GAMMA-RAY BURSTS - THE SECOND REVOLUTION

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Abstract

Gamma-ray bursts GRBs are among the most mysterious astronomical phenomenon ever discovered. Unlike most astronomical discoveries which were explained within weeks or months after their initial discovery, GRBs remain a puzzle for more than thirty years. During the last decade our understanding of GRBs has undergone two major revolutions. First, BATSE discovered that GRBs are distributed isotropically over the sky and thereby demonstrated their cosmological origin. The second revolution took place more recently when BeppoSAX discovered GRB afterglow. This confirmed the fireball model and led to a wealth of observational data, some of which has not been fully understood yet. The emerging picture is that GRBs are the most luminous objects and the most relativistic objects ever discovered: (i) GRBs involve relativistic motion at a velocity of 0.9999c or larger. (ii) Most current GRB models involve the formation of a black hole in one way or another. (iii) If binary neutron star mergers are the sources of GRBs then GRBs are also associated with gravitational radiation signals. Finally, (iv) as cosmological power-houses that are observed to high redshift GRBs might be used to measure cosmological parameters and to teach us about the epoch of galaxy formation.

1. Introduction

Our understanding of GRBs has undergone two major revolutions during the last decade. The first revolution took place at the early nineties when BATSE discovered that the angular distribution of GRBs is isotropic and there is a paucity of weak bursts (Meegan 1992). This discovery ruled out the then popular galactic disk neutron star model and established that GRBs are cosmological with a typical red-shift of order unity (Piran 1992; Fenimore et al. 1993; Cohen & Piran 1995). The immediate implication was that the total energy involved is of order $10^{52}$ ergs
or more. Since this energy is released within a few seconds GRBs are the most (electromagnetically) luminous objects in the Universe.

The rapid variability of GRBs suggests a compact source. When combined with the observed flux and the cosmological distance this implies enormous photon density. Such a source will have an huge optical depth for pair productions (by the high energy $\gamma$-rays). However, the observed spectrum extends far above 500KeV and the spectrum is non thermal - indicating that the sources are optically thin.

A solution for the problem was suggested even before BATSE’s discoveries. The compactness problem could be resolved if the emitting regions are moving relativistically with a Lorentz factor $\gamma \geq 100$. This have led to the fireball model. According to this model GRBs are produced when a relativistic flow is slowed down and its kinetic energy is extracted and converted to radiation. This model leaves open the questions what is the “inner engine” - the source that produces the relativistic flow and how is the flow produced? It deals only with the emitting regions, which are distant and separate from the source.

An immediate prediction (Paczyński & Rhoads 1993; Katz 1994; Mészáros & Rees 1997; Sari & Piran 1997) of the fireball model is the appearance of afterglow - a following radiation that results from stages when the flow is slower, but still relativistic. The afterglow is produced on much longer time scale and at longer wavelengths. The second GRB revolution occurred on 28 February 1997 when the Italian-Dutch satellite BeppoSAX discovered X-ray emission that accompanied GRB970228 (Costa et al. 1997). The X-ray emission continued for a few hours. The accurate X-ray position enabled follow up observations that detected a decaying optical source. GRB afterglow was discovered and an optical and X-ray counterparts were found. Since then about a dozen afterglows that accompanied GRBs were observed. Cosmological redshifts were measured in several cases, confirming the cosmological origin of GRBs. Evidence for relativistic motion and relativistic shocks was found and the fireball model was practically confirmed.

In this talk I review the fireball model. In particular I examine the external-internal shock model, according to which GRBs are produced by internal shocks within the flow while the afterglow is produced by external shocks with the ISM. I will show how the recent observations support this picture. However, as commonly happens when new data becomes available new puzzles arise. I will briefly discuss the new puzzles that arose in recent observations.

