COSMIC GAMMA-RAY BURSTS

The most energetic phenomenon in the Universe

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1. Abstract

GRBs have remained a puzzle for many high-energy astrophysicists since their discovery in 1967. With the advent of the X-ray satellites BeppoSAX and RossiXTE, it has been possible to carry out deep multi-wavelength observations of the counterparts associated with the GRBs just within a few hours of occurrence, thanks to the observation of the fading X-ray emission that follows the more energetic gamma-ray photons once the GRB event has ended. The fact that this emission (the afterglow) extends at longer wavelengths, has led to the discovery of the first optical/IR/radio counterparts in 1997-98, greatly improving our understanding of these sources. Now it is widely accepted that GRBs originate at cosmological distances but while the observed afterglow satisfies the predictions of the relativistic fireball models, the central engines that power these extraordinary events remain still unknown. Detailed results for nine selected GRBs are presented as well as a summary of the GRB counterparts and host galaxies found so far.

2. Introduction. General characteristics.

In 1967-73, the four VELA spacecraft (named after the spanish verb velar, to keep watch), that where originally designed for verifying whether the former Soviet Union abided by the Limited Nuclear Test Ban Treaty of
1963, observed 16 peculiarly strong events (Klebesadel, Olson and Strong 1973, Bonnell and Klebesadel 1996). On the basis of arrival time differences, it was determined that they were related neither to the Earth nor to the Sun, but they were of cosmic origin. Therefore they were named cosmic Gamma-Ray Bursts (GRBs hereafter).

GRBs appear as brief flashes of cosmic high energy photons, emitting the bulk of their energy above $\approx 0.1 \text{ MeV}$. They are detected by instruments somewhat similar to those used by the particle physicists at their laboratories, but the main difference is that GRB detectors have to be placed onboard balloons, rockets or satellites.

The KONUS instrument on Veneras 11 and 12 gave the first indication that GRB sources were isotropically distributed in the sky (Mazets et al. 1981, Atteia et al. 1987). Based on a much larger sample, this result was nicely confirmed by BATSE on board the CGRO satellite, launched in the spring of 1991, an instrument that has revolutionized the GRB field (Meegan et al. 1992). Since then, BATSE is detecting about 300 GRBs every year, but only very few can be localized accurately. The apparent isotropy of the bursts in the sky ruled out the models dealing with neutron stars in the Galactic Plane, and it was rather interpreted in terms of GRBs arising at cosmological distances, although the possibility of a small fraction of the sources lying nearby, within a galactic disc scale of few hundred pc, or in the halo of the Galaxy, could not be discarded by that time. Another result was that the time profiles of the bursts are very different, with some GRBs lasting a few ms and others lasting for several minutes. In general, there was no evidence of periodicity in the time histories of GRBs. However there was indication of a bimodal distribution of burst durations, with $\sim 25\%$ of bursts having durations around 0.2 s and $\sim 75\%$ with durations around 30 s. A deficiency of weak events was noticed in the log $N$-log $S$ diagram, as the GRB distribution deviates from the -$3/2$ slope of the straight line expected for an homogeneous distribution of sources assuming an Euclidean geometry. All these observational data led many researchers to believe that GRBs are indeed at cosmological distances. However, the GRB distance scale had to remain unknown for 30 years. A comprehensive review of these observational characteristics can be seen in Fishman and Meegan (1995).

3. The search and detection of counterparts at other wavelengths

It was well known that an important clue for solving the GRB puzzle was going to be the detection of transient emission -at longer wavelengths- associated with the bursts. A review on the unsuccessful search for counterparts prior to 1997 can be seen in Castro-Tirado (1998) and references therein.
Here I will summarize some results concerning nine selected bursts detected by the BeppoSAX (BSAX) and RossiXTE (RXTE) satellites in 1996-98. See also Piran (1999).

3.1. GRB 960720

This was the first GRB for which a precise position (5′ error radius) was obtained by BSAX (in’t Zand et al. 1997). The bright radio-loud quasar 4C 49.29 at z = 1.038 lies within the tiny GRB error box. The probability to find such object within the error box is \(2 \times 10^{-4}\) (Greiner and Heise 1997, Piro et al. 1997a), but no firm relationship could be established.

3.2. GRB 970111

The position for this GRB was rapidly distributed, allowing to perform deep optical imaging only 19 hr after the high energy event. No optical variability was found within the error box down to B = 23, R = 22.5 (Castro-Tirado et al. 1997, Gorosabel et al. 1998a). A careful analysis of the X-ray data revealed a weak fading X-ray source within the GRB error box (Feroci et al. 1998a), but its association to GRB 970111 could not be definitively proven.

