Gamma-Ray Bursts: Old and New

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ABSTRACT. Gamma-ray bursts are sudden releases of energy that for a duration of a few seconds outshine even huge galaxies. 30 years after the first detection of a gamma-ray burst their origin remains a mystery. Here I first review the "old" problems which have baffled astronomers over decades, and then report on the "new" exciting discoveries of afterglow emission at longer wavelengths which have raised more new questions than answered old ones.

1. Introduction

Gamma-ray bursts (GRBs) were first detected in 1967 with small gamma-ray detectors onboard the Vela satellites (Klebesadel et al. 1973) which were designed to verify the nuclear test ban treaty between the USA and the USSR. For many years the prevailing opinion was that magnetic neutron stars (NS) in the galactic disk were the sources of GRBs. No flaring emission outside the gamma-ray region could be detected, and no undisputable quiescent counterpart to a GRB could be established. Despite a distance "uncertainty" of 10 orders of magnitude, numerous theories (see a compilation in Nemiroff 1994) were advanced to explain the source of energy in GRBs. The measurements since 1991 of the Burst and Transient Source Experiment (BATSE) onboard the Compton Gamma-Ray Observatory have shown unequivocally that GRBs **are** isotropic even at the faintest intensities, and that there **is** a distinct lack of faint bursts as compared to a homogeneous distribution. An unprecedented wealth of additional information on each burst could be collected, yet the GRB origin remained a mystery.

Over the previous two decades, GRB coordinates came with two mutually exclusive properties: *arcmin accuracy* as provided by the interplanetary network (Hurley 1995) or *fast* as provided by the BATSE Coordinate Distribution Network (BACODINE) system (Barthelmy et al. 1996). Only since the launch and successful operation of the Italian/Dutch BeppoSAX satellite is it possible to obtain accurate GRB positions in reasonably short time (few hours) which allow quick follow-up observations (Heise et al. 1998). The discovery of X-ray afterglow emission with the BeppoSAX satellite and related optical and radio transients has given a dramatic boost to both observations and theoretical investigations of GRBs over the last few months. At the present time (late 1997), our knowledge is evolving extremely rapidly. Thus, it may not be surprising that the content of this review has been expanded considerably as compared to the oral version given in May 1997. As in the talk, I will not cover Soft Gamma Repeaters, reviews of which can be found in Kulkarni (1998) and Smith (1998).

2. Basic facts

About once per day, the most sensitive gamma-ray instruments detect a short burst of high-energy radiation from an unpredictable location in the sky. Most of its power is radiated in the 100–500 keV range, but photons up to 18 GeV or down to a few keV have also been registered. The bursts have durations of typically 0.1–10 sec, and the rise to maximum intensity can occur within fractions of a millisecond. During these short times GRBs are the brightest objects on the X-ray/γ-ray sky.

The majority of GRBs has a rather complex temporal structure (Fig. 1): in particular their variability time scale is significantly shorter than the duration (Meegan et al. 1996). The typical ratio between duration and the length of intensity peaks within a GRB is about 100. Note that the GRB durations scatter over six orders of magnitude (1 msec to 1 ksec), and given additional spectral variations from burst to burst and even within bursts, one is faced with a confusing diversity of the "simply measurable quantities".

