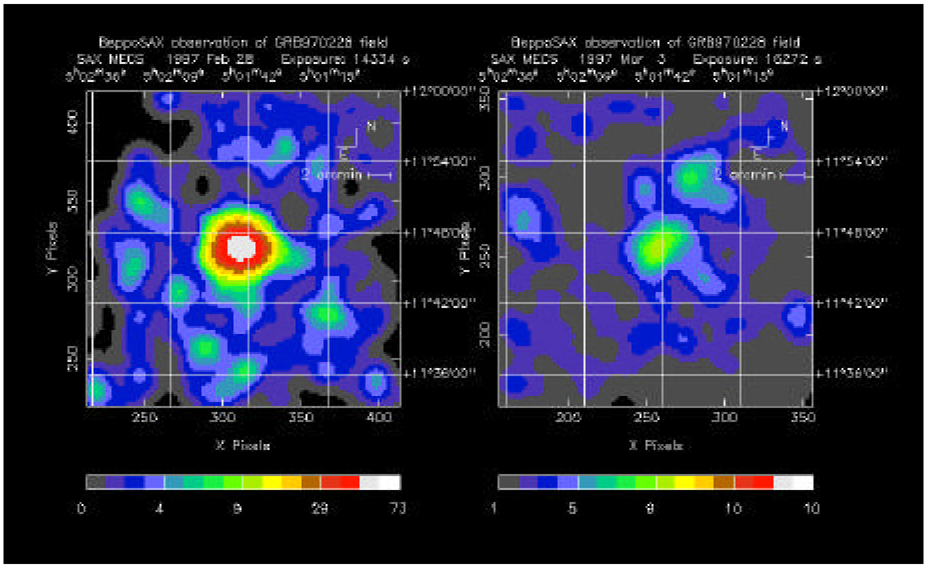


Fig. 2.6. Discovery images of the X-ray afterglow of GRB970228. From Costa et al., 1997.

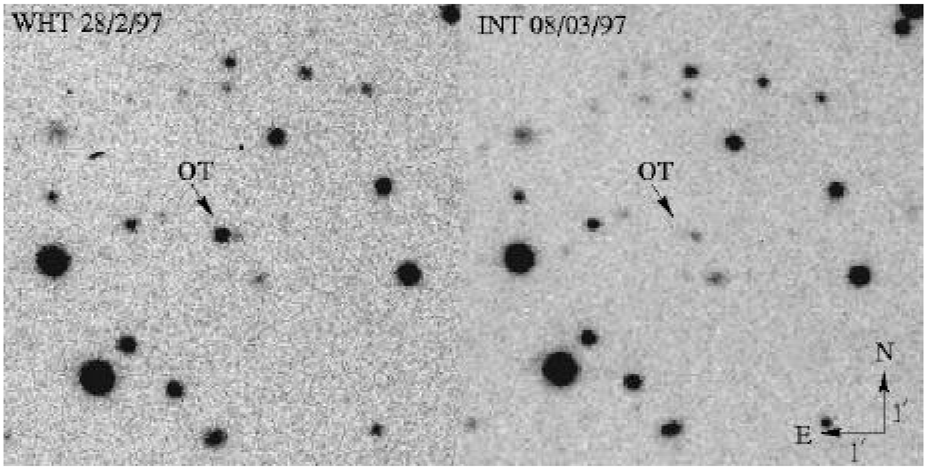


Fig. 2.7. Discovery images of the optical afterglow of GRB970228. From Groot et al., 1997.

