MULTIFREQUENCY STUDIES OF GAMMA-RAY BURSTS: TOWARDS THE UNDERSTANDING OF THE MYSTERY

ALBERTO J. CASTRO-TIRADO[1,2]

[1] *Laboratorio de Astrofísica Espacial y Física Fundamental (LAEFF-INTA), Apdo. 50727, E-28080, Madrid, Spain*

[2] *Instituto de Astrofísica de Andalucía (IAA-CSIC), Apdo. 03004, E-18080, Granada, Spain*

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 occurence, 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 1997-99, greatly improving our understanding of these sources. Now it is widely accepted that GRBs originate at cosmological distances. The observed afterglow satisfies the predictions of the ”standard” relativistic fireball model, and the central engines that power these extraordinary events are thought to be the collapse of massive stars or the merging of compact objects.

1. Introduction.

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, Strong and Olson 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 ≈ 0.1 MeV. The KONUS instrument on *Venera 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 (Meegan et al. 1992). 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. However, the GRB distance scale had to remain unknown for

30 years. A comprenhensive review of these observational characteristics can be seen in Fishman and Meegan (1995).

2. 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 present some results concerning six selected bursts detected by the *BeppoSAX* (*BSAX*) and *RossiXTE* (*RXTE*) satellites in 1996-99 and their impact on the current understanding on the physics of GRBs.

2.1. 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. (1997), 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. 1998). 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 (Groot et al. 1997, van Paradijs et al. 1997). The OA was afterwards found on earlier images taken by Pedichini et al. (1998) 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 ground-based and *HST* observations (van Paradijs et 1997, Sahu et al. 1997). New *HST* observations taken 6 months after the event were reported by Fruchter et al. (1997) and both the OA (at V = 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. Finally, after two years of work, the redshift of this object has been determined as z = 0.695 (Djorgovski et al. 1999a), confiming its extragalactic nature and implying a star-forming rate comparable to other galaxies at similar redshifts. Reichart (1999) proposed a type Ib/c supernova lies "behind" the GRB, overtaking the light curve two weeks after. This fact seems to be confirmed by the work of Galama et al. (2000).

2.2. 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 obtained during the maximum allowed a direct

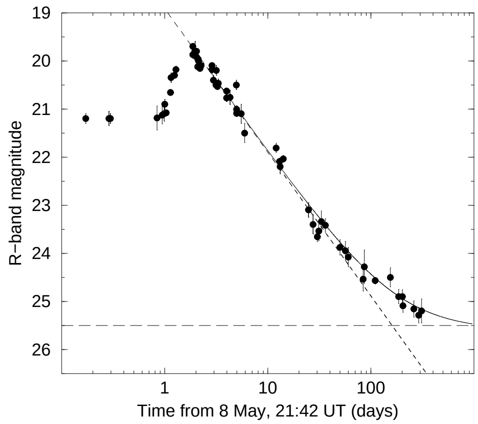

Fig. 1. The R-band light curve of the GRB 970508 optical afterglow, from data quoted in this paper. The dotted like is the contribution of the GRB afterglow itself, following F $\propto$ t$^{-1.19}$ two days after the burst. The horizontal dashed line is the R = 25.5 host galaxy, whereas the solid line is the contribution of both (afterglow plus host galaxy). From Castro-Tirado and Gorosabel (1999).

determination of a lower limit for the redshift of GRB 970805 ($z \geq 0.835$), implying E $\geq 7 \times 10^{51}$ erg and was the first proof that 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. 1998) revealed the contribution of a constant brightness source -the host galaxy- that was revealed in late-time imaging obtained in 1998 (Bloom et al. 1998, Castro-Tirado et al. 1998b, Zharikov et al. 1998). See Fig. 1. The maximum observed 1-day after the event has not been detected in other GRBs and it was interpreted by a delayed energy injection or by an axially symmetric jet surrounded by a less energetic outflow (Panaitescu et al. 1998). 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. 1998), with a star formation rate (SFR) of $\sim 1.0\ M_{\odot}$ year^{-1} (Bloom et al. 1998). 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 radiocounterpart 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 (Piro et al. 1999) was attributed to a thick torus surrouding the central engine (Mészáros