3.3. GRB 970228

Thanks to BSAX, it was possible on 28 Feb 1997 to detect the first clear evidence of a long X-ray tail - the X-ray afterglow - following GRB 970228. A previously unknown X-ray source was seen to vary by a factor of 20 on a 3 days timescale. The X-ray fluence was \(\sim 40\%\) of the gamma-ray fluence, as reported by Costa et al. (1997b), implying that the X-ray afterglow was not only the low-energy tail of the GRB, but also a significant channel of energy dissipation of the event on a completely different timescale. Another important result was the non-thermal origin of the burst radiation and of the X-ray afterglow (Frontera et al. 1998a). The precise X-ray position (1′) led to the discovery of the first optical transient (or optical afterglow, OA) associated to a GRB, identified on 28 Feb 1997, 20 hr after the event, by Groot et al. (1997). The OA was afterwards found on earlier images taken by Pedichini et al. (1997) and Guarnieri et al. (1997), in the rising phase of the light curve. The maximum was reached \(\sim 20\) hr after the event (V \(\sim 21.3\)), and followed by a power-law decay \(F \propto t^{-1.2}\) (Galama et al. 1997, Bartolini et al. 1998). An extended source was seen at the OA position since the very beginning by both ground-based and HST observations (van Paradijs et al. 1997, Sahu et al. 1997). New HST observations taken 6 months after the event were reported by Fruchter et al. (1997). Both the OA (at V
Figure 1. The R-band light curve of the GRB 970508 optical afterglow, from data quoted in this paper. The dotted line is the contribution of the GRB afterglow itself, following $F \propto t^{-1.9}$ two days after the burst. The horizontal dashed line is the $R = 25.5$ host galaxy, whereas the solid line is the contribution of both (afterglow plus host galaxy).

= 28) and the extended source ($V = 25.6$) were seen. The extended object surrounding the point-source was interpreted as a galaxy, according to the similarities (apparent size, magnitude) with objects in the HST Deep Field. Despite exhaustive efforts in order to get spectroscopic measurements, no emission lines were found, implying that the redshift of this galaxy should lie in the range $1.3 \leq z \leq 2.5$ (Fruchter et al. 1999).

3.4. GRB 970508

The second OA associated to a GRB was discovered by Bond (1997) within the GRB 970508 error box, and observed 3 hr after the burst in unfiltered images (Pedersen et al. 1998). The optical light curve reached a peak in two days ($R = 19.7$, Castro-Tirado et al. 1998a, Djorgovski et al. 1997, Galama et al. 1998a) and was followed by a power-law decay $F \propto t^{-1.2}$. Optical spectroscopy allowed a direct determination of a lower limit for the redshift of GRB 970805 ($z \geq 0.835$) and was the first proof that at least a fraction of the GRB sources lie at cosmological distances (Metzger et al. 1997). The flattening of the decay in late August 1997 (Pedersen et al. 1998, Sokolov et al. 1998a) revealed the contribution of a constant brightness source -the host galaxy- that was revealed in late-time imaging obtained in 1998 (Bloom et al. 1998a, Castro-Tirado et al. 1998b, Zharikov et al. 1998). See Fig. 1. The luminosity of the galaxy is well below the knee of the galaxy luminosity function, $L \approx 0.12 L^*$, and the detection of deep Mg I absorption (during the bursting episode) and strong [O II] 3727 Å emission (the latter mainly arising in H II regions within the host galaxy) confirmed $z = 0.835$ and suggested that the host could be a normal dwarf.
galaxy (Pian et al. 1998a), with a star formation rate (SFR) of $\sim 1.0 \, M_\odot \, \text{year}^{-1}$ (Bloom et al. 1998a). Prompt VLA observations of the GRB 970508 error box allowed detection of a variable radio source at 1.4, 4.8 and 8.4 GHz, the first radio-counterpart ever found for a GRB (Frail et al. 1997). The fluctuations could be the result of strong scattering by the irregularities in the ionized Galactic interstellar gas, with the damping of the fluctuations with time indicating that the source expanded to a significantly larger size. However VLBI observations did not resolve the object (Taylor et al. 1997). The transient was also detected at 15 GHz (Pooley and Green 1997) and as a continuum point source at 86 GHz with the IRAM PdBI on 19-21 May 1997 (Bremer et al. 1998). A Fe Kα line redshifted at $z = 0.835$ in the X-ray afterglow spectrum was reported (Piro et al. 1999), and could be attributed to a thick torus surrounding the central engine (Mészáros and Rees 1998).

