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Physics Reports 333–334 (2000) 529–553

PHYSICS REPORTS

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Gamma-ray bursts – a puzzle being resolved[☆]

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Abstract

For a few seconds a gamma-ray burst (GRB) becomes the brightest object in the universe, over-shining the rest of the universe combined! Clearly, this reflects extreme conditions that are fascinating and worth exploring. The recent discovery of GRB afterglow have demonstrated that we are on the right track towards the resolution of this long standing puzzle. These observations have confirmed the relativistic fireball model (more specifically the internal–external shocks model). The prompt optical emission seen 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 implies that GRBs signal the birth of stellar mass black holes. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 98.70.Rz; 97.60.Lf

Keywords: Gamma-ray bursts; Black holes

1. Prologue

It is a well kept secret that Dave Schramm wrote a paper on GRBs. Dave visited Jerusalem for the Supernovae winter school of 1989. Our discussions, together with Mario Livio and David Eichler, led to: “Nucleosynthesis, Neutrino Bursts and gamma-rays from Coalescing Neutron Stars” [1] that was published in Nature in May 1989. At that time it was well known that binary neutron star mergers are excellent sources of a characteristic gravitational radiation signal as well

[☆]Supported by the US–Israel BSF grant 95-328 and by NASA grant NAG5-3516.

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as a strong but undetectable MeV neutrino burst. Although the idea that cosmological neutron star mergers are sources of GRBs was mentioned in passing in some earlier works, this was the first systematic attempt to construct a “first principles” model [2]. Additionally, we have pointed out in this paper that these mergers could be important sites for r-process nucleosynthesis.

Dave was very excited about this paper. He predicted that it will be widely quoted as it was at the intersection of four different topics: gravitational radiation, neutrinos, GRBs and nucleosynthesis, and all four communities would refer to it. He was wrong, at least for a while. At first, the paper was ignored by all four communities. In 1989, GRBs were believed to be galactic and anything associated with a cosmological GRB model was too controversial to be taken seriously. Cosmological neutron star mergers were discussed only as sources of gravitational radiation. This has changed gradually after BATSE’s discovery in 1991 that GRBs are cosmological [3]. Eventually, neutron star mergers became the “canonical” GRB model, and the paper begun to be cited. Moreover, recent observations [4] and detailed calculations [5] suggest that neutron star mergers are indeed important sites for r-process nucleosynthesis. Even among the gravitational radiation community there seems to be a beginning of a discussion of the implication of a GRB association for the detection of gravitational waves [6]. Like in many other issue Dave was right. It just took the rest of us longer to realize that.

2. Introduction

Gamma-ray bursts (GRBs) are short and intense bursts of MeV range gamma-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 [7]. This enabled accurate position determination and the discovery of optical [8] and radio [9] afterglows and 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 viewed as an update of my recent *Physics Reports* review [10]. 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 does not deal directly with the “inner engine” – the source of the relativistic ejecta that powers the whole phenomenon. I review the implications of the current observations, as interpreted within the fireball model, to models of the source and I discuss some of the possible sources. I examine some open questions and in particular the possible “energy crisis”. I conclude with a “wish list” of new observations that might resolve this enigma.

3. Summary of GRB observations

GRBs are short and intense bursts of 100 keV – a few MeV gamma-rays. GRBs vary greatly from one to another. Even though there is no “typical” GRB, I show in Fig. 1 some features of