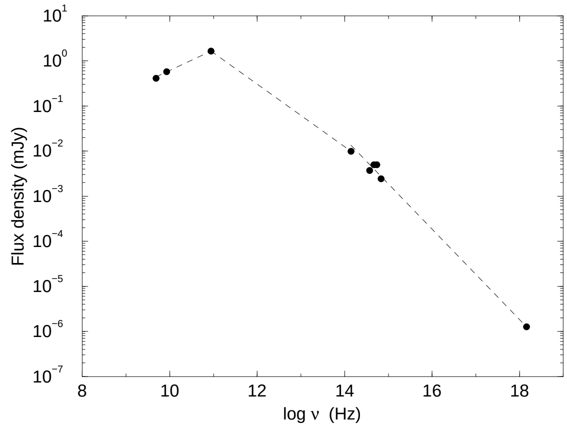

Fig. 2. The multiwavelength spectrum of GRB 970508, on May 22, 1997. Adapted from Gorosabel (1999). See also Wijers and Galama (1999).

and Rees 1998). GRB 970508 is the best observed afterglow so far. The broad band spectrum (see Fig. 2) is nicely explained by the standard relativistic blast wave model (Wijers and Galama 1999).

2.3. 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 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). The X-ray spectrum as seen by *ASCA* is strongly absorbed, suggesting that the event occurred in a dense medium. An excess at 6.7 keV was foud 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) and the host would be another dwarf galaxy (Gorosabel 1999). However, if the transient radiosource detected with the VLA is indeed associated to the event, the galaxy would be at a redshift of 0.96 (Frail et al. 2000).

2.4. GRB 980425

A peculiar type Ib/c supernova (SN 1998bw) was 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 ± 1 day of the GRB event, together with the relativistic expansion speed derived from the radio observation (Kulkarni et al. 1998a) strengths such a relationship. In that case, the total energy released would be 8×10^{47} erg which is about $\sim 10^5$ smaller than for "classical" GRBs. 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. 1999, Piro et al. 1998) cast some doubts on the SN/GRB

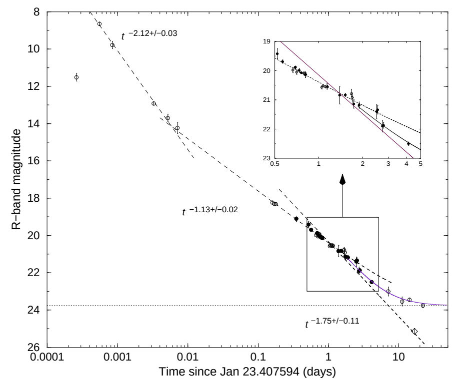

Fig. 3. The R-band light-curve of the GRB 990123 optical transient. Based on our observations (filled circles) and other data reported elsewhere (empty circles) (*11,23*). The doted line is the contribution of the underlying galaxy, with R $\sim$ 23.77 $\pm$ 0.10, from (*21*). The three dashed lines are the contribution of the OA, following F $\propto t^{\delta}$ with $\delta = -2.12$ up to $\sim$ 10 min, $\delta = -1.13$ up to $\sim$ 1.5 d, and $\delta = -1.75$ after that time. The solid line, only drawn after 1.5 d for clarity is the total observed flux (OA + galaxy). From Castro-Tirado et al. (1999).

association (Graziani et al. 1999). Although a deeper X-ray observation is pending, there is a general agreement now that the SN 1998bw/GRB 980425 relationship is real.

