Cosmic γ-ray bursts are one of the great frontiers of astrophysics today. They are a playground of relativists and observers alike. They may teach us about the death of stars and the birth of black holes, the physics in extreme conditions, and help us probe star formation in the distant and obscured universe. In this review we summarise some of the remarkable progress in this field over the past few years. While the nature of the GRB progenitors is still unsettled, it now appears likely that at least some bursts originate in explosions of very massive stars, or at least occur in or near the regions of massive star formation. The physics of the burst afterglows is reasonably well understood, and has been tested and confirmed very well by the observations. Bursts are found to be beamed, but with a broad range of jet opening angles; the mean γ-ray energies after the beaming corrections are $\sim 10^{51}$ erg. Bursts are associated with faint ($\langle R \rangle \sim 25$ mag) galaxies at cosmological redshifts, with $\langle z \rangle \sim 1$. The host galaxies span a range of luminosities and morphologies, but appear to be broadly typical for the normal, actively star-forming galaxy populations at comparable redshifts and magnitudes. Some of the challenges for the future include: the nature of the short bursts and possibly other types of bursts and transients; use of GRBs to probe the obscured star formation in the universe, and possibly as probes of the very early universe; and their detection as sources of high-energy particles and gravitational waves.

1 Introduction

Ever since their discovery, the nature of the cosmic γ-ray bursts (GRBs) has been one of the great puzzles of science. While a complete physical explanation of this remarkable phenomenon is still not in hand, there has been a great deal of progress in this field over the last few years. Studies of GRBs are now one of the most active areas of research in astronomy, with a publication rate of $\sim 500$ per year and the total number of GRB-related publications now exceeding 5000. GRBs represent a great laboratory in the sky for relativistic astrophysics, with Lorentz factors reaching $\Gamma \sim 10^2 - 10^3$.

The pre-1997 state of affairs was summarised well in many reviews. The distribution of bursts on the sky found by BATSE/CGRO is highly isotropic.
which provided the first solid hint about their cosmological origins. After many years of speculation based on a limited observational evidence, handicapped mainly by the lack of precise and rapid positional identifications, the field was revolutionized by the BeppoSAX satellite\textsuperscript{23}. The key was the enabling discovery of long-lived and precisely located GRB afterglows at longer wavelengths, in the X-rays\textsuperscript{29}, optical\textsuperscript{166}, and radio\textsuperscript{44}, and the resulting direct determination of the cosmological distance scale to the bursts\textsuperscript{115}.

Allowing for the observational selection and coverage, GRBs are detectable at a mean rate of \(\sim 10^3\) per year down to the limiting fluxes of \(\sim 10^{-7}\) erg cm\(^{-2}\) s\(^{-1}\), or fluences of \(\sim 10^{-6}\) erg cm\(^{-2}\). While there must be many fainter bursts, the flattening of the observed flux distribution suggests that their numbers are at most comparable\textsuperscript{c}. The cumulative distribution of fluxes indicates a radially non-uniform (i.e., non-Euclidean or evolving) spatial distribution\textsuperscript{90}.

Since we now know that the observed bursts are (at least in principle) detectable out to proper distances in excess of \(10^{28}\) cm, or redshifts \(z \sim 10\), i.e., reaching the earliest phases of galaxy formation, in rough numbers the bursts occur at a rate of a few per universe per day, or once per few million years per average galaxy, or \(\sim 10^{-91}\) cm\(^{-3}\) s\(^{-1}\) ... These numbers do not include any beaming corrections (see below), which would increase the actual rates (at the expense of the implied energetics per burst) by a factor of a few hundred. Comparison of the observed GRB rate with those of other astrophysical phenomena, e.g., supernovæ, which occur on average once per century per typical galaxy\textsuperscript{d}, or the expected rate of neutron star mergers, which may occur at a rate of \(\sim 10^{-6}\) per year per typical galaxy, etc., can be used to constrain the models of their origin.

While the bursts are the brightest sources on the \(\gamma\)-ray sky when they do occur (and could, at least briefly, achieve luminosities comparable to all of the rest of the universe, \(\sim 10^{54}\) erg s\(^{-1}\)), they do not last very long, and are not known to be a major contributor to the overall energy production in the universe: the observed local energy density due to GRBs (independent of the beaming corrections) is a few \(\times 10^{-21}\) erg cm\(^{-3}\), i.e., some 4 orders of magnitude less than the cosmic X-ray background, 6 orders of magnitude less than that of all the starlight ever emitted, and 6 orders of magnitude less than the local energy density of the CMBR.

Their high-energy spectra are featureless continua, typically a broken power-law, suggesting a non-thermal (e.g., synchrotron) origin, with the peak energies near \(\sim 0.1 - 1\) MeV. An interesting and as yet unsettled question is whether other, similar populations of transients may exist at lower energies (e.g., X-ray bursts). It is also not yet known what are the maximum energies of particles generated in bursts, but the TeV range certainly seems viable.

An important hint about their possible origins is provided by the timescales of the bursts (\(\sim 0.1 - 100\) s), and the intrinsic variability (\(\sim 10^{-3}\) s), suggesting a spatial scale comparable to that of stars and dense stellar remnants, i.e., black

\textsuperscript{c} We note that the nature of GRB detection data (time series) precludes detection of low amplitude, long duration bursts, if they do exist; this is a time-domain analogue of the familiar image-domain low surface brightness bias.

\textsuperscript{d} Note, however, that the SN rate from very massive progenitors must be much lower, and can be comparable to the GRB rate.
holes (BH) or neutron stars (NS). This is probably the strongest argument in favor of stellar origin models for GRBs.

Since distances to the bursts have now been measured for many cases (see below), the implied isotropic γ-ray energies span the range $E_{\gamma,iso} \sim 10^{51} - 10^{54}$ erg $\approx 10^{-3} - 1 M_\odot c^2$. At least at the lower end of the range, this is comparable to the energy release in supernovae, which again suggests (but does not compel) a physical connection with the death of massive stars, or at least the birth of stellar mass black holes. The implied mean energy density at the peak can reach that at the time of $\sim 10^{-3}$ s after the big bang, i.e., at the onset of the cosmic baryogenesis.

There are several distinct physical stages of a GRB, each with its own range of scales. The ratio of the empirically based understanding and knowledge to speculation $\to 0$ as $(t - t_{burst}) \to 0$.

1. **The Prime Mover:** $t \sim 10^{-3}$ s (?). While plausible models do exist, this is fundamentally unknown. It is possible that future observations of gravitational waves or high-energy cosmic rays and neutrinos would bring some direct insight into the central engine of GRBs.