As the focus of this conference, honoring Humitaka Sato, is on general relativity it is worthwhile mentioning that GRBs are not only the most luminous objects known, they are also the most relativistic objects ever discovered. First, the generic fireball model is based on a relativistic macroscopic motion at a ve-
locity of 0.9999c. This is closer to the speed of light than what was observed in any other macroscopic object. The GRB and the associated fireball involve relativistic shocks which are observed for the first time. Most models for the source that produces the fireball involve compact objects and end up in a black hole. Thus GRBs signal, most likely, the formation of black holes. The binary neutron star merge is currently the leading GRB model. In this case GRBs should appear in coincidence with the unique gravitational radiation signals produced by these mergers. Finally, GRBs are a cosmological population that is observed regularly and uniformly. Various cosmological relativistic effects such as redshift and time dilation have already been observed in the GRB data. When understood, GRBs could teach us a lot about the epoch of galaxy formation and possibly could provide new ways to measure cosmological parameters.

2. GRB Observations

GRBs are short and intense pulses of low energy gamma-rays. The bursts duration, $T$, varies from a fraction of a second to several hundred seconds. Within this time scale most bursts are highly variable and the variability time scale $\delta T \ll T$. A typical ratio is $\delta T/T \sim 0.01$. The spectrum is non thermal. It is fairly well approximated by the Band Spectrum - two power laws joint smoothly together. GRBs contain a significant power in the higher parts of the spectrum and GeV emission has been observed in many bursts. The nonthermal spectrum indicates that the radiation emerges from optically thin regions. The slope of the lower part of the spectrum indicates that GRBs are produced by synchrotron emission in relativistic shocks (Cohen et al. 1997). GRBs appear from random positions in the sky with no repetition. The distribution of GRBs on the sky is isotropic, suggesting their cosmological origin. The paucity of weak bursts is consistent with a cosmological origin as well. In fact one can infer from the peak flux distribution that BATSE detects a typical burst from a redshift of $z \sim 1$ (see e.g. Piran 1992; Fenimore et al. 1993; Cohen & Piran 1995). The agreement of the peak flux distribution with a cosmological standard candles distribution suggests that the luminosity function of GRBs is not too broad and that GRB luminosities do not vary by more than one order of magnitude (Cohen & Piran 1995).

3. The Fireball Model

The fireball model is a generic GRB model according to which GRBs form when a relativistic expanding shell (or a relativistic jet) is slowed down and its energy is converted to gamma-rays. This model was motivated by the need to overcome the compactness problem. It is the starting point of our discussion.
There are two variants of the fireball model, the *external shock model* and the *internal shock model*. I will show that both shocks take place in an *external-internal shock model*: the GRBs are produced by internal shocks while the afterglow is produced by an external shock that follows.

### 3.1. Compactness and Relativistic Motion

The key to understanding GRBs lies, I believe, in understanding how GRBs bypass the compactness problem. Consider a typical burst with a total energy of $10^{52}$ ergs (as inferred from the observed flux and the implied distance of a cosmological source) that varies on a time scale $\delta T \approx 10$ msec. Standard considerations suggest that the temporal variability implies that the sources are compact with a size, $R_i < c\delta T \approx 3000$ km. The resulting energy density and photon density at the source are enormous. Under these conditions photons with $h\nu \geq m_e c^2$ would interact with lower energy photons ($h\nu' \geq (m_e c^2)^2/h\nu$) and produce electron-positron pairs. The typical optical depth for this process is $\sim 10^{16}(E/10^{52}$ ergs)$/(\delta T/10$ msec)$^{-2}$ (Piran 1997). However, the observed non-thermal spectrum contains many high energy photons which indicate with certainty that the source must be optically thin.

The compactness problem can be resolved if the emitting region is moving towards us with a relativistic velocity characterized by a Lorentz factor, $\gamma \gg 100$. The photons’ energy at the source would be lower by a factor $\gamma$ than the observed energy. This implies that fewer photons have sufficient energy to produce pairs. Additionally, relativistic effects allow the radius from which the radiation is emitted to be larger than the previous estimate by a factor of $\gamma^2$: $R_e \leq \gamma^2 c\delta T$. The resulting optical depth is lower by a factor $\gamma^{(4+2\alpha)}$ (where $\alpha \sim 2$ is the spectral index). The source will be optically thin if it is moving towards us with a Lorentz factors $\gamma > 10^{16/(4+2\alpha)} \approx 10^2$.