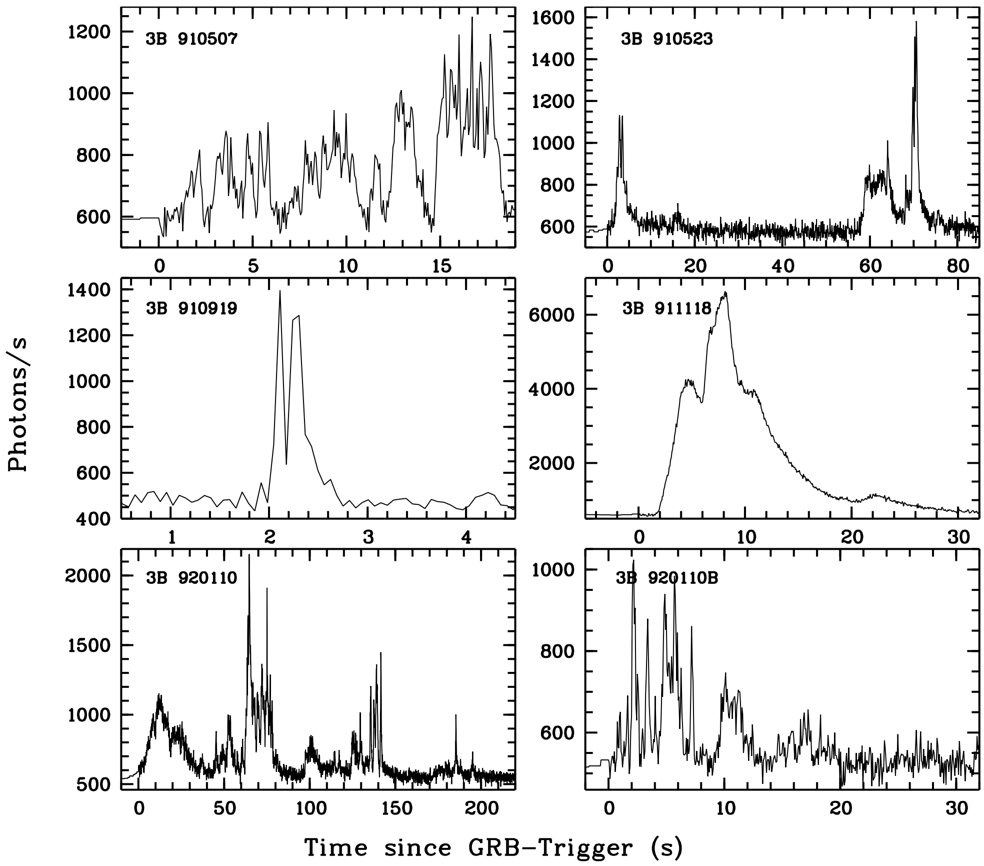

Fig. 1. Examples for GRB light curves as seen with BATSE: the photon count rate is plotted over time with a temporal resolution of 64 ms. Noteworthy are the diversity of structures within the bursts as well as their durations.

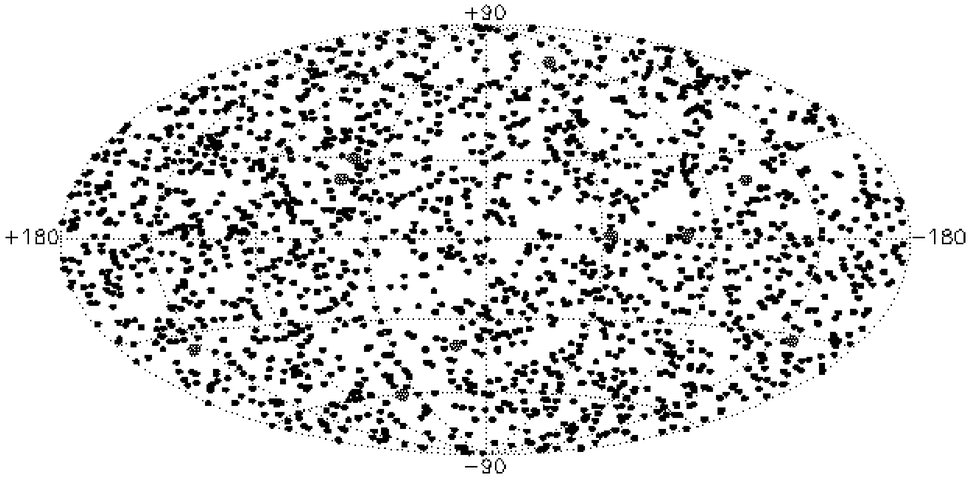

Fig. 2. Sky distribution of all GRBs detected with the BATSE instrument until July 10, 1997 (the galactic center is in the middle). (Adapted from the BATSE Web-page http://www.batse.msfc.nasa.gov/data/grb/skymap/)

The most direct hint for the spatial distribution of GRB sources comes from the distribution on the sky combined with the observed intensity distribution. The latter is a folding of the unknown radial with the unknown luminosity distribution. In an Euclidean space, a homogeneous source distribution will display an intensity distribution of $N(>S) \propto S^{-3/2}$. This is seen for bright bursts, but one observes an increasing deficit of bursts at faint intensities. Combined with the complete isotropy on the sky (Fig. 2) this implies a GRB distribution which is centered at the Earth and has a decreasing source density with increasing distance. Four different distance scales are possible in principle:

1. Oort's comet cloud is the nearest population which obeys these characteristics. Collisions among comets (White 1993) or between comets and primordial black holes (Bickert & Greiner 1993) have been proposed as possible scenarios. However, the Oort cloud radius is a sizeable fraction of the distance to nearby stars, and the expected significant clustering of GRBs around the nearest stars is not observed.
2. A distribution of sources along the galactic plane would appear to be isotropic if the sampling distance is smaller than the scale height of the disk distribution. Such distribution was very popular in the pre-BATSE era, and magnetic NS were the favourite sources of GRBs with typical luminosities of 10^{38} erg/s. Both, the observed quadrupole moment of the GRB distribution as well as the fact that we see the "faint end" clearly invalidate such a distribution (Briggs et al. 1996).
3. An extended halo around the Galaxy has been a viable alternative for galactic GRB distributions. Isotropy requires a distance $\geq$100 kpc while the lack of GRB clustering around M31 constrains the outer radius of the halo to less than $\approx$300 kpc. However, the original scenario of high-velocity NSs (Shklovski & Mitrofanov 1985) escaping from the galactic disk needs additional ad hoc assumptions to be in line with observations (Hartmann et al. 1990, Greiner 1991, Podsiadlowski et al. 1995).

4. If GRBs are at cosmological distances, their isotropy on the sky is a natural consequence. Originally proposed very soon after the discovery of GRBs (Usov & Chibisov 1975), this option became popular only after the suggested collision of compact objects as a viable mechanism (Paczynski 1991). With typical distances of $z \approx 1$ the corresponding luminosities are of the order of 10^{51} erg/s.

3. Theories for GRBs at cosmological distances

The basic scenario for the understanding of the properties of low-energy afterglows of GRBs is the dissipative (shock) **fireball model** (Meszaros & Rees 1993, 1997). It assumes a very large energy deposition inside a very small volume (constrained by causality and the variability timescales of GRBs to be of order 100 km or smaller) which leads to characteristic photon energy densities which produce an optically thick, highly super-Eddington $\gamma e^{\pm}$ fireball. The fireball initially is thermal and converts most of its radiation energy into kinetic energy, i.e. bulk motion of a relativistically expanding blast wave (Lorentz factor $\Gamma \sim 10^{2-3}$ required to avoid degradation of the GeV photons by photon-photon interactions). The kinetic energy is tapped by shocks as the most likely dissipation mechanism, and these shocks should probably occur after the fireball became optically thin, as suggested by the observed non-thermal GRB spectra.

Two types of fireball models can be distinguished which involve different explanations for the duration and variability of the GRB. In one type (called external shocks; Meszaros & Rees 1993) the shocks are caused by the interaction (collision) of the fireball ejecta with the surrounding medium. The typical duration of a GRB is then given by the Doppler delayed arrival times of the emission from the two boundaries of the ejecta shell, or from the delay between different surface elements within the light cone. Detailed investigations have shown (Fenimore et al. 1996, Sari & Piran 1997) that it is difficult to produce the variety of temporal structures observed in GRBs. The other type of model (called internal shocks; Rees & Meszaros 1994, Paczynski & Xu 1994) relates the shocks to inhomogeneities within the relativistic outflow, e.g. catching up of faster portions with slower portions of the flow. The duration of these shocks is likely to be given by the intrinsic duration of the energy release, while any intrinsic variability (of arbitrary scale) caused by the central engine will be responsible for the GRB time history.

If GRBs occur e.g. inside galaxies where the external medium has an appreciable density, one would expect internal shock bursts to be followed by external shock bursts/emission, which has twofold relevance: (1) External shocks could be related to the observed delayed GeV emission (Meszaros & Rees 1994), and (2) the external shocks could radiate at lower energies and longer timescales as compared to internal shocks, and thus are thought to produce the afterglow emission.

The afterglow emission at longer wavelengths thus is most probably due to synchrotron or Inverse Compton cooling from a decelerating relativistic shell. As the Lorentz factor of the shell decreases, the typical synchrotron frequency also decreases, causing a delay of emission towards longer wavelengths. Several variants of this basic scenario have been proposed including adiabatic versus radiative hydrodynamics, fast versus slow cooling of the electrons, and synchrotron versus synchrotron self-Compton emission. Not all combinations are possible, and so far there is no single model that fits all results of afterglow observations. Some versions of the external shock models predict a relation between the energy spectral slope α (power law photon index) of the afterglow emission and the slope of the intensity decay δ ($I \propto t^{\delta}$; $\delta = 3/2\ (\alpha+1)$).