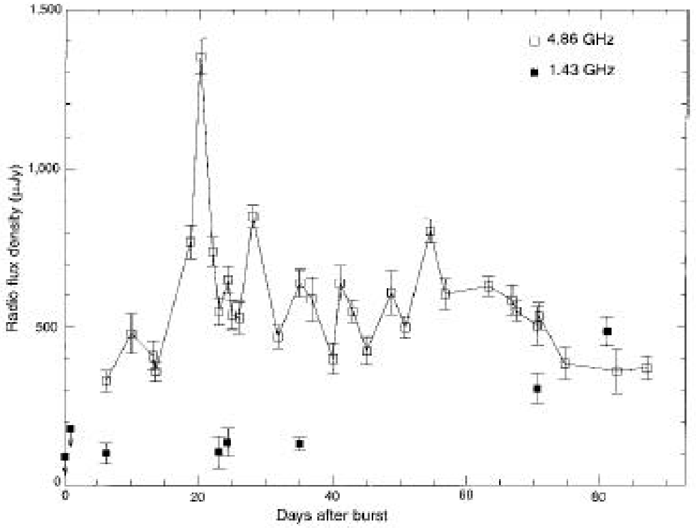


Fig. 2.8. Radio variations of the afterglow of GRB970508. From Frail et al., 1997.

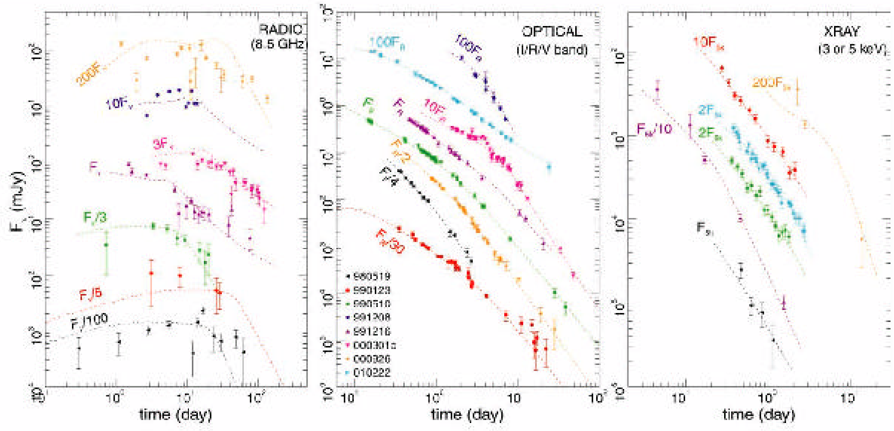


Fig. 2.9. Afterglow light curves in three bands for various GRBs. From Panaitescu & Kumar, 2001b.

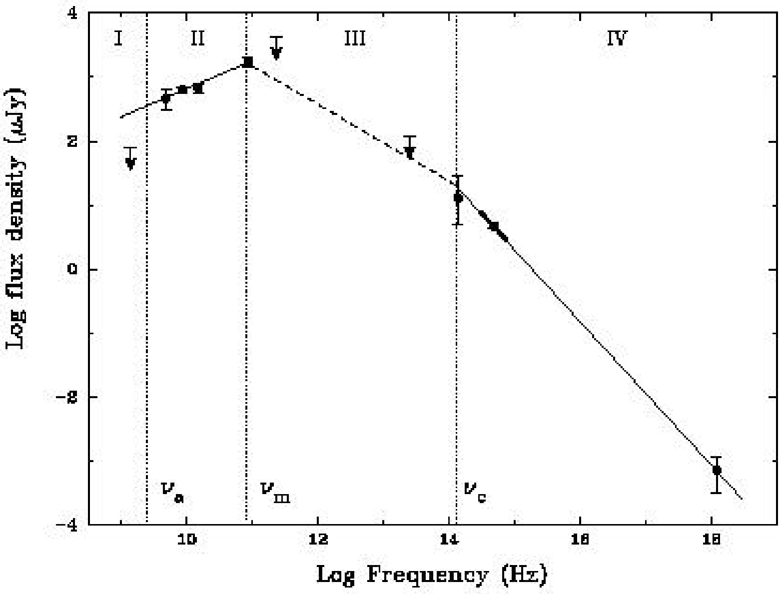


Fig. 2.10. The spectrum of the afterglow of GRB970508, 12 days after trigger. From Galama et al., 1998a.