Relativistic motion does not necessarily mean that the center of mass of the source is moving towards us at such a high velocity. In fact energetic considerations suggest that this is highly unlikely. Instead the motion towards us (the observers) could occur most naturally from a spherical shell that is expanding relativistically. A relativistically expanding spherical shell would be observed from all directions. Relativistic beaming will take place here in the sense that each observer will see only a small portion of the shell. It will see radiation only from a region $\gamma^{-1}$ away from the line of sight to the center. This means that when we observe a source we cannot know whether it is actually spherical. In fact the burst may originate from a jet with an angle $\theta$. In this case it will be observed within a solid angle $\max[\theta^2, \gamma^{-2}]$ along the jet. If $\theta > \gamma^{-1}$ we wouldn’t be able to tell that we are observing a jet.
The potential of relativistic motion to resolve the compactness problem was realized in the eighties by Goodman (Goodman 1986), Paczyński (Paczyński 1986) and Krolik & Pier (Krolik & Pier 1991). While Krolik & Pier (Krolik & Pier 1991) considered a kinematical solution, Goodman (Goodman 1986) and Paczyński (Paczyński 1986) realized that required relativistic motion could arise naturally when a large amount of energy is released within a small volume. The large optical depth of the radiation leads to a formation of a photon pairs-radiation fluid which expands relativistically under its own pressure. This was called a fireball. A pure radiation fireball expands until it becomes optically thin and then all the radiation escapes. However, the resulting spectrum turns out to be almost thermal (Goodman 1986) and thus a pure radiation fireball cannot serve as a model for GRBs.

Shemi & Piran (Shemi & Piran 1990) and Paczyński (Paczyński 1990) have shown that the resulting fireball will be drastically different if it contains even a small amount of baryonic mass. First the electrons associated with the baryons will dominate the opacity and the fireball will become optically thin at a latter stage. More important however is the dynamical results. All the initial energy will be given eventually to the kinetic energy of the baryons. If the rest mass is sufficiently small \( (Mc^2 \ll E) \) the fireball will become relativistic with an asymptotic Lorentz factor \( \gamma = E/Mc^2 \). The baryons form a cold shell. The width of the shell, \( \Delta \), equals the initial size of the fireball if the source producing the fireball is “explosive” and it release all its energy at once. If, on the other hand the source operates for a long time (long compared to its light crossing time) then \( \Delta = ct \). In this case we expect that fluctuations in the flow (which are essential for the formation of internal shocks) would be on a length scale \( \delta \) greater or equal to the size of the source, \( R_{\text{source}} \).

Relativistic velocities were suggested as a theoretical concept as the only way to overcome the compactness problem. Their appearance in GRBs was recently established observationally in afterglow observations (Frail et al.1997). This is one of the great successes of the “second GRB revolution”.

3.2. Relativistic Shocks

The shell’s kinetic energy could be converted to “thermal” energy of relativistic particles (and then to gamma-rays via synchrotron or inverse Compton) via shocks (Mészáros & Rees 1992). Both the low energy spectrum of GRBs and the high energy spectrum of the afterglow provide indirect evidence for relativistic shocks in the GRB (Cohen et al.1997) and in the afterglow (Wijers, Rees & Mészáros 1997). The shocks could be (i) external - due to interaction with an external medium like the ISM (Mészáros & Rees 1992) or (ii) internal due to ir-
regularities in the flow itself (Narayan, Paczyński & Piran 1992; Rees & Mészáros 1994; Paczyński & Xu 1994). In either case these shocks must take place at sufficiently large radii where the flow is optically thin, allowing the emission of a non-thermal spectrum.

Consider a shell of width $\Delta$. The interaction of the shell with the ISM will take place in the form of two shocks. A forward shock propagating into the ISM and a reverse shock propagating into the shell. The behaviour of external shocks depends on a dimensionless parameter $\xi \equiv (l/\Delta)^{1/2} \gamma^{-4/3}$, where $l = (3E/4\pi n_{ism} m_p c^2)^{1/3}$ is the Sedov length, the radius of a sphere in which the external rest mass equals the energy of the fireball. The shell’s kinetic energy is converted to shocked particles via external shocks at the radius:

$$R_{ext} = \begin{cases} \frac{l}{\gamma^{2/3}} & \text{if } \xi > 1, \\ \frac{l^{3/4} \Delta^{1/4}}{\Delta} & \text{if } \xi < 1. \end{cases}$$

(1)

Clearly to produce the non-thermal GRBs, this should take place in an optically thin region. Thus: $R_{ext} < R_\tau = \sqrt{\sigma T n_{ism} l^{3}/\gamma}$.

