Optical Observations of Afterglows

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Abstract. Optical, infrared and ultraviolet observations of GRB fields have allowed detection of counterparts and host galaxies of the high energy transients, thus crucially contributing to our present knowledge of the GRB phenomenon. Measurements of afterglow variable emission, polarized light, redshifted absorption and emission line spectra, as well as host galaxies brightnesses and colors have clarified many fundamental issues related to the radiation mechanisms and environments of GRBs, setting the background towards disclosing the nature of their progenitors.

1 Introduction

GRB counterparts are multiwavelength emitters, unlike supernovae, which emit most of their power at the optical frequencies. However, observations in the optical band have had the biggest impact in the study of the GRB phenomenon, by sampling the time histories of the GRB counterparts from a few seconds up to years after the explosion, by establishing the nature of the afterglow emission (synchrotron radiation), and by unambiguously assessing the extragalactic origin of GRBs. GRB optical counterparts can be initially extremely bright. However, the delayed emission, even though it is long lived with respect to the prompt event, still fades quite rapidly, and the host galaxies of GRBs are very small and faint, because of their cosmological distances. Therefore, telescopes of all aperture sizes have been involved in the investigation of the optical afterglows. The smaller telescopes are more flexible for an efficient search and the larger ones (including HST) play a leading role in early spectroscopy and polarimetry, as well as in the photometric monitoring at late epochs, and in the study of the host galaxies. The most important observations of optical afterglows and their host galaxies, which have led to the current understanding of the physics of these sources, are discussed. Previous reviews on this subject include [232,128,118,136,36,225,115]. Although the present review focuses on the optical observations, information provided by the scanty infrared and ultraviolet data is also included, considering the proximity of these bands to the optical. The chapter is organized as follows: in Section 2 the steps which led to the first detection of optical afterglow emission are summarized and the observational problems related to the afterglow investigation are described; in Section 3 the temporal behavior of the optical prompt and afterglow emission is reviewed; in Section 4 the observed spectral continuum at infrared, optical and ultraviolet wavelengths is compared to the standard afterglow model based on
the propagation of an external shock, and the characteristics of the afterglow absorption spectra are illustrated. Section 5 is devoted to a discussion of those aspects of GRB host galaxies which seem to be relevant to the afterglow investigation. Future perspectives in the exploration of GRB optical counterparts are sketched in Section 6.

2 Optical searches of GRB error boxes

The search for optical counterparts of GRBs started soon after GRB discovery in the belief that they held the key toward the physical origin of the GRB phenomenon. The first searches in the 1970’s were based on inspection, on archival plates or on photographic images of the GRB field, of the large error boxes yielded by the early high energy missions (see [232] for a review of these pioneering attempts). The reasons of their failure, as we now understand, reside in the inadequacy of the methods. Since GRB afterglows fade quickly, only timely and sensitive surveys of accurate, rapidly disseminated GRB error boxes can be effective in detecting optical counterparts.

The first identification of an optical afterglow was made possible on 28 February 1997 by the BeppoSAX satellite [24], whose Wide Field Cameras (WFC, [122]) determined the position of a GRB with a 3′ uncertainty radius and disseminated it to the community within a few hours [39]. Optical observations made 21 hours and ∼1 week after the GRB allowed the detection of a variable source in the GRB error area, which had been meanwhile refined and reduced to ∼1 arcmin². Variability and positional coincidence suggested association of the optical transient with the GRB [231]. Five years later, out of about 100 GRBs accurately and rapidly localized by BeppoSAX or by other spacecrafts, and timely followed by optical telescopes (delays of a few hours to a few days of the GRB explosion), ∼30 have a detected optical afterglow. These are reported in Table 1, together with those GRBs for which, despite the lack of optical afterglow detection, the precise afterglow positioning at other wavelengths has allowed the identification of a host galaxy (in these cases the lower limit on the magnitude of the transient counterpart is reported, as determined in the earliest search). Col. 2 of Table 1 reports the instrument, or suite of instruments, which have localized the GRB: “BeppoSAX” means that the event has triggered the Gamma-Ray Burst Monitor (GRBM) of the BeppoSAX satellite [28], and has been localized with arcminute precision by the onboard WFC. In two cases the BeppoSAX WFC detected in the X-rays and localized an event which triggered BATSE, but not the GRBM. For almost all GRBs localized by the Rossi XTE satellite, the accurate positioning was obtained with its All Sky Monitor, the exception being GRB990506, which was localized precisely only after the RXTE Proportional Counter Array (PCA) detected its X-ray afterglow [26]. Many GRBs have been localized by the Interplanetary Network (IPN) of spacecrafts, whose synergy allows triangulation of the GRB position, yielding in many cases arcminute-sized error areas, although with delays seldom shorter than 12 hours, and often longer than 24 hours [117,118]. For most cases, a refine-
ment of the localization error box has been possible after detection of the X-ray afterglow by the BeppoSAX Narrow Field Instruments, by the RXTE PCA, or by Chandra (see also chapter by F. Frontera).

