GRBS - A PUZZLE BEING RESOLVED

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ABSTRACT

For a few seconds a GRB becomes the brightest object in the Universe, overshining the rest of the Universe combined! Clearly this reflects extreme conditions that are worth exploring. The combination of black holes, ultra relativistic large scale motion, ultrarelativistic shocks and large magnetic fields suggest that this is a very promising cite for production of other high energy particles as well. Among the possible candidates are UCHERs, high energy neutrinos, gravitational radiation and TeV photons. The recent discovery of GRB afterglow have lead to a great leap forwards in our understanding of GRBs and the mystery of GRBs is unfolding at an accelerated rate. These observations have confirmed the relativistic fireball model (more specifically the internal-external shocks model). The prompt optical emission observed in GRB 990123 have demonstrated that GRBs involve ultra-relativistic motion. The breaks in the light curves of GRB 990123 and GRB 990510 and the peculiar light curves of GRB 980519 and GRB 980326 disclosed that these GRBs are beamed. I examine these recent developments and discuss their implications to the models of the source. I argue that the current understanding of GRBs implies that they most likely signal the birth of stellar mass black holes.

1. Introduction

Gamma-Ray Bursts (GRBs) are short and intense bursts of MeV range γ-rays. During the last decade observational progress has revolutionized our understanding of GRBs. BATSE on Compton-GRO have found that GRBs are distributed isotropically revealing their cosmological origin. More recently BeppoSAX discovered X-ray afterglow[1)]. This enabled accurate position determination and the discovery of optical[2)] and radio[3)] afterglows and in most cases host galaxies. Remarkably the afterglow is a simple phenomenon that can be analyzed using a rather simple model. The resulting information tells us a lot about the properties of the GRB.

In this review I summarize the recent developments in GRB physics. It can be views as an update to my recent Physics Reports review[4)]. My goal, here, is to confront the predictions of the "Relativistic Fireball" model with recent observations. This model had recently several successes in predicting the afterglow, the prompt optical flash and the beaming break in the light curve. The fireball model deals with the "outer" radiating regions. It doesn't deal directly with the "inner engine" - the source of the relativistic ejecta that powers the whole phenomenon. I review

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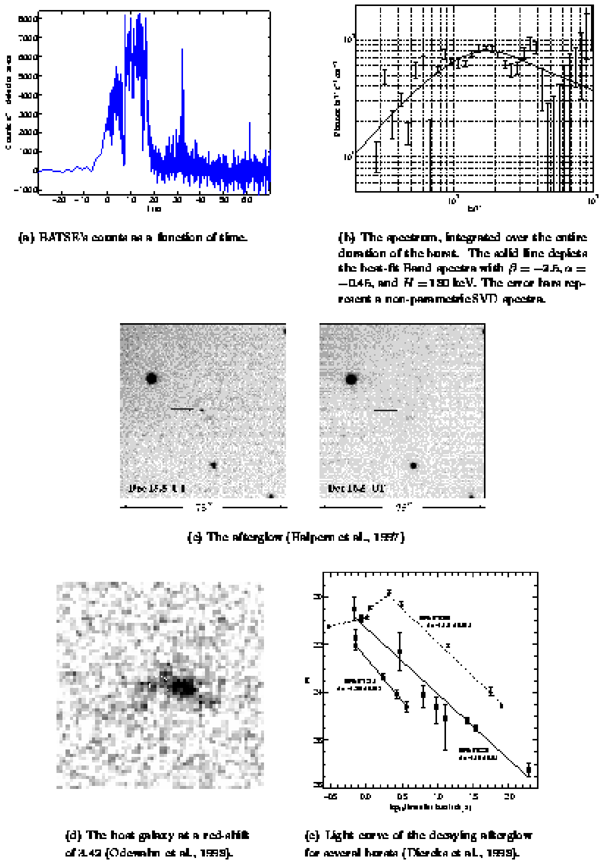

(a) BATSE's counts as a function of time.

(b) The spectrum, integrated over the entire duration of the burst. The solid line depicts the best-fit Band spectra with $\beta = -2.5$, $\alpha = -0.45$, and $E = 190$ keV. The error bars represent a non-parametric SVD spectra.

(c) The afterglow (Halpern et al., 1997)

(d) The host galaxy at a red-shift of 3.42 (Odewahn et al., 1998).

(e) Light curve of the decaying afterglow for several bursts (Djorgovski et al., 1998).

Fig. 1. GRB 971214: Top left gamma-ray light curve; Top right the spectrum; Middle the afterglow[5)]; Bottom left the host galaxy[6)]; Bottom right optical light curve for GRB 971214, GRB 970508 and GRB 970228,.

the implications the current observations, as interpreted within the fireball model, to models of the source and I discuss some of the possible sources. I examine the possible "energy crisis". Finally, as the main topic of this meeting is neutrinos and high energy physics I conclude in examining the relation between GRBs, high energy neutrinos, UCHERs and gravitational radiation.

2. Summary of GRB Observations

GRBs are short and intense bursts of 100keV - a few MeV gamma-rays. GRBs vary greatly from one to another. Even though there is no "typical" GRB I show in Fig. 1 GRB 971214 as an indication of what is a GRB. In the following I summarize briefly some observational facts concerning GRBs. I focus on those observations that provide the basic clues for the theoretical modeling.

- The observed fluence on earth is $10^{-5} - 10^{-7}$ ergs/cm^2 (the lower limit depends, of course, on the detector). Redshift measurements of half a dozen GRBs indicate that for isotropic emission the total energy is of the order $10^{51} - 10^{54}$ergs. Recent observations suggest that the radiation is beamed, lowering this energy by a factor of several hundred.

- The GRB spectrum in nonthermal. In most cases there is a strong power law high energy tail extending to very high energies (up to GeV). This nonthermal spectrum, which confused researchers at first, provided the first and the most important clue to the nature of GRBs. The spectrum can be fitted by the schematic Band function[7]: two power law joined smoothly together. The lower energy spectral index, $dN(E)/dE$, is, quite generally, in the range (1/3, -1/2) which is compatible with the synchrotron model[8]. However, there are indications[9] that in some bursts the lower energy slope is steeper, contradicting this model.

- The duration ranges from a fraction of a second to several hundred seconds. The light curve is extremely irregular and large fluctuations on a time scale of up to the detection limit of msec are observed. This high variability provides a second important clue to the nature of GRBs.

- There are indications that shorter GRBs compose a different subgroup. It is more difficult to detect short bursts and the observed short bursts are, therefore, nearer than longer ones[10]. As a result the short bursts distribution is compatible with a homogenous Eucleadian distribution[11,12] in which $d\ln N/d\ln S = -3/2$. There have been claims that long bursts with no high energy component (no emission in the higher BATSE channels) are also distributed with a $-3/2$ slope[13]. However, it is not clear if there is a real need to consider those as a separate subgroup[14].