The generic nature of the fireball model is based on the fact that the detailed nature of the primary energy mechanism is largely undetermined, i.e. it can be reconciled with most of the proposed scenarios, such as a binary compact object merger (Paczynski 1986), a failed supernova (Woosley 1992), a young highly magnetic pulsar (Usov 1992), or a hypernova (Paczynski 1998).

4. Rapid and accurate burst localisation

BeppoSAX bringing the break-through: With the launch of BeppoSAX, the combination of two new features allowed the exciting new discovery of X-ray afterglows, and optical/radio transients: first, the combination of a GRB monitor (Frontera et al. 1997c) with two Wide Field Cameras (WFC; Jager et al. 1997) with a 40° field of view each which can localize about 10/yr at the few arcmin level (in't Zand et al. 1997); second, the ability to point within hours after the discovery to the GRB location has enabled the detection of fading X-ray emission of a GRB for the first time (Piro et al. 1998a).

RXTE/PCA scanning of BATSE GRB positions: The discovery of long-lasting X-ray afterglows has led to the establishment of a procedure to scan the smallest BATSE GRB error circles with the one degree field of view (FOV; collimated) PCA detector on RXTE. Two afterglows have been seen so far.

RXTE/ASM locations: The all-sky monitor (ASM) on RXTE observes the sky with its three cameras (FOV of $6°\times90°$) in 90 s stationary exposures followed by an instrument rotation of 6°. The sky coverage implies an X-ray afterglow detection rate of 8-10 GRBs per year, and several GRBs have been localized in 1997 (Smith et al. 1998).

Interplanetary network (IPN): The Ulysses spacecraft has been operational for more than 7 years now, but has been the only interplanetary mission with a GRB detector since the failure of the Mars missions. Thus, GRB locations as provided by BATSE could be reduced only in one dimension to a few arcmin width (Hurley 1995). Over the last months, the γ-ray spectrometer on the Near Earth Asteroid Rendezvous (NEAR) spacecraft has been reconfigured to allow measurements of GRBs (the spectrometer was not originally planned to begin working until NEAR reached Eros in Feb. 1999). The first detection of a GRB occurred on Sep. 15, 1997 and several more GRBs have been detected since then several of which have been seen also by the BATSE, Ulysses or Wind spacecrafts. Thus, the new capability of NEAR adds a new dimension to the IPN and enables to obtain locations of moderate and strong GRBs with arcmin accuracy.

The future: The future seems bright for detection of X-ray afterglows of GRBs: after the launch of the original HETE mission it is presently being rebuilt with soft X-ray cameras replacing the UV cameras. The all-sky monitor MOXE onboard the Russian SRG mission will monitor the sky nearly continuously with a spatial resolution down to 1 arcmin. And the German ABRIXAS satellite will scan the sky with its seven identical 40 arcmin FOV telescopes on great circles, similar to ROSAT (Trümper 1983). All these instruments are scheduled for launch in 1999, so a substantial improvement in the rate of GRB X-ray afterglow detections can be expected in the near future.

5. Fading Counterparts

5.1. X-ray afterglows

5.1.1. BeppoSAX narrow-field instruments pointings

The ability to rapidly point the narrow-field instruments (NFI) towards GRB positions has enabled the discovery of long-lasting X-ray emission which decayed according to a $\approx t^{-1}$ power law. While neither the power law nor the slope are unique, the occurrence within a $3'$ GRB error box right after the burst and the correlation with similarly decaying optical transients is convincing evidence for its relationship to the GRB.

With only one exception so far, BeppoSAX NFI pointings have been performed for all GRBs localized with the WFC (see Tabs. I, II). With the exception of GRB 970111 X-ray afterglow emission has been clearly detected in all pointings which occurred within less than 2 days of the GRB; there is recent evidence for a possible X-ray afterglow also of GRB 970111: an X-ray source is detected in the first half of the observation (Feroci et al. 1998). Unfortunately, not in all cases were detections made in both detectors (LECS: 0.1–10 keV; MECS: 2–10 keV), and in most cases the detected LECS rates are too small to allow any detailed spectral investigations. However, three important results could be established (e.g. Frontera et al. 1998b): (i) the afterglow X-ray spectrum seemingly is well fitted by an absorbed power law model, but not with thermal models (bremsstrahlung or blackbody), (ii) there are no obvious changes in the shape of the X-ray spectrum along the intensity decay, and (iii) within the accuracy of measurements indeed the intensity decay slope δ is related to the spectral slope of the energy spectrum of the GRB tail and afterglow.

