Gamma-Ray Bursts in the 1990's – a Multi-wavelengths Scientific Adventure

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Abstract

In 1997 the first optical afterglow of a cosmic Gamma-Ray Burst was discovered, and substantial progress has been achieved since then. Here we present a short review of some recent developments in this field, with emphasis on observational aspects of the GRB phenomenon.

1 Introduction

Gamma-Ray Bursts (GRBs) are bright, transient events in the gamma-ray sky, unpredictable in time and location, with a typical duration of $\sim$ seconds (for a review, see Fishman 1995; 1999; Fishman & Meegan 1995; Kouveliotou 1995a; Meegan 1998). The brightest bursts have gamma-ray fluences of order 10^{-4} erg cm^{-2}, strong enough to lead to detectable disturbances of the Earth's upper atmosphere (Fishman & Inan 1988). Most of the energy of the bursts is released in the 0.1–1 MeV range. Spectra generally display featureless smooth continua (for a review, see Teegarden 1998).

The first GRB was recorded with the *Vela* satellites on July 2, 1967 (Klebesadel, Strong, & Olson 1973; Strong, Klebesadel, & Olson 1974; for a historical review see Bonnell & Klebesadel 1996). The precise localization of a GRB on the sky has been an unsolved challenge for ground-based astronomy for 30 years, although more than 2000 bursts were detected by numerous space-based experiments during this timespan. This unsatisfactory observational situation led to an enormous flood of publications (see Hurley 1998a), and culminated in more than 100 theories about the nature of the bursters, ranging from solar-wind models to topological defects at cosmological distances (in the early years of GRB research there were in fact more theories than bursts; see Nemiroff 1994; Ruderman 1975). The main reason for the missing identification of the burster population was that prior to 1997 no small, arcmin-sized GRB error boxes were available for rapid follow-up observations.

In the mid 1980's it was recognized that there is a subclass among the GRBs which are distinguished from the majority of the bursts (Laros et al. 1986, 1987). These bursts have a soft, thermal Bremsstrahlung spectrum (kT about 30 keV), short durations, and come from certain, well-localized regions in the sky. These *Soft Gamma-Ray Repeaters* (SGR) represent a population of objects in the Galaxy and the Large Magellanic Cloud which occasionally emit soft GRBs. This class of objects, currently consisting of four confirmed sources (SGR 0525–66, 1627–41, 1806–20, 1900+14), is not considered here, although great progress was also achieved in SGR research in recent years (for reviews, see Hartmann 1995; Kouveliotou 1995b; Hurley 1999a).

2 Steps toward the GRB distance scale

2.1 The period 1991–1996

The 1990's have seen two observational breakthroughs in GRB research. The first came with the *Burst and Transient Source Experiment (BATSE)* on the *Compton Gamma-Ray Observatory* (*CGRO*; Fishman 1981; Fishman et al. 1993, 1994). It characterizes the period from 1991 to 1996. During this period several GRB experiments aboard various satellites were carried out, but *BATSE* was most successful.

In operation since 1991, *BATSE* detects about 1 burst/day, corresponding to a full sky rate of about 800 a year (Meegan et al. 1992). Based on *BATSE* observations it became obvious in the early 1990's that the bursters must be located either deep in a Galactic halo or at cosmological distances (Meegan et al. 1992; for reviews, see Blaes 1994; Dermer & Weiler 1995; Fishman & Meegan 1995; Harding 1994; Hartmann 1994, 1996; Hurley 1994; Lamb 1997; Mészáros 1997). Compared to the observational situation in the 1970's and 1980's (for a review, see Higdon & Lingenfelter 1990; Houston & Wolfendale 1983; Puget 1981) this evidence represented substantial progress. However, it also meant that the distance scale of the bursters was still unknown by orders of magnitude, lying either at the kpc level or in the Gpc range (for a detailed study see, e. g., Mao & Paczyński 1992a, b). Correspondingly uncertain was the GRB luminosity distribution. The arguments for and against GRBs inside or outside the Galaxy led to a lively debate, which was eventually presented to the general public (see the dedicated publications of 'The Great Debate': Fishman 1995; Lamb 1995; Nemiroff 1995; Paczyński 1995; Rees 1995; Trimble 1995).

The most promising way to distinguish between the Galactic halo model and the cosmological model of GRBs seemed to be either to check with high precision the angular isotropy of the bursts on the sky (cf. Briggs et al. 1996; Hakkila et al. 1994; Lamb 1997; Tegmark et al. 1996b), or to search for GRBs and their accompanying optical and X-ray flashes from a potential Galactic halo population of bursters in M31 (cf. Klose 1995a; Lamb 1995; Li & Liang 1992). Evidence for the latter was not found, but the former method worked very well and based on *BATSE* gamma-ray data alone over the years it became more and more difficult to postulate a Galactic halo origin of all bursts. This included constraints on burst repetition (cf. Meegan et al. 1995; Tegmark et al. 1996a).