3. Afterglow Observations

The Italian Dutch satellite, BeppoSAX, discovered X-ray afterglow on Feb 28th 1997[1]. By now X-ray afterglow has been observed from two dozen bursts. As BeppoSAX can trigger only on long bursts it is not known if short bursts are also followed by afterglow. Hopefully, the planed mission of HETE II and the proposed missions SWIFT and BALLERINA will answer this question. Optical[2] and radio[3] afterglows were discovered using the exact position obtained by BeppoSAX in about half of the cases in which X-ray afterglow was seen. It is not clear what determines whether optical and radio afterglow are observed.

- The energy involved can be estimated from the late phases of the optical [15,16] and the radio[17] afterglows. The overall energy emitted in the afterglow is of order $10^{50} - 10^{52}$. Quite generally it is a small fraction, a few percent of the energy emitted during the GRB.

- The afterglow light curve decays, in most cases, as a single power law in time[a] $F_\nu \propto t^{-\alpha}$, with $\alpha \sim 1.2$. In two cases (GRB 980326 and GRB 980519) $\alpha \sim 2$ and in two cases GRB 990123 and GRB 990510 there is a clear break from a flat decay $\alpha \sim 1.1 - 1.2$ to a much faster decline. We show latter that these features indicate that these GRBs are narrowly beamed (we also clarify in that section the confusion between relativistic and geometric beaming).
- Prompt optical emission was observed from GRB 990123. This emission peaked with a ninth magnitude signal which lagged 70 seconds after the gamma-ray peak and coincided with the prompt X-ray peak.

4. The Relativistic Internal-External Shocks Fireball Model

The nonthermal spectrum indicates that the observed emission emerges from an optically thin region. A simple estimate of the number of photons above 500keV and the size of the source (as implied by the observed variability) shows that such a source must be extremely optically thick to pair creation. This is the Compactness problem.

The simplest way to overcome this problem is if the source is moving ultra-relativistically towards us. This has lead to the relativistic fireball model. According to this model slowing relativistic ejecta produces the GRBs and their afterglow. Relativistic electrons that have been accelerate in the relativistic shocks that form, emit the observed gamma-rays via synchrotron or synchrotron self-Compton emission. Both the energy density of these electrons and of the magnetic fields should be close to equipartition for efficient emission. To bypass causality and the compactness limits the shocks must be extremely relativistic with $\gamma \geq 100$.

This suggests that GRBs involve three stages:

- First a source produces a relativistic energy flow. The observed fluctuations in the GRB light curves and the huge energy released indicates that the source is compact. This "inner engine" is hidden and it is not observed directly. This makes it difficult to constrain GRB models and leaves only circumstantial evidence on the nature of the sources.
- The energy is transfered relativistically from the compact source to distances larger than $\sim 10^{13}$cm where the system is optically thin. This is most likely in the form of a relativistic particles flow but the possibility of a Poynting Flux should also be considered. As we discuss shortly the flow must be highly irregular to produce internal shocks.

[a]Sari, Piran and Narayan[18)] have introduced in the astro-ph version the notation $F_\nu \propto t^{-\alpha}\nu^{\beta}$. This notation was changed to $t^{-\beta}\nu^{\alpha}$ in the Ap. J. version and in my review[4)]. However, the astro-ph notation caught so well that I return to this original notation here and elsewhere.

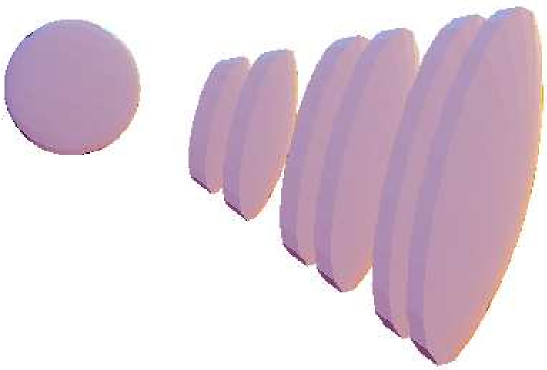

Fig. 2. Internal shocks: Faster shells catch up with slower ones and collide, converting some of their kinetic energy to internal energy.

- The relativistic ejecta is slowed down and the shocks that form convert the kinetic energy to internal energy of accelerated particles, which in turn emit the observed gamma-rays.

External shocks arise due to the interaction of the relativistic matter with the surrounding matterh[19], like the ISM or with a circumstellar wind that took place during an earlier epoc. These shocks are the relativistic analogues of SNR remnants. Like in SNRs these shocks are collisionless. External shocks become effective at[20] $\min(R_\gamma, R_\Delta)$, where $R_\gamma \equiv l/\gamma_0^{2/3}$ and $R_\delta \equiv l^{3/4}\Delta^{1/4}$. γ and Δ are the Lorentz factor and the width of the shell (in the observer frame) and the subscript 0 indicated, here and elsewhere the initial value. The Sedov length, $l \equiv (E_0/[(4\pi/3)n_{ism}m_pc^2]$, is the radius within which the rest mass energy of the external material, whose density is n_{ism} equals the initial energy of the ejecta, E_0. Typical values are: $l \sim 10^{18}$cm and $R_\gamma \sim R_\Delta \sim 10^{15} - 10^{16}$cm.

Sari and Piran[21] and Fenimore, Madras and Nayakshin[22] have shown that that external shocks cannot produce efficiently the observed highly variable temporal structure seem in GRB[b] Thus, GRBs are produce by the only other alternative, internal shocks[24,25,26]. These shocks arise in irregular flow when faster shells overtake slower ones (see Fig. 2). If the flow varies on a scale length δ then internal shocks would take place at $R_{int} \sim \delta\gamma_0^2$. $\delta = c\delta t$ can be inferred from the observed temporal variability $\delta t \leq 1$sec indicating that these shocks take place at $\sim 10^{13}$cm. If the shocks arise earlier the system is still optically thick and the radiation does not escape. The observed GRB time scales reflect the time scales of the "inner engine"[27]. The GRB duration corresponds to the time that the "inner engine" is active.

Within the external shocks model late subpulses, which are produced when the

[b]Dermer and Mitman [23] suggest that within external shocks with a very inhomogeneous media (see Fig. 3), subpulses close to the line of sight could produce the observed peaks. But these subpulses cannot produce the large variability in amplitude observed. Additionally, there is no explanation why the expected correlation between arrival time and subpulses duration is not seen.

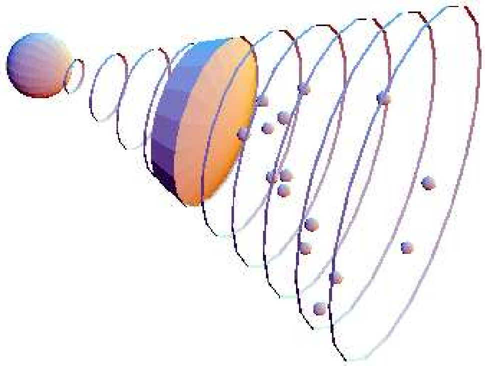

Fig. 3. To produce variability in external shocks the relativistic ejecta must encounters interstellar bubbles. However, most of the shell passes between the bubbles and its kinetic energy is lost.