2. **The Burst Itself:** $t \sim 10^{-1} - 10^2$ s. This is mainly probed by the burst γ-ray light curves and spectra. Some physical understanding of this phase (internal shocks, etc.) exists.

3. **The Afterglow:** $t \sim 10$ s $\to \infty$. This is the best probed and best understood phase, with detailed observations over a broad range of wavelengths and time scales. In many ways, the physics and the behavior of afterglows are independent of the actual physical mechanism behind the bursts: given a certain (large!) amount of energy deposited in a relatively small volume, a relativistic fireball is inevitable, with subsequent expansion, shocks, etc.

In addition, observations of GRB host galaxies (or their environments in general), possible association with coincident supernovae, etc., can provide indirect clues about the nature of progenitors.

Well over a 100 distinct theoretical models for GRBs have been proposed, with many more sub-variants. The establishment of the cosmological distance scale to the GRBs (and therefore the energetics scale) has focused the debate considerably. While many interesting, novel (and possibly even correct) ideas continue to be generated (see, e.g., [10]), the prevailing view nowadays is focused on two types of models: explosions of very massive ($> 30 M_\odot$?) stars (also known as “collapsar” or “hypernova” type models) and mergers of compact stellar remnants (NS, BH, or even white dwarfs; but with at least one mergee being a NS or a BH).

In both cases, the end product is a stellar mass scale BH, surrounded by a rapidly rotating torus, whose orbital kinetic energy can be extracted via MHD processes and used to power the GRB. If the BH itself is threaded by the magnetic field (which has to be amplified to $\sim 10^{15}$ G!), its spin energy can be extracted via the Blandford-Znajek mechanism. Both mechanisms can extract $\sim 10^{54}$ erg, and both provide a natural collimation (spin) axis, for energy release via Poynting jets. Additional energy ($\sim 10^{51}$ erg) can be provided by thermal neutrino cooling, $\nu \bar{\nu} \to e^\pm, \gamma$. The gravitational wave component is strongly model-dependent and
is highly uncertain at this point; hopefully it will be settled observationally with LIGO and LISA.

Regardless of the exact model for GRBs, it appears highly likely that black holes are involved. While quasars (and AGN in general) represent probes of the BH physics in the $M_\bullet \sim 10^{6-9} M_\odot$ range, GRBs can be a powerful observational probe of the BH physics on the stellar mass scales, $M_\bullet \sim 10^{9.5-1.5} M_\odot$, and on correspondingly shorter time scales.

As we will see below, the evidence for the collapsar/hypernova type of models is becoming increasingly compelling, at least for the well-studied long bursts, but the case is still not closed. It is entirely possible that more than one physical model is at work, by analogy with novae and supernovae, where very different physical mechanisms lead to a roughly comparable observed phenomenology. On that agnostic note, we will not summarise or even reference any particular models (thus offending all of the relevant authors equally), and simply direct the interested reader to recent reviews.

Much of the pre-1997 work was based on the CGRO mission and the IPN network. Today, several space missions and a large number of ground-based telescopes and teams are studying bursts and their afterglows. Another critically important technological development in studies of GRBs is the rapid dissemination of time-critical observations via email and WWW, mainly through the GCN Circulars (S. Barthelmy, NASA GSFC). An excellent on-line archive of GRB observations is maintained by J. Greiner (Astr. Inst. Potsdam).

In this review we summarise some of the recent developments, mainly from an observational point of view, as of the early/mid-2001. We apologize for any undue omissions and incompleteness. Other recent reviews provide additional information.

2 GRB Afterglows: Physics and Observations

The extreme characteristics of GRBs lead to a paradox (the “compactness problem”). Assuming that $\sim 10^{52}$ erg worth of photons, distributed according to the GRB spectrum, is released in a small volume of linear dimensions $R \leq c \Delta t$, then the optical depth for pair creation is $\tau \sim 10^{15}$. If so, all the photons would have interacted to create pairs and thermalize. However, the observed spectrum of GRBs is highly non-thermal! The only known solution to this problem is relativistic motion. If the emission site is moving relativistically, with a Lorentz factor $\Gamma$, toward the observer, then the optical depth is reduced, compared to the stationary estimate, due to two effects: First, the size of the source can be bigger by a factor of $\Gamma^2$. This
will still produce variability over a short time scale given by \( \Delta t = R/\Gamma^2 c \) since not all the source is seen as the radiation for a relativistically moving object is beamed. Second, the photons in the local frame are softer by a factor of \( \Gamma \), and therefore only a small fraction of them, at the high energy tail, have enough energy to create pairs. The combination of these two effects reduces the optical depth by a factor of \( \sim \Gamma^{-6.5} \). Therefore, the optical depth is reduced below unity if \( \Gamma > 100 \) or so.

This leads to a generic scenario for GRBs. First, a compact source ("the prime mover") releases \( \sim 10^{52} \) erg in a small volume of space (\( \sim 10^7 \) cm?) and on a short time scale (\( \sim 0.1 - 100 \) s). This large concentration of energy (a relativistic fireball) expands due to its own pressure; particle pairs are produced and coupled to the radiation field. If the rest mass present within the burst region is not too large, \( \lesssim 10^{-5} M_\odot \), this will result in relativistic expansion with \( \Gamma > 100 \) (the requirement for such a peculiar, small baryonic contamination presents an interesting fine-tuning problem by itself). Finally, at a large enough radius, the kinetic energy of the expanding material is converted to internal energy and radiated, mainly in \( \gamma \)-rays. At this stage the system is optically thin and high energy photons can escape.

In order to convert the kinetic energy into photons, two scenarios were proposed: external shocks\(^{110}\) and internal shocks\(^{118,140}\). In the external shocks scenario, the relativistic material is running into some (external) ambient medium, probably the interstellar medium or a wind that was emitted earlier by the progenitor. In the internal shocks scenario the inner engine is assumed to emit an irregular flow, that consists of many shells, that travel with a variety of Lorentz factors and therefore colliding into each other and thermalizing some of their kinetic energy. Observed variability in most GRBs provides a way of distinguishing between the two scenarios. External shocks require a complicated surrounding with a relatively simple source that explodes once, while internal shocks require a more complicated source that will explode many times to produce several shells. A variety of arguments\(^{41,147}\) favors the internal shock model.

We also note that in the currently favorite models for the central engine (with the production of a rapidly rotating BH and a torus), the orbital time scales (\( \sim 10^{-3} \) s) are several orders of magnitude shorter than the observed burst time scales, thus imposing an interesting stability problem.