Optical afterglows are generally identified for being previously unknown sources and for their variability, either by comparing deep images of the GRB field, acquired soon after the GRB detection, with the Digitized Sky Survey (DSS), or, for transients fainter than the DSS limit, with images obtained at later epochs. An alternative technique for the selection of GRB counterpart candidates is based on the characteristic power-law spectral shape of afterglows, and can be successfully employed when sufficient color information is available [207,87]. The method may suffer from redshift-dependent biases and possible contamination by other classes of sources; however, it can be advantageously applied to a single set of images, instead of two (or more) sets of images taken at different epochs.

It should be specified that so far optical counterparts have been detected only for long duration GRBs, which represent one of the two populations into which GRBs are subdivided (see, however, [167] for the possible existence of a third class). According to their duration, the GRBs of the BATSE sample are divided into long (75% of the total) and short events (25%), with average durations of \( \sim 20 \) s and \( \sim 0.2 \) s, respectively. This bimodality is reflected also in the spectral hardness, with long GRBs tending to be softer than sub-second GRBs [130], and may be due to a different origin of the two classes of sources. Sub-second GRBs could not be accurately localized by the BeppoSAX WFC [82]: four of them have been localized with arcminute precision by the IPN, and followed up in the optical with delays no shorter than \( \sim 20 \) hours. No afterglow has been detected; the upper limits show that, within the limited statistics, the optical afterglow behavior of sub-second GRBs may not differ from that of long ones [119,88]. The GRB000301C, which was detected by the IPN with a 2 s duration and exhibited a bright, variable counterpart (see §3.2), cannot be unambiguously classified as a long, sub-second hard, or intermediate GRB [124].

Considering only GRBs for which the angular localization is better than \( \sim 30 \) arcmin\(^2\) and was disseminated within 24 hours, the statistics of detected optical afterglows is \( \sim 40\% \) of the total. Therefore, many GRBs are optically “dark”, though nearly all of these have X-ray and/or radio afterglows. Many causes can concur to make optical searches unsuccessful (see also [49]). Optical afterglows can be intrinsically faint, rapidly decaying, or dim because of the large redshift, causing the Ly\( \alpha \) break to affect the optical spectrum. Therefore, in some cases, the lack of an optical detection may be due to the insufficient sensitivity of the search [229,72,57]. The different decay rates of the optical afterglows on the one hand and the rather wide range of magnitudes measured, at equal intervals after the GRB, for optical counterparts with comparable decay rates on the other (see Table 1), indicate that the chance of detection may be very different from case to case for similarly prompt and deep exposures. This, together with the lack of a straightforward correlation between optical emission and gamma-ray brightness of the prompt event, makes it difficult to predict the detection level and to devise an optimal observing strategy.
In addition, optical afterglows may be affected by extinction in the plane of our Galaxy (which is instead transparent to gamma- and hard X-rays and to radio wavelengths), and by absorption in their host galaxies, which makes their detection all the more challenging. By simulating the absorption experienced at the center of a dense dust clump, similar to those found in star forming regions in our Galaxy and in external ones, in a number of directions randomly distributed, Lamb [141] determined that in only 35% of the lines of sight the optical depth is \( \tau = 1 \), while in the remainder it is \( \tau \gg 1 \). This statistic is consistent with the percentage of dark GRBs, supporting the idea that local dust absorption may hamper or completely prevent optical detection of the GRB afterglow and strengthening the importance of infrared observations (see §4.1). The presence of substantial quantities of dust at the burst explosion site favors, in turn, the association of GRBs with star forming regions (see §5). Although the result of this test would relate all dark GRBs to the effect of dust extinction, perhaps this is only one of the possible causes for a failed optical detection. An alternative view [144] is that dark GRBs can be heavily extincted only if dust sublimation by the strong UV/optical [240] and X-ray radiation [69] following the explosion does not play a significant role. If dust destruction around the burst site is important [81], then dark GRBs should belong to a distinct population with respect to GRBs with detected optical afterglows.

3 Temporal characteristics

3.1 The Optical “Flash”

Prompt emission at optical and near-infrared wavelengths simultaneous with a GRB, or delayed by a few seconds, is expected to take place as a consequence of a reverse shock propagating into the explosion ejecta, and is therefore distinct from the afterglow, which is produced by the interaction of the forward shock with the interstellar medium [158,159,174,213]. This low energy early emission can be very bright, in principle up to the \( \sim 5 \)th magnitude in the visual band, for an intense GRB at \( z \sim 1 \), but is expected to last only tens of seconds.