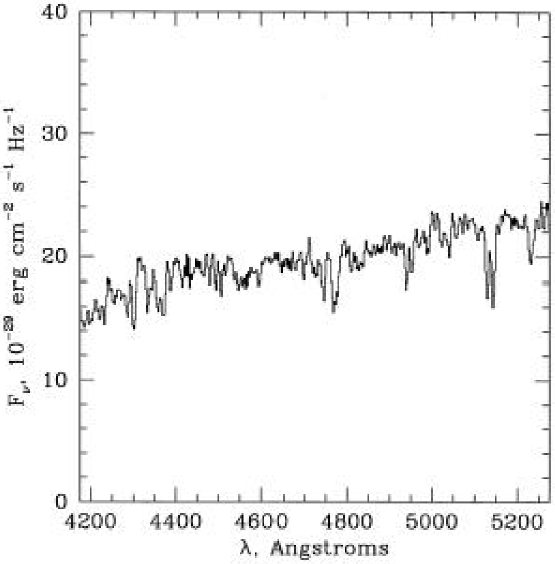


Fig. 2.11. The spectrum of the optical afterglow of GRB970508. From Metzger et al., 1997.

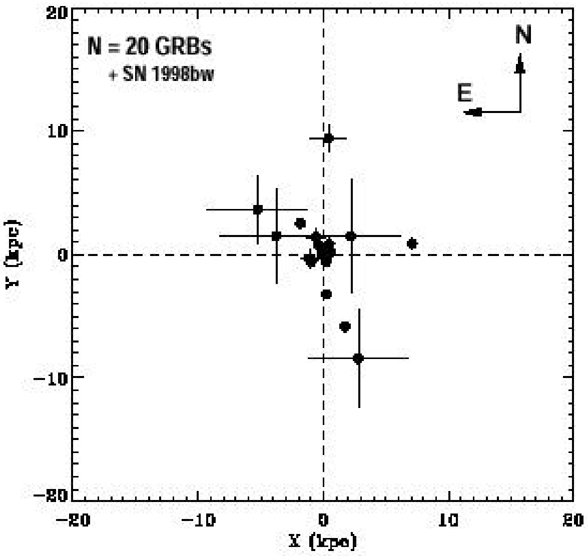


Fig. 2.12. The offset distribution of GRBs inside their host galaxies. From Bloom et al., 2002a