Lorentz factor is lower and at larger radii, are expected to be longer. The lack of any correlation between the width of subpulses and their time of arrival is inconsistent with this model[28)]. The lack of a direct scaling between the GRB and the afterglow is another evidence for the internal shocks model. This is a very important clue on the nature of the source. External shocks can be produced by an explosive event in which the "inner engine" releases all its energy at once. The observed temporal structure could have been produced in this case within the shocks due to irregularities in the surrounding material (see Fig. 3). However this would have be extremely inefficient[21)]. This rules out the possibility of an explosive "inner engine".

Internal shocks can extract only a fraction of the total energy[29,27,30)]. Sari and Piran[21)] suggested that the remaining energy will be extracted later via external shock giving rise to additional emission at different wavelength - the afterglow. Thus, GRB have a forth stage:

- The relativistic flow, which have been slowed down, but has not been stopped, is slowed further by the surrounding material producing the afterglow. This phase is regular and it can be modeled rather well by the adiabatic Blandford-McKee[31)] adiabatic self-similar solution.

5. The Afterglow: A Predictions and a Confirmation of the Fireball Model

Paczyński and Rhoads[32)] and independently Katz[33)] realized early on that the long term interaction of the relativistic ejecta with the surrounding matter will produce a low frequency afterglow. Paczyński and Rhoads[32)] discuss radio afterglow. Katz[33)] discusses optical afterglow. Later, Mészáros and Rees[34)] and independently Vietri[35)] developed detailed models of this afterglow. In all these studies, it was thought that both the GRB and the afterglow are produced by external shocks. This afterglow would have been the long time extrapolation of the GRB and it should scale with the GRB properties.

If GRBs arises due to internal shocks and the afterglow is produced by external shocks[21] we don't expect direct scaling between the two. In this "Internal-External" model the GRB and the afterglow are produced by two different processes. The recent afterglow observation provide a significant evidence for this picture.

The afterglow provided additional direct confirmation of the fireball model. The radio afterglow of GRB 970508 showed significant flickering during the first few weeks. This flickering decreased and eventually stopped after about a month. Goodman[36] quickly suggested that the flickering arises arose due to scintillation. Initially the source is small and it is within the scintillation regime. As the source expands the scintillation stop. Using this idea Frail et. al[3] estimated that the size of the afterglow of GRB 970508 was $\sim 10^{17}$cm one month after the burst. Even before GRB 970508 Katz and Piran[37] suggested that synchrotron self-absorption would result in a rising spectrum in radio frequencies for which the source is optically thick. Using the observed flux and using an estimate of the temperature of the emitting regions one could estimate the size of the emitting region. Frail et. al.,[3] obtain a size of $\sim 10^{17}$cm after one month. The agreement between the two independent estimates is reassuring. These observations imply that the fireball is expanding relativistically, and provided, for the first time a confirmation of the notion of relativistic motion in GRBs.

6. Synchrotron spectrum and Afterglow Observations

The generic emission process for both the GRB and the afterglow is synchrotron. It is generally assumed that the emitting electrons have a power law energy distribution: $N(E) \propto E^{-p}$. A typical value that fits both the GRB and the afterglow observations is $p \sim 2.5$ [c] With $p = 2.5$ the distribution diverges at low energies, and there must be a low energy cutoff, which is determined by the energy density available: $E_{min} = e_e/[(p-2)n_e]$. The largest number of electrons is around E_{min} and hence this is also the characteristic electron energy. We denote by ν_m the synchrotron frequency of an electron with this energy. This is the "typical" synchrotron frequency. The electrons' energy density as well as the magnetic field energy density are characterized as fractions ϵ_e and ϵ_B of the total internal energy[38].

These definitions enable Sari, Piran and Narayan[18] to estimate the instantaneous spectrum: The low (but not extremely low) frequency spectrum is given by the low energy synchrotron tail: $F_\nu \propto \nu^{-1/3}$. At intermediate frequencies the spectrum depends on the whether the "typical" electrons are cooling within the hydrodynamic time t_{hyd}. In a fast cooling system an electron with E_{min} cools faster than t_{hyd}. We define the cooling frequency, ν_c, as the synchrotron frequency of an electron that cools during the local hydrodynamic time scale: $E_c/P_{\nu_c}(E_c) = t_{hyd}$. For fast cooling $\nu_c < \nu_m$ and $F_\nu \propto \nu^{-1/2}$ for slow cooling $\nu_m < \nu_c$ and $F_\nu \propto \nu^{-(p-1)/2}$. The highest part of the spec-

[c] One can expect that this number will be universal and won't vary from one burst to another.

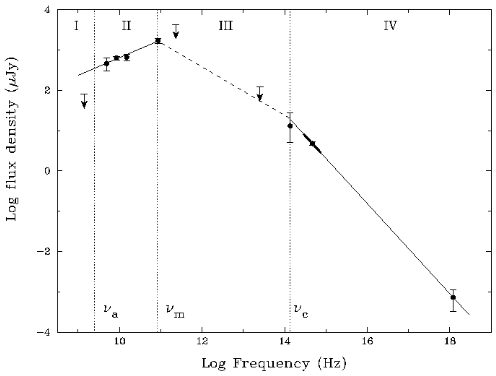

Fig. 4. The X-ray to radio spectrum of GRB 970508 on May 21.0 UT (12.1 days after the event). The fit to the low-frequency part, $\alpha_{4.86-86\mathrm{GHz}} = 0.44 \pm 0.07$, is shown as well as the extrapolation from X-ray to optical (solid lines). The local optical slope (2.1–5.0 days after the event) is indicated by the thick solid line. Also indicated is the extrapolation $F_\nu \propto \nu^{-0.6}$ (lines). Indicated are the rough estimates of the break frequencies ν_{a}, ν_{m} and ν_{c} for May 21.0 UT from Galama et al.,[15].

trum is always dominated by emission from fast cooling electrons with: $F_\nu \propto \nu^{-p/2}$. At very low frequencies, usually at radio frequency, the system may become optically thick to synchrotron self absorption. We denote by ν_{sa} the self absorption frequency for which $\tau(\nu_{sa}) = 1$. Unlike the common discussion of synchrotron self absorption in text books (which assumes $\nu_{sa} > \nu_m$ and obtain $F_\nu \propto \nu^{5/2}$), here $\nu_{sa} \ll \nu_m$. In this case $F_{\nu_{sa}} \propto \nu^2$, just like the usual Wien part of a black body spectrum. Combined we have $F_\nu \propto \nu^\beta$ with :

$$\beta = \begin{cases} 2 & \text{for } \nu < \nu_{sa} \text{ - self absorption;} \\ 1/3 & \text{for } \nu_{sa} < \nu < \min(\nu_m, \nu_c); \\ -1/2 & \text{for } \nu_c < \nu < \nu_m \text{ and } \nu_c < \nu_m \text{ - fast cooling;} \\ -(p-1)/2 & \text{for } \nu_m < \nu < \nu_c \text{ and } \nu_m < \nu_c \text{ - slow cooling;} \\ -p/2 & \text{for } \max(\nu_m, \nu_c) < \nu. \end{cases} \tag{1}$$

The resulting spectrum is a combination of four power laws, with three of the four slopes fixed and one depending on whether the electron are fast cooling or not. A comparison of the theoretical model and the observation is shown in Fig. 4 [15]. The agreement is remarkable for such a simple model.