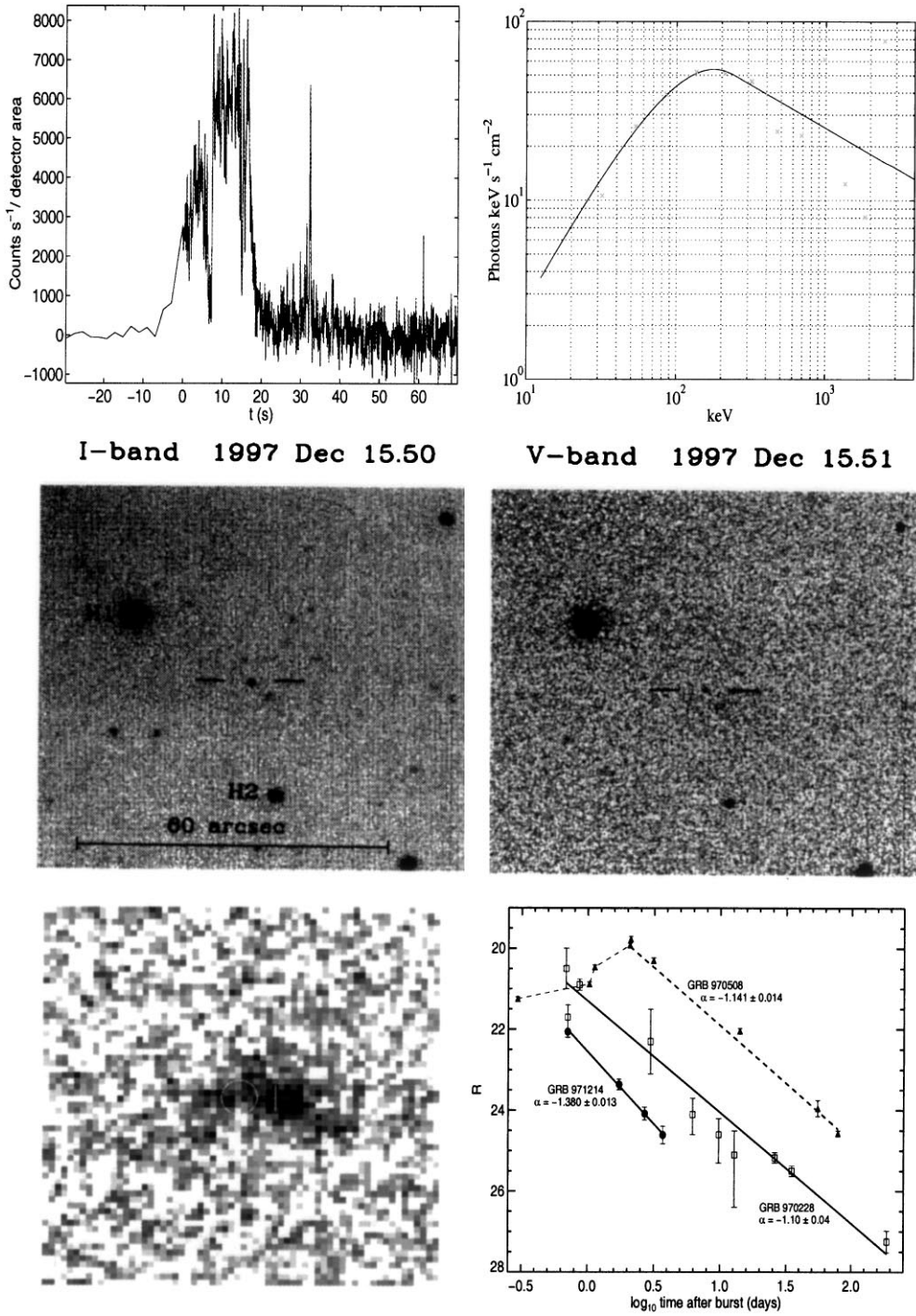


Fig. 1. GRB 971214: Top left gamma-ray light curve; top right the spectrum; middle the afterglow [11]; bottom left the host galaxy [12]; bottom right optical light curve for GRB 971214, GRB 970508 and GRB 970228 [13].

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} erg/cm² (the upper limit depends, of course, on the duration of the observations while 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 is nonthermal. In most cases there is a strong power law high-energy tail extending to very high energies (up to a few 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 [14]: two power law joined smoothly together. The lower energy spectral index, $dN(E)/dE$, is, quite generally, in the range $(\frac{1}{3}, -\frac{1}{2})$ which is compatible with the relativistic synchrotron model [15]. However, there are indications [16] 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 ms 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 [17]. As a result the short-bursts distribution is compatible with a homogeneous Eucladian distribution [18,19] in which $d \ln N / d \ln S = -\frac{3}{2}$. There have been claims that long bursts with no high energy component (no emission in the higher BATSE channels) are also distributed with a $-\frac{3}{2}$ slope [20]. However, it is not clear if there is a real need to consider those as a separate subgroup [21].

4. Afterglow observations

The Italian Dutch satellite, BeppoSAX, discovered X-ray afterglow on February 28 1997 [7]. 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.² Optical [8] and radio [9] afterglows were discovered using the accurate 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 [22–25] and the radio [26] afterglows. The overall energy emitted in the afterglow is of order 10^{50} – 10^{52} . Quite generally it is only a fraction of the energy emitted during the GRB.

² Hopefully, the planned mission of HETE II and the proposed missions SWIFT and BALLERINA will answer this question.

- The afterglow light curve decays, in most cases, as a single power law in time:³ $F_\nu \propto t^{-\alpha}$, 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 later 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 s after the gamma-ray peak and coincided with the prompt X-ray peak.

5. The relativistic internal–external shocks fireball model

The nonthermal spectrum indicates that the observed emission emerges from an optically thin region. However, a simple estimate of the number of photons above 500 keV and a simple estimate of the size of the source ($c\delta t$ as implied by the observed variability) shows that such a source must be extremely optically thick to pair creation [27–30]. Such a source cannot emit nonthermal emission. This is the Compactness problem.