Since current instrumentation disseminates accurate GRB localizations with delays of a few hours, GRB fields are usually imaged in optical starting no earlier than some hours after the explosion. Even if dissemination occurred in real time (as was the case for the large BATSE error boxes), the observer reaction at a traditional optical telescope would still take at least several minutes. Small robotic telescopes, which can slew automatically and rapidly to the GRB position in response to a localization delivered in real time, are therefore the most efficient instruments for GRB follow-up at the earliest epochs.

On 23 January 1999, an optical flare was detected by the ROTSE-I robotic telescope (consisting of a two-by-two array of 35 mm lenses), starting 22 seconds after the onset of a GRB which triggered both BeppoSAX and BATSE. At maximum, the optical transient reached \( V \sim 9 \), implying a power output in the optical of about \( \sim 1\% \) of that at the gamma-ray energies [78], in agreement with the reverse shock interpretation, and allowing an estimate of the plasma initial
Lorentz factor \[214\]. In Fig. 1 the ROTSE-I data are reported (from immediately after the light maximum, to \(\sim 10\) minutes after the GRB, before the decreasing flux level becomes undetectable), along with the measurements of the successive afterglow taken at bigger telescopes. The ROTSE-I points are fitted by a steeper temporal power-law than the afterglow points, indicating two different radiation mechanisms. Owing possibly to the exceptional brightness of the event, to the rapidity of the ROTSE-I slew, to the precise BeppoSAX localization (which allowed identification of the transient in the \(16^\circ \times 16^\circ\) ROTSE-I CCD image), and to the limited sensitivity of state-of-the-art robotic telescopes, GRB990123 still remains the unique case of detection of an “optical flash” simultaneous with the GRB event itself. Prompt searches of other GRB error boxes both with ROTSE-I and with other robotic systems have yielded no detection to limiting magnitudes spanning from \(\sim 4\) to \(\sim 15\) at epochs comprised between 10 seconds and 30 minutes after the GRB \[2,127,181,182,35,25\].

**Fig. 1.** R-band light curve of the GRB990123 afterglow. All points, except for the HST point (rightmost filled square), represent measurements taken from the ground (see \[61\] for references) and are reduced to a common flux standard with the galaxy flux subtracted. Error bars (1\(\sigma\)) are shown where available, and arrows indicate 95% confidence upper limits (from \[61\]).

### 3.2 Optical afterglow emission

At epochs between a few hours and \(\sim 1\) day after the GRB the afterglow decays following approximately a temporal power-law \(t^{-\alpha}\) with an index \(\alpha\) ranging from
∼0.7 to ∼2 (see Table 1, Col. 4, and Fig.[1]). This behavior was predicted before the detection of the first afterglow as a consequence of the simplest version of the fireball model \[159\]. According to this scenario (see chapter by E. Waxman), the GRB explosion triggers a relativistic forward shock which develops into the interstellar medium (or in a wind pre-ejected by the GRB stellar progenitor \[190,137\]) and accelerates the particles. These interact with the magnetic field and radiate at all frequencies through the synchrotron mechanism (significant contribution from the inverse Compton scattering emission is also predicted and observed in some cases \[216,177,103\]). Linear polarization, measured in the optical afterglows of GRB990510 and GRB990712 at the level of a few percent \[243,40,208\], represents a good test of the synchrotron mechanism \[151,93\] and of collimated emission \[86\] (see below). Near-infrared polarimetry of GRB000301C yielded an upper limit of 30%. Although not very constraining, this is consistent with a synchrotron origin of the continuum in a relativistic jet \[228\].

On average, the initial luminosities of GRB optical afterglows are two orders of magnitude larger than maximum supernova luminosities, and obviously outshine their parent galaxies. At longer intervals after the GRB, when the flux of the transient subsides under the brightness of the host galaxy, it is possible to measure the magnitude of the latter. In some cases (notably GRB970228, GRB980326 and GRB011121), the light curve of the optical afterglow exhibits a rebrightening with respect to a power-law behavior at few weeks after the GRB. Following claims for the possible association of GRB980425 with the close-by \((z = 0.0085)\) SN1998bw \[77,133\] (see also chapter by T. Galama), the light curves of those optical transients have been decomposed into a non-thermal, pure afterglow contribution and a supernova profile, using SN1998bw as a template, appropriately redshifted. In some cases the results are convincing \[10,3,23\], while in other cases they are not decisive \[21,13,23\]. Systematic decomposition into non-thermal and supernova emission components has been attempted also by Dado et al. \[41,42,43\] for the afterglows of GRBs with known redshift, in the framework of the Cannonball model, and good results have been obtained in most cases. The afterglow magnitudes reported in Table 1 (Col. 6) have been obtained from a fit with a single or double power-law after subtraction of the host galaxy flux, and in some cases after decomposition of a possibly underlying supernova (see references for individual cases in Col. 9). In those cases where the few optical measurements did not allow a proper fit, the optical magnitude measured closest to 1 day after explosion was used (e.g., GRB980613).