In reality the emitting region is inhomogeneous and different parts are moving with a different Lorentz factors. A specific example[16] of integration over an inhomogeneous Blandford-McKee solution including different viewing angles results in a spectrum which is basically similar to the one shown above but with the sharp corner replaced by smooth curves.

This instantaneous spectrum is valid during the GRB phase and during the latter afterglow phase. However, the GRB phase involves simultaneously emission from multiple shocks and the combined spectrum might be more complicated. We still expect generically that the low frequency (say X-ray, for the GRB phase) slope will always be less steep then 1/3. Cohen et al.[8] find that this is satisfied in several strong bursts that have a well determined spectrum. Preece et. al.[9)] have found that a few percent of the bursts have a steeper low energy slope, suggesting that some modification to the simple synchrotron model may be needed. On the other hand, at high frequency, one should consider the effects of inverse Compton scattering which might dominate over synchrotron cooling[39)]. Ghisellini and Celotti[40)] even suggest that numerous pairs are produces and their inverse Compton emission dominate the observed gamma-ray emission during the GRB.

To determine the light curve we need ν_{sa}, ν_m, ν_c, and $F(\nu_m)$ (or F_{ν_c}) as a function of time (all other fluxes are determined by these quantities). These depend, in turn, on the energy density, e, the electron density, n_e, and on R and γ. Sari, Piran and Narayan[18)] used the scaling laws of the Blandford-McKee solution (which assumes adiabatic evolution and propagation into a constant density surrounding medium) to obtain specific light curves. The two most important equations are the adiabatic energy equation and the photon's arrival time (the detector's time) equation[d]

$$E_0 = M(R)c^2\gamma^2, \tag{2}$$

and

$$t_{obs} = \frac{R}{2c\gamma^2}, \tag{3}$$

where $M(R)$ is the accumulated the mass at a radius R. Using these equations we can express R and γ as a function of the detector's time, and from this we can obtain the rest of the equations. The most important feature of the hydrodynamic solution is that the radius is changing much slower with time than the Lorentz factor. The system can almost be viewed as standing still with the Lorentz factor decreasing in time. However, the weak dependence of R on t does make some difference as this is the main feature that varies from one solution (e.g. adiabatic) to another (e.g. radiative).

A nice feature that arises is a simple relation between α, β and p.

$$\alpha = \begin{cases} 3\beta/2 = 3(p-1)/4 & \text{for } \nu < \nu_c, \\ (3\beta-1)/2 = (3p-2)/4 & \text{for } \nu > \nu_c. \end{cases} \tag{4}$$

These relations are satisfied, for example, for the afterglow of GRB 970508 for which $\alpha = 1.12$ and $\beta = 1.14$ corresponding to $p \sim 2.4$.

7. The Early Afterglow and the Prompt Optical Flash

Radio flickering and the rising radio spectrum of the afterglow of GRB 970508 have shown that this afterglow was expanding relativistically one month after the burst. However, at this stage it has slowed down significantly and its Lorentz factor

[d]When using the full Blandford-McKee solution there are factors of order unity on the l.h.s of these equations[41)].

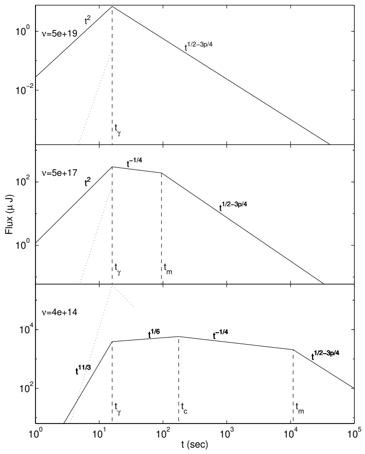

Fig. 5. The early gamma-ray, X-ray and optical afterglow. The dashed curve on the optical range is due to the reverse shock emission[44,45].

was of order a few. This is not the ultra-relativistic motion expected during the burst itself. Can we determine what is the initial Lorentz factor? This important question could provide another clue to the nature of the relativistic flux and could distinguish between different source models. An extremely high Lorentz factor (of order 10^5 or so) would indicate a Poynting flux[42,43]. While a lower Lorentz factor does not rule out a Poynting flux, it is an indication in favor of a Baryonic flow.

There are already some limits on the initial Lorentz factor. The Compactness problem provide a lower limit of ~ 100. Modeling of the internal shocks emission suggests an upper limit of[39] ~ 1000. However, we would like a direct measurement. For this our best bet is to turn to the very early afterglow - to the initial stages of the interaction of the ejecta with the ISM. This phase is almost simultaneous with the GRB itself[41]. Thus, its detection poses an observational challenge in obtaining quickly an accurate position and following it up with a rapid response.

Unlike the late adiabatic afterglow, the early afterglow is most likely radiative. Namely, the energy carried away by the emitted radiation is significant compared to the total energy and these losses influence the dynamics. A radiative system must be fast cooling (if the "typical" electron does not cool there cannot be efficient energy losses). To obtain the radiative light curve we replace the adiabatic energy equation 2 by the radiative energy equation:

$$E_0 = M(R)c^2\gamma(R)\gamma_0\gamma. \tag{5}$$

We also replace the emissivity equation. For slow cooling the emitted flux is: N_eP, where N_e is the number of emitting electrons and P is the synchrotron emissivity. For fast cooling the emitted flux is dE_{hyd}/dt: all the energy produced by the shock is radiated away.

The early afterglow peaks in the soft gamma-ray or hard X-ray[45]. This emission could be viewed as a superposition of a longer and smoother and somewhat softer

	$\nu_c > \nu_{op}$	$\nu_c < \nu_{op}$
$\nu_m > \nu_{op}$	$\left(\frac{\min(\nu_c,\nu_m)}{\max(\nu_c,\nu_m)}\right)^{\frac{1}{2}} \left(\frac{\nu_{op}}{\min(\nu_c,\nu_m)}\right)^{\frac{4}{3}}$	$\left(\frac{\nu_{op}}{\nu_m}\right)^{1/2}$
$\nu_m < \nu_{op}$	$\left(\frac{\nu_{op}}{\nu_m}\right)^{-(p-2)/2} \left(\frac{\nu_{op}}{\nu_c}\right)^{1/2}$	$\left(\frac{\nu_{op}}{\nu_m}\right)^{-\frac{p-2}{2}}$

Table 1. The fraction of the energy emitted in the optical frequency ν_{op}, as function of the cooling frequency ν_c and the typical frequency ν_m[45].

component on top of the variable, hard internal shocks signal[41]. This signal should be scaled and compared with the late afterglow as they arise from the basically the same phenomenon. Indeed in many cases BeppoSAX's late time X-ray data extrapolates nicely with a $t^{-1/3}$ power law decay to the initial observations.