The simplest way to overcome this problem is if the source is moving ultra-relativistically towards us [31–33]. This has led to the relativistic fireball model. According to this model slowing relativistic ejecta produces the GRBs and their afterglow. Relativistic electrons that have been accelerated 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 transferred 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.
- 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 matter [35], like the ISM or with a circumstellar wind that took place during an earlier epoch. These shocks are the relativistic analogues of SNRs. Like in SNRs these shocks are collisionless. External

³ Sari et al. [34] have introduced in the astro-ph version the notation $F_\nu \propto t^{-\alpha} v^\beta$. This notation was changed to $t^{-\beta} v^\alpha$ in the Ap. J. version and in my review [10]. However, the astro-ph notation caught so well that I return to this original notation here and elsewhere.

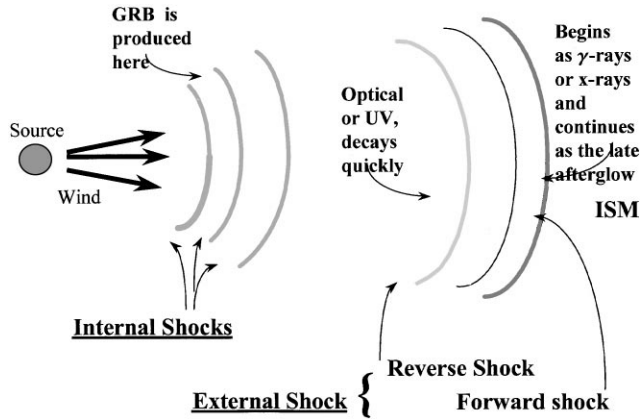


Fig. 2. The internal–external shocks scenario. An inner compact source produces a variable relativistic wind. Relativistic internal shocks arising in this wind produce the GRB. The wind continues and interact with the surrounding circumstellar matter. The relativistic forward shock produces first a gamma-ray or X-ray signal, while a reverse shock produces a prompt optical flash and early radio emission. Later the ejecta rearranges itself according to the Blandford McKee solution which produces the long lived afterglow.

shocks become effective at [36] $\min(R_\gamma, R_A)$, where $R_\gamma \equiv l/\gamma_0^{2/3}$ and $R_A \equiv l^{3/4}\Delta^{1/4}$. 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, $l \equiv (E_0/[(4\pi/3)n_{\text{ism}}m_p c^2])^{1/3}$, 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 $R_\gamma \sim R_A \sim 10^{15}$ – 10^{16} cm.

Sari and Piran [37] and Fenimore et al. [38] have shown that external shocks cannot produce efficiently the observed highly variable temporal structure seen in GRB.⁴ Thus, GRBs are produced by the only other alternative, internal shocks [40–42]. 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 $R_{\text{int}} \sim \delta\gamma_0^2$. $\delta = c\delta t$ can be inferred from the observed temporal variability $\delta t \leq 1$ s 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” [43]. 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 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 [44]. 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

⁴Dermer and Mitman [39] 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.

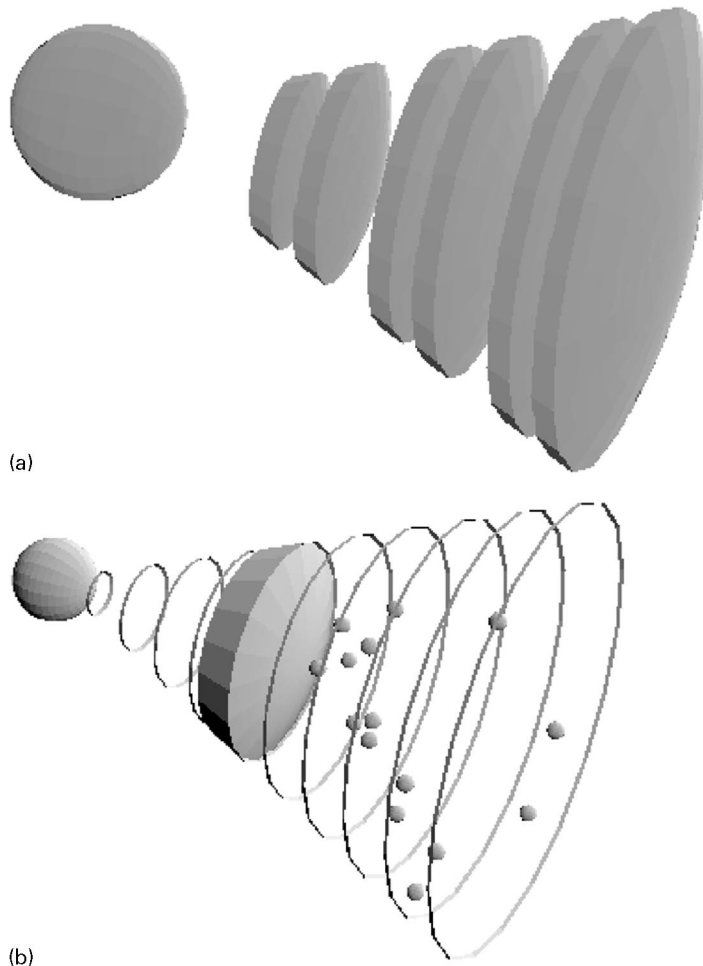


Fig. 3. (a) The internal shocks: faster shells catch up with slower ones and collide, converting some of their kinetic energy to internal energy. (b) To produce variability in external shocks the relativistic ejecta must encounter interstellar bubbles. However, most of the shell passes between the bubbles and its kinetic energy is lost.