TABLE I
GRBs localized by BeppoSAX and RXTE

GRB	GRB X-ray position	Error	Instrument	IPN[a]	XA[a]	OT[a]	Ref.[b]
960720	$17^h30^m37^s+49°05'.8$	$3'$	SAX/WFC	n	n	n	1, 3
970111	$15^h28^m15^s+19°36'.3$	$3'$	SAX/WFC	y	y?	n	2, 3
970228	$05^h01^m57^s+11°46'.4$	$3'$	SAX/WFC	y	y	y	4
970402	$14^h50^m16^s-69°19'.9$	$3'$	SAX/WFC	n	y	n	5
970508	$06^h53^m28^s+79°17'.4$	$3'$	SAX/WFC	n	y	y	6, 7
970616	$01^h18^m57^s-05°28'.0$	$40'$x$2'$	XTE/Uly	y	y	n	8, 9
970815	$16^h08^m43^s+81°30'.6$	$6'$x$3'$	XTE ASM	n	y	n	10
970828	$18^h08^m29^s+59°18'.0$	$2'.5$x$1'$	XTE ASM	y	y	n	11–13
971024	$18^h24^m51^s+49°28'.9$	$9'.0$x$1'$	XTE ASM	n	y	n	priv. comm.
971214	$11^h56^m30^s+65°12'.0$	$4'$	SAX/WFC	y	y	y	14, 15
971227	$12^h57^m35^s+59°15'.4$	$8'$	SAX/WFC	n	y?	y?	16

[(a)] IPN = interplanetary network detection; XA = X-ray afterglow; OT = optical transient.
[(b)] (1) Piro et al. 1996, (2) Costa et al. 1997a, (3) in't Zand et al. 1997, (4) Costa et al. 1997b, (5) Feroci et al. 1997, (6) Costa et al. 1997d, (7) Heise et al. 1997a, (8) Marshall et al. 1997, (9) Hurley et al. 1997a, (10) Smith et al. 1997a, (11) Remillard et al. 1997, (12) Smith et al. 1997b, (13) Hurley et al. 1997b, (14) Heise et al. 1997b, (15) Kippen et al. 1997, (16) Coletta et al. 1997

TABLE II
BeppoSAX NFI pointed observations of GRBs

GRB	Exposure (sec; MECS)	Delay	N_X [a]	X-ray afterglow flux (erg/cm^2/s; 2–10 keV)	Ref. [b]
960720	56 000	43 days	1	–	1
970111	52 000	16 hrs	2	2×10^{-13}	2, 3
970228	15 000	8 hrs	1	3×10^{-12}	4
	16 270	87 hrs	1	2×10^{-13}	4
970402	25 000	8 hrs	1	6×10^{-13}	5
	50 000	41 hrs	0	$<2\times10^{-13}$	5
970508	25 000	5.7 hrs	1	6×10^{-13}	6, 7
	24 000	6.6 hrs	1	4×10^{-13}	8
	12 000	99 hrs	1	2.4×10^{-13}	8
	73 000	137 hrs	1	5×10^{-14}	8
971214	101 200	6.5 hrs	1	4×10^{-13}	8, 9
971227	14 200	14 hrs	2	3×10^{-13}	8, 10

[a] N_X is the number of X-ray sources found inside the GRB error box.
[b] (1) Piro et al. 1998a, (2) Butler et al. 1997, (3) Feroci et al. 1998, (4) Costa et al. 1997c, (5) Piro et al. 1997a, (6) Piro et al. 1997b, (7) Piro et al. 1998b, (8) priv. comm., (9) Antonelli et al. 1997, (10) Piro et al. 1997c.

5.1.2. Quick ASCA and ROSAT follow-up observations of GRBs

Motivated by the occurrence of a few very long lasting GRBs and the detection of distinct spectral softening over the burst duration a number of attempts have been made in the past to observe well-localized GRB locations with ROSAT and ASCA as quickly as possible after the GRB event, in the hope to find the "smoking gun". To this end, the GRB had not only to be localized quickly, but the GRB location also had to be within the ROSAT/ASCA observing windows (≈30–40% of the sky at any moment). With the quick and accurate location capabilities of BeppoSAX, these attempts have been intensified and since then practically every observable location of a well-localized GRB has been observed with ROSAT and ASCA. The fastest response with ASCA (ROSAT) so far is 1.2 (5) days, which is near the minimum possible time achievable due to the various scheduling constraints. The primary goals are to determine accurate positions at the 10″ level (ROSAT), to measure the afterglow X-ray spectrum (ASCA) and to follow the intensity decay curve beyond the abilities of BeppoSAX (ROSAT/ASCA). Tab. III lists the GRBs which have been observed as TOO together with the time delay between the GRB and the ROSAT/ASCA observation.