While the detailed understanding of the physics of the bursts is still not complete, and the nature of the triggers is still largely hypothetical, we do have a reasonable physical understanding of the subsequent stages of the phenomenon, i.e., the burst afterglows. The afterglows were predicted well before they were observed\(^{124,108,11}\). The afterglow theory is relatively simple, and it has been confirmed (at least in a broad sense) spectacularly well by the observations. It deals with the emission on much longer timescales, and thus the poorly known details and complexities of the initial conditions are relatively unimportant, and the physical description of afterglows depends on a small number of parameters, such as the total energy and the density of the external medium.

After the internal shocks produced the GRB itself, the expanding shells interact with the surrounding medium and decelerate. The emission shifts into lower and lower frequencies. The observed afterglows usually show a power-law decay \( t^{-\alpha} \) in the optical and X-ray where a typical value is \( \alpha \approx 1.2 \). Some afterglows show a
steeper decline with $\alpha \approx -2$. In the radio wavelengths, the flux seems to rise on timescale of weeks and then decays with a similar power-law.

The basic model assumes that electrons are accelerated by the shock into a power-law distribution $N(\gamma_e) \sim \gamma_e^{-p}$ for $\gamma_e > \gamma_m$. The lower cutoff of this distribution is assumed to be a fixed fraction $\epsilon_B$ of the equipartition. It is also assumed that a considerable magnetic field is being built behind the shock, it is again characterized by a certain fraction $\epsilon_B$ of the equipartition. The relativistic electrons then emit synchrotron radiation which is the observed afterglow. The broad band spectrum of such emission was given by Sari, Piran & Narayan \cite{148} (see Figure 1).

At each instant, there are three characteristic frequencies:

(i) $\nu_{\text{m}}$ which is the synchrotron frequency of the minimal energy electrons, having a Lorentz factor $\gamma_m$.

(ii) The cooling time of an electron is inversely proportional to its Lorentz factor $\gamma_e$. Therefore, electrons with a Lorentz factor higher than a critical Lorentz factor $\gamma_c > \gamma_e$ can cool on the dynamical timescale of the system. This characteristic Lorentz factor corresponds to the “cooling frequency” $\nu_c$.

(iii) Below some critical frequency $\nu_c$, the flux is self absorbed and is given by the Rayleigh-Jeans portion of a black body spectrum.

The evolution of this spectrum as a function of time depends on the hydrodynamics. The simplest, which also describes the data well, is the adiabatic model with a constant density surrounding medium. The rest mass collected by the shock at radius $R$ is about $R^3 \rho$. On the average, the particles move with a Lorentz factor $\Gamma^2$ in the observer frame, and therefore the total energy is given by $E \sim \Gamma^2 R^3 \rho c^2$. Assuming that the radiated energy is negligible compared to the flow energy, we obtain that $\Gamma \sim R^{-3/2}$ or in terms of the observer time, $t = R/\Gamma^2 c$, we get $\Gamma \sim t^{-3/8}$. If the density drops as $R^{-2}$ (as is expected if the surrounding is a wind produced earlier by the progenitor of the burst) we get $\Gamma \sim t^{-1/4}$. These simple scaling laws lead to the spectrum evolution (see Figure 2).

One can then construct light curves at any given frequency. These will consist of power laws, changing from one power law to the other once the break frequencies sweep through the observed band. These power laws are in very good agreement with the observations.

Observations of GRB afterglows span a broad range of frequencies, roughly from $\sim 1 \text{ GHz}$ to $\sim 10^9 \text{ GHz}$, and time scales from hours (or even minutes) to a few years after the burst. Their broad-band, time-dependent modelling, as illustrated, e.g., in Figs. 3 and 4, can provide considerable insights into the physics and geometry of afterglows and even the nature of the progenitors.

Afterglows typically have energies $< 10^{51} \text{ erg}$, and power-law electron energy distributions with index $p \approx 2.3$. However, some afterglows appear to have harder electron energy distributions, with $p \approx 1.5$ and a high energy cutoff $E_{\text{cutoff}} \approx 10^{51} \text{ erg}$. It is currently difficult to distinguish between models in which the ejecta expand into a $\rho \sim r^{-2}$ wind-stratified ISM, and models in which the ejecta expand into a $\rho \sim \text{const.}$ ISM, although the latter appears to be preferred in some cases.\cite{24} Early-time measurements may help distinguish between these possibilities. There have
Figure 1: Theoretical spectra of synchrotron emission from a power-law distribution of electrons. (a) Fast cooling, which is expected at early times. The characteristic frequencies decrease with time as indicated; the scalings above the arrows correspond to an adiabatic evolution, and the scalings below, in square brackets, correspond to a fully radiative evolution. (b) Slow cooling, which is expected at late times. The evolution is always adiabatic. Electron energy power-law index $p \approx 2.2 - 2.4$ fits well the observed spectra. The temporal scalings correspond to the case of a spherical fireball shock expanding into a constant density medium. From [14].
Figure 2: Theoretical lightcurves corresponding to the afterglow models shown in Fig. 1, in the high frequency (a) and low frequency (b) regimes. The four segments that are separated by the critical times as labeled correspond to the spectral segments in Fig. 1. The observed flux varies with time as indicated; the scalings within square brackets are for radiative evolution, and the other scalings are for adiabatic evolution. From [148].
Figure 3: The $BVRIJHK_S$ light-curves of the afterglow of GRB 000926, from 8 hours to 80 days after the GRB, with model fits corresponding to an isotropic ISM and an $\rho \sim r^{-2}$ (i.e., simple stellar wind) medium. Also evident is a break in the light-curve at $t \sim 1.5$ days, interpreted as evidence for collimation of the ejecta. Fluxes from the underlying host galaxy and another contamination galaxy have been subtracted using late-time HST observations.

been suggestions that the particle density of the ISM can be very low in some cases, $\sim 10^{-3} - 10^{-4}$ cm$^{-3}$. While this may present difficulties for the collapsar-type models, it might be explained in terms of pre-existing superbubbles.