2.5. GRB 990123

This is the first for which contemporaneous optical emission was found simultaneous to the gamma-ray burst, reaching V $\sim$ 9 (Akerloff et al. 1999). This optical flash did not track the gamma-rays and did not fit the extrapolation of theSAX and BATSE spectra towards longer wavelengths. This optical emission was interpreted as the signature of a reverse shock moving into the ejecta (Sari and Piran 1999). A brief radiotransient was also detected (Frail et al. 1999a) coincident with the optical counterpart (Odewahn et al. 1999) and spectrocopy indicated a redshift z = 1.599 (Kulkarni et al. 1999, Andersen et al. 1999). A break observed in the light curve $\sim$ 1.5 days after the high energy event suggested the presence of a beamed outflow (Castro-Tirado et al. 1999, Fruchter et al. 1999, Kulkarni et al. 1999). See Fig. 3. A weak magnetic field in the forward shock region could account for the observed multiwavelength spectrum in contrast to the high-field for GRB 970508 and it seems that the emission from the three regions was first seen in this event (Galama et al. 1999a): the internal, reverse and forward shocks.

2.6. GRB 990510

Following the BSAX/WFC detection, an optical counterpart was reported by Vreeswijk et al. (1999a). The acromatic break seen in the light curve was also interpreted as a jet,

TABLE I
GRBs detected by *BeppoSAX* and *RXTE* in 1996-99

GRB	X-rays	optical-IR	radio	GRB	X-rays	optical-IR	radio
960720				990123	yes	yes	yes
970111	yes ?	no	no	990217	no	no	
970228	yes	yes	no	990308	yes ?	yes	
970402	yes	no		990506	yes	no	yes ?
970508	yes	yes	yes	990510	yes	yes	
970616	yes ?	no	no	990520	yes	no	no
970815	yes ?	no	no	990625			
970828	yes	no		990627	yes	no	
971214	yes	yes	no	990704	yes		
971227	yes ?	yes ?		990705	yes	yes	
980109		yes ?		990712		yes	
980326	yes ?	yes		990806	yes	no	
980329	yes	yes	yes	990907	yes ?	no	
980425	yes ?	yes ?	yes ?	990908		no	
980515	yes ?			991014	no	no	
980519	yes	yes	yes	991105		no	
980613	yes	yes		991106	yes ?	no	
980703	yes	yes	yes	991208		yes	yes
980706	yes ?	no		991216	yes	yes	yes
981220	yes			991217		no	
981226	yes		yes ?				

with a model yielding an opening angle of 0.08 and a beaming factor of 300 (Harrison et al. 1999). This is the first burst for which polarized optical emission was detected ($\Pi = 1.7 \pm 0.2$ %), by means of an observation performed $\sim$18.5 hr after the event (Covino et al. 1999) and later on (Wijers et al. 1999). This confirms the synchrotron origin of the blast wave itself and represents the second case for a jet-like outflow (Stanek et al. 1999).

Further X-ray afterglows were observed by *BSAX* and *RXTE* in 1997-99. The optical afterglow of GRB 980326 was suggested to resemble a SN at late times (Castro-Tirado and Gorosabel 1999) and indeed the late time light curve of GRB 980326 was explained by an underlying SN 1998bw SN at redshift of around unity (Bloom et al. 1999), thus strenghtening a possible SN-GRB connection.

Exponents for the power-law decay in the X-rays and in the optical are in the range α = 1.10-2.25 for a dozen of bursts. These results are given on Table 1. See also Greiner (2000) for an updated information. About 50% of the GRBs with X-ray counterparts are not detected in the optical, and this could be due to intrinsic faintness because of a low ambient medium, high absorption in a dusty enviroment, or Lyman limit absorption in high redshift galaxies ($z > 7$). Table 2 summarizes the properties of the host galaxies found so far.