In a large fraction of the best monitored optical and/or near-infrared afterglows the initial power-law decline steepens at times ranging from ∼0.5 to ∼5 days after the GRB explosion. The effect is clearly seen as a smooth increase of the flux decay rate \[83,61,134,226,21,100,153,208,243,74,103,197,227,56\], and is suggested also by the X-ray data in a few cases \[159,103,194,244\]. In Table 1 (Cols. 4 and 5) the early and late temporal indices are reported as determined via empirical fits to the optical light curves with double power-laws (see also Fig.[1]). The change in the temporal slope is thought to witness the presence of a decelerating jet. Collimation of the radiation in a jet structure
would reduce the huge energy outputs ($\sim 10^{52} - 10^{54}$ erg) derived from the observed gamma-ray brightnesses and the measured distances of GRBs, in the assumption of isotropy, and thus help resolving the paradox of energy conversion efficiency. When the aperture of the radiation cone (beaming angle), which progressively increases as the relativistic plasma decelerates, becomes larger than the jet opening angle, the observer perceives a faster light dimming, independent of wavelength, due to the jet edge becoming visible and/or to jet sideways expansion. The change in fading rate is however smooth, due to light travel time effects at the ending surface of the jet. The steepening of the afterglow light curve would then be a probe of the GRB and afterglow emitting geometry. Stanek et al. note an anti-correlation between the slope change $\Delta \alpha$ and the isotropic gamma-ray energy of the burst, suggesting that the different jet opening angle may be responsible for it. Specific jet models for individual cases have been proposed, and afterglow emission from jets has been modeled in the firecone scenario as a function of the viewing angle, as also suggested by Dado et al.

If jets are unavoidable to relax the energy crisis in GRBs and a light curve steepening is their signature, one may wonder why all observed optical afterglows do not exhibit a detectable steepening in their light curve. This may simply be due to undersampling: when not detected, the steepening may have occurred at early, not well-sampled epochs (many afterglows are described by power-laws with temporal indices steeper than 2, see Table 1), or at late epochs, when the afterglow behavior is significantly contaminated by the emerging host galaxy or possible supernova, so that discerning a decay rate variation is more difficult (see e.g., [22]). On the other hand, light curve steepening cannot be univocally ascribed to a decelerating jet, but may be caused instead, or in addition, by the transition of a spectral break through the observing frequency band (see §4.1) or by the propagation of the external shock in a non homogeneous medium (although in these cases the steepening would be frequency dependent; see however [30] for detectability of a jet in a stratified medium), or by the transition of the plasma kinematic conditions from relativistic to Newtonian in a dense medium. In some cases the interpretation is not unique, although simultaneous multiwavelength observations may resolve the ambiguity. We finally note that some months after the GRB a flattening of the afterglow light curve may be expected instead.

Optical interday or intraday variations superimposed to the overall afterglow decline are rarely detected, because of the limited photometric precision of the measurements. Two cases where significant deviations from a steady decay have been observed during the optical monitoring are GRB970508, which exhibited an initial shallow decline, followed by a 2-day re-bursting of a factor $\sim 5$ amplitude, correlated with an X-ray flare, and GRB000301C, which showed intraday achromatic variability of 20-30% amplitude. For both events, an interpretation based on microlensing has been proposed. Rapid variability can otherwise be produced by small scale inhomogeneities of
the plasma flow, or irregularities of the external medium in which the blast wave propagates \[239,114\], or local re-energization episodes \[175\].

4 Spectral properties

4.1 The infrared-optical afterglow continuum

The classical fireball model has specific predictions for the temporal evolution of the broad-band spectral shape \[212\]. This has been modified to include the detectable effects of the presence of a jet \[215\]. Both the spectral slope and the temporal decay rate depend on the index $p$ of the electron energy distribution $N(\gamma) \propto \gamma^{-p}$ (where $\gamma$ denotes the electron energy above a certain cutoff). The radio-to-X-ray spectral shape is characterized by smooth breaks at typical frequencies (self-absorption, peak and cooling frequencies), which evolve with time in a predicted way \[51\], so that simultaneous multiwavelength observations at various epochs during the evolution of the afterglow allow the measurement of the spectral slopes and breaks and the estimate of the relevant physical parameters of the afterglow (see e.g., \[242,178,180\], and chapter by F. Fronda).

When the optical photometric observations are accurate and sufficiently extended in time to make a good signal-to-noise ratio measurement of the spectral and temporal slopes possible, they show that the spectra of some afterglows, corrected for Galactic extinction, are steeper (i.e., redder) than expected from the fireball theory based on comparison with the temporal decay rate. This has been commonly attributed to absorption intrinsic to the source or, especially for GRBs at very high redshift, intervening along the line of sight \[199,203,222\]. A small amount of reddening by dust in the GRB host galaxy has been invoked in many cases to reconcile the observations with the theoretical scenarios, using extinction curves typical of our own Galaxy, of star-forming galaxies, or of the LMC and SMC \[171,236,156,103,147,124,42,43\]. While even a moderate quantity of dust at the GRB source redshift may significantly attenuate the observed optical spectrum (which corresponds, at the average $z \sim 1$, to rest-frame ultraviolet wavelengths), or even completely obscure it (see §2), near-infrared data are less affected and may be more effective in determining the overall afterglow spectrum, when combined with data at other frequencies \[171,16,133\]. Observations in the near-infrared range are therefore critical for the study of afterglows.