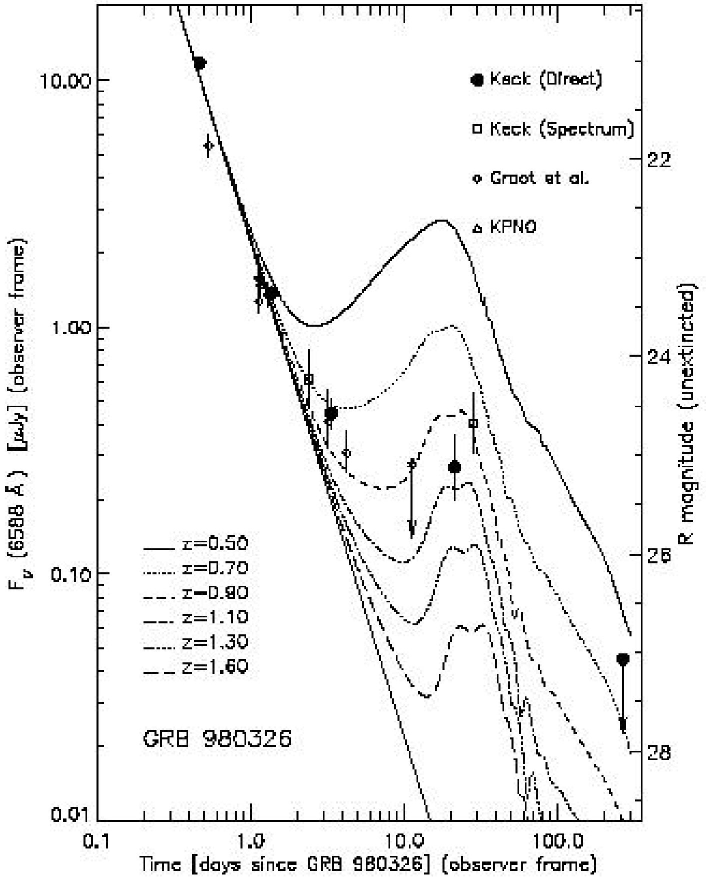


Fig. 2.13. - The R-band light curve of the afterglow of GRB 980326. Overlaid is a

power-law afterglow decline summed with a bright supernova light curve at different redshifts. From Bloom et al., 1999.

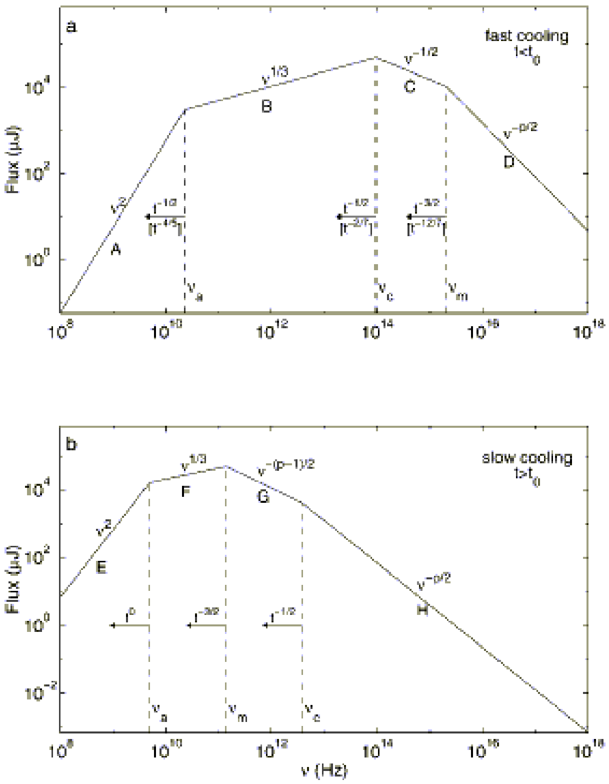


Fig. 3.1. - Theoretical integrated synchrotron spectrum from a power-law distribution of electrons, for a spherical explosion in a constant density ambient medium. From Sari et al., 1998.