TABLE II
"classical" GRB host galaxies

GRB	R_{host}	z	SFR ($M_\odot$ year^{-1})	References
970228	25.2	0.695	0.5	Djorgovski et al. (1999a)
980828	24.2 ?	0.33 ? 0.96 ?		Yoshida et al. (1999),
				Frail et al. (2000)
970508	25.7	0.835	1	Bloom et al. (1998)
971214	25.6	3.418	5	Kulkarni et al. (1998b)
980329	26.3			Djorgovski et al. (2000)
980519	∼26			Hjorth et al. (1999)
980613	23.8	1.096	3	Djorgovski et al. (1999b)
980703	22.5	0.966	63	Djorgovski et al. (1998)
981226	24.9			Frail et al. (1999b)
990123	23.8	1.599		Kulkarni et al. (99),
				Andersen et al. (1999)
990506	24.8			Frail et al. (2000)
990510	≥27	1.619		Vreeswijk et al. (1999b)
990712	21.8	0.430		Galama et al. (1999b)
991208	24	0.707		Dodonov et al. (1999)
				Djorgovski et al. (1999c)
991216	24	1.02		Vreeswijk et al. (1999c)

3. The relativistic blast wave model

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 in a region smaller than 10 km. The opaque radiation-electron-positron plasma accelerates to relativistic velocities (the fireball). The GRB itself are thought to be be produced by a serie of "internal shocks" due to collisions amongst layers expelled with different Lorentz factors that are being caught up to each other. When the fireball runs into the surrounding medium, a "forward shock" ploughs into the medium, and sweeps up the interstellar matter, decelerating and producing an afterglow at frequencies gradually declining from X-rays to radio wavelenghts (Mészáros and Rees 1997). A "reverse shock" impinges on the ejecta. An extensive review 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 and a cooling break (Sari, Piran and Narayan 1998). The determination for every GRB of the six observables: the synchrotron, break and self-absorption frequencies, the maximum flux and the power-law decay exponent (all from the multiwavelength spectrum) and z (from optical or X-ray spectroscopy) allows to obtain the total energy per solid angle, the fraction of the shock energy in electrons and post-grb magnetic fields, and the density of the ambient medium.

How does the GRB take place? The most popular model is that of a "failed" type-I SN (Bodenhaimer 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 Kerr black hole (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 (Lee et al. 1999) or via the accretion energy from the disk. In any case, a "dirty fireball", is produced reaching a luminosity ~ 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 (Krumholz et al. 1998, Totani et al. 1999).

The coalescence of neutron stars in a binary system has been also proposed (Narayan et al. 1992): lifes 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 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 black hole 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). It fact, there it has been suggested that the short duration (< 1 s) bursts could be due to compact star mergers, whereas the longer ones are caused by the collapse of massive stars.

4. Summary

The existence of X-ray afterglow in *most* bursts is confirmed. Out ot 26 *BSAX* pointings, 17 revealed a clear afterglow, leading to the detection of several optical/IR/radio counterparts in 1997-99. The determination of z for the host galaxies by means of absorption edges or emission lines in the X-ray afterglow seems to be very promising. 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. Energy releases of $\sim 10^{54}$ erg (as derived for GRB 980329 and 990123) are difficult to reconcile with theoretical models and non-isotropic emission, such as intrinsic beaming appears as the most plaussible resolution of this problem.

References

Akerloff, C. et al. 1999, *Nature* **398**, 400.
Andersen, M. et al. 1999, *Science* **283**, 2075.
Atteia, J.-L. et al. 1987, *Astrophys. J. Suppl.* **64**, 305.
Bartolini, C. et al. 1998, in *Gamma-Ray Bursts*, C. A. Meegan, R. Preece and T. Koshut eds., AIP Conf. Proc. 428, p. 540.
Bloom, J. S. et al. 1998, *Astrophys. J. Lett.* **507**, L25.
Bloom, J. S. et al. 1999, *Nature*, 401, 453.
Bodenhaimer, P. and Woosley, S. 1983, *Astrophys. J.* **269**, 281.
Bond, H. 1997, IAU Circ. 6655.

Bonnell, J. T. and Klebesadel, R. W. 1996, in *Gamma-Ray Bursts*, C. Kouveliotou, M. F. Briggs and G. J. Fishman eds., AIP Conf. Proc. 384, p. 977.

Bremer, M. et al. 1998, *Astron. Astrophys. Lett.* **332**, L13.