Broad-band modelling is complicated by several effects:

- Interstellar scintillation in the radio lightcurve
- Extinction in the optical-NIR (rest-frame UV) which has the primary effect of altering the observed optical spectral slope
- The possibility of inverse-Compton scattering, which can dominate the electron cooling and can also produce excess emission in the X-ray
- The presence of a host galaxy, which may obscure the afterglow evolution

However, each of these complications can also provide useful additional information. Interstellar scintillation can be used to super-resolve the afterglow. Extinction can be used to probe the environment of the GRB. Detection of inverse-Compton emission gives a better handle on the density of the medium. Detection of the host galaxy in the radio or sub-mm can give more complete estimates of the star-formation rate, while optical host studies can also give clues to the nature of the progenitors.
Radio observations in particular provided the first direct evidence for relativistic motions in GRBs, through the use of interstellar scintillation to measure the physical expansion rate of an afterglow. Another interesting phenomenon was the detection of a bright (9th magnitude), prompt optical emission simultaneous with GRB 990123. Theoretical explanation for such a flash is that there are initially two shocks in a GRB: a forward shock going into the surrounding medium, and a reverse shock going into the expanding shell. This model could neatly account for the observed optical properties of GRB 990123. It takes tens of seconds for the reverse shock to sweep through the ejecta and produce the bright flash. Later, the shocked hot matter expands adiabatically and the emission quickly shifts to lower frequencies and considerably weakens. Another new ingredient that was found in GRB 990123 is a radio flare. In most afterglows the radio peaks around few weeks and then decays slowly, but this burst had a fast rising flare, peaking around a day and decaying quickly. The optical flash and the radio flare are closely related. Similar radio flares were detected from a few other bursts as well.

3 Host Galaxies and Redshifts

Host galaxies of GRBs serve a dual purpose: First, in most cases redshifts are measured for the host galaxy, rather than the afterglow itself (sometimes both). This is mainly because most optical afterglows so far have been discovered too
late for an effective absorption-line spectroscopy, but also in some cases no optical transient (OT) is detected, but a combination of the X-ray (XT) and radio transient (RT) unambiguously pinpoints the host galaxy. Second, properties of the hosts and the location of OTs within them can provide valuable clues about the possible nature of the progenitors, e.g., their relation to the massive star formation, etc.

Table 1 summarizes the host galaxy magnitudes and redshifts known to us as of mid-June 2001. The median apparent magnitude is $R = 24.8$ mag, with tentative detections or upper limits reaching down to $R \approx 29$ mag. Down to $R \sim 25$ mag, the observed distribution is consistent with deep field galaxy counts, but fainter than that, selection effects may be playing a role. We note also that the observations

Figure 5: Image of the host galaxy of GRB 990123 at $z = 1.600$, obtained with the HST. The cross marks the position of the optical afterglow, from the ground-based measurement. The host is an irregular, possibly merging system.

Figure 6: The host galaxy system of GRB 980613 in $R$ (left), $I$ (middle) and $K$ bands (right), from images obtained at the Keck. The “×” marks the location of the OT. Note the complex morphology of the system, suggestive of mergers, and a variety of colors among the galaxy components.
in the visible probe the UV in the restframe, and are thus especially susceptible to extinction.

The redshift distribution of GRB hosts to date (Fig. 11) is about what is expected for an evolving, normal field galaxy population at these magnitude levels. There is an excellent qualitative correspondence between the observations and simple galaxy evolution models\(^7\). The majority of redshifts so far are from the spectroscopy of host galaxies, and some are based on the absorption-line systems seen in the spectra of the afterglows (which are otherwise featureless power-law continua). Reassuring overlap exists in some cases; invariably, the highest-\(z\) absorption system corresponds to that of the host galaxy, and has the strongest lines. A new method for obtaining redshifts may come from the X-ray spectroscopy of afterglows, using the Fe K line at \(\sim 6.55\) keV\(^{132,133}\) or the Fe absorption edge at \(\sim 9.28\) keV\(^{179,177}\). In general, rapid X-ray spectroscopy of GRB afterglows may become a powerful tool to understand their physics and origins.

Almost all GRB redshifts measured to date required large telescopes (this is certainly true for the measurement of host galaxy redshifts), although it is certainly possible to measure absorption redshifts of OTs, if they are identified quickly\(^8\). The redshifts are still in a short supply, and there has been a considerable interest in trying to produce a photometric redshift estimator for GRBs from their \(\gamma\)-ray light curves alone\(^{160,42,120,143}\) (Fig. 13). While rough redshifts (perhaps good to a factor of 2?) can be predicted, the practical utility of these relations remains to be tested.

Returning to the issue of GRB host galaxies, the first question is, are they special in some way? Their magnitude and redshift distributions are typical for the normal, faint field galaxies, as are their morphologies\(^7\) when observed with the HST: often compact, sometimes suggestive of a merging system\(^3\), but that is not unusual for galaxies at comparable redshifts.

If GRBs are somehow related to the massive star formation (e.g.,\(^{164,125}\), etc.),
Figure 8: Spectrum of the OT associated with GRB 990123, obtained at the Keck. The prominent absorption lines correspond to the host galaxy redshift, $z = 1.600$.

Figure 9: Spectrum of the host galaxy of GRB 970228, obtained at the Keck. Prominent emission lines [O II] 3727 and [O III] 5007 and possibly [Ne II I] 3869 are labeled assuming the lines originate from the host at redshift $z = 0.695$. The notation “ns” refers to Noise spikes from strong night sky lines are labeled “ns”.
Figure 10: Spectrum of the host galaxy of GRB 970508, obtained at the Keck telescope. Note the strong [Ne III] line, indicative of the high-temperature H II regions, presumably powered by UV radiation from massive stars.

Figure 11: Histogram of the GRB redshifts as of June 2001. The solid line is a Gaussian-smoothed distribution. The median for this sample is $z = 1.1$. The decline at $z > 1.3$ or so can due in part to the observational selection effects (both due to the more distant galaxies being fainter, and the absence of strong emission lines for spectra at $z \sim 1.3 - 2$).
Figure 12: Observed γ-ray fluence (top) and the corresponding isotropic γ-ray energy (bottom), for the bursts with measured redshifts and published fluences, as of June 2001. Note the complete lack of correlation between the fluence (roughly proportional to the mean flux) and the redshift. In computing the energies, a simple Friedmann cosmology with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.2$, and $\Lambda_0 = 0$ was used. The dashed line in the bottom panel corresponds to the limiting fluence of $2 \times 10^{-6} \text{ erg cm}^{-2}$. It is clear that even with the present generation of instruments, we can in principle detect bursts out to very high redshifts. For a more detailed discussion of k-corrected, bolometric fluxes and energies, see [20].

Figure 13: A correlation between the apparent isotropic γ-ray energy vs. a variability parameter, from [14]. Solid and dashed lines represent the best fit power-law $\pm 1 \sigma$. The fit includes bursts with actual measurements, and upper limits.
it may be worthwhile to examine their absolute luminosities and star formation rates (SFR), or spectroscopic properties in general. This is hard to answer from their visible (∼ restframe UV) luminosities alone: the observed light traces an indeterminate mix of recently formed stars and an older population, cannot be unambiguously interpreted in terms of either the total baryonic mass, or the instantaneous SFR.