A remarkable new component that appears in Fig. 5 is the prompt optical flash. Early Gamma-rays and X-rays and late optical afterglow emission arises from the forward shock: i.e. from shocked ISM material. During the early interaction of the ejecta with the ISM, before the solution has settled down to the Blandford-McKee self similar solution, there is also a reverse shock that heats the ejecta[e]. The emission from the reverse shock peaks at lower frequencies: $\nu_{m_{rev}} \approx \nu_{m_{for}}/\gamma^2$. If $\nu_{m_{for}}$ is in the X-ray and $\gamma_0 \sim 100$ we expect $\nu_{m_{rev}}$ to be in the optical or UV. Comparable amounts of energy are generated by the forward and the reverse shocks, and this energy is comparable to the energy of the GRB itself. A strong 5th magnitude optical flash would have been produced if the fluence of a moderately strong GRBs, 10^{-5}erg/s/cm^2 would have been released on a time scale of 10sec in the optical band. Even a small fraction of this would be easily observed.

While the synchrotron frequency of the reverse shock is much lower than the synchrotron frequency of the forward one, both have the same cooling frequency (both have the same magnetic field and the same Lorentz factor). As the forward shock must be radiative: $\nu_{c_{for}} < \nu_{m_{for}}$. If $\nu_{c_{rev}} = \nu_{c_{for}} \gg \nu_{m_{rev}}$ the reverse shock might not be radiating efficiently and this might lower the observed signal. Table from [45] show this reduction. even with these factors, one can hardly avoid a strong optical emission from the reverse shock. Additional effects like as inverse Compton scattering and self absorption can somewhat reduce this flux, but even so a signal stronger than 15th magnitude is expected.

Sari and Piran[44] presented this detailed prediction of a strong optical flash in the Rome meeting, that took place in October 1998. The possibility of strong optical emission was noticed by Mészáros & Rees[34] in two of several models they examined. This prediction was almost in contradiction with the LOTIS upper limits on several bursts (see e.g. Williams et al.[46]). Less than two month latter on January 23 1999 ROTSE[47] was triggered by the GCN network[48] and detected a 9th magnitude optical

[e]This notation is somewhat confusing as this reverse shock propagate backwards only in the fluid's frame. It is propagating relativistically towards the observer in the observer frame.

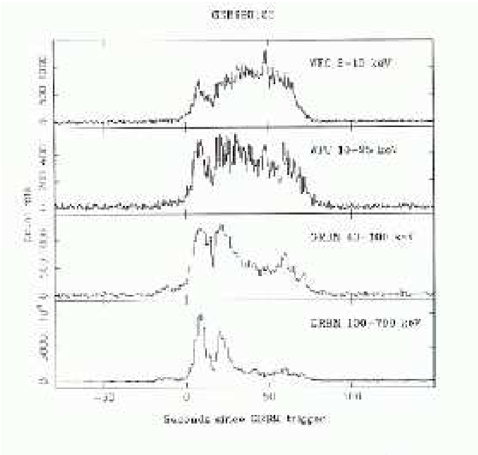

Fig. 6. The light curves of GRB 990123 in different bands[50]: from top to bottom: 2-13keV; 13-40keV; 40-100keV and 100-700keV. The increasing X-ray flux at late time is seen clearly. Note that BeppoSAX's trigger is $\sim$ 25sec after BATSE's trigger.

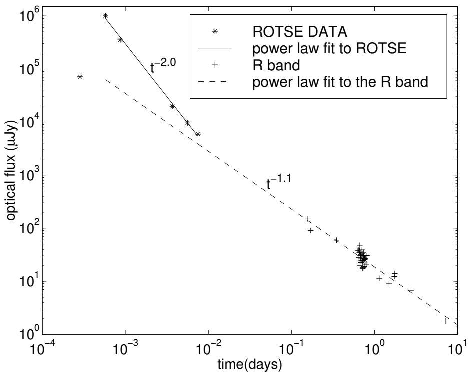

Fig. 7. The early optical light curve of GRB 990123[51].

signal accompanying GRB 990123. A careful examination of the different light curves of GRB 990123 (see Fig. 6) reveals that the peak optical emission was offset by at least 25 seconds from the peak gamma-ray emission. In fact, there is no correlation between the gamma-rays and the optical photons. Moreover, the soft X-ray signal peaks at the time of the optical peak and quite generally the spectrum evolves from hard to soft. All this is in complete agreement with the picture presented above. The early afterglow slightly lags after the GRB. The forward shock emission peaks in X-rays while the reverse shock emission peaks at the optical or UV band. The optical light curve shows an initial phase or rapid decline $\sim t^{-2}$ again in a complete agreement with the prediction of the reverse shock emission[44,45,49]. Latter on this turns to the common $t^{-1.1}$ decay seen in other bursts (see Fig. 7).

These observations provide us with three independent estimates of the Lorentz factor during the early afterglow[44]:

- The time of the optical flash peak, $\sim$ 70sec $\sim l/(c\gamma^{8/3})$. For $l \sim 10^{18}$cm equation

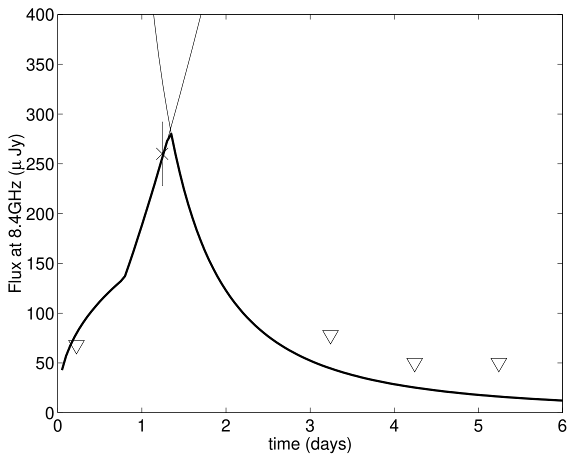

Fig. 8. Observations and theoretical light curve for the early radio signal of GRB 990123[51)].

3 yields: $\gamma_0 \sim 200$.

- The initial decay like t^{-2} suggests that the typical synchrotron frequency was below the optical early on. This suggests $\gamma_0 \sim 200$.
- The initial decline of the X-ray suggests that already initially the typical synchrotron frequency was below the 1.5-10keV band. Using the initial ratio $\nu_{m_{for}}/\nu_{m_{rev}}$ we find that $\gamma_0 \sim 70$.

Radio emission was observed from GRB 990123[52,53)]. This radio emission peaked around one day with marginal detections prior and latter than that (see Fig. 8). This radio emission is also produced by the reverse shock. The expected radio light curve (see Fig. 8) was calculated using the optical data[51)]. The fit to the observations is almost too nice. The radio emission is suppressed early on due to synchrotron self absorption. This enables us to estimate the size of the system at about one day after the burst to be $\sim 10^{15}$cm!

8. Beaming, Jets and Flying Pancakes

If we assume isotropic emission then the energies emitted by GRB 971214, at z=3.418 and by GRB 990123 at z=1.65 are $\sim 3\times10^{53}$ergs and 4×10^{54}ergs respectively. The first is comparable to the binding energy of a neutron star, the second is greater than a solar rest mass energy. Clearly, these values are problematic for most GRB models.

8.1. Theory

If the GRB emission is beamed into some angle, θ, the overall energy would be lower by a factor $\theta^2/4$ (the overall event rate will be larger by the inverse factor).