5.1.3. Deep ROSAT/ASCA observations of GRB error boxes

Over the last seven years nearly a dozen GRB error boxes were observed with the ROSAT and ASCA satellites for up to 80 ksec exposure time (see Tab. 1 in Greiner (1998) for a complete listing of ROSAT pointings), thus improving considerably the sensitivity limits obtained with earlier X-ray observations at soft energies. X-ray sources have been found

TABLE III
Rapid ROSAT and ASCA target-of-opportunity observations (TOO) towards GRB locations

GRB	ROSAT				ASCA			
	Exposure (sec)	Delay	N_X	Ref.[a]	Exposure (sec)	Delay	N_X	Ref.[a]
920501	2 748	18 days	1	1	40 000	3 yrs	1	2
920711	2 432	28 weeks	0	3, 4	–	–	–	–
930704/940301	3156/1385	4 weeks	25	5	–	–	–	–
960720	6 960	42 days	1	6, 7	45 630	60 days	0	8
	2 791	24 weeks	1	4	–	–	–	–
961027–29	2065/2499	13 weeks	54	4	–	–	–	–
970111	1 198	5 days	0	9	–	–	–	–
	777	38 days	0	4	–	–	–	–
970228	34 280	11–14 days	1	10, 11	19 930	7 days	1	12
970402	–	–	–	–	39 100	2.8 days	0	13
970616	21 950	7–9 days	2	14	50 000	3.5 days	2	15
970815	17 115	5–7 days	1	16	46 000	3.2 days	0	17
970828	61 275	6–8 days	1	18	38 950	1.2 days	1	19, 20
971024	14 898	6 days	0	4	–	–	–	–

[a] (1) Hurley et al. (1996), (2) Murakami (1996a), (3) PI: Hurley, (4) Greiner (unpubl.), (5) Greiner et al. (1997a), (6) Greiner et al. (1996), (7) Greiner & Heise (1997), (8) Murakami et al. (1996b), (9) Frontera et al. (1997a), (10) Frontera et al. (1997b), (11) Frontera et al. (1998a), (12) Yoshida et al. (1997), (13) Murakami et al. (1998), (14) Greiner et al. (1997b), (15) Murakami et al. (1997a), (16) Greiner (1997), (17) Murakami et al. (1997b), (18) Greiner et al. (1997c), (19) Murakami et al. (1997c), (20) Murakami et al. (1997d).

inside the error boxes of some of these GRB. While originally the discovery of a quiescent X-ray source inside a small GRB error box was considered as probable evidence for an association of a GRB with a quiescent counterpart, the continuing discovery of further X-ray sources and in particular the detection of more than one X-ray source even in small GRB error boxes makes this association doubtful. Also, the optical identification of these X-ray sources, though not yet completely established in all cases, does not provide evidence for unusual objects. The present knowledge of properties of fading X-ray afterglows also argues against an association of these X-ray sources with the GRB, and makes the lack of "success" of these deep pointings understandable.

An estimate of the chance probability for the occurrence of a quiescent X-ray source inside a small GRB error box depends on how the question is asked in detail (see Hurley et al. 1996 for various possibilities). However, at the low sensitivity limits reached, the number density of X-ray sources is already remarkably high. From the results of many deep pointed observations and combined with the very deep Lockman hole observations of ROSAT, an improved $\log N$–$\log S$ distribution of X-ray sources has been derived (Hasinger 1997) which gives 100–700 X-ray sources per $1\,\square^\circ$ at the level of $10^{-14}...10^{-15}$ erg/cm^2/s. Thus, the probability for a chance coincidence of a quiescent, soft X-ray source with a GRB location is 25%–100% for a 10 arcmin^2 size error box.