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 been extremely inefficient [37]. This rules out the possibility of an explosive “inner engine”.

Internal shocks can extract only a fraction of the total energy [45,43,46]. Sari and Piran [37] suggested that the remaining energy will be extracted later via external shock giving rise to additional emission at different wavelengths – the afterglow. Thus, GRB have a fourth 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 [47] adiabatic self-similar solution.

6. The late afterglow: a prediction and a confirmation of the fireball model

Paczynski and Rhoads [48] and independently Katz [49] realized early on that the long-term interaction of the relativistic ejecta with the surrounding matter will produce a low-frequency afterglow. Paczynski and Rhoads [48] discuss radio afterglow. Katz [49] discusses optical afterglow. Later, Mészáros and Rees [50] and independently Vietri [51] 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 arise due to internal shocks and the afterglow is produced by external shocks [37] we do not 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 provides 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 [52] quickly suggested that the flickering arises due to scintillation. Initially, the source is small and it is within the scintillation regime. As the source expands the scintillation stops. Using this idea Frail et al. [9] 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 [53] suggested that synchrotron self-absorption would result in a rising spectrum in radio frequencies for which the source is optically thick and using the observed flux and an estimate of the temperature of the emitting regions one could estimate the size of the emitting region. Frail et al. [9] 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.

7. 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 $p \sim 2.5$.⁵ 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: $E_{\min} = [(p + 2)e_e / (p + 1)n_e]$, where n_e and e_e are the electrons' density and their energy density. 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 [54].

⁵ One can expect that this number will be universal and will not vary from one burst to another.

These definitions enable Sari et al. [34] 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 whether the “typical” electrons are cooling within the hydrodynamic time t_{hyd} . In a fast cooling system the cooling time of an electron with E_{min} is shorter 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: $E_c/P_{\nu_c}(E_c) = t_{\text{hyd}}$. 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 spectrum 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 $\tau(\nu_{\text{sa}}) = 1$. Unlike the common discussion of synchrotron self-absorption in text books (which assumes $\nu_{\text{sa}} > \nu_m$ and obtain $F_\nu \propto \nu^{5/2}$), here $\nu_{\text{sa}} \ll \nu_m$. In this case $F_{\nu_{\text{sa}}} \propto \nu^2$, just like the usual Wien part of a black body spectrum. Combined we have $F_\nu \propto \nu^\beta$ with

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

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 [22]. 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 [23] 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 later 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 than $\frac{1}{3}$. Cohen et al. [15] find that this is satisfied in several strong bursts that have a well-determined spectrum. Prece et al. [16] 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 [55]. Ghisellini and Celotti [56] even suggest that numerous pairs are produced 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 et al. [34] used the scaling laws of the Blandford–McKee solution (which assumes adiabatic evolution and propagation into a constant density surrounding

