A Massive Star Odyssey, from Main Sequence to Supernova
Proceedings IAU Symposium No. 212, © *2003 IAU*
K.A. van der Hucht, A. Herrero & C. Esteban, eds.

Gamma-ray bursts: the most powerful cosmic explosions

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Abstract. With the detection of gamma-ray burst (GRB) afterglows, the cosmological origin of GRBs has been firmly established. Recent observations suggest that (long-duration) GRBs are due to the collapse of a massive star forming a black hole. Besides theoretical arguments, observational evidence supporting this hypothesis comes from the coincidence of several GRBs with a supernova. Also, all accurately located GRBs are contained in the optical (restframe UV) extent of distant, blue galaxies. Some of these host galaxies show relatively high star-formation rates, which is expected when massive stars and GRBs are physically linked. Alternatively, GRBs can be produced by the merging of a binary neutron star system, such as the Hulse-Taylor binary pulsar. Very likely GRBs trace the massive-star populations in distant galaxies. With their enormous brightness, GRBs are powerful probes of the early universe, providing information on the properties of their host galaxies, the cosmic star-formation history, and potentially the first generations of massive stars.

1. Introduction

Gamma-ray bursts (GRBs) are brief flashes of cosmic γ-rays, first detected in 1967 by the US military *Vela* satellites that were launched to verify the Nuclear Test Ban Treaty (Klebesadel *et al.* 1973). GRBs have a duration ranging from several milliseconds to tens of minutes, and in most cases an observed peak energy around 100 keV. The γ-ray lightcurves are extremely diverse, some very smooth, others with numerous spikes. Data obtained with the *GRO*-BATSE experiment onboard the *Compton Gamma-Ray Observatory* showed that there are two distinct classes of GRBs: a class with a short duration (less than 2 seconds) and relatively hard spectra, and a class of long-duration bursts with softer spectra (Kouveliotou *et al.* 1993, Figure 1).

Lacking a distance scale, the physical nature of GRBs remained a mystery for thirty years. Their cosmological origin was suggested by the isotropic sky distribution (Figure 1); also, the number of weak bursts is less than expected from a source sample that is homogeneously distributed in a Euclidean space (Meegan *et al.* 1992; Paciesas *et al.* 1999). However, the definite proof of their distant, extragalactic nature came from the discovery of rapidly fading GRB *afterglows* at X-ray, optical, and radio wavelengths in 1997, thanks to the Italian-Dutch *BeppoSAX* satellite (Costa *et al.* 1997; van Paradijs *et al.* 1997; Metzger *et al.* 1997). With this satellite, the position of a GRB could be determined with arcminute precision, just a few hours after the burst. Arcminute-sized error boxes match the typical field size of modern (optical) detectors, thus enabling

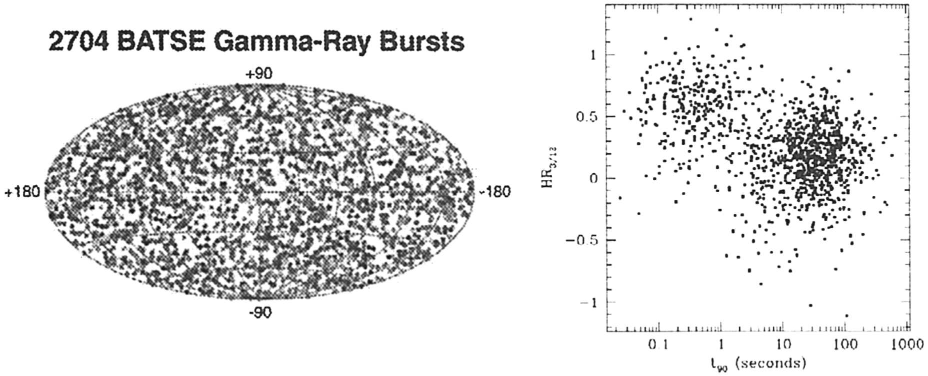

Figure 1. *Left:* The isotropic sky distribution of bursts detected by the BATSE experiment on board the *Compton Gamma-Ray Observatory. Right:* Gamma-ray spectral hardness *vs.* burst duration. This plot clearly suggests that GRBs are divided into two classes: short and hard, long and soft (4th BATSE catalogue, Paciesas *et al.* 1999).

the detection of GRB afterglows. These fade very quickly, on a timescale of only a few days (the typical decay goes as $t^{-\alpha}$, with $\alpha \sim 1 - 2$). For a review on GRBs and the properties of their afterglows see, *e.g.*, Fishman & Meegan (1995); van Paradijs *et al.* (2000).