4.2 Absorption features

Low and medium resolution spectra of bright optical afterglows have allowed, in a number of cases, the detection of absorption lines of metallic species caused by intervening absorbers, and the measurement of lower limits to the GRB redshift (see Table 1 and Fig.2). Frequently, the evidence of a low-ionization, high density medium (e.g., related to the detection of Mg I in absorption) suggests that the absorbing system is actually the host galaxy \[163,236,156\]. Spectroscopy of the
likely host galaxy generally shows that the highest absorption redshift coincides with the redshift of the galaxy emission lines, confirming the association of the GRB with the proposed host. No variability of the absorption line equivalent widths is detected at the 20% level (which represents the 1-σ uncertainty on the measurements) in time scales of some hours to few days [236].

For GRB000301C and GRB000131 the redshift has been determined through identification of absorption edges with the Lyman limit and intervening Lyα forest, respectively. The afterglow of the former GRB is the only one which has been observed by HST at ultraviolet wavelengths: in the low-resolution spectrum taken 5 days after explosion with the STIS instrument equipped with the NUV MAMA prism a discontinuity at ∼2800 Å is clearly detected, which has been identified with the hydrogen ionization edge [223], implying z ≃ 2 (see Fig.3). The measurement was then confirmed and refined from optical spectroscopy at the Keck and VLT telescopes [28,124]. The redshift of GRB000131, z ≃ 4.5, was determined photometrically from simultaneous near-infrared and optical observations (see Fig.4), and supported by optical spectrophotometry [4].

The distance of GRB980329 is controversial: the afterglow photometry suggests a redshift as large as z ∼ 5 or lower, 3 ≤ z ≤ 4.4, according to whether the observed continuum suppression shortward of ∼6500 Å is identified with Lyα intervening absorption [59], or with molecular hydrogen dissociation by the strong initial ultraviolet flash [52]. A redshift z < 3.9 would be suggested by the absence of the Lyα break in the host galaxy spectrum [138,51].

The redshifts measured so far either with spectroscopy or broad-band photometry span the range ∼0.4 to ∼4 (Table 1), excluding the peculiar case of GRB980425 (see chapters by T. Galama and K. Iwamoto), and prove that long
duration GRBs have an extragalactic, cosmological origin, which makes their early bright optical afterglows excellent probes of the high redshift universe.

5 Host galaxies

For almost every well studied optical afterglow, deep late epoch optical or near-infrared observations from the ground or with HST have detected a galaxy close to the point-like optical transient or at its position after it has faded away (see Table 1). Host galaxies have been detected also for some dark GRBs with arcsecond afterglow localizations from radio telescopes or from Chandra. Few observations of host galaxies have been made at longer wavelengths [224,101,11,57]. The hosts optical magnitudes (and upper limits) are consistent with those expected for a reasonable redshift distribution and galaxy population [107]. This solves the “no-host galaxy” problem [217,3,113], which, a posteriori, turns out to be clearly related to the very faint flux of the host galaxies, which are usually detected only with long exposures at telescopes larger than 2m.

HST observations taken at early stages of the afterglow evolution, when the transient is still bright (see Fig.3), show that this lies always within the stellar field of its host galaxy. If only late epoch HST images are available, their comparison with accurate astrometry of the bright transient on early epoch ground-based images still yields projected angular offsets of a fraction of an arcsecond.

Fig. 3. Deconvolved, flux-calibrated, ultraviolet spectrum of GRB 000301C taken with the HST STIS NUV MAMA prism. A break is clearly seen at 2797 Å. If caused by the onset of Lyman continuum absorption due to H I gas associated with the host galaxy, the redshift is $z = 2.067 \pm 0.025$. This matches with the ground-based measurement of the redshift (from [229]).
Spectral energy distribution of the GRB000131 afterglow, corrected for Galactic reddening, as derived from broad band VLT and NTT photometry. The uncertainties of the $H$- and $K$-band fluxes include the formal error from the extrapolation of the light curves back to the epoch of the optical measurements, $t = 3.5$ days. A fit with a power-law spectrum with Ly$\alpha$ forest absorption and SMC reddening is shown as a dashed curve. This yields $A_V = 0.18$, when an intrinsic spectral slope $\beta = 0.70$ and a redshift of 4.5 is assumed. The solid curve shows the corresponding spectrum with its Lyman absorption edges (from [4]).

between the transient and the galaxy center. When normalized to the individual hosts half-light radii, the median offset is 0.98 [21]. This has led to the conclusion that GRBs are associated with star forming regions, which would support their origin as hypernovae [109] (or collapsars [152]) or as supranovae [234], as opposed to progenitor scenarios which envisage the explosion as taking place at many kiloparsecs from the parent galaxy, in its halo (like binary neutron star systems, see chapter by E. Waxman).