The observed duration is $T$:

$$T = \frac{R_{shock}}{c \gamma_{shock}^2} = \begin{cases} \frac{l}{c \gamma^{8/3}} & \text{if } \xi > 1, \\ \Delta/c & \text{if } \xi < 1. \end{cases}$$

(2)

where $\gamma_{shock}$ is the Lorentz factor of the shocked material.

An observer detects emission from up to an angle $\gamma^{-1}$ from the line of sight. Radiation from different angle arrives at different times with a typical spread of $R_{ext}/c \gamma_{shock}^2$. This is of the same order of magnitude as $T$ given by equation (2) and consequently external shock must be smooth and they cannot show a variable temporal structure. Since most bursts are highly variable Sari & Piran (1997) concluded that GRBs cannot be produced by external shocks. The afterglow is, on the other hand, smooth and it can be naturally generated via the interaction of the shell with the ISM.

Internal shocks are an alternative mechanism for conversion of the kinetic energy. Such shocks take place when the flow is irregular. Let a typical irregularity have a distance scale $\delta$. Then internal shocks will occur at:

$$R_{int} = \delta \gamma^2.$$  

(3)

For consistency, $R_{int}$ should be smaller than $R_{ext}$, otherwise external shocks will take place first. It should also take place in the optically thin regime: $R_{int} < R_\tau$. For internal shocks $\Delta > R_{int}/\gamma^2$ and the burst’s duration is $T = \Delta/c$. The burst varies on a time scale $\delta t = \delta/c = R_{int}/\gamma^2 c$. since $\delta \ll \Delta$ the variability condition $\delta t \ll T$ can be easily satisfied. However this requires $R_{source} \leq \delta \leq 10^3$km.
Internal shocks can convert only a fraction (at most 40%) of the kinetic energy of the shell to radiation (Kobayashi, Piran & Sari 1997; Mochkovitch, Maitia & Marques 1995). Sari & Piran (1997) suggested that the rest of the energy will be emitted later when the shell encounters the ISM. According to this internal external shock model the resulting radiation from this external shock will not necessarily be in gamma-rays - it would appear as a following emission in other parts of the electromagnetic spectrum - afterglow. Afterglow was predicted earlier by various authors (Paczyński & Rhoads 1993; Katz 1994; Mészáros & Rees 1997). However it was generally assumed that the GRB and the afterglow are produced by different stages of the same external shock. In this case the afterglow would have been directly related and scaled to the GRB. However, GRB and afterglow observations have revealed that there is no direct scaling between the two phenomena. This fits naturally the prediction of the internal-external model (Sari & Piran 1997) in which the GRB and the afterglow are produced by two different phenomena.

It should be stressed that within the fireball model the GRB and the afterglow are produced when a relativistic ejecta is slowed down. According to this picture the “inner engine” the source of the GRB remains hidden and unseen. No observed radiation emerges directly from it.

4. Afterglow - The second Revolution

GRB observations were revolutionized on February 28 1997 with the discovery of an X-ray counterpart to GRB970228 by the Italian-Dutch satellite BeppoSAX (Costa et al.1997). X-ray observations by BeppoSAX, ROSAT and ASCA revealed a decaying X-ray source whose flux \( \propto t^{-1.33\pm0.11} \). The accurate position determined by BeppoSAX enabled the identification of an optical afterglow (van Paradijs et al.1997) - a decaying point source surrounded by a red nebulae. The nebula’s intensity does not vary, while the point source decays as a power law \( \propto t^{-1.2} \) (Galama 1997). Afterglow was also detected from GRB970508. Variable emission in X-rays, optical (Bond, 1997) and radio (Frail et al.1997) followed the \( \gamma \)-rays. The spectrum of the optical transient revealed a set of absorption lines associated with Fe II and Mg II with a redshift \( z = 0.835 \) (Metzger et al.1997) demonstrating the cosmological origin of GRBs. Radio emission was observed first one week after the burst (Frail et al.1997). This emission showed intensive oscillations which were interpreted as scintillation (Goodman 1997). The subsequent disappearance of these oscillations after about three weeks enabled Frail et al., (Frail et al.1997) to estimate the size of the fireball at this stage to be \( \sim 10^{17} \text{cm} \). The observation that the radio emission was initially optically thick
(Frail et al. 1997), yielded a similar estimate to the size (Katz & Piran 1997). This size immediately implies that the afterglow is expanding relativistically!