Fig. 14 shows the distribution of absolute $B$-band luminosities of GRB hosts identified to date, under two extreme assumptions about evolutionary corrections. The hosts appear to be somewhat subluminous relative to a present-day average ($L_*$) galaxy. This is generally expected, since much of the SFR activity at $z \sim 0.5−1$ (and probably beyond) among the field galaxies appears to be in subluminous systems [15], and thus the GRB hosts would be representative of the normal, star-forming field galaxy population. One could also speculate that the trend towards lower luminosity galaxies may be really selecting on average lower metallicity systems, where the mean extinction may be lower, making them easier to detect, or whose stellar IMF may be biased towards more massive stars (this is highly speculative). A much larger sample of GRB hosts is needed in order to better understand this issue.

Spectroscopic measurements provide direct estimates of the recent, massive SFR in GRB hosts. Most of them are based on the luminosity of the [O II] 3727 doublet [15], the luminosity of the UV continuum at $\lambda_{rest} = 2800$ Å [15], in one case so far [15] from the luminosity of Ly$\alpha$ 1216 line [15], and in one case [15] from the luminosity of Balmer lines [15]. All of these estimators are susceptible to the internal extinction and its geometry, and have an intrinsic scatter of at least 30%. The observed SFR’s range from a few tenths to a few $M_{\odot}$ yr$^{-1}$, again typical for the normal field galaxy population at comparable redshifts.

Equivalent widths of the [O II] 3727 doublet in GRB hosts, which may provide a crude measure of the SFR per unit luminosity (and a worse measure of the SFR per unit mass), are on average somewhat higher [15] than those observed in magnitude-limited field galaxy samples at comparable redshifts [15]. Another intriguing hint comes from the flux ratios of [Ne III] 3869 to [O II] 3727 lines: they are on average a factor of 4 to 5 higher in GRB hosts than in star forming galaxies at low redshifts. These strong [Ne III] require photoionization by massive stars in hot H II regions, and may represent an indirect evidence linking GRBs with massive star formation.

The interpretation of the luminosities and observed star formation rates is vastly complicated by the unknown amount and geometry of extinction. The observed quantities (in the visible) trace only the unobscured stellar component, or the components seen through optically thin dust. Any stellar and star formation components hidden by optically thick dust cannot be estimated at all from these data, and require radio and sub-mm observations (see below). Thus, for example, optical colors of GRB hosts cannot be used to make any meaningful statements about their net star formation activity. The broad-band optical colors of GRB hosts are not distinguishable from those of normal field galaxies at comparable magnitudes and redshifts [15].

A great deal about the progenitors can be gleaned from the locations of GRBs in and around galaxies. GRBs from collapsars are expected to occur where mas-
Figure 14: Distribution of estimated absolute $B$-band magnitudes for GRB host galaxies with known redshifts, as of June 2001. These restframe magnitudes were computed from the observed $R$-band magnitudes by approximating the galaxy spectra as $f_\nu \sim \nu^{-1}$ and no additional extinction correction. Standard Friedmann cosmology with $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.2$, and $\Lambda_0 = 0$ was used (the results are not strongly sensitive to these assumptions). The top panel shows the magnitudes as they are observed, i.e., assuming no evolution from the observed host redshift to the present day. The bottom panel incorporates a simple evolutionary fading correction (i.e., galaxies were assumed to have been brighter in the past, and so they would be fainter today), as $\Delta m = 0.5z$; this is about as strong as suggested by the modern field galaxy evolution studies. Solid lines indicate the values of $M_B$ corresponding to an $L_*$ galaxy today; dashed lines are the sample medians.
Figure 15: Example GRB-host galaxy offsets, from 22. The 3-σ error contours of the GRB afterglow locations are shown as ellipses. In the top left panel, the afterglow of GRB 970228 is still visible the the south of the center of the host. In the other three, the afterglow has faded from view by the epoch of the respective HST observations.

Sizable stars are formed, in molecular clouds and HII regions, whereas GRBs from degenerate binaries that merge after at least one SN in the system (e.g., NS-NS and NS–BH binary systems) can merge a few to hundreds of kiloparsecs from their birthsite. This is because of the large systemic kicks imparted to binary systems following a SN explosion. Modeling of the location of merging binaries suggests that ≈ 1/3 – 1/2 of all GRBs should occur > 10 kpc in projection from the centers of their host galaxies 22,35,55.

The proximity of OTs associated with GRB 970228 and GRB 970508 to their hosts already posed a difficulty for the merger scenario.13,125 We completed the first comprehensive study of the offset location of 20 well-localized cosmological GRBs using extensive ground-based and space-based imaging data.22 Fig. 15 shows some examples of GRB-host offsets. The 3-σ error contour of the GRB location is marked as well as a physical scale for each galaxy. We find that all well-localized GRBs to-date fall within 1.2 arcsec (~ 10 kpc in projection) from the nearest detected galaxy. Statistically, most if not all of these nearby host galaxies are indeed physically associated with the respective GRB and not spurious superpositions: the chance of superposition of more than 3 GRB hosts is < 1%.

The distribution of GRB-host offsets closely follows the light of their hosts, which is roughly proportional to the density of star formation (especially for the high-z galaxies). It is thus fully consistent with a progenitor population associated with the sites of massive star formation. Fig. 16 shows the observed offsets distribution compared with a simple exponential disk model for the distribution of massive
star formation. The observed distribution also appears to be inconsistent with the merger scenario, where progenitors travel far from their birthsites.

4 The GRB-Supernova Connection

A direct consequence of the collapsar model is that GRBs are expected to be accompanied by supernovae (SNe). The first evidence for a possible GRB/SN connection was provided by the discovery of SN 1998bw in the error box of GRB 980425. The temporal and spatial coincidence of SN 1998bw with GRB 980425 suggest that the two phenomena are related, however, the actual identification of the SN with the X-ray afterglow remains somewhat uncertain. An additional indication that SN 1998bw may be related to GRB 980425 comes from the fact that the radio emitting shell in SN 1998bw must be expanding at relativistic velocities, $\Gamma \geq 2$, which was previously never observed in a SN. From minimum energy arguments, it was estimated that this relativistic shock carried $5 \times 10^{49}$ erg, and could well have produced the GRB at early time. Further, detailed analysis of the radio light curve showed additional energy injection one month after the SN event – highly suggestive of a central engine (i.e., a BH vs. NS formation) rather than a purely impulsive explosion.