There is specific evidence that host galaxies of GRBs undergo strong star formation: 1) their integrated colors are remarkably blue [60, 61]; 2) they are usually underluminous (luminosities of a fraction of the characteristic luminosity $L_\ast$ of the Schechter [219] luminosity function), small, and have often a compact morphology [103, 188, 62], which are characteristics common to galaxies hosting star formation at the typical GRB redshifts, $z \sim 1$ [60]; 3) their spectra exhibit star formation emission lines like [O II], [Ne III] (Fig.3), [O III], Ly$\alpha$ and Balmer series [14, 32, 14, 236, 7]; 4) their star formation rates, derived either from the emission line intensities or from the ultraviolet rest frame galaxy continuum are high, compared with the galaxy size [10, 43, 113, 236, 15], although sometimes substantially obscured [49, 3] and possibly measurable only at rest frame far-infrared wavelengths [57]; 5) they sometimes have morphologies consistent with being mergers or interacting systems [61, 13, 50], where star formation is
enhanced. Furthermore, the imprints of local extinction on the afterglow spectra (see §4.1) point to dusty and likely star forming environments as the favored GRB explosion sites. Finally, the observed host galaxy magnitudes and redshifts are consistent with a model in which the comoving rate density of GRBs is proportional to the cosmic star formation rate density [107,153,131,200,241]. These suggestions are consistent with the fact that most measured GRB redshifts are around \( z \sim 1 \), where the cosmic star formation rate is one order of magnitude larger than locally [139]. Since this is predicted to increase monotonically back to \( z \sim 10 \), one may expect that, given the opportunity of detecting GRBs up to that redshift, it would be possible to select the youngest star forming galaxies in the universe.

6 Conclusions: open problems and future prospects

The enormous progress achieved over the last few years through the optical afterglow follow-up study has also indicated some fundamental, unclear aspects of GRB and afterglow physics: 1) the conversion of energy into radiation; 2) the structure and geometry of the emitting regions; 3) the nature, density and composition of the circumburst medium; 4) the cosmological evolution of the GRB population. The solution of these problems would ultimately lead to unveiling the major unknown, i.e. the identity of GRB progenitors. While at the present stage these issues remain a matter of investigation, current knowledge suggests the observational approach to tackle them most effectively.

The most serious limitation of present day observations is the substantial temporal delay between GRB trigger and follow-up of its field at lower frequen-
Fig. 6. Spectrum of the host galaxy of GRB970508, obtained at the Keck telescope. Prominent emission lines are labeled (from [14]).

Light changes (a few hours). This causes a lack of sampling of the initial portions of the light curves. Bridging this gap will be possible when real-time disseminated localizations, made available by the coming generation of high energy satellites, can be rapidly followed by small, fast reacting telescopes with suitably large fields of view. Thanks to the UVOT camera onboard the GRB mission SWIFT (to be launched in 2003) and to the advent of ground-based robotic telescopes [18, 21, 73, 23], the monitoring will start as early as few tens of seconds after GRB detection, allowing astronomers to catch the transient counterpart in its maximum emission state, and to follow the temporal evolution of its optical-to-infrared continuum. It is at these early epochs that the models differ most in their predictions [41, 177, 212, 161], and the strength of the signal can discriminate them with the highest confidence. Early, simultaneous optical/near-infrared searches will either detect more counterparts, and reduce the number of dark GRBs, or put stronger constraints on the “darkness”. With respect to robotic systems, all-sky optical monitoring cameras [183, 70] present the advantage that they would be independent from spacecraft triggers, and therefore they could detect possible precursors of GRBs and “burstless” afterglows [4], which would be obviously missed by robotic telescopes.

Weeks after the GRB explosion, the light curve will result from the sum of different components of comparable brightness: the fading afterglow, the possible supernova rising to maximum light, and the host galaxy. To disentangle these contributions we will need sensitive and densely sampled photometric observations at late epochs in the optical and infrared. These will also possibly

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1 Highly collimated jets misaligned with respect to the line of sight would prevent detection of the GRB, while its optical afterglow may become detectable after jet spreading [160].
discern the presence of a light echo, due to dust scattering [5,20] or sublimation [24,23]. This task is a prerogative of the sensitive, high resolution optical and near-infrared cameras in space, such as the HST WFPC2, STIS, NICMOS, and the newly-deployed Advanced Camera for Surveys. The future NGST will collect the legacy of these instruments and push the research on GRB late afterglows and hosts toward even larger redshifts.