There have been several other proposals to determine the distance scale of the bursters (cf. Paczyński 1991a, b). *At gamma-ray energies* these investigations involved attempts to detect a cosmological signature in GRB durations and spectral hardness (cf. Brainerd 1994; Fenimore & Bloom 1995; Horack, Mallozzi, & Koshut 1996; Lee & Petrosian 1997; Norris et al. 1994, 1995), studies of luminosity function effects on the observed brightness distribution of the bursts (cf. Fenimore et al. 1993; Horváth, Mészáros, & Mészáros 1996; Mao & Paczyński 1992a; Mészáros & Mészáros 1995, 1996; Mészáros et al. 1996), analyses of the spectral energy distribution of the bursts in combination with pair production opacities in GRB photon fields (cf. Baring & Harding 1998), and theoretical estimates of the energy reservoir of potential Galactic neutron stars as GRB sources (cf. Hartmann & Narayan 1996). *In the X-ray band* a Galactic origin of the burster population would have been revealed by scattering and absorption of GRB X-rays by the Galactic interstellar medium (Klose 1994, 1995b; Owens, Schaefer, & Sembay 1995). However, this required a dedicated X-ray satellite, which was not available at that time. *At optical/infrared/radio wavelengths* one way was to perform rapid follow-up searches for transients following or accompanying GRBs, the occurrence of which was predicted in theoretical models (cf. Mészáros, Rees, & Papathanassiou 1994). Another way was to look for a potential GRB source population in GRB error boxes. Both strategies were confronted with the problem that *BATSE* 1σ error boxes are several degrees in radius (cf. Briggs et al. 1999). Although this is a very small localization size for a gamma-ray telescope, it is a giant error box for follow-up observations in the radio, optical, or near-infrared bands. Searches for optical transients in GRB error boxes on wide-field photographic plates fortuitously taken at the right time and area of the sky have been one method to address the problem (cf. Greiner et al. 1992; Schaefer 1990; for a review, see Hudec 1993). In general, this method was not very efficient since the chance of finding suitable photographic plates is very small (cf. Greiner et al. 1996), and variable stars could mimic optical transients (cf. Greiner & Motch 1995; Hudec & Wenzel 1996; Klose 1995c; Pedersen 1994). Indeed, these searches did not lead to the unambiguous detection of a GRB source. A more promising way was to set-up automatic wide-field cameras, which could be triggered on-line by GRB detections on board the *CGRO*. Based on dedicated international distribution networks for GRB data (cf. Barthelmy et al. 1998; Kippen et al. 1998a; McNamara, Harrison, & Williams 1995), response times on the order of seconds were achieved, however no optical transients were discovered with this method either (cf. Akerlof et al. 1995; Lee et al. 1997; Park et al. 1997; Vanderspek, Krimm, & Ricker 1995).

Another technique to observe a burster was based on GRB error boxes provided by the Interplanetary Network (IPN) of satellites operating in the solar system (cf. Laros et al. 1998). For most of the 1990's the IPN consisted only of *Ulysses*-spacecraft (cf. Hurley et al. 1995) and *CGRO*. The IPN makes use of the light travel time delays between different satellites to localize a burst on the sky (cf. Cline et al. 1980). Compared to *BATSE*-only error boxes, if triggered, the IPN can provide GRB error boxes with considerable smaller sizes (for a review, see Lund 1995), but not in real-time. International campaigns of follow-up observations of the most promising half-dozen well-localized IPN bursts only provided upper limits to the flux density of any transient source in the X-ray, optical, or radio band (cf. Frail et al. 1994; Galama et al. 1997a; Greiner et al. 1997a; Hurley et al. 1994; Laros et al. 1997; Palmer et al. 1995; Pedersen 1994; Schaefer et al. 1994; for a review, see McNamara, Harrison, & Williams 1995). Furthermore, deep surveys of arcmin-sized IPN error boxes have been performed, mostly months or years after the corresponding burst, with the aim of finding evidence for a statistical excess of a certain class of astronomical objects in GRB error boxes. No unambiguous GRB sources were found in the optical (cf. Gorosabel et al. 1995; Schaefer et al. 1997; Vrba, Hartmann, & Jennings 1995; Webber et al. 1995), although in the case of quasars and active galactic nuclei the situation is still somewhat controversial (cf. Burenin et al. 1998; Fruchter et al. 1999b; Hurley et al. 1999a; Luginbuhl et al. 1995, 1996; Schartel, Andernach, & Greiner 1997; Vrba et al. 1994, 1999a). Similar surveys in the radio (cf. Palmer et al. 1995; Schaefer et al. 1989), the X-ray band (cf. Boër et al. 1993, 1997; Greiner et al. 1991; Hurley et al. 1999b; Pizzichini et al. 1986), and the near-infrared (Blaes et al. 1997; Klose, Eislöffel, & Richter 1996; Klose et al. 1998; Larson & McLean 1997; Larson, McLean, & Becklin 1996) also failed to identify the burster population. The deepest optical survey (Vrba, Hartmann, & Jennings 1995) and the near-infrared surveys revealed, however, that there is no lack of potential GRB host galaxies in IPN error boxes. The missing item was the direct observational proof of an extragalactic origin of the bursts.