So far (July 2002), 39 X-ray afterglows have been detected, 32 optical afterglows, and 20 radio afterglows[1]. A better impression of the 'success rate' is obtained by considering the 45 most accurately located bursts ($< 5'$ error circle) only: for a fraction of respectively 58, 38, and 24 % an X-ray, optical, and/or radio afterglow has been detected. Thus, often no GRB afterglow is found. Adverse observing conditions can explain many of these non-detections. In some cases, however, another explanation is needed. For example, the extinction by gas and dust in the circumburst environment might hinder the detection of an afterglow at rest-frame UV and optical wavelengths, or the afterglow may be intrinsically very faint or even absent. The nature of these *dark* bursts remains to be resolved.

For 24 GRBs the distance has been determined. The GRB spectrum itself is featureless (consistent with optically thin synchrotron emission), but absorption and/or emission lines formed in the GRB host galaxy, or the position of the Lyman break (912 Å), provide the redshift (Figure 2). The majority of redshifts is in the range between 0.5 and 1.5. The current record holder is GRB 000131 with $z = 4.5$, corresponding to a 'distance' (look-back time) of 13 billion lightyear (Andersen *et al.* 2000).

That GRBs are potential probes of the very distant universe was demonstrated by That GRBs are potential probes of the very distant universe was demonstrated by the impressive burst detected in January 1999: GRB 990123 (Figure 3). Within the first minutes after the burst, its optical afterglow reached

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[1] see Jochen Greiner's webpages at `http://www.aip.de/People/Greiner/grbgen.html`

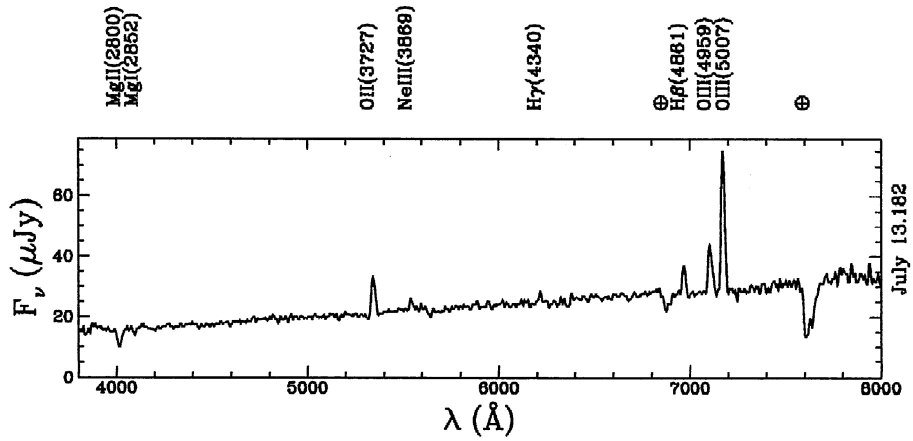

Figure 2. Spectrum obtained with the ESO-VLT of the afterglow of GRB 990712, 12 hours after the burst. Interstellar absorption lines of Mg I and Mg II are detected, as well as several emission lines ($z = 0.43$) from the underlying, bright ($V \simeq 22$) host galaxy (Vreeswijk *et al.* 2001).

visual magnitude $V = 9$ (Akerlof *et al.* 1999), *i.e.*, observable with a pair of binoculars. Briefly, it was one million times brighter than a supernova. This particular burst, at $z = 1.6$, would have been detectable (at its maximum, in the K-band) with a 10m-class telescope up to a redshift of about 15. With the *Swift* satellite (launch in 2003), which will provide accurate burst positions within a few minutes, many of such bright early afterglows become detectable.

2. The physics of Gamma-Ray Bursts — evidence for collimation

There are strong indications that GRBs are caused by highly relativistic, collimated outflows. Assuming isotropic emission, the measured distances imply peak luminosities of $10^{52}\,\mathrm{erg\,s^{-1}}$. Thus the peak luminosity of each event corresponds to about 1 % of the luminosity of the visible universe! The resulting energy budget is about 10^{53} erg, comparable to the total amount of energy released during a stellar collapse (supernova). If GRBs emit γ-rays in all directions, the measured rate (two per day) corresponds to about one GRB per million year per galaxy.