The measurement of a large number of redshifts, through early absorption spectra of optical afterglows as well as emission line spectra of the host galaxies, is necessary to construct a luminosity function of GRBs to be compared with models of star forming rate evolution. This will allow us to test the link between GRBs and star formation history up to very high redshifts, many hints of which have been so far collected [13]. A primary role in early and late sensitive optical and infrared spectroscopy will be played by the ground-based 4 to 8 m class telescopes in both hemispheres. Early bright counterparts will be excellent targets for spectroscopic monitoring; variations in the equivalent widths of the absorption lines will be measured with good signal-to-noise ratio, thus making it possible to place constraints on the density and distribution of the circumburst medium [14,18,13], which is a critical diagnostic of the GRB progenitor. Furthermore, the intense initial optical flares associated with GRBs will also act as background “light bulbs” to probe the ionization state and metallicity of the intergalactic medium through high resolution spectroscopy. More generally, multiwavelength observations of GRBs allow a series of cosmological tests on a wide range of redshifts [14,12186] (see also chapter by A. Loeb).

Prompt, long and intensive polarimetric monitoring of afterglows will detect possible changes of polarized light percentage and position angle and thereby set constraints on the most important open issue of afterglow physics, the generation of magnetic fields [9,94,95,157,85]. Moreover, knowledge of the magnetic field geometry and of the circumburst density profile will be instrumental to defining the structure of the jet and its interaction with the ambient medium.

Finally, real time dissemination of accurate localizations of sub-second GRBs and the prompt follow-up of these fields in the optical will hopefully afford detection of their elusive counterparts, and will allow us to get clear insights into their genesis and physics.

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### Table 1. Parameters of GRB Optical Counterparts

| GRB     | Instr.  | $z$  | $\alpha_1$ | $\alpha_2$ | $R_{OT}^{a,b}$ (mag) | $R_{host}^{d,e}$ (mag) | $A_R^{g}$ (mag) | Refs.   |
|---------|---------|------|-------------|-------------|----------------------|-----------------------|----------------|---------|
| 970228  | BeppoSAX | 0.695 | 1.7         |            | 20.3 ± 0.2          | 24.6 ± 0.2            | 0.63                | [77, 73, 24] |
| 970508  | BeppoSAX | 0.835 | 1.3         |            | 21.0$^b$ ± 0.1     | 25.0 ± 0.2            | 0.13                | [163, 140, 62] |
| 970828  | BATSE/RXTE | 0.9578 | ...         | ...         | > 23.7 (4 h)        | 23.8 ± 0.1            | 0.10                | [160, 123]  |
| 971214  | BeppoSAX | 3.418 | 1.4         |            | 23.0 ± 0.1          | 26.2 ± 0.2            | 0.04                | [132, 77, 168] |
| 980326  | BeppoSAX | ∼ 1$^i$ | 2.0         |            | 22.8 ± 0.1          | $V = 29.0 ± 0.3$      | 0.21                | [53, 92, 76] |
| 980329  | BeppoSAX | 3-5   | 1.2         |            | 23.7 ± 0.2          | 27.8 ± 0.3            | 0.19                | [59, 137, 70, 108, 112] |
| 980425  | BeppoSAX | 0.0085 | ...         | ...         | 15.60 ± 0.05        | 14.11 ± 0.05          | 0.17                | [230, 77, 72] |
| 980519  | BATSE/WFC | ...   | 1.73 - 2.22 |            | 20.64 ± 0.03        | ∼ 25.5                | 0.69                | [123, 100, 108] |
| 980613  | BeppoSAX | 1.097 | ∼ 0.2 - 1  |            | 23.1 ± 0.1          | 24.3 ± 0.2            | 0.23                | [105, 48, 98, 117] |
| 980703  | BATSE/RXTE | 0.966 | 1.4         |            | 21.00 ± 0.05        | 22.4 ± 0.1            | 0.15                | [37, 32, 133] |
| 981226  | BeppoSAX | ...   | ...         | > 23 (10 h)    | 24.2 ± 0.1          | 0.06                 | [140, 11]          |
| 990123  | BeppoSAX | >1.004 | 1.13 - 1.8  |            | 20.4 ± 0.1          | 23.9 ± 0.1            | 0.04                | [134, 83, 61] |
| 990308  | BATSE/RXTE | ...   | ∼ 1.2       |            | 20.7 ± 0.1          | > 28.4                | 0.07                | [215, 109] |
| 990506  | BATSE/RXTE | 1.3   | ...         | > 19 (1 h)    | 24.8 ± 0.3          | 0.18                 | [18, 247, 110] |
| 990510  | BATSE/WFC | >1.619 | 0.82 - 2.18 |            | 19.00 ± 0.05        | $V = 27.4 ± 0.3$      | 0.53                | [236, 102, 11] |
| 990705  | BeppoSAX | ~0.86 | 1.7 - 2.6   |            | $V = 19$           | 22.0 ± 0.1            | 0.20                | [154, 211] |
| 990712  | BeppoSAX | 0.4331 | 0.97        |            | 21.25 ± 0.05        | 21.90 ± 0.15          | 0.08                | [236, 210, 13] |
| 991208  | IPN      | 0.706 | 2.3$^f$ - 3.2| 18.5 ± 0.1 (2 d) | 24.2 ± 0.2          | 0.04                 | [35, 15]           |
| 991216  | BATSE/RXTE | 1.02  | 1.0 - 1.8   |            | 18.0 ± 0.1          | 25.3 ± 0.2            | 1.64                | [237, 193, 100] |
| 000131  | IPN      | 4.5   | 2.3         |            | 23.0 ± 0.1 (3 d)    | > 25.6                | 0.14                | [3]          |
| 000210  | BeppoSAX/CXO | 0.846 | ...         | > 22 (12.4 hr)| 23.5 ± 0.1          | 0.05                 | [195]              |
| 000301C | IPN      | 2.04  | 1.1 - 2.9   |            | 20.1 ± 0.1 (2 d)    | 28.0 ± 0.3            | 0.13                | [124, 223, 83, 153, 67] |
| 000418  | IPN      | 1.118 | 1.22        |            | 21.9 ± 0.1 (3 d)    | 23.8 ± 0.2            | 0.08                | [163, 29, 164] |
| 000630  | IPN      | ...   | 1.0         |            | 23.2 ± 0.2          | 26.7 ± 0.2            | 0.03                | [73, 1426] |
| 000911  | IPN      | 1.058 | 1.4         | 20.40 ± 0.08 (1.4 d) | ∼ 25               | 0.31                 | [31, 46, 173] |
| 000926  | IPN      | 2.037 | 1.5 - 2.3   |            | 19.50 ± 0.02        | ∼ 25               | 0.06                | [29, 174, 107] |
| 001007  | IPN      | ...   | 2.05        | 20.2 (3.5 d)  | 24.73 ± 0.15        | 0.11                | [196, 30]          |
| 001011  | BeppoSAX | ...   | 1.33        |            | 22.4 ± 0.1          | 25.1 ± 0.3            | 0.26                | [87]          |
| 001018  | IPN      | ...   | ...         | > 22.6 (> 2 d)  | 24.50 ± 0.09        | 0.06                | [19]              |
| 010222  | BeppoSAX | 1.476 | 0.65 - 1.7  |            | 20.15 ± 0.05        | 25.7 ± 0.2            | 0.06                | [123, 156, 227, 68] |
Table 1. (Continued)