3.5. GRB 970828

This burst was detected by RXTE (Remillard et al. 1997) and was followed up by ASCA and ROSAT (Murakami et al. 1997, Greiner et al. 1997). The X-ray spectrum as seen by ASCA is strongly absorbed (Yoshida et al. 1999), suggesting that the event occurred in a dense medium. The fact that no optical counterpart down to $R = 23.8$ was detected between 4 hr and 8 days after the event, could support the idea that the non-detection was due to photoelectric absorption (Groot et al. 1998). An excess at 6.7 keV was found by ASCA in the X-ray afterglow spectrum. If this is due to highly ionized Fe, then $z \sim 0.33$ (Yoshida et al. 1999).

3.6. GRB 971214

The third optical transient was related to GRB 971214 and identified by Halpern et al. (1997) as an $I = 21.2$ object that faded 1.4 mag in 1 day. Independently, this source was also noticed as suspicious by Itoh et al. (1997). Further observations proved that the decay followed a power-law decline (Diercks et al. 1997, Castander et al. 1997) with $F \propto t^{-1.4}$, similar to, but steeper than, the previous GRBs with optical counterparts. GRB 971214 was detected in the K-band 4 hr after the burst (Gorosabel et al. 1998b) and rapidly decreasing in the J-band (Tanvir et al. 1997). However, no source was detected at 850 μm at the James Clerk Maxwell Telescope. The upper limit was 1 mJy on Dec 17-22 (Smith et al. 1999). Spectroscopy of the host galaxy ($R = 25.6$) one month later revealed a strong emission-line attributed to Ly-α redshifted at $z = 3.42$ (Kulkarni et al. 1998a), implying a SFR of $1.0 \pm 0.5 \, M_\odot \, \text{year}^{-1}$, similarly to other galaxies at comparable redshift. The emitted energy, assuming isotropic emission, was $3 \times 10^{53}$
Together with GRB 970111, this burst is among the top 2% burst with larger gamma-ray fluences as detected by BATSE. The detection of a variable radiosource (Taylor et al. 1998) within the GRB error box led to the identification of an optical transient (Klose et al. 1998, Palazzi et al. 1998). The evidence for a dusty host (R-K = 4.7) was confirmed by a SCUBA detection at 850 $\mu$m (Smith et al. 1999) and Fruchter (1999) proposed that the host could lie at $z \sim 5$. In that case, if the gamma-rays were radiated isotropically, the implied energy would be $5 \times 10^{54}$ erg!

3.8. GRB 980425

A peculiar supernova (SN 1998bw) has been found in the WFC error box for this soft GRB (Galama et al. 1998b). The SN lies in the galaxy ESO 184-82 (at $z = 0.0085$). The fact that the SN event occurred within \pm 1 day of the GRB event, together with the relativistic expansion speed derived from the radio observation (Kulkarni et al. 1998b) strengthens such a relationship. In that case, the total energy released would be $8 \times 10^{47}$ erg. However, the fact that a fading X-ray source -as in all the previous cases- unrelated to the SN was detected by BSAX in the GRB error box (Pian et al. 1998b, Piro et al. 1998) cast some doubts on the SN/GRB association (Graziani et al. 1999).

3.9. GRB 980703

A variable radiosource was found by Frail et al. (1998), and the optical counterpart was independently discovered by Frail et al. (1998) and Zapatero-Osorio et al. (1998) in the error box provided by RXTE. The host galaxy is the brightest one so far detected (R = 22.5, H = 20.5) according to Bloom et al. (1998b) and Castro-Tirado et al. (1999). Optical spectroscopy revealed the [O II] emission line at $z = 0.966$, as well as some Fe II and Mg II absorption ones. The derived SFR is $\sim 63 M_\odot$ year$^{-1}$ (Djorgovski et al. 1998). The released energy during the GRB event amounts to $\sim 3 \times 10^{52}$ erg.