There has been some confusion between such "geometric" beaming and the relativistic beaming that arises due to the relativistic motion. It is worthwhile to discuss this issue first. The radiation from a source moving with a Lorentz factor γ towards the observer is beamed into a narrow cone with an opening angle γ^{-1}. Typical values during the GRB and the afterglow are $\gamma \sim 200$ and $\gamma \sim 2-10$ respectively, corresponding to a relativistic beaming of 10^{-2}rad and $0.1-0.5$rad. These are the maximal (smallest angle) beaming possible. However, this is just a lower limit on the beaming angle. If the source has an opening angle $\theta > \gamma^{-1}$ then the beaming is determined by θ and not by γ^{-1}. Observers with a viewing angle up to θ from the center can see the source. However, each observer sees a local patch whose size is only γ^{-1}. There are $(\theta\gamma)^2$ such patches. As all these patches are causally disconnected, different observers that are more than γ^{-1} apart will observe different emitting regions and may record a a different time profile and a different spectrum from the same burst. The causally connected regions grow as γ decreases. Thus, during the afterglow there are fewer and fewer such regions and when $\gamma^{-1} \sim \theta$ there is only one. We will return to this issue latter, when I discuss the implications of this phenomenon to the implied energy emission and efficiency of GRBs.

What distinguishes the dynamics of a spherical ejecta from a nonspherical one? Initially there is little difference. The proper time required for the matter to reach a radial distance R is $R/c\gamma$. The maximal sideway expansion is therefore R/γ. Hence the angular size of a causally connected region is γ^{-1}. As long as $\gamma^{-1} < \theta$ the matter simply does not have enough time to expand sideways and to know that it is not a part of a spherical shell[54]. However, once $\gamma^{-1} \approx \theta$ the matter suddenly "discovers" its nonspherical structure and it begins to expand sideways. As the matter at the front is constantly shocked to relativistic energies Sari, Piran and Halpern[55] expect it to expand with the speed of light: $\theta \sim \gamma^{-1}$. Rhoads[56] assumes that this sideway expansion is at the sound speed which results in $\theta \sim \gamma^{-1}/\sqrt{3}$. This sideway expansion is so rapid that it dominates completely the radial expansion. For an expansion into a homogeneous ejecta this yields[57][f] $\gamma \propto R^{-3/2} \exp[-[3/(2\gamma_o\theta_o)(R^{3/2}/R_o^{3/2}-1)]$. Additionally the radiation is now beamed into a larger cone since $\gamma^{-1} > \theta_0$. Both effects reduce the observed emission and will cause a break in the light curve, roughly by an additional factor[g] of t^{-1}. Within the adiabatic synchrotron model we have new relations between α, β and p:

$$\alpha_{beam} = \begin{cases} 2\beta+1=p & \text{for } \nu<\nu_c, \\ 2\beta=p & \text{for } \nu>\nu_c. \end{cases} \tag{6}$$

[f] Rhoads[56] obtained a different exponent. This does not influence, however, the rest of Rhoads' conclusions.

[g] The beaming break takes place at $\gamma \approx \theta_0^{-1}$. If the hydrodynamic break is only at $\gamma \approx (\sqrt{3}\theta_0)^{-1}$ then two successive breaks will take place[58].

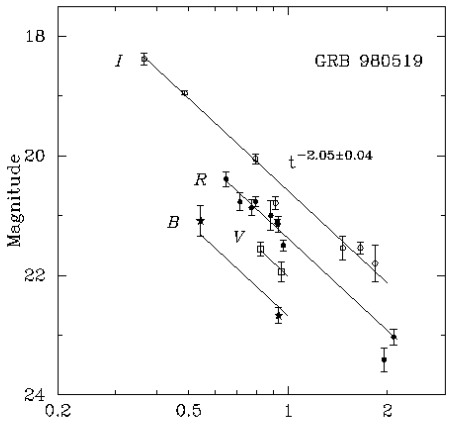

Fig. 9. An optical light curve for GRB 980519. The fast decline indicate a spreading beam[59].

8.2. Observations

The notion of beamed emission was accepted with some difficulty at first as the first two and up to now the longest and best observed light curves from GRB 970228 and GRB 970508 show a single power law decay with no indication for a beaming break. However, other bursts were different. GRB 980519 was unique among GRB afterglows with its most rapidly fading $t^{-2.05\pm0.04}$ in optical as well as in X-rays[59]. The optical spectrum of this burst shows: $\beta = 1.15 \pm 0.$ (see Fig. 9). These values are in perfect agreement with an expanding beamed emission with $p \approx 2.2$. As transition is not seen in the light curve the sideway spreading must have begun before the first optical observation, namely, less than 8.5 hours after the burst. Using the detector's time equation (equation 3) we find that the corresponding opening angle must have been rather small: $\theta < 0.05$, leading to a beaming factor of 500 or larger!

GRB 980326 was another burst with a rapid decline. Groot et al.[60] derived a temporal decay slope of $\alpha = 2.1 \pm 0.13$ and a spectral slope of $\beta = 0.66 \pm 0.7$ in the optical band, suggesting once more beaming. As Groot et al.[60] note, the large uncertainty in the spectral index allows in this case also a spherical expansion interpretation (with somewhat unusual values $p = 4.2$ or $p = 5.2$). However, this measured temporal decay was dependent upon a report of a host galaxy detection at $R = 25.5 \pm 0.5$, which was included as a constant term. The detection of a host has since been determined to be spurious; better data show no constant component to a limiting magnitude of[61] $R = 27.3$. If the last detection is interpreted as a different phenomenon[61] then the remaining points show a rapid decline - in agreement with a spreading beam interpretation.

GRB 990123 provided the first direct evidence for a beaming break[62]. The prompt optical flash, which we interpret to arise from the reverse shock decayed like t^{-2}, and disappeared quickly. The intermediate optical afterglow showed a power law decay with $t^{-1.1\pm0.03}$. The decay and the spectrum fit well an electron distribution with $p = 2.5$. This behavior continued from the first late observation (about 3.5 hours after the burst) until about 2.04 ± 0.46 days after the burst. Then the optical emission began to decline faster. The simplest explanation is that we have observed the transition from a spherical like phase to a sideway expanding phase. The transition took place at ~ 2 days, corresponding to $\theta_0 \sim 0.1$. This implies a beaming factor of about 100 reducing the energy of the burst to 3×10^{52} ergs.

Finally, just last May, GRB 990510 depicted a beautiful transition from $t^{-0.82\pm0.02}$ to $t^{-2.18\pm0.05}$ at 1.2 ± 0.08days after the burst[63]. The isotropic energy of this burst is 2.7×10^{53}ergs. With a beaming factor of 300 this becomes a "modest" 10^{51} ergs.