This second observational breakthrough was initiated by the Italian-Dutch gamma-ray/X-ray satellite *BeppoSAX* launched in 1996 (Boella et al. 1997; Costa et al. 1998; Frontera 1998), and later it included successful GRB localizations with RXTE (see Bradt & Smith 1999; Smith et al. 1999). It characterizes the period from 1997 to 1999. The observational situation before that time is summarized by e. g. Greiner (1995), Lamb (1997), McNamara, Harrison, & Williams (1995), Mészáros (1997), and Vrba (1996).

2.2 The period 1997–1999

Contrary to *BATSE, BeppoSAX* can provide an arcmin-sized GRB error box within hours after the GRB trigger, though only about ten times a year because of its small field of view. The first burst detected by *BeppoSAX* in 1997 was GRB 970111 with an error box of 10 arcmin radius provided to observatories via electronic mail only hours after the occurrence of the burst (Costa et al. 1997a). Although no GRB afterglow was detected either in the optical (cf. Galama et al. 1997b) or in the radio band (Frail et al. 1997a), this burst made it immediately clear that an observational breakthrough was near. It came with GRB 970228 (Costa et al. 1997b, c) when for the first time the optical afterglow of a burst was discovered (Groot et al. 1997; van Paradijs et al. 1997), meaning that the burst was localized with high angular precision. Since then much has been learned about GRBs based on multi-wavelengths observations of afterglows. The establishment of a sophisticated electronic network for GRB messages, the GRB coordinated network GCN (Barthelmy et al. 1998, see appendix), was another milestone on this route. Various aspects of these exciting, new discoveries have been summarized by numerous authors from the theoretical as well as from the observational point of view (e. g., Blinnikov 1999; Castro-Tirado 1999; Frontera 1998; Ghisellini 1999; Greiner 1998; Hartmann 1999; Hurley 1998b; Lamb 1999; McNamara & Harrison 1998; Mészáros 1999a,c; Mészáros, Rees, & Wijers 1999; Paczyński 1999; Piran 1999a, b; Rees 1998, 1999; Stern 1999; Vietri 1999).

3 Recent observations of GRB afterglows

The occurrence of broad-band afterglows following GRBs was expected on theoretical grounds (cf. Rees 1998, and references therein). Compared to the duration of the bursts, afterglows in the long-wavelengths bands can be long-lived, making the precise localization of the bursters possible and extending GRB research into international multi-wavelength observing campaigns. Greiner's WWW-page at the Astrophysical Institute Potsdam (see appendix) provides informations about ongoing observational activities in GRB follow-up studies.

According to the currently most accepted theoretical GRB model, the afterglows are due to external shocks when a relativistically expanding fireball (a γ-ray fireball, see Cavallo & Rees 1978) released by a compact source sweeps up matter from the "interstellar" medium surrounding the burster (for an introduction into this subject and/or a review, see Mészáros 1997, 1999a; Piran 1997, 1999a, b; Rees 1999). This medium could be, for example, the ordinary interstellar medium in a spiral galaxy, or the stellar wind environment from the GRB progenitor (cf. Chevalier & Li 1999; Halpern et al. 1999). The afterglow emission process is most likely synchrotron radiation (see, e. g., Sari, Piran, & Narayan 1998; Wijers, Rees, & Mészáros 1997, and references therein).

At the date of submission of this review, long-lasting optical afterglows have been observed from about a dozen GRBs, and about ten radio afterglows were discovered (see Greiner's WWW-page [appendix]; see also Table 2 in Wheeler 1999). Evidence for a short-lived afterglow in the gamma-ray band has been reported too (Giblin et al. 1999). About half of all GRB afterglows seen in the X-ray band showed no detectable optical emission, whereas almost all GRBs detected by *BeppoSAX* exhibited an X-ray afterglow (Costa 1999).

To date, there are eleven reported spectroscopic redshift measurements of GRB afterglows and/or host galaxies (mid December 1999; Table 1), confirming the cosmological distance scale of GRBs, which was considered soon after

Table 1: Gamma-ray bursts with reported spectroscopic redshifts

GRB	z [a]	Ref.	F_γ [b]	band [c]	Ref.	E_γ [d]
970228	0.695	1	2	$35 \ldots 1000$	11	2.4×10^{51}
970508	0.835	2	3	$20 \ldots 1000$	12	5.3×10^{51}
970828	0.96	3				
971214	3.418	4	11 ± 1	> 20	14	3.5×10^{53}
980425	0.0085	5	4 ± 1	> 20	15	7.4×10^{47}
980613	1.096	6	2	> 20	16	6.1×10^{51}
980703	0.966	7	30 ± 10	$40 \ldots 700$	17	7.1×10^{52}
990123	1.600	8	509 ± 2	> 20	18	3.4×10^{54}
990510	1.619	9	26 ± 1	> 20	19	1.8×10^{53}
990712	0.430	10				
991208	0.707	20				

[a] redshift; [b] observed gamma-ray fluence [10^{-6} erg cm^{-2}] based on measured photon flux; [c] corresponding energy band [keV]; [d] released gamma-ray energy [erg], isotropic emission assumed and calculated for a standard Friedmann cosmology with $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_0 = 0.2$