The shortest timescale of the observed variations δt, about a millisecond in GRB lightcurves, and the speed of light c constrain the maximum size of the source: about 300 km. In such a compact space, the γ-ray photon density must be enormous (where $L_\gamma > 10^{49}$ ergs) and implies that the plasma is extremely optically thick to pair creation. However, the observed non-thermal spectrum indicates optically thin synchrotron emission, up to energies $\gg$ MeV. This contradiction is known as the *compactness problem*. Cavallo & Rees (1978) suggested that this problem can be solved if one introduces bulk relativistic motion. Then the true variation timescale dt at the source is $2\Gamma^2$ larger than δt (Rees 1964), where $\Gamma = 1/\sqrt{1-(v/c)^2}$ is the Lorentz factor. With $\Gamma = 100$, dt becomes 20 s, corresponding to a source size of 6×10^7 km. The high Γ factor also strongly reduces the efficiency of pair formation, due to the relativistic beam-

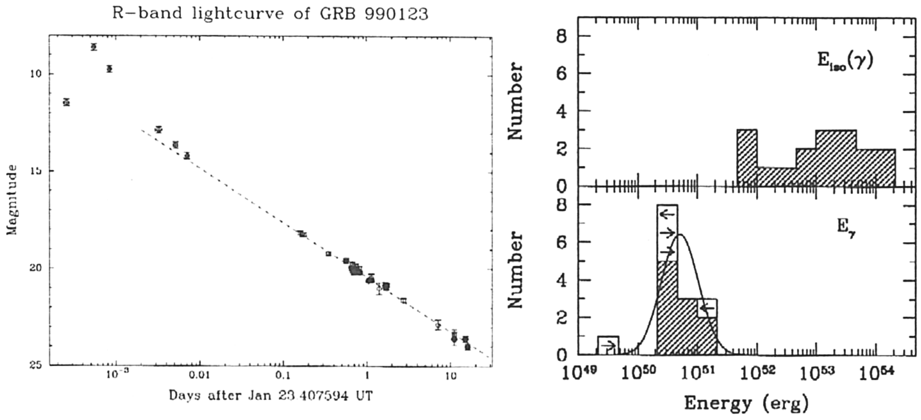

Figure 3. *Left:* R-band lightcurve of the afterglow of GRB 990123. The first six datapoints were obtained with the robotic ROTSE telescope, just a few minutes after the burst (Galama *et al.* 1999). *Right:* Distribution of the apparent isotropic energy of GRBs with known redshifts (top panel) versus the geometry-corrected energy for those GRBs for which the jet opening angle could be constrained from observations (Frail *et al.* 2001).

ing of the radiation in the direction of motion (aberration). These and other arguments lead to the *relativistic fireball* model proposed to explain the GRB phenomenon (Rees & Mészáros 1992, for a review see Piran 1999).

There is mounting evidence that γ-ray bursts are collimated into jets, with opening angles of a few degrees only. This evidence comes from the interpretation of the occurrence of a break in the slope of the afterglow lightcurves, and from the detection of polarization (Covino *et al.* 1999; Rol *et al.* 2000). Also, the total isotropic energy inferred for GRB 990123 is uncomfortably high (to be explained by a stellar-collapse model), but would be reduced by a factor of 500 if the energy were emitted into a cone with an opening angle of 5°.

Frail *et al.* (2001) determine the jet opening angle of several GRB afterglows and show that the spread in the output energy distribution of their sample becomes much narrower when taking the collimation into account, with a mean energy output of 2×10^{51} erg (Figure 3). They suggest that this may be the standard energy reservoir for all GRBs. Though speculative, the implications of this finding are great if these intrinsically bright GRBs could be used as standard candles at high redshifts, *e.g.*, to measure the expansion rate of the universe. Another consequence of the collimation is that the GRB rate also increases with a factor of 500, and that the vast majority of bursts escapes detection.

3. The origin of GRBs: possible progenitors

From a variety of arguments, such as their total energy and the evidence for collimation, the general expectation is that a system consisting of a black hole and a surrounding accretion torus is powering the GRB. Such a setting, just before the GRB goes off, can be reached in several ways. One way is the merging of a binary neutron star system, like the Hulse-Taylor binary pulsar, or a neutron star