8.3. On Jets, Bullets or Flying Pancakes

Probably because of the analogy with AGNs in which beautiful jets are observed the terminology jets has been used to describe beamed emission from GRBs. Unfortunately this terminology is somewhat misleading. A jet is long and narrow. It corresponds to continuous activity. The jets seen in AGNs reflect activity on scales of 10^7 to 10^8 years. Much longer than the typical time scales of the inner black holes. Here we observe a transient phenomenon and the length of the ejecta (its direction along its motion) is much shorter. At first one may think that the term bullet would be more appropriate. A bullet is not so extended in length and it clearly represents a transient phenomenon. However, a more detailed consideration reveals that the perpendicular size of the ejecta is larger than its length. The angular size is $R\theta$ and the "length" is $\Delta \sim cT$. Typical values are $\Delta \sim 10^{12}$cm (for $T = 30$sec) and $\theta \sim 0.1$. Thus, quite generally, $R\theta > \Delta$. This is not even a bullet. This is a pancake flying at relativistic velocity perpendicular to its flat direction (see Fig. 2). One may wonder if relativistic contraction has played some tricks on us. When we look at the ejecta in its own rest frame we find that it is longer by a factor γ so initially it is actually a bullet. However, as R increases it expands sideways quickly and even in its own frame is looks like a pancake.

9. On The Nature Of The "Inner Engine"

We turn now to summarize the evidence concerning the "inner engine":

- **Energy:** The energy, $\sim 10^{51} - 10^{52}$ergs, is a significant fraction of the binding energy of a solar mass compact object.

- **Internal Shocks:** To produce internal shocks the "inner engine" must produce long and irregular wind. Single explosions won't work.

- **Variability** The variability time scale, δt, suggests a a solar mass compact object.
- **Duration:** The duration, T, suggests a prolonged activity which is much longer than the source's gravitational time scale.
- **Relativistic Flow:** The central engine must produce efficiently a relativistic flow. The baryonic load is less then about $10^{-5} M_\odot$.
- **Beaming:** The emitted flow is sometimes highly nonspherical with an opening angle of few degrees. Since late afterglow is less beamed than the GRB this suggest a search for "orphan" afterglows that are not accompanied by GRBs. This also suggest some similarity to AGNs.
- **Rate:** The observed rate corresponds approximately to one burst per 10^7years per galaxy. The actual rate may be higher by a factor of a hundred or so if most GRBs are beamed. The rate is still uncertain. Because of the width of the GRB luminosity function (more than a factor of a hundred) one cannot easily infer the rate of GRBs from the $\log N/\log S$ distribution.
- **Host Galaxies:** Host galaxies have been detected for most GRBs with optical afterglow. The long standing no-host problem has disappeared. Most bursts are located at the central regions indicating that the progenitors have not escaped from their host galaxies, as would have been the case in long lived binary neutron stars in dwarf galaxies[24)].
- **Association with star forming regions:** There is some evidence that host galaxies of GRBs are star forming galaxies[64)] (see however [65)]). This would support short lived progenitors: collapsing massive stars or short lived[h]($10^4 - 10^5$ years) binary neutron stars[66)].
- **GRB 980525, SN1999bw and the GRB-SN association:** The error box of GRB 990525 contains the bright supernova SN1999bw which is at $z = 0.085$[67)]. This has lead to a debate on the association of GRBs with type Ic supernovae[68,69,70)].

This evidence, and more specifically, the energy and the time scale considerations suggest that GRBs are powered by accretion of a massive $\sim 0.1 M_\odot$ accretion disk onto a compact object, most likely a black hole. Such a massive accretion disk must form simultaneously with the black hole, most likely from matter that was ejected by centrifugal forces. Thus GRBs signal the formation of black holes. The gravitational energy of a $0.1 M_\odot$ can supply the energy required for the process, the accretion time

[h]The life time of the observed galactic neutron star binaries is $10^8 - 10^9$years. On the other hand there is a strong observational bias against detection of short lived neutron star binaries.

would determine the overall duration while the variability would be determined by the gravitational time scale of the central object or by the hydrodynamic time scale of the accretion disk. Both are rather short. A variation on the theme involves the Blandford-Znajek effect[71)] which extract the rotational energy of the black hole - a larger reservoir than the gravitational energy of the accreting disk. As this effect involves electromagnetic fields it is likely that it is easier to produce, using this effect, a clean relativistic flow, possibly Poynting flux.

Several routes can lead to a black hole - accretion torus system:

- **Binary neutron star merger:** Binary neutron star mergers[72)] have been considered the canonical cosmological GRB sources for some time. These mergers are known to take place at a rate of one per $\sim 10^6 - 10^7$ years per galaxy[73)]. This rate is comparable to the rate of GRBs[74)]. The final outcome of such a merger[75,76,77)] is a $\sim 2.4 M_\odot$ black hole surrounded by a $0.1 - 0.2 M_\odot$ thick accretion disk, which could power the burst[24)].

- **Neutron star - Black hole merger:** This is a simple variation on the previous theme. One expect here that the neutron star will be torn apart by the black hole again leaving a massive disk (possibly slightly more massive than in the binary neutron star case), which will power the burst. If the mass of the black hole is $\sim 10 M_\odot$ we expect slightly different time scales and different behavior between the neutron star binary and this case. While black hole - neutron star binaries are expected to be as common as neutron star - neutron star binaries[73)], or even more common[78)] none was observed so far.

- **"Failed Supernova", Collapstar of Hypernova:** These are all different name for a collapsing star that produces a GRB. Both Woosley's[79)] Failed supernova model and Paczyński's[80)] hypernova's model assume that the rapidly rotating collapse produces a rotating massive black hole surrounded by a thick torus that accrets on it.

- **White dwarf - Neutron star merger:** A white dwarf orbiting a neutron star will be pushed inwards via gravitational radiation emission. If the mass ratio is small it will become unstable [i]when it reached the Roche limit and it will dump its mass into an accretion disk within its hydrodynamics time scale, a few seconds, producing a solar mass torus surrounding a neutron star. Once accretion from the disk begins this neutron star will turn into a black hole. Depending on the viscosity and on neutrino losses the accretion rate may be high enough so that the accretion time would be of order few seconds which will be the duration of the GRB.

[i]The expected mass ratio in a white dwarf - black hole binary is small and we expect these systems to be stable.

It is interesting to note that there this sources can be arranged as a sequence in terms of their maximal time scale with neutron star binaries the shortest, followed by black hole - neutron star merger, a white dwarf - neutron star merger and a failed supernova. The same sequence also arranges the sources from less to more baryons surrounding the source.

10. Some Open Questions

In a conference called "Some Open Questions in Astrophysics" that took place in the fall of 1995, I[54)] have summarized our understanding of GRBs by the following four open questions: Where? What? How? and Why? This was of course an exaggeration. Still it reflected the ongoing debates at that time.

This has changed drastically. We know with certainty that GRBs are cosmological. As for how - the "Internal-External Shocks, Relativistic Fireball Model" is supported very well by all recent observations. What is producing the GRBs is not determined yet. But there is a reasonably good case for the "Accretion onto a Newborn Black Hole" scenario, with binary neutron star mergers and Failed Supernova-Collapstar-Hypernova competing on its origin.

The question, why - or what can we do with these bursts, is still wide open, even though there have been numerous suggestions on the role that GRBs could take place, from destroying life[j] to discovering life[82)]. A more mundane proposals is to explore the high redshift universe and in particular to measure, using GRBs, the high redshift star formation rate. The wide GRB luminosity function failed the idea to use GRBs to measure cosmological parameters - GRBs are not standard candles. Still one can obtain, using lensing (or lack of it) some limits on cosmic parameters[83)].