Castro-Tirado, A. J. 1998, in *Ultraviolet Astrophysics: beyond the IUE Final Archive*, R. Gonzalez-Riestra, W. Wamsteker and R. Harris eds., ESA Conference Proceedings SP-413, p. 659 (http://xxx.lanl.gov/abs/astro-ph/9803007).

Castro-Tirado, A. J. et al. 1998a, *Science* **279**, 1011.

Castro-Tirado, A. J. et al. 1998b, IAU Circ. 6848.

Castro-Tirado, A. J. et al. 1999, *Science* **283**, 2069.

Castro-Tirado, A. J. and Gorosabel, J. 1999, *Astron. Astrophys. Suppl. Ser.*, 138, 449.

Costa, E. et al. 1997, *Nature* **387**, 783.

Covino, S. et al. 1999, *Astron. Astrophys. Lett.* **348**, L1.

Djorgovski, S. G. et al. 1997, *Nature* **387**, 876.

Djorgovski, S. G. et al. 1998, *Astrophys. J. Lett.* **508**, L17.

Djorgovski, S. G. et al. 1999a, GCN Circ. 289.

Djorgovski, S. G. et al. 1999b, GCN Circ. 189.

Djorgovski, S. G. et al. 1999c, GCN Circ. 481.

Djorgovski, S. G. et al. 2000, *Astrophys. J.*, in press.

Dodonov, S. et al. 1999, GCN Circ. 461.

Fishman, G. J. and Meegan, C. A. 1995, *Ann. Rev. Astron. Astrophys.* **33**, 415.

Frail, D., Kulkarni, Nicastro, L., Feroci, M. and Taylor, G. 1997, *Nature* **389**, 261.

Frail, D. et al. 1999a, GCN Circ. 211.

Frail, D. et al. 1999b, *Astrophys. J. Lett.* **525**, L81.

Frail, D. et al. 2000, Proc. of the 5th Hunstville GRB Symposium (in press).

Frontera, F., Costa, E., Piro, L. et al. 1998, *Astrophys. J. Lett.* **493**, L67.

Fruchter, A. et al. 1999, *Astrophys. J. Lett.* **519**, L13.

Galama, T. et al. 1997, *Nature* **387**, 479.

Galama, T. et al. 1998a, *Astrophys. J. Lett.* **497**, L13.

Galama, T. et al. 1998b, *Nature* **395**, 670.

Galama, T. et al. 1999a, *Nature* **398**, 394.

Galama, T. et al. 1999b, GCN Circ. 388.

Galama, T. et al. 2000, *Astrophys. J.*, in press (astro-ph/9907264).

Ginzburg, V. L. & Syrovatskii, S. I. 1965, *Ann. Rev. Astron. Astrophys.* **3**, 297.

Goodman, J. 1986, *Astrophys. J. Lett.* **308**, L47.

Gorosabel, J. 1999, Ph.D. Thesis, Universitat de València, Spain.

Graziani, C. et al. 1999, *Astron. Astrophys. Suppl. Ser.*, 138, 469.

Greiner, J., Englhauser, J., Groot, P. J. and Galama, T. 1997, IAU Circ. 6757.

Greiner, J. 2000, in http://www.aip.de/People/JGreiner/grbgen.html

Groot P.J. et al. 1997, IAU Circ. 6584.

Groot P.J. et al. 1998, *Astrophys. J. Lett.* **493**, L27.

Guarnieri, A. et al. 1997, *Astron. Astrophys. Lett.* **328**, L13.

Harrison, F. et al. 1999, *Astrophys. J. Lett.* **523**, L121.

Hjorth, J. et al. 1999, *Astron. Astrophys. Suppl. Ser.*, 138, 461.

Katz, J. I. 1997, *Astrophys. J.* **490**, 633.

Klebesadel, R., Strong, I. and Olson, R. 1973, *Astrophys. J. Lett.* **182**, L85.