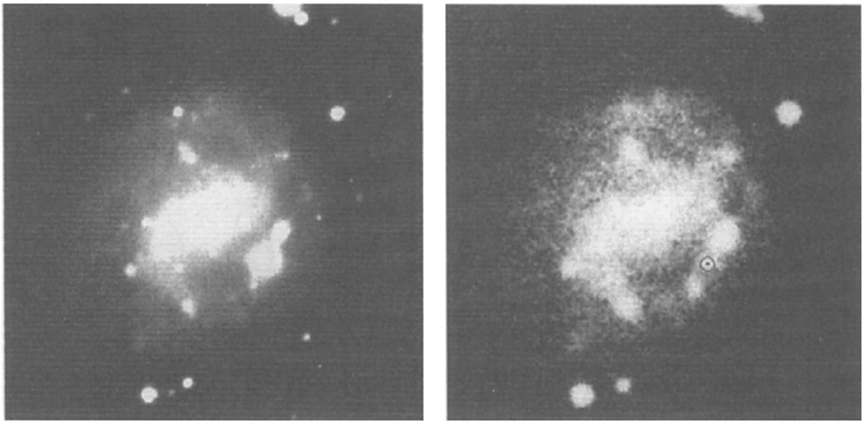

Figure 4. The host galaxy of SN 1998bw before (*right*) and after (*left*) the supernova explosion. *Left:* image taken with the ESO-NTT in early May 1998, showing the new bright point source. *Right:* the position of the supernova is shown in this COSMOS scan of a 1978 DSS Schmidt plate (Vreeswijk 2002).

and a black hole (*e.g.*, Lattimer & Schramm 1974; Eichler *et al.* 1989). Another popular model involves the core collapse of a rapidly rotating massive star, the 'collapsar' model (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999).

There are several indications that the observed population of GRB afterglows, *i.e.*, the long-duration bursts, is best explained by the latter model. The first indication comes from the models themselves. The collapsar model naturally produces bursts that have a duration longer than a few seconds, but cannot make short bursts. On the other hand, the merger model can produce short bursts, but has problems keeping the engine on for longer than a couple of seconds. The clear distinction between short- and long-duration bursts suggests that both progenitor models may be at work in nature.

3.1. The supernova connection

Another indication that long-duration GRBs are related to the core collapse of a massive star is that some GRBs seem to be associated with a supernova (SN). The first evidence for a supernova connection came from GRB 980425/SN 1998bw (Galama *et al.* 1998, Figure 4). This supernova, approximately coincident in time and position with GRB 980425, was of the rare Type Ic, and at radio wavelengths the brightest supernova ever detected. Interpretation of the lightcurve indicated that during this supernova a black hole was formed (Iwamoto *et al.* 1998). However, the amount of prompt γ-ray emission was very modest, which makes GRB 980425, the closest GRB at a redshift of $z = 0.0085$, a peculiar event.

In the mean time, evidence has been found that several GRB afterglow lightcurves show a so-called supernova bump, *i.e.*, a bump in the lightcurve at a time interval compatible with the rise time of a SN, assuming it has gone off simultaneously with the GRB. The bump would thus represent the SN maximum light (Bloom *et al.* 1999, 2002; Greiner *et al.* 2002). The signature of supernova ejecta is also seen in spectra of some X-ray afterglows, obtained with the new generation X-ray observatories *Chandra* and *XMM-Newton* (Piro *et al.* 1999; Reeves et al. 2002)

3.2. GRB host galaxies

For practically all GRB afterglows with an accurate location, a host galaxy has been detected. In nearly all cases the burst is located within the optical (rest-frame UV) extent of the galaxy. This, in combination with the blue colours of the galaxies, suggests that GRBs originate in galaxies with a relatively high star-formation rate. The collapsar model predicts that GRBs will occur in regions where active star formation is taking place. Neutron-star binaries do not necessarily reside in star-forming regions. Due to the kick velocities received during the two supernova explosions forming the neutron stars, such binaries are high-velocity objects. As the merging process of the binary, driven by the emission of gravitational radiation, can take up to a billion years, the binary may have traveled several kpc before producing a GRB.

For several host galaxies the star-formation rate has been determined. The emission lines in the VLT spectrum of the host galaxy of GRB 990712 (Figure 2) are produced by H II regions in that galaxy. The strengths of these lines indicate an (extinction-corrected) star-formation rate of about 35 $\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ (Vreeswijk *et al.* 2001). For some host galaxies even higher rates of star-formation are claimed, up to 1000 $\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ (*e.g.*, Berger *et al.* 2001). These observations show that at least some of the GRB host galaxies belong to the class of *starburst* galaxies.

Thus, the observations of GRB host galaxies support the collapsar model. Since these galaxies, due to their distance, are often very faint, the bright GRB afterglow provides a unique opportunity to study the gas and dust content of the host galaxy. The metallicity and star-formation rate of these relatively young galaxies can be measured. If the collapsar model is right, the GRB rate is a direct measure of the formation rate of massive stars in the early universe, an important quantity for the study of the star-formation rate as a function of redshift.