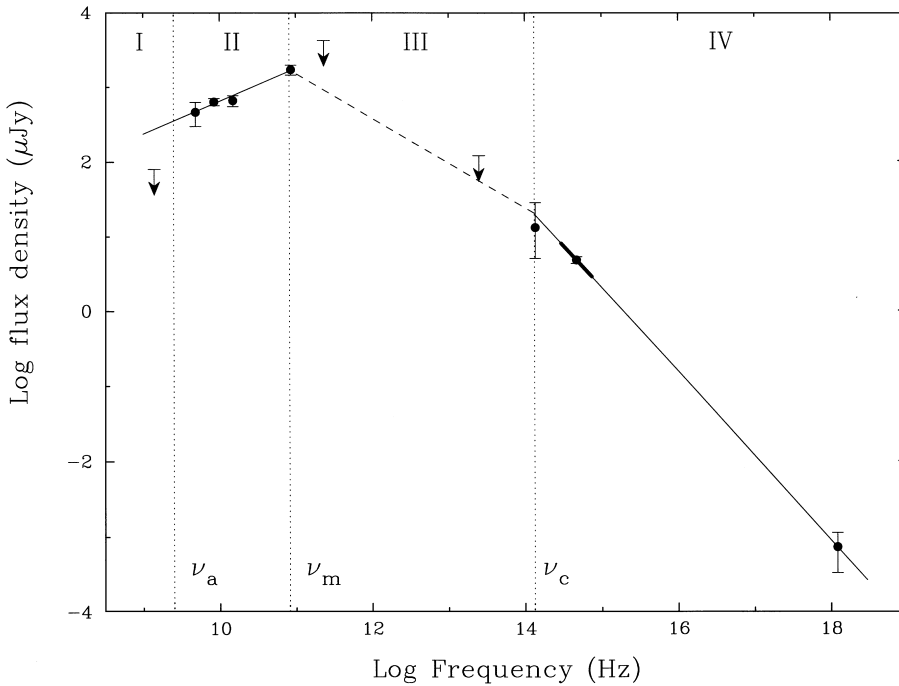


Fig. 4. The X-ray to radio spectrum of GRB 970508 on May 21.0 UT (12.1 days after the event). The fit to the low-frequency part, $\alpha_{4.86-8.6 \text{ GHz}} = 0.44 \pm 0.07$, is shown as well as the extrapolation from X-ray to optical (solid lines). The local optical slope (2.1–5.0 days after the 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. [22].

medium) and the scaling laws of a radiative solution 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:⁶

$$E_0 = M(R)c^2\gamma^2 \quad (2)$$

and

$$t_{\text{obs}} = \frac{R}{2c\gamma^2}, \quad (3)$$

where $M(R)$ is the accumulated 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

⁶ When using the full Blandford–McKee solution there are factors of order unity on the l.h.s. of these equations [57].

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 . For the spherical adiabatic case we have

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

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

8. 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 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 [58,59]. 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 ~ 1000 [55]. 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 [57]. 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:

$$E_0 = M(R)c^2\gamma(R)\gamma_0 . \quad (5)$$

We also replace the emissivity equation. For slow cooling the emitted flux is $N_e P$, 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-rays or hard X-rays [61]. This emission could be viewed as a superposition of a longer and smoother and somewhat softer component on top of the variable, hard internal shocks signal [57]. This signal should be scaled and compared with the late afterglow as they arise from 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.

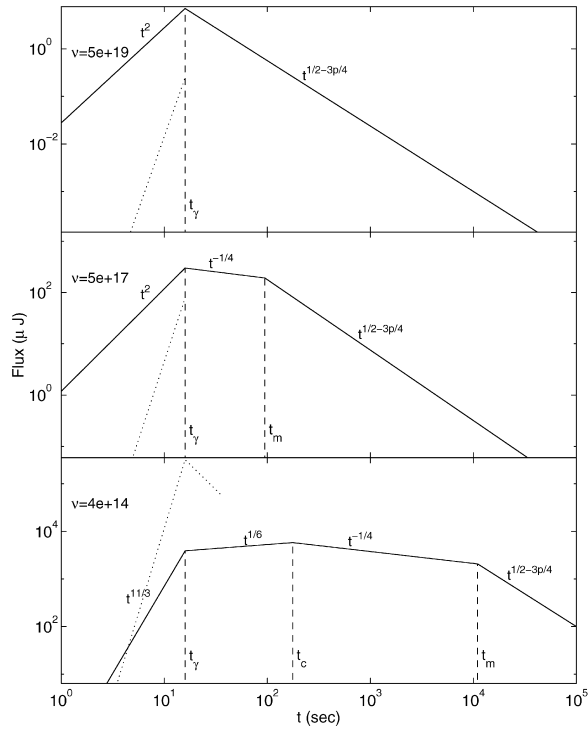


Fig. 5. The early gamma-ray, X-ray and optical afterglow. The dashed curve on the optical range is due to the reverse shock emission [60,61].

A remarkable new component that appears in Fig. 5 is the prompt optical flash. Early gamma- 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.⁷ The emission from the reverse shock peaks at lower frequencies: $\nu_{\text{m,rev}} \approx \nu_{\text{m,for}}/\gamma^2$. If $\nu_{\text{m,for}}$ is in the X-ray and $\gamma_0 \sim 100$ we expect $\nu_{\text{m,rev}}$ 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/cm² would have been released on a time scale of 10s 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 bulk Lorentz factor). As the forward shock must be radiative: $\nu_{\text{c,for}} < \nu_{\text{m,for}}$. If $\nu_{\text{c,rev}} = \nu_{\text{c,for}} \gg \nu_{\text{m,rev}}$ the reverse shock might not be radiating efficiently and this might lower the

⁷This 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.