References: 1: Djorgovski et al. 1999, GCN 289; 2: Bloom et al. 1998, ApJ 507, L25; 3: Frail 1999, 5th Huntsville meeting on GRBs; 4: Kulkarni et al. 1998, Nature 393, 35; 5: Tinney et al. 1998, IAU Circ. 6896; 6: Djorgovski et al. 1999, GCN 189; 7: Djorgovski et al. 1998, ApJ 508, L17; 8: Keson et al. 1999, IAU Circ. 7096; Hjorth et al. 1999, GCN 219; 9: Vreeswijk et al. 1999, GCN 324; 10: Galama et al. 1999, GCN 388; 11: Palmer et al. 1997, IAU Circ. 6577; 12: Kouveliotou et al. 1997, IAU Circ. 6660; 14: Kippen et al. 1997, IAU Circ. 6789; 15: Kippen et al. 1997, GCN 67; 16: Woods et al. 1998, GCN 112; 17: Amati et al. 1998, GCN 146; 18: Kippen et al. 1999, GCN 224; 19: Kippen et al. 1999, GCN 322; 20: Dodonov et al. 1999, GCN 475.

their discovery (e. g., Usov & Chibisov 1975; van den Bergh 1983; Paczyński 1987). The data seem to indicate that the redshift distribution of the bursters peaks around 1, with a long tail towards higher redshifts (for model fits see, e. g., Schmidt 1999). There is also one burst that came from the local universe (z=0.0085; GRB 980425). The question if all GRBs are of extragalactic nature is not yet completely solved, however (cf. Cline, Matthey, & Otwinowski 1999; Tavani 1998).

Usually the optical transient following a GRB has an R-band magnitude of about $18 \ldots 22$ when it is detected some hours after the burst, provided that no strong extinction occurs in the GRB host galaxy or in our Galaxy. This can make the optical transient detectable to 1-m class telescopes. For example, the optical afterglow of GRB 970508 was discovered with the Kitt Peak 0.9-m reflector (Bond 1997), the afterglow of GRB 980329 with the

Tautenburg 1.34-m (Klose, Meusinger, & Lehmann 1998; Reichart et al. 1999), and the afterglow of GRB 990308 with the Venezuelan 1-m Schmidt telescope (Schaefer et al. 1999). The burst 980329 is the only GRB afterglow detected in the submm-band (Smith et al. 1999). Presumably, there was something special about this burst, which is also indicated by the color of its afterglow (for a discussion see, e. g., Draine 1999; Fruchter 1999; in 't Zand et al. 1998; Palazzi et al. 1998). Detailed color measurements of afterglows are published for, e. g., GRB 980703 (Vreeswijk et al. 1999) and 990510 (Israel et al. 1999).

The time-dependent flux density of an afterglow follows a power-law decay, $F_\nu(t) \sim t^{-\beta}$, in accordance with fireball models (cf. Sari, Piran, & Narayan 1998; Wijers, Rees, & Mészáros 1997). For example, a decay constant in the optical of $\beta = 1.2$ leads to a dimming of the optical transient by 3 photometric magnitudes between day 1 and day 10 after the occurrence of the burst. Rapid follow-up observations are therefore crucial for the detection of GRB afterglows. Exceptions to this rule do occur, however. The afterglow flux of GRB 970508 showed a fall and rise during the first 2 days, before it entered a power-law decline (cf. Castro-Tirado et al. 1997; Fruchter et al. 1999b; Pedersen et al. 1998; for a possible theoretical explanation, see Panaitescu, Mészáros, & Rees 1998; Pugliese, Falcke, & Biermann 1999).

In its early phase a GRB afterglow can outshine its host galaxy, which becomes visible weeks or months after the burst when the light curve of the afterglow seems to flatten. This was first seen for GRB 970508 (Zharikov & Sokolov 1999). This was also the first burst where a radio counterpart of the afterglow was detected with the Very Large Array (VLA) which suggested extreme relativistic expansion velocities of the radio source (Frail et al. 1997b; Waxman, Kulkarni, & Frail 1998) based on the radio scintillation technique (Goodman 1997). Meanwhile, it has been proven that observations in the radio band can localize GRB afterglows in *BeppoSAX* error boxes when optical identifications are still missing (Taylor et al. 1998a, b, in case of GRB 980329; Frail et al. 1999a, in case of GRB 991208) and even when they do not exist at all (Frail 1999, in case of GRB 970828; Frail et al. 1999b, in case of GRB 981226).

4 Afterglows and GRB energetics

Perhaps the most impressive property of the bursts is the huge amount of electromagnetic energy released (Table 1). This is especially apparent in the case of GRB 990123, where an optical flash was detected for the first time when the burst was still in progress in the gamma-ray band (Akerlof et al. 1999). This phenomenon was predicted from theory (Mészáros 1999a, and references therein; Sari & Piran 1999, and references therein; for a phenomenological approach, see Ford & Band 1996). The optical flash peaked about 45 sec after the onset of the burst at a mean V-band magnitude of about 9 on a frame with a 5 sec exposure (Akerlof et al. 1999). The (minimum) redshift of the burster was found to be 1.60 (Andersen et al. 1999; Kulkarni et al. 1999), so that the optical flash translates into an ultraviolet rest-frame luminosity of about 3×10^{16} $L_\odot$ (Kulkarni et al. 1999). If the burster had been at a distance corresponding to that of M81, its V-band magnitude would have reached –9 (a cosmological K-correction neglected). If it had been located at the Galactic center, but assuming no extinction, it would have peaked at a V-band magnitude of –22, comparable to the apparent magnitude of the Sun. Assuming isotropic emission, the gamma-ray energy emitted by this burst amounts to 3.4×10^{54} erg (Table 1), about twice the rest mass energy of the Sun and an order of magnitude higher than the previous record holder, GRB 971214 (Kulkarni et al. 1998a). The term 'hypernova' (Paczyński 1998a, b) has become a popular word to describe such energetic events.