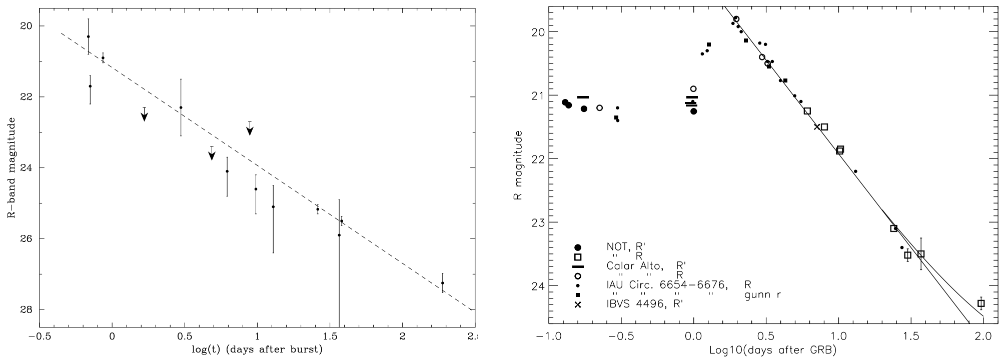

Fig. 3. R band lightcurves of GRB 970228 (left; Galama et al. 1998) and GRB 970508 (right; Pedersen et al. 1998). The intensity decay is well described by a power law of $T^{-1.1}$ and $T^{-1.2}$, respectively. Note the plateau and initial rise during the first 2 days in GRB 970508.

5.2. Optical transients

Optical transients have been discovered so far for three well-localized GRBs with a fourth one (GRB 971227) being disputed. Only a short summary is given here, and much more details can be found on the GCN pages (http://gcn.gsfc.nasa.gov/gcn/gcn_main.html) or on a nearly systematic data collection at http://www.aip.de:8080/~jcg/grbgen.html and references/links therein:

GRB 970228: The first optical transient (OT) associated with a GRB was discovered on deep images taken 21 hrs after the GRB as a 20 mag object fading by more than 3 magnitudes during the first 4 days (van Paradijs et al. 1997). The optical power law intensity decay of GRB 970228 is unbroken until the latest observations (8 months after the burst; Fruchter et al. 1998), thus arguing for an early onset of the adiabatic expansion regime of the fireball and indicating that the nonrelativistic regime still has not been reached. The OT is surrounded by fuzzy emission, most probably a galaxy, and this association first suggested that GRBs lie at cosmological distance. The proper motion of the OT reported by Caraveo et al. (1997) has been disputed (e.g. Sahu et al. 1997).

GRB 970508: The spectrum of the OT of GRB 970508 has shown a pattern of absorption lines which are interpreted as strongly redshifted (z=0.835) Fe and Mg lines. If the spectrum of the optical counterpart is featureless (according to theoretical prediction) it may have been absorbed by a faint galaxy on the line of sight, implying a distance to this GRB of z>0.835 (Metzger et al. 1997), thus providing the first direct distance determination of a GRB. The "unusual" optical lightcurve, i.e. a rise after a two day long plateau, followed by the power law decay similar to that in GRB 970228, has been interpreted as emission from a hot cloud where the spectrum peaks well above optical frequencies and gradually shifts down during its expansion (Katz 1994, Meszaros 1998).

GRB 971214: The optical transient of GRB 971214 was rather faint (I≈21 mag) right from the first observations 10 hrs after the burst. The point-like OT decayed quickly to below 25th mag within the first three days. Optical spectra obtained on Dec. 17 and 28, 1997 revealed extended emission features, but did not allow a unique redshift determination yet (Kulkarni et al. 1998).

5.3. Radio transient(s)

Despite intensive monitoring of GRBs from a few hours to several months after its occurrence (Frail 1998) radio emission has been securely detected only from one burst - GRB 970508. First detected with the VLA on May 13, the radio emission rose and fell several times over the next weeks, and the shape of the radio spectrum also changed (Frail et al. 1997, Taylor et al. 1997). Nearly at the same time, Goodman (1997) predicted that irregularities in an extremely tenuous ISM could cause fluctuations in the radio intensity if the source size is small enough. Scattering produces multiple images of the source, and interference between the multiple images may produce a diffraction pattern (perpendicular to the line of sight), leading to a strong flux variation on a time scale of $\approx$3 hrs as the observer (with Earth's and Sun's peculiar motion of $\approx$30 km/s) moves across the pattern.

Comparison of the expansion rate of the fireball model (see above) suggests that on a time scale of weeks the apparent fireball size grows to the maximum size for which diffractive scintillation is possible (Waxman et al. 1998). This is exactly what is observed: after about 2 months the radio "twinkling" of GRB 970508 slowly decreased. Thus, once a cosmological distance is adopted for GRB 970508 (based on the absorption line systems in the optical spectrum), the radio measurements imply an apparent size of $\approx 10^{17}$ cm about 1 months after the GRB and an expansion velocity near the speed of light.