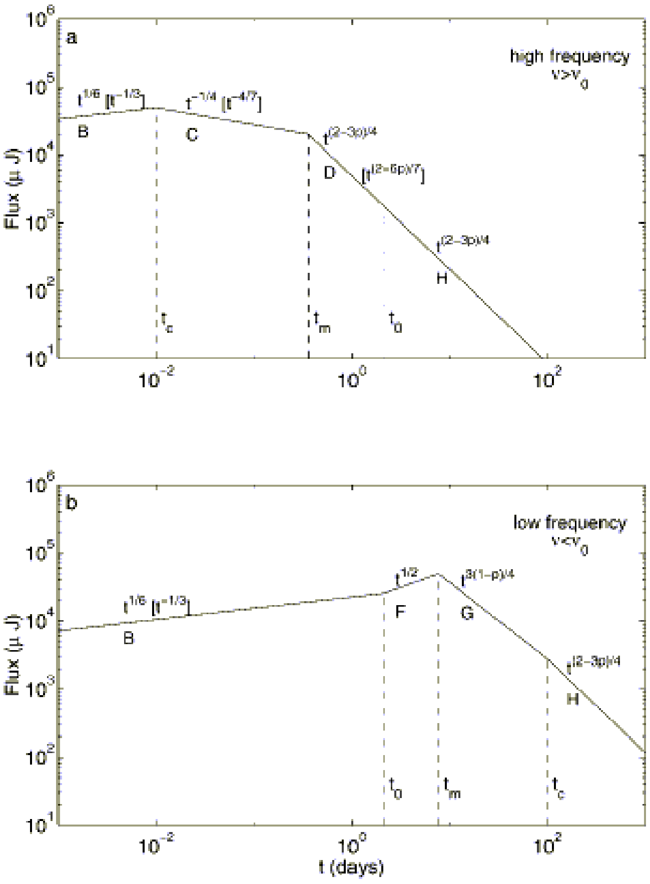
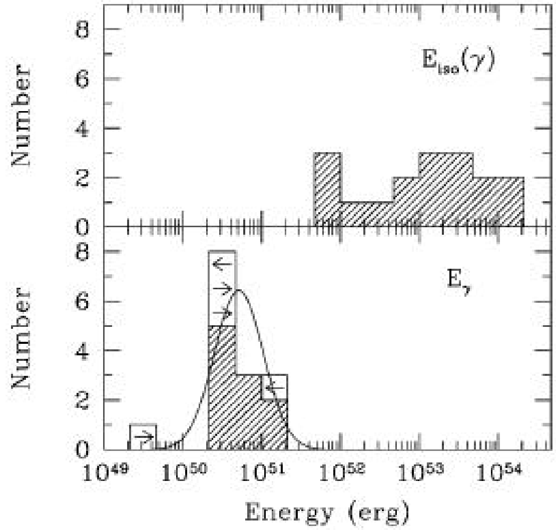


Fig. 3.2. - Light curves of synchrotron emission from a power-law distribution of electrons, for a spherical explosion in a constant density ambient medium. From Sari et al., 1998.

Figure 3.3


Number
8
6
4
2
0
$E_{iso}(\gamma)$
Number
8
6
4
2
0
E_γ
10^{49}
10^{50}
10^{51}
10^{52}
10^{53}
10^{54}
Energy (erg)

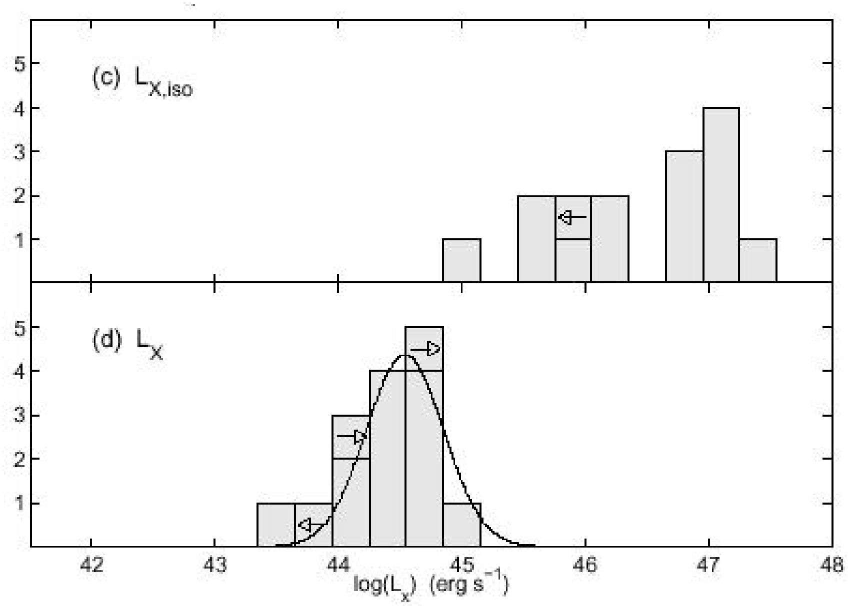


Fig. 3.3. - Distributions of the isotropic energy and collimated-corrected energy. From Frail et al., 2001.