A dozen GRB afterglows have been discovered so far. It will be impossible to discuss all those here. Worth mentioning are however, GRB971214 and GRB980425. GRB971214 was a rather strong burst. A redshift of 3.42 was measured for the galaxy that is at the position of GRB971214 (Kulkarni et al. 1998). For isotropic emission this large redshift implies an energy release of $10^{53}$ ergs in $\gamma$-rays alone.

GRB980425 was a moderately weak burst with a peak flux of $3 \pm 0.3 \times 10^{-7}$ ergs cm$^{-2}$ sec$^{-1}$. It was a single peak burst with a rise time of 5 seconds and a decay time of about 25 seconds. The burst was detected by BeppoSAX (as well as by BATSE) whose WFC obtained a position with an error box of 8$'$. Inspection of an image of this error box taken by the New Technology Telescope (NTT) revealed a type Ic supernova SN1998bw that took place more or less at the same time as the GRB (Galama et al. 1998b). Since the probability for a chance association of the SN and the GRB is only $1.1 \times 10^{-4}$ it is likely that this association is real. The host galaxy of this supernova (ESO 184-G82) has a redshift of $z = 0.0085 \pm 0.0002$ putting it at a distance of $38 \pm 1$ Mpc for $H=67\text{km/sec Mpc}$. The corresponding $\gamma$-ray energy is $5 \times 10^{47}$ ergs.

5. Afterglow Models

Afterglow observations provide a wealth of data in different wavelengths and over a period of days, weeks and months. This should be compared with the brief few second emission of the GRB. At the same time modeling the afterglow is much simpler than modeling the GRB. Consequently many efforts were devoted during the last year to this problem.

5.1. General Considerations

According to the general picture afterglow is produces by shock accelerated particles when the relativistic shell encounters the surrounding ISM. We can estimate the conditions of the shock accelerated particles if we know the Lorentz factor of the ejecta, $\gamma$, and the density of the ISM, $n_{ism}$. Using the relativistic shock conditions and assuming equipartition between the different energy channels (protons energy, electrons energy and magnetic field energy) we can estimate the typical electron’s energy $\gamma_{e} \sim \epsilon_{e} (m_{p}/m_{e}) \gamma$ and the typical magnetic field: $B \sim \epsilon_{B} \gamma \sqrt{m_{p}c^{2}n_{ism}}$ ($\epsilon_{e}$ and $\epsilon_{B}$ are parameters of order unity). Given

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1 This value is obtained for $\Omega = 1$ and $H_{0} = 65\text{km/sec Mpc}$. The familiar value of $3 \times 10^{53}$ (Kulkarni et al. 1998) is obtained for $\Omega = 0.3$ and $H_{0} = 0.55\text{km/sec Mpc}$
\( \gamma_e \) and \( B \) and assuming that the electrons energy distribution follows a power law: \( N(\gamma_e) \propto \gamma_e^{-p} \) one can calculate the resulting synchrotron radiation spectrum. These calculations has been quite successful as can be seen, for example, in the observational fit of Galama et al., (Galama et al.1998a) to the theoretical spectrum of Sari et al., (Sari, Piran & Narayan 1998).