If this identification is correct, GRB 980425 is most certainly not a typical GRB: the redshift of SN 1998bw is 0.0085 and the corresponding $\gamma$-ray peak luminosity of GRB 980425 and its total $\gamma$-ray energy budget are about a factor of $\sim 10^5$ smaller than those of “normal” GRBs. But if the identification is correct, such SN-GRBs may well be the most frequently occurring GRBs in the universe.
Figure 17: R-band light curve of GRB 980326 and the sum of an initial power-law decay plus SN Ic light curve for redshifts ranging from $z = 0.50$ to 1.60. The best-fit redshift for the SN is $z \approx 0.95$, and it is consistent with the observed spectrum taken during the reburst. From [17].
A probable association of a “normal” GRB with a SN-like event was the discovery of the late-time rebrightening (with a much redder spectrum than that of the early-time afterglow) of GRB 980326 (see Fig. 17). Similar deviations in the light curve and colors were also seen in the case of GRB 970228, with the same physical interpretation. However, it should be noted that many other GRB afterglows did not show such lightcurve deviations, even if they were detectable in principle. An alternative explanation for this phenomenon involves light echoes.

5 Jets and Beaming

The question of jets and beaming in GRBs has been discussed for some years, but it was really brought into focus when the redshift measurements of GRB 971214 and GRB 990123, implied the isotropic $\gamma$-ray energy releases approaching $\sim 10^{54}$ erg. If GRBs are collimated, there are two important implications: First, the true total energy emitted by the source is smaller by a factor of $\Omega/4\pi \sim \theta_j^2/4$ than if the ejecta was spherical. Second, the true event rate must be bigger by the same factor to account for the observed rate.

The first attempts to constrain the beaming in GRBs were through searches for the so-called “orphan afterglows”, corresponding to GRBs beamed away from us. The basic idea is that the relativistic beaming produces a visibility cone with an opening angle $\sim 1/\Gamma$. In the early phases of a GRB, $\Gamma \sim 100$ and the $\gamma$-ray emission would be highly beamed. As the afterglow spectrum evolves towards the lower frequencies, and as $\Gamma$ decreases, afterglow emission at longer wavelengths (first X-ray, then optical, then radio) would be progressively less beamed. One could thus see numerous weakly beamed afterglows without accompanying GRBs.

Several searches have been made in X-rays, but no convincing population of orphan afterglows has been found, and giving (weak) limits on the beaming factor $f_b \approx 10^{-3}$ or so. Comparable limits have been found for the existing radio surveys. One serendipitously found candidate has been reported in the optical.

A more convincing evidence that GRB fireballs are not spheres but rather have conical (jet-like) geometries comes from their light curves. The observational signature of conical geometry manifests itself as a panchromatic “break” in the power law decay of the afterglow emission, which declines more rapidly relative to a spherical case. This is due to two effects. The first is an edge effect that occurs at a time $t_j$ when the bulk Lorentz factor of the blast wave $\Gamma$ has slowed down to $\Gamma < \theta_j^{-1}$ (where $\theta_j$ is the opening angle of the jet). The second effect that also becomes important after $t_j$ is the lateral spreading of the jet. The ejecta, now encountering more surrounding matter, decelerate faster than in the spherical case.

The first claim of a jet was made for the radio afterglow of GRB 970508, which showed deviations from the predictions of a simple spherical adiabatic model. However, it was the spectacular isotropic energy release of GRB 990123 – approaching the rest mass of a neutron star – which emphasized the possible importance of jets in GRBs. A case for a jet in the afterglow of this burst was made on the basis of a sharp break ($\Delta \alpha \geq 0.7$) in the optical afterglow and upper limits in...
Figure 18: The observed distribution of light curve jet break times, $t_j$ (top), and jet opening angles, $\theta_j$ (bottom). A heuristic model fit (line) assumes two power laws: $p_{\text{obs}}(f_b) = (f_b/f_0)^{\alpha+1}$ for $f_b < f_0$ and $p_{\text{obs}}(f_b) = (f_b/f_0)^{\beta+1}$ for $f_b > f_0$. Since for every observed burst there are $f_b^{-1}$ that are not observed, the true distribution is $p_{\text{true}}(f_b) = f_b^{-1} p_{\text{obs}}(f_b)$. Fits poorly constrain $\alpha$, and $\beta = -2.77_{-0.24}^{+0.34}$, log $f_0 = -2.91_{-0.06}^{+0.07}$. Thus, the true differential probability distribution (under the small angle approximation, $f_b \propto \theta_j^2$) is given by $p_{\text{true}}(\theta_j) \propto \theta_j^{-2.54}$ with the observed distribution being $p_{\text{obs}}(\theta_j) \propto \theta_j^{-2.54}$. The distribution $p_{\text{true}}(f_b)$ allows us to estimate the true correction factor, $\langle f_b^{-1} \rangle$ that has to be applied to the observed GRB rate in order to obtain the true GRB rate. We find $\langle f_b^{-1} \rangle = f_0^{-1} [(\beta - 1)/\beta] \sim 520 \pm 85$. From

the radio. The clearest evidence for a jet is a sharp break over a broad range of frequencies and such a signature was seen in the lightcurves of GRB 990510 at optical and radio wavelengths and was found to be consistent with the X-ray light curve. Furthermore, the detection of polarization from this event gave further credence to the jet hypothesis: the non-spherical geometry leads to polarized signal, from which the geometry of the jet can be inferred.

More recently, the identification of jets has shifted from single frequency measurements to global model fitting of joint optical, radio and X-ray datasets. This approach has the advantage that by simultaneously fitting all the data, the final outcome is less sensitive to deviations in small subsets of the data. In addition, since the character of the achromatic break is different above and below the peak of the synchrotron spectrum, broad-band measurements give more robust determinations of the jet parameters. This approach was crucial in distinguishing the jet break for GRB 000301C whose decaying lightcurves exhibited unusual variability now attributed to microlensing. Likewise, radio measurements were useful in determining $t_j$ for GRB 000418 because the light of the host galaxy masked the jet break at optical wavelengths.

We have recently determined the values (or limits) of jet breaks $t_j$ for a complete sample of all GRBs with known redshifts. Within the framework of this conical jet model, we are able to derive the opening angle $\theta_j$. The distribution of the
The distribution of the apparent isotropic $\gamma$-ray burst energy of GRBs with known redshifts (top) versus the geometry-corrected energy for those GRBs whose afterglows exhibit the signature of a non-isotropic outflow (bottom). The mean isotropic equivalent energy $\langle E_{\text{iso}}(\gamma) \rangle$ for 17 GRBs is $110 \times 10^{51}$ erg with a 1-$\sigma$ spreading of a multiplicative factor of 6.2. In estimating the mean geometry-corrected energy $\langle E_{\gamma} \rangle$ we applied the Bayesian inference formalism and modified to handle datasets containing upper and lower limits. Arrows are plotted for five GRBs to indicate upper or lower limits to the geometry-corrected energy. The value of $\langle \log E_{\gamma} \rangle$ is $50.71 \pm 0.10$ (1-$\sigma$) or equivalently, the mean geometry-corrected energy $\langle E_{\gamma} \rangle$ for 15 GRBs is $0.5 \times 10^{51}$ erg. The standard deviation in $\log E_{\gamma}$ is $0.31 \pm 0.09$, or a 1-$\sigma$ spread corresponding to a multiplicative factor of 2.0. From [4].