Two basic ideas are being discussed on how to reduce the required energy budget; gravitational lensing and non-isotropic emission. This discussion peaked when GRB 990123 was detected and its redshift measured (see the archive of the GCN circulars; appendix). Direct observational support for lensing has never been found in GRB data (cf. Marani et al. 1999) but evidence for beaming seems to be present. Beaming reduces the energy requirement by a factor of order 10–100, depending on the assumed or calculated solid angle of emission, but it increases by the same factor the required GRB event rate.

It was recently predicted that beaming of the relativistic outflow should lead to a break in the afterglow light curve (Mészáros & Rees 1999b; Panaitescu, Mészáros, & Rees 1998; Piran 1999b; Rhoads 1997, 1999; Sari, Piran, & Halpern 1999) and to a non-zero and time-dependent polarization in the optical/near-infrared (Ghisellini & Lazzati 1999; Gruzinov 1999; Sari 1999). This is expected to occur when the decreasing bulk Lorentz-factor of the radiating shock front which runs into the ambient interstellar medium of the burster allows the observer to see the edge of the jet (Piran [1999b] notes that 'jet' is not the appropriate description of the phenomenon, since this is a transient collimated outflow). The smaller the opening angle of the jet, the earlier the observer should see a break, a steepening in the afterglow light curve. Within this theoretical context it would be interesting to learn if a time-delayed signal from the counterjet is expected to be seen too.

Observational evidence for beaming was first found in the optical afterglow of GRB 990123, where the light curve steepened two days after the burst (Castro-Tirado et al. 1999; Kulkarni et al. 1999). The measured steepening is in agreement with the picture that at this time the observer began to see the edge of a jet. Recently, a steepening in the light curve has also been observed for another burst, GRB 990510 (Beuermann et al. 1999; Harrison et al. 1999; Stanek et al. 1999). In both cases a beaming factor in the order of $200 \ldots 300$ has been deduced from the observations (Harrison et al. 1999; Mészáros 1999b; Sari, Piran, & Halpern 1999). This seems to bring very energetic bursts to the energy output of less energetic ones (Table 1), for which no observational evidence for strong beaming has been found, like GRB 970228 and 970508 (Sari, Piran, & Halpern 1999). More afterglow observations are required, however, to check this hypothesis.

An exciting consequence of beaming is that there could exist GRBs which develop an X-ray, optical, or radio afterglow, but have no detected gamma-ray burst (for a discussion see, e. g., Mészáros, Rees, & Wijers 1998, 1999; Perna & Loeb 1998b; Rhoads 1997). Archived X-ray data have been searched for such events, but no strong evidence for them was found (Greiner et al. 1999a, b; Grindlay 1999). However, possible evidence for a relation of optical transients detected on photographic plates to underlying blue galaxies was reported by Hudec et al. (1996). Results of wide-field CCD surveys to search for this phenomenon have not yet been published.

There are numerous possible causes for a break in the light curve of an afterglow (for a discussion see, e. g., Kulkarni et al. 1999; Wei & Lu 1999). An independent observational test for beaming is therefore desirable. It could be provided by polarimetric observations. According to recent theoretical studies, optical afterglows could be linearly polarized up to the 10 % level if the radiation comes from a collimated outflow moving with relativistic velocity toward the observer and the observer is not directed exactly at the center of the jet (Ghisellini & Lazzati 1999; Gruzinov 1999; Sari 1999; see also Hughes, Aller, & Aller 1985). However, microlensing is also considered as a possible option for producing time-dependent linearly polarized afterglows (Loeb & Perna 1998a). If the degree of linear polarization of an afterglow can be as high as predicted, even if no beaming occurs (Gruzinov & Waxman 1999), this could allow observers to detect an afterglow in a GRB error box at high Galactic latitude without the need of second-epoch data. This holds particularly in the near-infrared bands (Klose, Stecklum, & Fischer 1999).

Linear polarization was first detected at the 2 % level in the afterglow of GRB 990510 about 1 . . . 2 days after the burst based on observations with the ESO Very Large Telescope (Covino et al. 1999; Wijers et al. 1999). Unfortunately, only three data points could be obtained, and within the measurement errors no time-dependency of the degree of linear polarization was found. However, such a time-dependence appears to be present in the afterglow of GRB 990712 (Rol et al. 1999).