Estimating the light curve requires the knowledge of how the conditions at the shock change with the observer time. Since those depend on \( \gamma \) we need to know \( \gamma(t_{\text{obs}}) \). The \( \gamma(R) \) relation is given by the hydrodynamics of the ejecta. Two extreme limits of this relation arise: \( \gamma \propto R^{-3/2} \) for an adiabatic expansion (Blandford & McKee 1976), and \( \gamma \propto R^{-6} \) for a radiative expansion (when all the energy generated by the shock is radiated away) (Cohen, Piran & Sari 1998). Emission of a significant fraction but not all the energy would lead to intermediate \( \gamma(R) \) relation. For a given model the \( \gamma(R) \) relation can be substituted into the common equation for the observer time: \( t_{\text{obs}} = \frac{R}{2c\gamma^2} \) to yield \( \gamma(t_{\text{obs}}) \). For \( \gamma \propto R^{-n} \) we have \( \gamma \propto t_{\text{obs}}^{-1/(2+1/n)} \). Thus \( \gamma \propto t_{\text{obs}}^{-3/8} \) for adiabatic expansion and \( \gamma \propto t_{\text{obs}}^{-6/13} \) for radiative expansion. Note that if \( R \) is practically constant (as would be the case during the sideways expansion of a jet - discussed later) this power law will change only slightly to \( \gamma \propto t_{\text{obs}}^{-1/2} \). The number of emitting electrons behaves like \( R^3 \) and varies like \( \gamma^{-3/n} \propto t_{\text{obs}}^{3/(2n+1)} \).

5.2. Afterglow Transitions

Both light curves of GRB970228 and GRB970508 shows a single unbroken power law for as long as the afterglow could be detected. It is interesting to compare this fact with afterglow models.

Several transitions should occur during the expansion of the ejecta and the afterglow emission. At first the expansion should be radiative as the shock accelerated particles cool rapidly compared with the hydrodynamic time scale. As the shell slows down the particles become less energetic, the cooling time increases and the evolution becomes adiabatic. The expansion at this stage becomes self-similar and it is described by the Blandford-McKee (Blandford & McKee 1976) solution. A second transition takes place when enough external mass has been accumulated and the shell becomes Newtonian with \( \gamma \sim 1 \). At this stage the

\begin{itemize}
  \item[\textit{Note}]{Note that this power is different from the commonly assumed \( \gamma \propto R^{-3} \) for a radiative solution.}
  \item[\textit{Care}]{Care should be exercised when using this last equation as strictly speaking it is valid only for a shell moving at a constant velocity and it considers only radiation that emerges along the line of sight. Taking into consideration the fact that in the realistic situation the shell is decelerating and that one detects photons that are not just from the line of sight one obtains a similar relation but the factor 2 is replaced by another constant (which varies between 4 and 10) depending on the specific model (Sari 1998, Waxman 1997, Panaitescu & Mészáros 1998).}
\end{itemize}
solution switches to the well known Sedov-Taylor solution. For adiabatic evolution with no energy losses this transition should take place at the Sedov length $R \sim l$. For a spherical shell with $10^{52}$ ergs and $n_{\text{ism}} = 1 \text{cm}^{-3}$, we find $l \sim 2 \times 10^{18} \text{cm}$ corresponding to a transition around two years after the GRB. Any radiation losses shorten the time for this transition.

A third transition from quasi-spherical to non-spherical expansion occurs if the ejecta is non-spherical. For an ejecta with an opening angle $\theta$ this transition take place when $\gamma \sim \theta^{-1}$. For $\gamma > \theta^{-1}$ the shell behaves as if it is a part of a spherical shell. For $\gamma < \theta^{-1}$ the non-spherical behaviour dominates, the jet expands rapidly sideways collecting more and more ISM and slowing down rapidly with $\gamma(R) \sim \exp[-R/l\theta^{2/3}]$ (Rhoads 1998). In this non-spherical expansion regime the radiation which was earlier beamed with an opening angle $\theta$, is beamed into a cone with an opening angle $\gamma^{-1}$. This leads to a strong decreases of the observed flux as a function of observed time. The solid angle into which the radiation is beamed increases like $\gamma^{-2} \propto t_{\text{obs}}$. Therefore the observed flux decreases by approximately one power of $t_{\text{obs}}$ relative to a corresponding quasi-spherical expansion. Assuming, again, adiabatic expansion the transition to non-spherical expansion takes place at $t_{\text{obs}} = (l/2c)\theta^{10/3}$, corresponding for canonical parameters and for $\theta = 0.1 \sim 6^\circ$ to less than one day after the GRB.