The most problematic open question concerning all these models is the issue of efficiency and the possibility of an "Energy Crisis":

10.1. Energy, Energy Distribution and Efficiency

The most basic and fundamental issue is energetics. Is there an energy crisis? The implied isotropic energy can be as high as 4×10^{54}ergs. Even with beaming the energy is reduced to a gigantic 10^{52}ergs. Internal shocks can convert under reasonable conditions $\sim 10\%$ of the kinetic energy to thermal energy[29,27,30)]. External shocks are even less efficient. Then there is the question of radiative efficiency[45)] and of additional energy losses[84)]. Even before all that one should wonder what was efficiency of the source in accelerating the relativistic flow? We are most likely faced with an energy crisis. This had led some to resort to more powerful central engines, namely more massive compact object such as $10M_\odot$ black hole powered by rotation or by

[j] Quite unlikely as supernova are much more frequent and hence the expected fluxes from a "typical" nearby supernova would exceed the flux from a distant galactic GRB.

mode massive accretion disk. But there is a limit to this route as some bursts show submillisecond variability that would pose an upper limit on the central mass.

A related issue is the question of the energy distribution between the GRB and its afterglow. According to the internal-external shocks model a comparable amount of energy should be released in the GRB and in the early afterglow. Actually the early afterglow should be more powerful than the GRB by a factor of a few. However, early afterglow observations show the opposite. The prompt X-ray emission (which could be interpreted as early afterglow) is at most 10% of the GRB energy. The impressive optical flash from the reverse shock of GRB 990123 was only 1% of the gamma-ray energy. Has anything gone wrong?

There is one simple answer to both question: even after the beaming correction we are over estimating the GRB energy. There are two possible reasons for that: First, the GRB luminosity might be dominated by hot spots[85)], whose angular size γ^{-1} is much smaller that the overall geometrical beaming θ_0. During the afterglow these regions grow and their emission is spread over larger angular regions. This effect could also explain the wide GRB luminosity function. The observed sample of GRBs with afterglows is biased towards strong bursts and hence towards cases in which such a hot spot have been observed. A second phenomenon that has similar effect is spreading of the beam from the internal shocks phase to the early afterglow phase[57)]. Here we expect expansion only by a factor of a few, but this could be sufficient to explain the discrepancy between the GRB and the early afterglow luminosities.

10.2. Acceleration, Shocks and Microphysics

A second set of theoretical open questions involve unknown microphysics: How does the "inner engine" accelerate particles to relativistic velocities? How do the collisionless shocks arise within the emitting regions? How do these shocks accelerate particles and enhance the magnetic fields? These questions are wide open. They could be an extremely challenging tasks for ambitious PhD projects, with not too good chances of success. Should we fail this model because of this ignorance? Here, one can just look around and realize that related question have not been answered in other, much better studied, astronomical source: AGNs, pulsars and our own solar corona to name a few.

11. Neutrinos, UCHERS, Gravitational Radiation and TeV photons

The extreme conditions that arise in GRBs can lead to emission of other particles apart from gamma-ray photons. For any specific particle that could be produced one should calculate the ratio $f_{x\gamma}$ and then compare the expected fluxes with with the capabilities of current detectors. One should distinguish between two types of predictions: (i) Predictions of the generic fireball model which include high energy neutrinos[86,87], low energy cosmic rays[88] and UCHERs[89,90] and TeV photons[38,91,92]; (ii) Predictions of specific models that depend on the specific sources. These include low energy neutrinos and gravitational waves[72,93].

Before turning to all these suggestions one word of caution is needed. All these suggestions require additional energy which strain the already limited energy budget of most models. Just on the basis of simple energy considerations I would guess that it is unlikely that significant observable fluxes of all the following particles could accompany GRBs.

11.1. High Energy Neutrinos

Waxman & Bahcall[86] and Vietri[87] suggested that collisions between protons and photons within the relativistic fireball shocks produce pions. These pions produce high energy neutrinos with $E_\nu \sim 10^{14}$eV and $f_{\text{high energy } \nu-\gamma} > 0.1$. The flux of these neutrinos is comparable to the flux of atmospheric neutrinos but those will be correlated with the position of strong GRBs. This signal might be detected in future km^2 size neutrino detectors.

11.2. Low Energy Neutrinos

Most of the energy generated in any core collpase event is released as low energy ($\sim 5-10$MeV) neutrinos. These emission depends on the source but it is common to most sources that we have discussed so far, neutron star mergers, black hole neutron star mergers and failed supernova. The total energy is quite large $\sim$ a few $\times 10^{53}$ergs, leading to $f_{\text{low energy } \nu-\gamma} \approx 10$. However, this neutrino signal will be quite similar to a supernova neutrino signal, and at present only galactic SN neutrinos can be detected. Supernovae are ten thousand times more frequent then GRBs and therefore low energy neutrinos associated with GRB constitute an insignificant contribution to the background at this energy range.

11.3. Cosmic Rays and UCHERs

Already in 1990, Shemi & Piran[88] pointed out that fireball model is closely related to Cosmic Rays. A "standard" fireball model involved the acceleration of $\sim 10^{-5} M_\odot$ of baryons to a typical energy of 100GeV per baryon. Protons that leak out of the fireball will become low energy cosmic rays. However, a comparison of the GRB rate (one per 10^6 years per galaxy) with the observed low energy cosmic rays flux, suggests that even if $f_{CR-\gamma} \approx 1$ this will amount only to 1% to 10% of the observed cosmic ray flux at these energies. Cosmic rays are believed to be produced by SNRs. Since supernovae are ten thousand times more frequent than GRBs, unless GRBs are much more efficient in producing Cosmic Rays in some specific energy range their contribution will be swamped by the SNR contribution.

More recently, Waxman[89] and Vietri[90] have shown that the observed flux of UCHERs (above 10^{19}eV) is consistent with the idea that these are produced by the fireball shocks provided that $f_{UCHERs-\gamma} \approx 1$. The relativistic fireball shocks that appear in GRBs are among the few astronomical objects that satisfy the conditions for shock acceleration of UCHERs. GRBs are sufficiently frequenct[k]that there are enough sources within the GZK limit.

11.4. TeV Photons

Inverse compon scattering by an electron with a Lorentz factor γ_e increases the photon's energy by a factor γ_e^2. Thus the ultra high energy electrons that are present in the relativistic shocks could accelerate some of the observed 100 keV photons to TeV energies, providing a souce of such high energy photons[38,91,92].

11.5. Gravitational Waves

All current candidate for sources emit also gravitational radiation. Among those binary neutron star mergers and black hole neutron star mergers are unique as they produce a clean chirping gravitational radiation signal. This signal is the prime target of LIGO and VIRGO, the large interferometers that are build now in the USA and in Europe, suggesting that we can hope for a simultaneous detection of a gravitational waves and a GRB in that not too distant future.

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[k]Magnetic fields deflect the UCHERs and lead to time delays of 10^5years or higher between the GRB and the arrival of the UCHERs. There are enough nearby GRBs within within the GZK distance over such a period.

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