5 What is the nature of the bursters?

Among the most exciting discoveries about the nature of the GRBs is the bimodality of their duration distribution (Kouveliotou et al. 1993; Mazets et al. 1981; McBreen et al. 1994). Recently, evidence for an intermediate class of bursts was also reported (Horváth 1998; Mukherjee et al. 1998). Short burst durations range between 0.01 to 2 seconds, long bursts last from about 2 to a few hundred seconds. Since *BeppoSAX* is only sensitive to long bursts, it is currently unknown whether short bursts do also produce detectable GRB afterglows. It is also unknown what the origin of this bimodality is although various studies have been performed to gain insights into this issue (cf. Balázs, Mészáros, & Horváth 1998; Balázs et al. 1999; Dezalay et al. 1996; Katz & Canel 1996; Mao, Narayan, & Piran 1994; Mészáros, Bagoly, & Vavrek 1999; Mitrofanov 1998).

One working hypothesis is that the bimodal duration distribution reflects different GRB engines. According to the most accepted picture of the bursters today, GRBs can be made either by merger events that include compact stars and/or stellar-mass black holes, or by the gravitational collapse of single stars (cf. Fryer & Woosley 1998; Fryer, Woosley, & Hartmann 1999; Fryer et al. 1999; in 't Zand 1998; Ruffert & Janka 1998, 1999; Woosley, MacFadyen, & Heger 1999; for a discussion see also, e. g., Mészáros 1999a; Rees 1999). In all cases it is believed that the relic of the explosion is a stellar-mass black hole. In other words, within this picture every detected GRB (excluding SGR bursts) represents either a black hole formation event in the universe, or at least a signal from a pre-existing stellar-mass black hole.

Although the central engine of a GRB is hidden from observation, both classes of burst models make certain predictions that can be tested by observations, mainly based on the ages of the objects involved (cf. Bloom, Sigurdsson, & Pols 1999; Fryer, Woosley, & Hartmann 1999). As noted by Paczyński (1998b), massive stars will be close to their birthplaces when they explode and hence they could be embedded in a dust-rich environment. Several pieces of evidence seem to favor this GRB model: *First,* within the context of the fireball models, multi-wavelength observations of afterglows can be used to determine the gas density of the "interstellar" medium surrounding the burster (cf. Vreeswijk et al. 1999; Wijers & Galama 1999). Model fits led to the conclusion that the density of the external medium into which the fireball of GRB 980329 expands (see section 3) is $\approx$1000 cm^{-3} (Lamb et al. 1999). In other words, this burst presumably occurred in an interstellar gas cloud in a remote galaxy. (In contrary cases, e. g. GRB 970508, an ambient gas density of about 1 cm^{-3} or less was deduced from the afterglow data [Waxman 1997; Wijers & Galama 1999].) *Second,* only about 50 % of all GRBs whose X-ray afterglows were detected have been discovered in optical bands. This could be due to extinction by dust in the GRB host galaxies. An example of an optically obscured burst is GRB 970828. The burst developed a bright X-ray afterglow detected by *RXTE* (Marshall et al. 1997; Remillard et al. 1997), *ASCA* (Murakami et al. 1997), and *ROSAT* (Greiner et al. 1997b), but it was not seen in the optical down to an R-band magnitude of 24 (Groot et al. 1998), although follow-up observations started only hours after the burst.[1] *Third,* the GRB hosts detected so far are actively star-forming galaxies (Fruchter et al. 1999a). Their star-formation rates range between about 1 to 10 $M_\odot$ yr^{-1} (cf. Bloom et al. 1998b,1999b; Djorgovski et al. 1998; Kulkarni et al. 1998a; Odewahn et al. 1998), although this is not unusual for galaxies at these redshifts. There is presently no evidence for GRBs occurring in elliptical galaxies.

[1] The only near-infrared follow-up observations of this event were reported by Klose, Eislöffel, & Stecklum (1997), but they were performed 13 days after the burst. A red object was detected by these authors in the 30″ *ASCA* X-ray error circle (Murakami et al. 1997) which was later found to be also located in the 10″ *ROSAT* HRI error circle (Greiner et al. 1997b). However, second epoch observations five months later showed this object again (Klose 1998, unpublished). So, it is not the GRB afterglow, despite it having an underlying faint galaxy (Pedersen 1997, private communication).

A number of future tests of the GRB environment have been proposed in the literature. For example, the gaseous component of the GRB environment could manifest itself by certain spectral features in the X-ray afterglow (cf. Böttcher et al. 1999; Lazzati, Campana, & Ghisellini 1999; Mészáros & Rees 1999a; Piro et al. 1999b) or in the optical afterglow (cf. Perna & Loeb 1998a), whereas a test of the dusty component could make use of the scattering properties of the dust grains in the soft X-ray band (Klose 1998).

6 Evidence for a GRB – Supernova association

The idea of a GRB-Supernova (SN) association was first considered by Colgate (1968, 1974; see also the review by Chupp 1976) but it was not supported by observations at that time. About 30 years later it turned out that a GRB-SN link does indeed exist.