Further X-ray afterglows were observed by BSAX and RXTE in 1998 (GRB 980706, GRB 981220 and GRB 981226). Exponents for the power-law decay in the X-rays and in the optical are in the range $\alpha = 1.10-2.25$ for a dozen of bursts. These results are given on Table 1 whereas Table
TABLE 1. GRBs detected by \textit{BeppoSAX} and \textit{RXTE} in 1996-98

| GRB   | X-rays | optical-IR | radio | References (X-ray detection) |
|-------|--------|------------|-------|-------------------------------|
| 960720 | yes    | no         | no    | Piro et al. (1996)            |
| 970111 | yes    | no         | no    | Costa et al. (1997a)          |
| 970228 | yes    | yes        | no    | Costa et al. (1997b)          |
| 970402 | yes    | no         | yes   | Piro et al. (1997c)           |
| 970508 | yes    | yes        | no    | Costa et al. (1997b)          |
| 970616 | yes    | yes        | no    | Marshall et al. (1997)        |
| 970815 | yes    | no         | no    | Smith et al. (1997)           |
| 970828 | yes    | no         | yes   | Piro et al. (1997c)           |
| 971214 | yes    | no         | yes   | Antonelli et al. (1997)       |
| 971227 | yes    | yes        | no    | Sofitta et al. (1997)         |
| 980109 | yes    | yes        | no    | in’t Zand et al. (1998)       |
| 980326 | yes    | yes        | no    | Celidonio et al. (1998)       |
| 980329 | yes    | yes        | yes   | Frontera et al. (1998b)       |
| 980425 | yes    | yes        | yes   | Softita et al. (1998)         |
| 980515 | yes    | yes        | yes   | Feroci et al. (1998b)         |
| 980519 | yes    | yes        | yes   | Muller et al. (1998)          |
| 980613 | yes    | yes        | yes   | Smith et al. (1998a)          |
| 980703 | yes    | yes        | yes   | Levine et al. (1998)          |
| 980706 | yes    | yes        | yes   | Hjorth et al. (1998)          |
| 981220 | yes    | yes        | yes   | Smith et al. (1998b)          |
| 981226 | yes    | yes        | yes   | Di Ciolo et al. (1998)        |

TABLE 2. GRB host galaxies

| GRB   | R (host) | z        | SFR ($M_\odot$ year$^{-1}$) | References |
|-------|----------|----------|-----------------------------|------------|
| 970228| 25.2     | $1.3 \leq z \leq 2.5$ | Fruchter et al. (1998)     |
| 980519| ~26      |          | Fruchter (1999)             |
| 98058 | 28       | 0.33 ?   | Yoshida et al. (1999)       |
| 97505 | 25.7     | 0.385    | 1                           | Bloom et al. (1998a) |
| 971214| 25.6     | 3.418    | 5                           | Kulkarni et al. (1998a) |
| 980326| ≥27.3    |          |                              | Bloom and Kulkarni (1998) |
| 980329| ≥25.5    | ~5 ?     | Fruchter (1999)             |
| 980613| 23.8     | 1.096    | 3                           | Djorgovski et al. (1999) |
| 980703| 22.5     | 0.966    | 63                          | Djorgovski et al. (1998) |

2 summarizes the properties of the host galaxies found so far. See also (Greiner 1999) for an updated information.
4. Theoretical models

The observational characteristics of the GRB counterparts can be accommodated in the framework of the relativistic fireball models, first proposed by Goodman (1986) and Paczyński (1986), in which a compact source releases $10^{53}$ ergs of energy within dozens of seconds. See also Mészáros et al. (1994), Mészáros and Rees (1997), Tavani (1997), Vietri (1997), Waxman (1997) and Wijers et al. (1997). The opaque radiation-plasma accelerates to relativistic velocities (the fireball). The blast wave is moving ahead of the fireball, and sweeps up the interstellar matter, producing an afterglow at frequencies gradually declining from X-rays to visible and radio wavelengths. An extensive discussion is given by Piran (1999).

The properties of the blast wave can be derived from the classical synchrotron spectrum (Ginzburg and Syrovatskii 1965) produced by a population of electrons with the addition of self absorption at low frequencies and a cooling break (Sari, Piran and Narayan 1998). Thus, the four main quantities involved are:

i) the synchrotron frequency: the population of electrons has a power-law distribution of Lorentz factors $\Gamma_e$ following $dN/d\Gamma_e \propto \Gamma_e^{-p}$ above a minimum Lorentz factor $\Gamma_e \geq \Gamma_m$, corresponding to the synchrotron frequency $\nu_m$;

ii) the break frequency: if the electrons are energetic they will cool rapidly for a break frequency $\nu_c < \nu_m$, and low energy electrons will have always slow cooling for $\nu_c > \nu_m$,

iii) the self-absorption frequency: synchrotron self absorption becomes important below a critical frequency $\nu_a$, and

iv) the maximum flux $F_{\nu,max}$.