The lack of breaks in the observed light curves suggest that we have not seen any transitions. Is this consistent with the theory? The transition from radiative - adiabatic transition take place quite early after the GRB. Furthermore it does not have a strong effect on the light curve. It could have easily been missed due to lack of early observations, or because the data is not accurate enough to show it. The Newtonian transition is rather late - a year or so after the burst. In most cases the afterglow would be too weak to be detected so late.\footnote{Recall that relativistic effects enhance strongly the observed radiation. During the Newtonian phase the afterglow is not much stronger than a usual SNR.}

The regular power law behaviour of the optical afterglow of GRB970228 and GRB970508 suggests that there was no significant beaming in these two events. The optical light curve of GRB970508 shows a rapid rise during the first two days and only then the power law decline begins. It has been suggested that GRB970508 was beamed and we were outside the initial beam. The rise corresponds to the increase in the observed emission as the beam of this afterglow broadened after the transition from quasi - spherical to non - spherical expansion. There are two problems with this interpretation. First the decay of the optical afterglow like $t^{-1.2}$ fits well a spherical or quasi - spherical expansion and it does not fit the much faster decline of the non - spherical phase of a jet. Second, it is not clear how was the GRB detected in the first place if we were outside the
viewing angle of the original jet.

6. New Puzzles

Afterglow observations fit well the fireball picture that was developed for explaining the GRB phenomena. The available data is not good enough to distinguish between different specific models. But in the future we expect to be able to distinguish between those models and even to be able to determine the parameters of the burst (like $E$ and $\gamma_0$ if the data is taken early enough), the surrounding ISM density and the intrinsic parameters of the relativistic shock $\epsilon_e$, $\epsilon_B$ and $p$. Still the current data is sufficient to raise new puzzles and present us with new questions.

- Why afterglow accompany some GRBs and not others?

X-ray, Optical and radio afterglows have been observed in some bursts but not in others. According to the current model afterglow is produced when the ejecta that produced the GRB is shocked by the surrounding matter. Possible explanations to this puzzle invoke environmental effects. A detectable afterglow might be generated efficiently in some range of ISM densities and inefficiently in another. High ISM densities would slow down of the ejecta more rapidly. This could make some afterglows detectable and others undetectable. ISM absorption is another alternative. While most interstellar environments are optically thin to gamma-rays high density ISM regions can absorb and attenuate efficiently x-rays and optical radiation.

- Jets and the Energy of GRB971214

How can we explain the $10^{53}$ ergs required for isotropic emission in GRB971214? This amount is larger than what all current models can produce. This problem can be resolved if we invoke beaming, with $\theta \sim 0.1$. However, such beaming is ruled out in other afterglows for which there are good data. It would have been much simpler if a possible (but unlikely) interpretation of the observed spectrum to have a redshift of 0.444 (Kulkarni et al.1998) could be adopted.

- GRB980425 and SN1998bw

SN1998bw (and the associated GRB980425) is a factor of a hundred nearer than a typical GRB (which are expected to be at $z \sim 1$). The corresponding (isotropic) gamma-ray energy, $\sim 5 \times 10^{47}$ ergs, is four order of magnitude lower than a regular burst. This can be in agreement with the peak flux distribution only if the bursts with such a low luminosity compose a very small
fraction of GRBs. This leads naturally to the question is there an observa-
tional coincidence between GRBs and SNs? To which there are conflicting
answers (Wang & Wheeler 1998, Kippen et al.1998, Bloom et al.1998).

7. The Inner Engine - What Powers GRBs

As have been stressed earlier we cannot observe the “inner engine” that
powers a GRB. The observed variability time scale implies that this source must
be compact - smaller than 10⁹km. Even if such a source would have produced
gamma-rays it would have been optically thick and undetectable. The source
produces a relativistic particle flow and the observed radiation is produced by this
flow far away from the center. This is not an unfamiliar situation in astronomy.
The sun’s core could not be observed directly until solar neutrino experiments
began. As the source is not observed directly we can infer on its nature only
indirectly:

• (i) Energetics: The source should produce the needed energy - ∼ 10^{52}ergs
for isotropic emission, θ²/4π times that for a jet with an opening angle θ.
It should also be capable of producing (or rare occasions?) the observed
10^{53}ergs required for events like GRB971214.