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 [61]

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

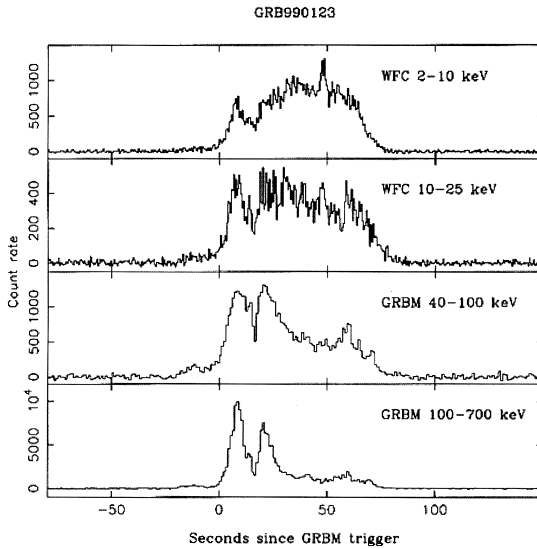


Fig. 6. The light curves of GRB 990123 in different bands [66]: from top to bottom: 2–13; 13–40; 40–100 and 100–700 keV. The increasing X-ray flux at late time is seen clearly. Note that BeppoSAX’s trigger is ~ 25 s after BATSE’s trigger.

observed signal. Table 1 from [61] show this reduction. Even with these factors, one can hardly avoid a strong optical emission from the reverse shock. Additional effects such 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 [60] 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 and Rees [50] in two of several models they examined. This prediction was almost in contradiction with the LOTIS upper limits on several bursts (see e.g. Ref. [62]). Less than two month later on January 23 1999 ROTSE [63] was triggered by the GCN network [64] and detected a 9th magnitude optical 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

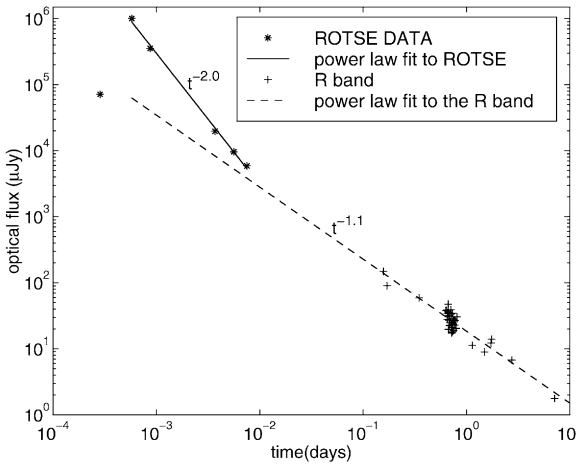


Fig. 7. The early optical light curve of GRB 990123 [67].

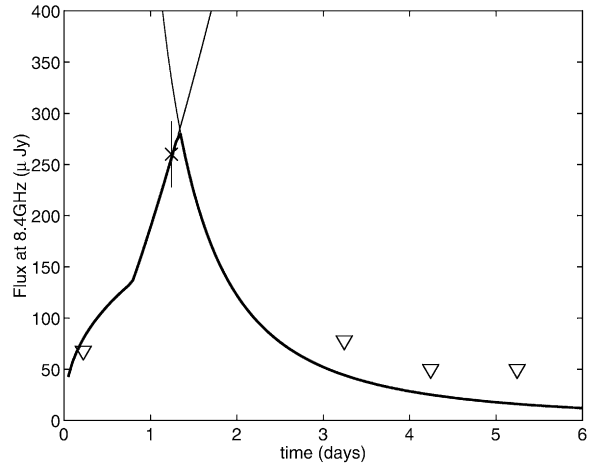


Fig. 8. Observations and theoretical light curve for the early radio signal of GRB 990123 [67].

at least 25 s 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 of rapid decline $\sim t^{-2}$ again in a complete agreement with the prediction of the reverse shock emission [60,61,65]. Later 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 [60]:

- The time of the optical flash peak, $\sim 70 \text{ s} \sim l/(c\gamma^{8/3})$. For $l \sim 10^{18} \text{ cm}$ Eq. (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 1.5–10 keV band. Using the initial ratio $v_{\text{m,ror}}/v_{\text{m,rev}}$ we find that $\gamma_0 \sim 70$.

Radio emission was observed from GRB 990123 [68,69]. This radio emission peaked around one day with marginal detections prior and later 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 [67]. 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 perpendicular size of the system, γct , at 1 day after the burst to be $\sim 10^{15} \text{ cm}$!

9. 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 $\sim 3 \times 10^{53}$ and 4×10^{54} erg, respectively.⁸ 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.

9.1. 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 $\gamma \sim 2\text{--}10$, respectively, corresponding to a relativistic beaming of 10^{-2} and $0.1\text{--}0.5$ 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 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 later, 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 [70]. 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 et al. [71] expect it to expand with the speed of light: $\theta \sim \gamma^{-1}$. Rhoads [72] 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 [73]⁹ $\gamma \propto R^{-3/2} \exp[-[3/(2\gamma_0\theta_0)(R^{3/2}/R_0^{3/2} - 1)]]$, which is valid before, during and after the transition. 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 factor¹⁰ of

⁸This values depend, of course, on the cosmological model assumed.

⁹Rhoads [72] obtained a different exponent. For clarity we drive this expression in an appendix. This does not influence, however, the rest of Rhoads’ conclusions.