| GRB   | Instr.\textsuperscript{b} | $z$  | $\alpha_1$ | $\alpha_2$ | $R_{OT}^{d,e}$ (mag) | $R_{host}^{d,\text{f}}$ (mag) | $A_R^{g}$ (mag) | Refs. |
|-------|---------------------------|------|-------------|-------------|----------------------|--------------------------|----------------|-------|
| 010921 HETE-2 | 0.45 | 1.59 | 19.29 ± 0.06 | 21.40 ± 0.05 | 0.38 | 19\textsuperscript{8} |
| 011030\textsuperscript{k} BeppoSAX | ... | ... | >21 (8 hr) | $V \sim 25$ | 1.00 | 71, 166 |
| 011121 BeppoSAX | 0.36 | 1.7 | 19.47 ± 0.05 | 24.70 ± 0.05 | 1.26 | 27, 124 |
| 011211 BeppoSAX | 2.14 | 0.83 | 1.7 | 20.9 ± 0.1 | 25.0 ± 0.3 | 0.11 | 70, 14, 27 |

\textsuperscript{a} Detected before the end of year 2001.

\textsuperscript{b} Instrument, or suite of instruments, which localized the GRB.

\textsuperscript{c} Temporal decay index in the $R$ band, $f(t) \propto t^{-\alpha}$.

\textsuperscript{d} Magnitudes are in the Cousins system.

\textsuperscript{e} Magnitude of the transient 1 day after the explosion (unless noted otherwise), corrected for the host galaxy contribution and for Galactic extinction.

\textsuperscript{f} Host galaxy magnitude, corrected for Galactic extinction.

\textsuperscript{g} Galactic extinction derived from the dust maps of Schlegel et al. [220], except for GRB970228 [60].

\textsuperscript{h} At 1 day after the explosion, the afterglow was still rising, therefore this magnitude is observed, and not derived from a fit.

\textsuperscript{i} Estimate based on decomposition of the optical transient light curve [3].

\textsuperscript{j} Castro-Tirado et al. [26] argue that the slope may be flatter at times earlier than 2 days, based on an upper limit obtained soon after the GRB by sky patrol films.

\textsuperscript{k} This event belongs to the class of X-ray rich GRBs (a.k.a. X-ray flashes), see chapter by F. Frontera.
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