Krumholz, M., Thorsett, S. and Harrison, F. 1998, *Astrophys. J. Lett.* **506**, L81.
Kulkarni, S. et al. 1998a, *Nature* **395**, 663.
Kulkarni, S. et al. 1998b, *Nature* **393**, 35.
Kulkarni, S. et al. 1999, *Nature* **398**, 389.
Lee, H. K., Wijers, R. A. M. J. and Brown, G. E. 1999, *Physics Reports*, in press (astro-ph/9906213).
MacFadyen, A. and Woosley, S. 1999, *Astrophys. J. Lett.* **524**, L62.
Mazets, E. P. et al. 1981, *Astrophys. Space Sci.* **80**, 3.
Meegan, C. A. et al. 1992, *Nature* **355**, 143.
Mészáros, P. and Rees, M. J. 1997, *Astrophys. J. Lett.* **476**, L232.
Mészáros, P. and Rees, M. J. 1998, *Mon. Not. R. Astr. Soc.* **299**, L10.
Metzger, M. R. et al. 1997, *Nature* **387**, 878.
Murakami, T. et al. 1997, IAU Circ. 6732.
Narayan, R. et al. 1992, *Astrophys. J. Lett.* **395**, L83.
Odewahn, S. C. et al. 1999, GCN Circ. 201.
Paczyński, B. 1986, *Astrophys. J. Lett.* **308**, L43.
Paczyński, B. 1998, *Astrophys. J. Lett.* **494**, L45.
Paczyński, B. 1991, Acta Astronomica 41, 257.
Panaitescu, A., Mészáros, P. & Rees, M. J. 1998, *Astrophys. J. Lett.* **503**, L314.
Pedersen, H. et al. 1998, *Astrophys. J.* **496**, 311.
Pedichini, F. et al. 1998, *Astron. Astrophys. Lett.* **327**, L36.
Pian, E. et al. 1998, *Astrophys. J. Lett.* **492**, L103.
Pian, E. et al. 1999, *Astron. Astrophys. Suppl. Ser.*, 138, 463.
Piran, T. et al. 1999, *Physics Reports*, 314, 575 (astro-ph/9810256).
Piro, L. et al. 1998, GCN Circ. 155.
Piro, L. et al. 1999, *Astrophys. J. Lett.* **514**, L73.
Pooley, G. and Green, D. 1997, IAU Circ. 6670.
Reichart, D. 1999, *Astrophys. J. Lett.* **521**, L111.
Remillard, R., Wood, A., Smith, D. and Levine, A. 1997, IAU Circ. 6726.
Sahu, K. et al. 1997, *Nature* **387**, 476.
Sari, R., Piran, T. and Narayan, R. 1998, *Astrophys. J. Lett.* **497**, L17.
Sari, R. and Piran, T. 1999, *Astrophys. J. Lett.* **520**, L641.
Sokolov, V. V. et al. 1998a, *Astron. Astrophys.* **334**, 117.
Stanek, K. Z. et al. 1999, *Astrophys. J. Lett.* **522**, L39.
Taylor, G. B. et al. 1997, *Nature* **389**, 263.
Totani, T. 1999, *Astrophys. J.* **511**, 41.
van Paradijs, J. et al. 1997, *Nature* **386**, 686.
Vreeswijk, P. et al. 1999a, GCN Circ. 310.
Vreeswijk, P. et al. 1999b, GCN Circ. 324.
Vreeswijk, P. et al. 1999c, GCN Circ. 496.
Wijers, R. A. M. J. and Galama, T. J. 1999, *Astrophys. J.* **523**, 171.
Wijers, R. A. M. J. et al. 1999, *Astrophys. J. Lett.* **523**, L33.
Woosley, S. 1993, *Astrophys. J.* **405**, 273.
Yoshida, A. et al. 1999, *Astron. Astrophys. Suppl. Ser.*, 138, 433.
Zharikov, S. V., Sokolov, V. V., Barishev, Yu. V. 1998, *Astron. Astrophys.* **337**, 356.