$t_j$ and $\theta_j$ is shown in Fig. 18. Corresponding to the wide range in $t_j$ values from $\leq 1$ d to 30 d, we obtain a range in $\theta_j$ from $3^\circ$ to more than $25^\circ$ with a strong concentration near $4^\circ$. This result suggests that the broad range of fluence and luminosity observed for GRBs is largely the result of a wide variation of opening angles.

With the values of $\theta_j$ known, it is then possible to correct the isotropic equivalent $\gamma$-ray energy, $E_{\text{iso}}(\gamma)$ for the effects of conical geometry and derive the true $\gamma$-ray energy release (i.e., $E_\gamma = f_b \times E_{\text{iso}}(\gamma)$ where $f_b \approx \theta_j^2/2$). The distributions of $E_{\text{iso}}(\gamma)$ and $E_\gamma$ values are shown in Fig. 19. The somewhat surprising result is that $E_\gamma$ is tightly clustered around $5 \times 10^{50}$ erg. Evidently, it appears that the central engines of GRBs produce approximately a similar amount of energy, and a significant part, about $10^{51}$ erg, escapes as $\gamma$-rays.

In addition to the implications that this result has on the luminosities and energies of GRB central engines, it also affects determinations of the mean beaming fraction and the GRB rate. Since conical fireballs are visible to only a fraction, $f_b$, of observers, the true GRB rate, $R_t = \langle f_b^{-1} \rangle R_{\text{obs}}$, where $R_{\text{obs}}$ is the observed GRB rate and $\langle f_b^{-1} \rangle$ is the harmonic mean of the beaming fractions. We find that the
true GRB rate is $\langle f^{-1}_b \rangle \sim 500$ times larger than the observed GRB rate, a result that provides some constraints for GRB progenitor models.

6 GRBs as Probes of Obscured Star Formation

Already within months of the first detections of GRB afterglows, no OT's were found associated with some well-localised bursts despite deep and rapid searches; the prototype was GRB 970828. There an XT was found, and a one-time radio flare within its error circle (Fig. 20), which at the time was puzzling, being different from the “standard” RT behaviour, as exemplified, e.g., by GRB 970508. But it was realised after the discovery of a radio flare from GRB 990123 that such phenomena (ostensibly caused by reverse shocks) can indeed point towards GRB afterglows. GRB 970828 was thus the first case of a “dark burst” (at least in the visible light) \[36\).

Perhaps the most likely explanation for the non-detections of OT’s when sufficiently deep and prompt searches are made is that they are obscured by dust in their host galaxies. This is an obvious culprit if indeed GRBs are associated with massive star formation.

Support for this idea also comes from detections of RTs without OTs, including GRB 970828, 990506, and possibly also 981226 (see \[32\). Dust reddening has been detected directly in some OTs (e.g., \[32\), etc.); however, this only covers OTs seen through optically thin dust, and there must be others, hidden by optically thick dust. An especially dramatic case was the RT and IR transient associated with GRB 980329. We thus know that at least some GRB OTs must be obscured by dust.

The census of OT detections for well-localised bursts can thus provide a completely new and independent estimate of the mean obscured star formation fraction in the universe. Recall that GRBs are now detected out to $z \sim 4.5$ and that there is no correlation of the observed fluence with the redshift (Fig. 12), so that they are, at least to a first approximation, good probes of the star formation over the observable universe. As of mid-June 2001, there have been $\sim 52 \pm 5$ adequately deep and
Figure 21: Keck $R$ band image of the host galaxy system of GRB 970828 at $z = 0.9579$. The morphology of the system is suggestive of a merger. The ellipse indicates the position of the RT, close to what may be a dust lane between two visible components. Obscuration by dust is the most likely cause of the non-detection of an OT associated with this burst. From \[\text{[Ref]}.\]

rapid searches for OTs from well-localised GRBs \[\text{[Ref]}\]. Out of those, $\sim 27 \pm 2$ OTs were found (the uncertainty being due to the questionable nature of some candidates). Some OTs may have been missed due to an intrinsically low flux, an unusually rapid decline rate, or very high redshifts (so that the brightness in the commonly used $BVR$ bands would be affected by the intergalactic absorption). Thus the maximum fraction of all OTs (and therefore massive star formation) hidden by the dust is $(48 \pm 8)\%$.

This is a remarkable result. It broadly agrees with the estimates that there is roughly an equal amount of energy in the diffuse optical and FIR backgrounds (see, e.g., \[\text{[Ref]}\]). This is contrary to some claims in the literature which suggest that the fraction of the obscured star formation was much higher at high redshifts. Recall also that the fractions of the obscured and unobscured star formation in the local universe are comparable. GRBs can therefore provide a valuable new constraint on the history of star formation in the universe \[\text{[Ref]}\].

There is one possible loophole in this argument: GRBs may be able to destroy the dust in their immediate vicinity (up to $\sim 10$ pc?) \[\text{[Ref]}\], and if the rest of the optical path through their hosts ($\sim$ kpc scale?) was dust-free, OTs would become visible. Such a geometrical arrangement may be unlikely in most cases, and our argument probably still applies.

Further support for the use of GRBs as probes of obscured star formation in

\[\text{[Ref]}\] We define “adequate searches” as reaching at least to $R \sim 20$ mag within less than a day from the burst, and/or to at least to $R \sim 23–24$ mag within 2 or 3 days; this is a purely heuristic, operational definition. The uncertainty comes from the subjective judgement of whether the searches really did go as deep and as fast, based on what is published, mostly in GCN Circulars, and whether the field was at a sufficiently low Galactic latitude to cause concerns about the foreground extinction and confusion by Galactic stars.

\[\text{[Ref]}\] These ideas were presented in talks at conferences and seminars by the members of our group, starting in the spring of 1999. They were then co-opted and discussed in the same context by some other authors\[\text{[Ref]}\].