4. Discussion

Much progress has been made in understanding the GRB phenomenon. The bottom line of this contribution is that massive stars and GRBs are very likely physically related. However, many fundamental questions remain to be addressed. What is the origin and nature of the short-duration bursts? Do they produce afterglows, like the long bursts? Are all GRBs associated with a supernova, and if so, why do we rarely observe it? Do GRBs only occur in galaxies where massive stars are being formed?

GRB 980425/SN 1998bw suggests that γ-rays are produced during the core collapse of a massive star forming a black hole. Although this was quite a peculiar event, one might speculate that in 'ordinary' Type II supernovae a neutron star is formed, while GRBs produce black holes. The overabundance of α elements in the atmosphere of the companion of the black hole in Nova Sco 1994 indicates that this black hole might have formed in a similar event (Israelian *et al.* 1999).

That neutron stars and black holes form through different channels is suggested by their respective mass distributions (Charles 1999; Cherepashchuk, these Proceedings): neutron stars cluster around a mass of $1.4\,M_\odot$, while black holes have significantly higher masses (around $10\,M_\odot$). The maximum neutron-star mass depends on the equation of state (EOS) valid in the neutron-star interior, but the EOS of matter at supra-nuclear densities is not well known. Based on theoretical arguments (Srinivasan 2002), the maximum neutron-star mass is somewhere in the range $1.5 - 6\,M_\odot$; probably, it is between 2 and $3\,M_\odot$. The highest observed neutron-star mass is that of the X-ray pulsar Vela X-1: $1.86 \pm 0.16\,M_\odot$ (Barziv *et al.* 2001). In principle, black holes can have any mass, but low-mass black holes are not observed.

The canonical neutron star mass of $1.4\,M_\odot$ corresponds to the Chandrasekhar mass of the degenerate Fe-core at the moment of core collapse. When additional mass is added to the proto neutron star (fall-back), it might exceed its maximum allowed mass and will collapse into a black hole and produce a GRB. Future observations should show whether this scenario is correct. A challenging future lies ahead.

Acknowledgments. I would like to thank the organizers of this symposium for their invitation. Ed van den Heuvel, Paul Vreeswijk, Evert Rol, Isabel Salamanca, and our colleagues from the GRACE consortium are acknowledged for their contributions to this paper. LK is supported by a fellowship of the Royal Academy of Arts and Sciences in the Netherlands.

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Discussion

KELSEY JOHNSON: I don't really doubt that GRBs are associated with galaxies, but I am curious about the statistics. We all know from the Hubble Deep Field that when one observes deep enough, there are galaxies practically everywhere — and most of these are 'star forming'. What is the statistical likelyhood of a galaxy (down to our detection limit) being within 2″ of a GRB?

LEX KAPER: It is not only the coincidence with a galaxy that demonstrates the association of GRBs with their host galaxies. The host galaxy is also detected by the absorption and emission lines in the afterglow spectrum.

NORBERT LANGER: What is the currently estimated GRB rate compared to the supernova rate?

LEX KAPER: It is not straightforward to compare the GRB rate to the rate of supernovae, as they probe different volumes of the universe. If GRBs emit their radiation isotropically, the rate of one per million year per galaxy is about 10 000 times less than the supernova rate. In case of beamed emission, the GRB rate increases by a factor 100 or more.

ANTHONY MOFFAT: The energies emitted by GRBs are enormous and impressive. But are they still not 'only' a percent of the total energy from the gravitational core collapse, the rest coming out in neutrinos?

LEX KAPER: It is not so much the difference in total energy, but more the much shorter timescale on which this energy is emitted that makes GRBs so outstanding. If GRBs are collimated into jets, the total energy emitted in a GRB is about 2×10^{51} erg (Frail *et al.* 2001), *i.e.*, much less than the about 10^{53} erg typically released in a core collapse. If a GRB is precursed by the formation of a neutron star, it might well be that most of the gravitational energy escapes in the form of neutrinos.

Peter Hoeflich: You showed a bifurcation in the remnant masses of neutron stars and black holes. However, all masses are based on binary systems, which disrupt if during the supernova more than half of the total system mass is lost. Does this not mean that the lower limit for black-hole masses indicates that when you form a black hole, more mass is lost from the system? In other words, it may be an indicator for the mass of the exploding core rather than giving a limit for black-hole masses.

Lex Kaper: You might be very well right. As an aside, evolutionary scenarios explaining the formation of black holes with a low-mass companion (*e.g.*, the soft X-ray transients), and avoiding the disruption of the system, are still not very convincing.

Relaxation time after the bursts: Lex Kaper, Jesús Maíz-Apellániz, Grażyna Stasińska, Claus Leitherer, *et al.*