GRB 980425 was detected by *BeppoSAX* and an anomalous SN (1998bw) was found in the 8 arcmin error circle of the X-ray afterglow (Galama et al. 1998; Kulkarni et al. 1998b). The SN spectrum indicated ejection speeds approaching 60 000 km s^{-1} (Kulkarni et al. 1998b). SN 1998bw is classified as a peculiar Type Ic supernova. Its host galaxy is at a redshift of 0.0085 (Tinney et al. 1998), corresponding to a distance of 38 Mpc ($H_0 = 65$ km s^{-1} Mpc^{-1}). The gravitational collapse of a massive stellar iron core that formed a black hole can explain the observations (Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999; Woosley, MacFadyen, & Heger 1999). The radio-to-X-ray light curves of this event is not in conflict with the fireball model (Iwamoto 1999; for the optical light curve see McKenzie & Schaefer 1999). Since GRB 980425 was so close to our Galaxy, but not exceptionally bright, one has to conclude that *BATSE* does only see the 'tip of the iceberg' of all GRBs occurring in the universe.

Although up to December 1999 no other direct GRB-SN association has been found, there is in fact increasing observational evidence that at least a subclass of all bursts is associated with SNe. The strongest evidence comes from the recent discovery that the light curves of GRB 970228, 980326, and possibly 990712, show a bump at late times which cannot be explained within the context of simple afterglow models, but can be fitted as a redshifted SN 1998bw light curve which adds to the flux of the GRB afterglow (Bloom et al. 1999a; Dar 1999; Galama et al. 1999; Hjorth et al. 1999; Reichart 1999). If that interpretation is correct, then GRB 970228, the first burst with a detected optical afterglow, represents one of the most distant SNe ever seen (z=0.695; Djorgovski et al. 1999). Moreover, if it turns out that SN light curves do appear in GRB afterglows, this could represent a new powerful method to measure the cosmological parameters. A check of this potential application might be an interesting long-term project for 8-m class optical telescopes.

It has recently been proposed that SN 1997cy (Germany et al. 1999) and SN 1999E (Kulkarni & Frail 1999; Thorsett & Hogg 1999), which seem to resemble SN 1998bw, could be related to the *BATSE* bursts 970514 and 980910a, respectively, which were not seen by *BeppoSAX* (for a discussion, see Wheeler 1999). It has also been suggested that there is observational evidence for a relativistic jet from SN 1987A (Cen 1999). Finally, the detection of a red-shifted iron K_α emission line in the X-ray afterglows of GRB 970508 (Piro et al. 1999a, b) and possibly GRB 970828 (Yoshida et al. 1999) has been reported, which could indicate an SN event before the corresponding GRB (Lazzati, Campana, & Ghisellini 1999; Vietri & Stella 1998). Naturally, because of these findings the question arises if all GRBs are physically related to SNe. Several authors have therefore compared the *BATSE* GRB catalog (Meegan et al. 1998) with SN catalogs (Bloom et al. 1998a; Hudec, Hudcova, & Hroch 1999; Kippen et al. 1998b; Klose 1999; Norris, Bonnell, & Watanabe 1999; Wang & Wheeler 1998). However, no convincing statistical evidence for an excess of any subclass of SNe in GRB error boxes has been found in that way. The reason for this is that *BATSE*-only error boxes are very large in radius and that the SN database is very inhomogeneous. Therefore, these studies cannot exclude the existence of a general association of GRBs to SNe. In any case, GRB research gives a strong impulse to SN research (Wheeler 1999; Woosley, MacFadyen, & Heger 1999). If GRBs do indeed reflect certain SN explosions, *BATSE* detects more SNe per year than all current SN search campaigns combined.

Based on these findings, is it possible that we have already seen a few SN-GRBs in our Galactic neighborhood but not recognized them as such? A search for potential GRB afterglows in the CBAT SN catalog has not been successful (Klose 1999), although such a study is confronted with the lack of detailed observational data about most known SNe. Another way to tackle the question under consideration is to look for bright, nearby galaxies in arcmin-sized IPN error boxes. A working hypothesis can be that a SN-GRB association was not recognized in these cases because these GRB error boxes could not be determined in a timely manner, i. e., any SN light curve was already below the detection threshold when these error boxes were imaged in the optical. A visual inspection of published optical images of IPN error boxes of the 1970's (cf. Schaefer et al. 1998; Vrba, Hartmann, & Jennings 1995) reveals one potential candidate for such a case, GRB 781104b.[2] The only 14 arcmin^2 large error box of this burst contains a relatively bright galaxy (B=15, Simbad data base). This galaxy, MCG 04–47–011, is at a redshift of $z = 0.0024$ (Simbad data base), corresponding to a distance of about 11 Mpc ($H_0 = 65$ km s^{-1} Mpc^{-1}). The latter estimate is uncertain however, because the redshift is so small. Similar to the duration of GRB 980425 (Galama et al. 1998a; Pian et al. 1999), the duration of GRB 781104b was about 30 seconds (Mazets et al. 1981; Teegarden & Cline 1980). Although no SN is known in MCG 04–47–011, another way to check whether GRB 781104b was a nearby SN burst could be to search in the radio band for its potential GRB remnant.

A number of authors has recently addressed the question of how the relics of GRB explosions might look and where they are in our local universe (e. g.,

[2]Schaefer (1999) made a similar suggestion at the 5th Huntsville Symposium on GRBs, Huntsville, AL, October 1999.