¹⁰The 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 [74].

t^{-1} . Within the adiabatic synchrotron model we have new relations between α , β and p :

$$\alpha_{\text{beam}} = \begin{cases} 2\beta + 1 = p & \text{for } v < v_c, \\ 2\beta = p & \text{for } v > v_c. \end{cases} \quad (6)$$

9.2. 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 $t^{-2.05 \pm 0.04}$ in optical as well as in X-rays [75]. 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 sideways spreading must have begun before the first optical observation, namely, less than 8.5 h after the burst. Using the detector's time equation (Eq. 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. [76] 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. [76] 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 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

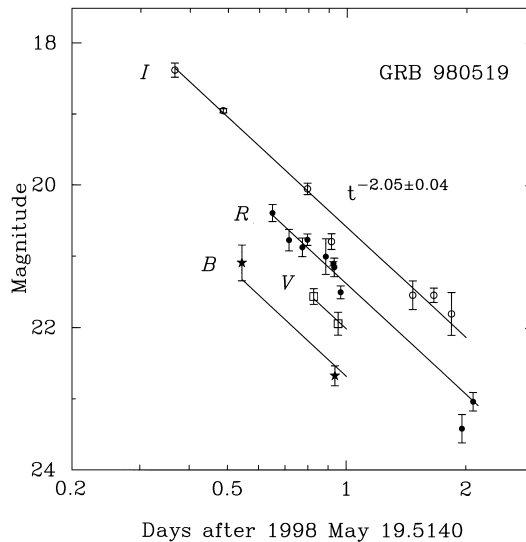


Fig. 9. An optical light curve for GRB 980519. The fast decline indicate a spreading beam [75].

determined to be spurious; better data show no constant component to a limiting magnitude of [77] $R = 27.3$. If the last detection is interpreted as a different phenomenon [77] 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 [78]. 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 $t^{-1.1 \pm 0.03}$. 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 h 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 sideways 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} erg.

Finally, just last May, GRB 990510 depicted a beautiful transition from $t^{-0.82 \pm 0.02}$ to $t^{-2.18 \pm 0.05}$ at 1.2 ± 0.08 days after the burst [79]. The isotropic energy of this burst is 2.7×10^{53} erg. With a beaming factor of 300 this becomes a “modest” 10^{51} erg.

9.3. 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 – 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 (in the 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 $T = 30$ s) 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, even at this early phase the ejecta expands sideways proportionally to R (unless it is continuously collimated) and even in its own frame it looks like a pancake.

10. 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 will not work.
- *Variability*: The variability time scale, δt , suggests 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 than 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 10^7 years 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 [40].
- *Association with star forming regions*: There is some evidence that host galaxies of GRBs are star forming galaxies [80] (see however [81]). This would support short-lived progenitors:¹¹ collapsing massive stars or short-lived (10^4 – 10^5 years) binary neutron stars [82].
- *GRB 980425, SN1999bw and the GRB-SN association*: The error box of GRB 990425 contains the bright supernova SN1999bw which is at $z = 0.085$ [83]. This has lead to a debate on the association of GRBs with type Ic supernovae [84–86].

This evidence, and more specifically, the energy and the time scale considerations suggest that GRBs are powered by accretion of a massive $\sim 0.1M_{\odot}$ accretion disk onto a compact object, most likely a black hole. Such a massive accretion disk must form simultaneously with the black hole, from matter that was slowed down by centrifugal forces. Thus GRBs signal the formation of black holes. The gravitational energy of a $0.1M_{\odot}$ can supply the energy required for the process, the accretion time 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 [87] 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 [1] 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 [88]. This rate is comparable to the rate of GRBs [89]. The final outcome of such a merger [90–92] is a $\sim 2.4M_{\odot}$ black hole surrounded by a 0.1 – $0.2M_{\odot}$ thick accretion disk, which could power the burst [40].

¹¹ The lifetime 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.

- *Neutron star – black hole merger*: This is a simple variation on the previous theme. One expects 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 $\sim 10M_{\odot}$ 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 [88], or even more common [93] none was observed so far.
- *“Failed supernova”, collapsar of hypernova*: These are all different names for a collapsing star that produces a GRB. Both Woosley’s [94] failed supernova model and Paczyński’s [95] hypernova’s model assume that the rapidly rotating collapse produces a rotating massive black hole surrounded by a thick torus that accretes 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 unstable¹² when it reaches 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.

It is interesting to note that these 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.

11. Some open questions

In a conference called “some open questions in astrophysics” that took place in the fall of 1995, I [70] 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 now 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-Collapsar-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 life¹³ to

¹² The expected mass ratio in a white dwarf – black hole binary is small and we expect these systems to be stable.

¹³ 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.

discovering life [96]. A more mundane proposal 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 [97].