5.4. Scaling of basic parameters

Relativistic fireball models predict that basic parameters of GRB afterglows are scaled to each other: total energy, initial Lorentz factor, surrounding gas density and distance. However, based on the measured fluxes from radio to γ-rays, all afterglows observed so far have exhibited completely unscaled behaviour in two ways. (a) X-ray afterglows in a rather tight range of intensity are detected from GRBs with a wide range of γ-ray parameters (e.g. peak flux, duration, temporal structure), and (b) optical and radio intensities are seemingly neither connected to peak γ-ray flux nor X-ray afterglow flux. In particular, the lack of optical transients in some GRBs with strong X-ray afterglow emission is hard to understand in terms of intrinsic properties related to the fireball model, since the optical emission in any case should be less beamed than the X-rays, and thus be more frequent. However, the external medium could play a significant role, i.e. possible absorption by interstellar gas or dust in the host (Jenkins 1997, Paczynski 1998). If absorption occurs in the host at cosmological distances, the measured low-energy cut-off in the X-ray spectrum will be lower than the intrinsic absorption by a factor of (1+z). Similarly, the observed optical emission has a wavelength shorter by a factor (1+z) thus suffering stronger extinction at a given absorbing column. As an example, at z=1 a column of 10^{22} cm^{-2} would correspond to an effective X-ray absorbing column of 1.5×10^{21} cm^{-2} and thus only marginally be distinguishable in the X-ray spectrum from galactic foreground absorption, but the observed I band emission actually is absorbed by the corresponding $A_{\rm V}$=7 in the host. Therefore, even small changes in the column within the GRB host can drastically reduce the optical flux while leaving the low-energy cut-off of the X-ray emission nearly unaffected.

While the above effect is important for the IR to X-ray range, the primary γ-rays as well as the radio emission are not affected. Thus, if more radio transients are discovered in the next months this should allow us to test directly the prediction of scaling among different GRBs by comparing their $F_\gamma/F_{\rm radio}$, avoiding the uncertainties imposed by the possible intrinsic host absorption.

5.5. Consequences for the sources of GRBs

If the explanation on the lack of optical transients relative to X-ray afterglows turns out to be correct, then GRBs would be linked to dense star forming regions, and thus possibly to a population of massive stars. Since the age of a massive star is not more than a few million years, it explodes within its star forming region. In the proposed hypernova scenario (Paczynski 1998), a massive and rapidly spinning star may release $\sim 10^{54}$ erg of kinetic energy extracted from the rotational energy of the black hole (Blandford & Znajek 1977). Only a small fraction of this kinetic energy is in the debris ejected with the largest Lorentz factors (which are required to generate the γ-rays), while most of the ejecta is sub-relativistic (speed of c/3 for a 10 $M_\odot$ object). Thus, when the fireball is slowed down by the ambient medium, the slower moving ejecta gradually catch up and provide a long lasting energy supply to the afterglow (longer than in the standard fireball model, but see Rees & Meszaros 1998).

If the GRB rate follows the massive star formation rate (with redshift) then an immediate consequence is an increase of the distance scale to GRBs (Sahu et al. 1997, Wijers et al. 1998). The increase in the comoving GRB rate with z compensates various redshift effects which are responsible for the roll-over in the counts. The higher energy per burst comes along with a reduced GRB rate. If the argument is turned around, then the redshift distribution of GRBs can, given enough statistics, be used as an independent test for the cosmic history of the star formation rate.

Alternatively, the gravitational collapse of supermassive stars ($M \geq 5\times10^4$ $M_\odot$) has been proposed as a cosmological source of GRBs (Fuller & Shi 1998, Zinnecker 1998). Since the formation, evolution and collapse of supermassive stars could be pregalactic, no galaxy hosts are required.

6. Conclusion

The discovery of long-wavelength afterglow emission lasting for days to months constitutes a turning point in GRB research. However, despite these exciting new data most of the basic questions remain unanswered. While a cosmological distance scale seems to be generally accepted, the nature of the GRB host remains open. Furthermore, the complexity of GRB time histories, duration and spectra as well as spectral evolution during the bursts are not easily explained in the various variants of the fireball model which is widely accepted as the main scenario for the production of the γ-ray burst emission. Finally, the origin of the GRB energy source remains a mystery. Possibly, knowledge of the history of the early cosmic evolution is required to understand the origin of GRBs. Thus, despite (or due to) the discovery of flaring counterparts at longer wavelengths GRBs remain an exciting field of research in the foreseeable future.

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