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remaining issues and future prospects

It has been known for some years that GRBs exhibit a bimodal distribution of durations, which is also weakly correlated with the spectral hardness ratio (see Fig. 22). Due to instrumental effects, all of the GRBs with identified afterglows so far are from the long/soft part of the distribution. It is likely that GRBs represent (at least) two distinct, although broadly similar, physical phenomena. The nature of the short/hard bursts, including their progenitors, manifestations on other wavelengths, etc., remains completely unknown as of this writing. It is hoped that the forthcoming precise localisations of such bursts by HETE-2 will help solve this problem.

This begs the question of how many different types of bursts really are? Multivariate statistical studies of the BATSE data produced conflicting and inconclusive results: there are at least two types (long and short), but there may be more. Moreover, if the identification of GRB 980425 with SN1998bw is correct, that would represent yet another class of sub-luminous GRBs (although it could also be interpreted as an orientation effect). There are also “X-ray rich GRBs”, which may also be a distinct population.

On the whole, we know very little about rapid variability (especially transient, i.e., non-repeatable sources) at any wavelength. GRBs are spectacular and exotic, drawing attention to themselves in the γ-ray regime, but similarly interesting phenomena may exist with energy peaks at lower frequencies. In most surveys and observations (other than γ-ray where photons are so scarce that anything counts) single-time events and detections are routinely discarded (with some justification) as “noise”. We may be missing important new classes of rapid transient phenomena. For example, serendipitous findings of fast, faint optical transients in deep
SN and lensing surveys\[23,65,61\] may be examples of something new and interesting. There is a great scientific opportunity in dedicated, synoptic surveys of the sky at all wavelengths, including (or especially?) optical.

Another exciting prospect is to use high-z GRBs as cosmological probes. Even the present-day missions can in principle detect highly luminous (or highly beamed) GRBs out to the expected epoch of initial galaxy formation and reionization of the universe, at $z \sim 10 - 20$. If GRBs are indeed associated with massive star formation, they may occur at such redshifts, and be the most luminous objects in the universe then. Straightforward computations\[14\] show that their afterglows would be detectable by the existing technology. Searches in the radio regime may be especially promising\[28\]. Such primordial GRBs would be predating the formation of luminous quasars (whose massive central black holes may need a few $\times 10^8$ years to grow and achieve comparable, albeit steady luminosities), and provide a unique probe of the early IGM and the reionization epoch, as well as the early star formation. In this context, it is especially interesting that all modern models of the primordial (i.e., metal-free) star formation suggest that the IMF of the first stars would be dominated by very massive stars, i.e., precisely the now favorite progenitors of GRBs\[24,100\].

While the studies of GRB afterglows and environments have generated much progress in the physical understanding of the GRB phenomenon, and even provided some strong hints about the possible progenitors, the nature of the GRB “central engines” is still unknown. In addition to the future observations of gravitational waves with LIGO, LISA and other instruments, two promising new information channels which may help us learn more about the origin of GRBs are high-energy cosmic rays and neutrinos. Both are expected in at least some models\[174,176\]. The probable detection of TeV emission from GRB 970417a may be the first glimpse of this new observational frontier. Searches for high-energy neutrinos with detectors like AMANDA\[69\] are also very promising\[6\].

In this review we hoped to convey the richness and the excitement of the field of GRBs, which now spans a broad range of astrophysical subjects. In anything, the future of GRB studies seem even more exciting than the spectacular progress of the past few years. In addition to BeppoSAX\[1\] and other current missions (e.g., Rossi XTE\[6\], HETE-2\[9\], Chandra\[14\], XMM-Newton\[17\] and the IPN\[10\]); future missions (e.g., SWIFT\[13\], GLAST\[15\], INTEGRAL\[16\], AGILE\[17\] etc.) as well as the ground-based networks of telescopes (e.g., REACT\[18\]) will continue to provide a steady stream of data and flashy discoveries in the years to come.

\[a\] http://amanda.berkeley.edu/amanda/amanda.html
\[b\] http://www.asdc.asi.it/bepposax
\[c\] http://heasarc.gsfc.nasa.gov/docs/xte/
\[d\] http://space.mit.edu/HETE/
\[e\] http://chandra.harvard.edu/
\[f\] http://xmm.vilspa.esa.es/
\[g\] http://ssl.berkeley.edu/ipn3/
\[h\] http://swift.sonoma.edu/
\[i\] http://glast.gsfc.nasa.gov/
\[j\] http://astro.estec.esa.nl/SA-general/Projects/Integral
\[k\] http://www.ifctr.mi.cnr.it/Agile/
\[l\] http://pulsar.ucolick.org/REACT/
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Table 1: GRB Host Galaxies and Redshifts

| GRB   | $R$ mag | Redshift | Type  | References |
|-------|---------|----------|-------|------------|
| 970228| 25.2    | 0.695    | e     | 29, 31     |
| 970508| 25.7    | 0.835    | a,e   | 13, 14, 15 |
| 970828| 24.5    | 0.9579   | e     | 26         |
| 971214| 25.6    | 3.418    | e     | 24, 22     |
| 980326| 29.2    | ~1?      |       | 15, 23     |
| 980329| 27.7    | <3.9     | (b)   | 29, 42     |
| 990425| 14      | 0.0085   | a,e   | 59         |
| 980519| 26.2    |          |       | 73         |
| 980613| 24.0    | 1.097    |       | 15, 25     |
| 980703| 22.6    | 0.966    | a,e   | 13, 15     |
| 981226| 24.8    |          |       | 23         |
| 990123| 23.9    | 1.600    | a,e   | 32, 44     |
| 990308| >28.5   |          |       | 74         |
| 990506| 24.8    | 1.30     | e     | 10, 20     |
| 990510| 28.5    | 1.619    | a     | 24, 172    |
| 990705| 22.8    | 0.86     | x     | 105, 133   |
| 990712| 21.8    | 0.4331   | a,e   | 74, 75, 77 |
| 991208| 24.4    | 0.7055   | e     | 25, 33     |
| 991216| 24.85   | 1.02     | a,x   | 171, 170, 13 |
| 000131| >25.7   | 4.50     | b     | 4         |
| 000214| 0.37−0.47| x       |       | 17, 173    |
| 000301C| 28.0    | 2.0335   | a     | 84, 87, 93, 94 |
| 000418| 23.9    | 1.1185   | e     | 13, 18     |
| 000630| 26.7    |          |       | 35         |
| 000911| 25.0    | 1.0585   | e     | 135        |
| 000926| 23.9    | 2.0369   | a     | 56, 77, 26 |
| 010222| >24     | 1.477    | a     | 74, 168, 84 |

Notes:
1 e = line emission, a = absorption, b = continuum break, x = x-ray
2 Association of this galaxy/SN/GRB is somewhat controversial
3 Association of the OT with this GRB may be uncertain