The most problematic open question concerning all these models is the issue of efficiency and the possibility of an “energy crisis”:

11.1. 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} erg. Even with beaming the energy is reduced to a gigantic 10^{52} erg. Internal shocks can convert under reasonable conditions $\sim 10\%$ of the kinetic energy to thermal energy [45,43,46,98]. External shocks are even less efficient. Then there is the question of radiative efficiency [54,55] and of additional energy losses [98]. 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 more 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 [99], whose angular size γ^{-1} is much smaller than 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 [73]. 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.

11.2. Acceleration, shocks and microphysics

A second set of theoretical open questions involve unknown microphysics: How does the “inner engine” accelerate the ejecta to relativistic velocities? How do the collisionless shocks arise within

the emitting regions? How do these shocks accelerate particles and enhance the magnetic fields (see however [100])? These questions are wide open. They could be an extremely challenging tasks for ambitious Ph.D. 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.

11.3. *An observational wish list*

Because of the accidental nature of GRBs, when discussing observational issues one can only state a wish list. We hope that new bursts will provide answers to this questions, even though some observers seem to know better how to make a wish list materialize.

The first group of questions deals directly with the sources. Answer to these questions could resolve, once for all, the mystery of GRBs.

- Is there a GRB-SN association?
- What is the relation between GRBs and star forming regions?
- Are there short-lived binary neutron star systems and/or black hole–neutron star binaries?

The second group of questions deals with the physical processes. Here detailed multiwavelength light curves of the prompt emission and the early afterglow could provide invaluable information on the extreme conditions that take place in these regions. The next generation GRB detectors with precise position capabilities and rapid response systems promise that these wishes will be fulfilled in the not to distant future. Among these the question whether afterglow is generic and arises also for short or for less intense bursts is an important and crucial issue.

12. Epilogue

Ten years after the neutron star merger paper [1], these sources are amongst the best candidates for GRB sources. The major problems facing them are the “energy crisis” that faces most compact GRB models and the issue of association with star forming regions, which is not expected for long-lived neutron star binaries. In spite of those problems even today neutron star mergers are still the only sources that can produce the enormous amounts of energy involved and are based on an independently observed phenomenon that is known to take place at a comparable rate [89]. Ironically, while the specific mechanism (pair creation via $\nu\bar{\nu}$ annihilation) discussed in this early paper [1] is most likely invalid in the context of neutron star mergers, it has been recently suggested that it might be important in the context of the competing failed supernovae-collapse model [101].

I have stressed repeatedly here and elsewhere that the GRBs’ “inner engine” is hidden. As such we cannot distinguish directly between different GRB models that potentially go via the same route and produce a black hole – accretion torus system believed to be capable of powering

a GRB. At this stage I can only turn, once more, to my wish list and add one final wish – the simultaneous detection of a GRB and a chirping gravitational radiation signal characterizing a neutron star merger. Such a coincidence will clearly enhance the significance of the detection of the gravitational radiation [102]. It will also verify this merger model and will resolve the GRB enigma.

Acknowledgements

I thank Re'em Sari for a wonderful and productive collaboration and J. Granot, J. Katz, S. Kobayashi, P. Kumar, R. Narayan and F.K. Thielemann, for many helpful discussions. This research was supported by the US-Israel BSF grant 95-328, by a grant from the Israeli Space Agency and by NASA grant NAG5-3516. I thanks Columbia University, NYU and Basel University for their hospitality while this research was done.

Appendix

Following Narayan and Piran [73] I derive here the exponential dependence of the Lorentz factor, γ , on R in an sideway expanding relativistic beam. R and R_\perp are along and perpendicular to the jet's axis in the observer frame. We write the adiabatic energy equation (2) as

$$\gamma = \gamma_0 \frac{R_{\perp 0} R_0^{1/2}}{R_\perp R^{1/2}}. \quad (\text{A.1})$$

The sideway propagation equation is

$$\frac{dR_\perp}{dR} = \frac{c_x}{\gamma} + \frac{R_\perp}{R} = \frac{c_x R_\perp R^{1/2}}{\gamma_0 R_{\perp 0} R_0^{1/2}} + \frac{R_\perp}{R}, \quad (\text{A.2})$$

where c_x is either the speed of light (1) or the speed of sound ($1/\sqrt{3}$). Integration yields

$$\frac{R_\perp}{R_{\perp 0}} = \frac{R}{R_0} \exp \left[\frac{3 c_x}{2 \gamma_0 \theta_0} \left(\frac{R^{3/2}}{R_0^{3/2}} - 1 \right) \right]. \quad (\text{A.3})$$

Finally, we substitute (A.3) in (A.1) to obtain

$$\gamma = \gamma_0 \left(\frac{R_0}{R} \right)^{3/2} \exp \left[- \frac{3 c_x}{2 \gamma_0 \theta_0} \left(\frac{R^{3/2}}{R_0^{3/2}} - 1 \right) \right]. \quad (\text{A.4})$$

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