• (ii) Relativistic Flow: The source must produce a relativistic particle flow.
This requires that there will be a small (but not too small) baryonic load:
m ∼ 5 × 10⁻⁵m☉(E/10^{52}ergs)(γ/100)⁻¹.

• (iii) Duration: According to the internal shocks scenario the duration of
the burst is Δ/c which in turn equals to the time that the inner engine is
active.

• (iv) Variability: The observed variability implies that the source should
be compact with R_{source} ≤ 10³km(δt/0.003sec). The combination of the
last two items rules out “explosive” sources that produce a single pulse with
T ∼ δt ∼ R_{source}/c.

• (v) Rate: GRBs take place at a rate of 10⁻⁵ – 10⁻⁶/year galaxy. beaming
will increase this estimate by 4π/θ²

Current models for the internal engine include: (1) Binary neutron star
merger (Eichler, Livio, Piran, & Schramm 1989; Paczyński 1986), (2) Failed Sup-
ernova (Woosley 1993) or hypernova (Paczyński 1997), and (3) Magnetic white
dwarf collapse (Usov 1992; Duncan & Thompson 1992). All these model can
produce, in principle 10^{52}ergs. In none of these models it is clear how is this
energy channeled to the essential relativistic flow. A black hole forms in (1) and (2) and the GRB is powered by an accretion disk that forms around it (Narayan, Paczyński & Piran 1992; Popham, Woosley & Fryer 1998). Narayan et al., (1992) suggested that the relativistic flow is produced via magnetic field recombination in the disk. Katz (1997) suggested that there is a pulsar like mechanism. The dynamical time of such an accretion disk is a few milliseconds. Accretion takes place on a viscous time, which is orders of magnitude larger. Thus the conditions concerning the duration and variability could in principle be satisfied. However, at present it is impossible to calculate from first principles how is this done (see however Popham, Woosley & Fryer 1998).

In the magnetic white dwarf collapse the relativistic energy flow is carried by Poynting flux and not by particles. Here the energy source is the magnetic field and the rotational energy of the magnetic neutron star. Different considerations determine the duration of the activity.

The energy condition (i) and the variability (or size) condition (iv) are satisfied by all three model. It is possible, but not calculable, that conditions (iii) concerning the overall duration is satisfied. In all three models the question how is the relativistic flow generated (condition (ii)) remains open.

The last condition concerning the rate is satisfied by the binary neutron star merger model (Piran 1992; Piran, Narayan & Shemi 1992), which is the only model based on an independently observed phenomenon. This agreement holds if the burst is more or less isotropic. Significant beaming will, of course, change this. Binary neutron star mergers produce a unique specific gravitational radiation signal that cannot be misinterpreted. They are the best candidates for sources of gravitational radiation signals. A clear prediction of this model is that such a signal should appear in coincidence with a GRB (Kochanek & Piran 1993). Thus, a unique feature of this model is that it can be tested and verified in the nearby future when gravitational detectors LIGO and VIRGO will become operational.

8. Concluding Remarks

GRB astronomy has undergone two major revolutions during the last decade. The first have shown that GRBs are cosmological, the second have confirmed the basic features of the prevailing fireball model.

Both revolutions were observationally driven by new satellites. Still their basic findings have been predicted earlier on by theoretical studies. The isotropy

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5 Paczyński (Paczyński 1997) in the hypernova model suggests that the relativistic flow is produced when an initially Newtonian shock is accelerating while interacting with external matter with a decreasing density profile.
of the pre-BATSE GRB sample has motivated several suggestions that GRBs are cosmological (Van Den Bergh 1983; Paczyński 1986; Hartman & Blumenthal 1989). On the other hand analysis of the neutron star merger phenomenon (Eichler, Livio, Piran, & Schramm 1989) has lead to the suggestion that it would generate a GRB. This has given another support to possibility of a cosmological origin.

Relativistic motion was then suggested to overcome the compactness problem. This problem posed a serious objection to cosmological (and hence very luminous) GRB sources. This has lead to the fireball model, whose general features, and in particular relativistic motion, were confirmed by afterglow observations.

In spite of all this progress the “inner engine” that powers GRBs is not understood yet. It remains hidden. All that we have at present is only indirect circumstantial evidence on its behaviour. The origin of GRBs is still a puzzle.

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