After some time, the evolution of the blast wave is adiabatic, and $\nu_c > \nu_m$ implying that $F_\nu \propto \nu^{-(p-1)/2}$ for $\nu_m \leq \nu < \nu_c$; $F_\nu \propto \nu^{-p/2}$ for $\nu > \nu_c$ and $F_\nu \propto \nu^{1/3}$ for $\nu < \nu_m$.

The time evolution of the flux as a function of a given frequency is a function of $\nu_c (\propto t^{-1/2})$ and $\nu_m (\propto t^{-3/2})$. For $\nu \leq \nu_c$ the flux decays following a power-law with exponent $\alpha$, $F \propto t^{\alpha}$ with $\alpha = (2-3p)/4$, thus allowing to determine $p$.

Thus, the determination for every GRB of the six observables $\nu_m$, $\nu_c$, $\nu_a$, $F_{\nu,max}$, $p$ (from the multiwavelength spectrum, see Fig. 2) and $z$ (from optical or X-ray spectroscopy) allows to obtain the total energy per solid angle ($E_{52}$), the fraction of the shock energy in electrons ($\epsilon_e$), the fraction of the shock energy in post-grb magnetic fields ($\epsilon_B$) and the density of the ambient medium ($n$). See for example, Wijers and Galama (1998).

How does the GRB take place? The fireball model is based on the existence of a “central engine”. However, current observations have been unable
to give any insight on this issue. Until 1994, the number of theoretical models amounted up to 150 (see Nemiroff 1994), but once the cosmological nature of GRBs was established, only those models dealing with mechanisms able to produce $10^{51-54}$ erg in a few seconds were taken into consideration. They can be classified into two groups:

i) coalescence of neutron stars in a binary system (Narayan et al. 1992): lives of such systems are of the order of $\sim 10^9$ years, and large escape velocities are usual, putting them far away from the regions where their progenitors were born. The likely result is a Kerr black hole (BH), and the energy released energy during the merger process is $\sim 10^{54}$ erg. It is also possible that a $\sim 0.1 M_\odot$ accretion disk forms around the BH and is accreted within a few dozen seconds, then producing internal shocks leading to the GRB (Katz 1997). There are variations of these models where one or two components are substituted for black holes (Paczyński 1991).

ii) a “failed” type-I SN (Bodenheimer and Woosley 1983, Woosley 1993) or hypernova (as it has been called by Paczyński (1998) on the basis of the observational consequences): very massive stars (Wolf-Rayet) collapse forming a Keck BH and a 0.1-1 $M_\odot$ torus. The matter is accreted at a very high rate and the energy is extracted via the rotational energy of the BH or via the accretion energy from the disk. In any case, a “dirty fireball”, is produced reaching a luminosity $\sim 300$ times larger that than of a normal SN. This would happen every $\sim 10^6$ yr. In this scenario, GRBs would be produced in dense enviroments near star forming regions (see also MacFadyen and Woosley 1999) and GRBs might be used for deriving the SFR in the Universe (Totani et al. 1998, Krumholz et al. 1998).
5. Summary

The existence of X-ray afterglow in most bursts is confirmed. Out of 15 BSAX pointings, 11 revealed a strong afterglow, and 4 displayed faint ones, leading to the detection of optical/IR/radio counterparts in 1997-98. Very promising seems to be the determination of $z$ for the host galaxies by means of absorption edges or emission lines in the X-ray afterglow. This requires prompt X-ray follow-up, as was achieved for GRB 970508 and GRB 970828. However, only the population of bursts with durations of few seconds has been explored. Short bursts lasting less than 1 s, like GRB 980706, that follow the -3/2 slope in the log $N$-log $S$ diagram (in contrast to the longer bursts) remain to be detected at longer wavelengths.

It is generally believed is that internal shocks produced by the "central engine" are responsible for the $\gamma$-ray emission, whereas the slowing down of a relativistic shell on the interstellar medium (an external shock) would cause the post-GRB emission at longer wavelengths (the afterglow). Energy releases of $\sim 10^{54}$ erg (as derived for GRB 980329) are difficult to reconcile with theoretical models and non-isotropic emission, such as intrinsic beaming appears as the most plausible resolution of this problem.

BSAX and RXTE have opened a new window in the GRB field and it is widely accepted now that most GRBs, if not all, lie at cosmological distances. It is expected that BSAX, RXTE and CGRO will facilitate the discoveries of many other counterparts and, together with the new high-energy observatories (AXAF, SPECTRUM X/Γ, XMM, INTEGRAL, HETE 2) and, hopefully SWIFT and BALLERINA, will help to solve the long-standing Gamma-Ray Burst mystery.

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