Hansen 1999). At a GRB rate in the order of 1 per $10^{6\pm1}$ yr per Milky-Way like galaxy, GRB remnants in the local universe could possibly be detectable. Woods & Loeb (1999) proposed to search for radio emission from GRB remnants in the Virgo cluster of galaxies (z=0.0038; Simbad data base). This would require surveying on the order of 1000 galaxies down to a flux level below 100 μJy. Efremov, Elmegreen, & Hodge (1998) as well as Loeb & Perna (1998b) brought attention to H I supershells (cf. Lee & Irwin 1997; Walter et al. 1998), whose energy content is comparable to the electromagnetic energy release of GRBs. Potential X-ray selected GRB remnant candidates in M101 have also been proposed (Wang 1999). First calculations of the emission spectrum of GRB remnants have been published and phenomenological differences to supernova remnants (SNRs) have been outlined (Perna, Raymond, & Loeb 1999). Since there are some similarities to SNRs, however, in the optical the search strategy for GRB remnant candidates could follow those for H II-regions/SNRs (cf. Elmegreen & Salzer 1999; Gordon et al. 1993; Matonick & Fesen 1997). The close-by, face-on spirals M33 and NGC 300 could be potential targets for such an investigation.

7 The future of GRB research

BeppoSAX currently detects about 10 X-ray afterglows of GRBs per year. The *HETE-2* satellite (Vanderspek et al. 1999), scheduled to be launched early 2000, will increase this rate by a factor of 3 to 5, and the *Swift* GRB mission (Gehrels 1999), scheduled to fly in 2003 ... 2005, will provide about 100 or more very small GRB error boxes per year. This, combined with the next generation high-energy satellites (*XMM, AXAF-Chandra, ASTRO-E, Integral*), will guarantee a large increase in our knowledge about GRBs in the coming decade (see also Hurley 1999b).

For optical telescopes there are three observing strategies: 1) *Imaging of GRB error boxes when the burster is still active in the gamma-ray band.* GRB 990123 has already demonstrated that this is feasible with current CCD cameras. Great progress will be achieved when automatic 1-m class telescopes will become available, like the Flagstaff 1.3-m (Vrba et al. 1999b) and the Super-Lotis 0.6-m (Park et al. 1999). Prism spectroscopy is another future option. 2) *Investigation of GRB afterglows.* In most cases this will require 'Target of Opportunity' observations scheduled within hours or days after a burst. 3) *Study of GRB host galaxies.* This can be performed even months after a burst. It requires the largest telescopes.

Some open questions for the coming decade are obvious: Are all GRBs related to SNe? What is the physical difference between the short and the long bursts? How many distinct populations of bursters are there? Do GRBs occur in elliptical galaxies? Do short bursts develop afterglows? Does any subclass of GRBs represent a cosmological standard candle? Can we measure GRB redshifts based on observations in the gamma-ray band alone? What are the most distant GRBs? Where are the GRB remnants in the local universe, in our Galaxy, and in M 31? Finally, do GRBs affect the evolution of life?

GRBs are the most energetic electromagnetic phenomena in the universe. Although for an individual GRB this holds only for a very small timespan, it can make GRBs a giant observational tool to investigate the high-z universe (cf. Lamb & Reichart 1999). This includes the cosmological parameters (cf. Holz, Miller, & Quashnock 1999; Horack et al. 1996; Marani et al. 1999), the cosmic radiation background (Mannheim, Hartmann, & Funk 1996), stellar evolution, the cosmic star formation rate (Hartmann & Band 1998; Jorgensen et al. 1995; Krumholz, Thorsett, & Harrison 1998; Mao & Mo 1998; Totani 1999; Wijers et al. 1998;), large-scale structure (Hartmann & Blumenthal 1989; Lamb & Quashnock 1993), etc. GRBs could also prove to be a useful tool to investigate the interstellar medium in our Galaxy (and in intergalactic space) through which they are observed. Thus, there are good reasons to believe that the future of GRB research is bright, in all bands of the electromagnetic spectrum.

Appendix: selected WWW-pages about GRBs

- GRB coordinated network GCN: `http://gcn.gsfc.nasa.gov/gcn/`
- GRB missions: Holger Pedersen's WWW-page at `http://www.astro.ku.dk/~holger/ddirGAMMA/dF/OFSAT.html`
- SGRs: Robert Duncan's WWW-page at the University of Texas Austin, `http://solomon.as.utexas.edu/~duncan/`
- IPN: Kevin Hurley's WWW-page at Berkeley, `http://ssl.berkeley.edu/ipn3/interpla.html`
- GRB bibliography: Kevin Hurley's WWW-page at Berkeley, `http://ssl.berkeley.edu/ipn3/bibliogr.html`
- reports about GRB follow-up observations: Jochen Greiner's WWW-page at the AIP, `http://www.aip.de/~jcg/grbgen.html`
- *BATSE*: `http://gammaray.msfc.nasa.gov/batse/`
- *BeppoSAX*: `http://www.sdc.asi.it/`
- *HETE-2* satellite: `http://space.mit.edu/HETE/`
- *Swift* mission: `http://swift.gsfc.nasa.gov/`

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