Are the hosts of Gamma-Ray Bursts sub-luminous and blue galaxies? ⋆, ⋆

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Abstract. We present $K$-band imaging observations of ten Gamma-Ray Burst (GRB) host galaxies for which an optical and/or radio afterglow associated with the GRB event was clearly identified. Data were obtained with the Very Large Telescope and New Technology Telescope at ESO (Chile), and with the Gemini-North telescope at Mauna Kea (Hawaii). Adding to our sample nine other GRB hosts with $K$-band photometry and determined redshifts published in the literature, we compare their observed and absolute $K$ magnitudes as well as their $R-K$ colours with those of other distant sources detected in various optical, near-infrared, mid-infrared and submillimeter deep surveys. We find that the GRB hosts galaxies, most of them lying at $0.5 \lesssim z \lesssim 1.5$, exhibit very blue colours, comparable to those of the faint blue star-forming sources at high redshift. They are sub-luminous in the $K$-band, suggesting a low stellar mass content. We do not find any GRB hosts harbouring $R$- and $K$-band properties similar to those characterizing the luminous infrared/submillimeter sources and the extremely red starbursts. Should GRBs be regarded as an unbiased probe of star-forming activity, this lack of luminous and/or reddened objects among the GRB host sample might reveal that the detection of GRB optical afterglows is likely biased toward unobscured galaxies. It would moreover support the idea that a large fraction of the optically-dark GRBs occur within dust-enshrouded regions of star formation. On the other hand, our result might also simply reflect intrinsic properties of GRB host galaxies experiencing a first episode of very massive star formation and characterized by a rather weak underlying stellar population. Finally, we compute the absolute $B$ magnitudes for the whole sample of GRB host galaxies with known redshifts and detected at optical wavelengths. We find that the latter appear statistically even less luminous than the faint blue sources which mostly contributed to the $B$-band light emitted at high redshift. This indicates that the formation of GRBs could be favoured in particular systems with very low luminosities and, therefore, low metallicities. Such an intrinsic bias toward metal-poor environments would be actually consistent with what can be expected from the currently-favoured scenario of the “collapsar”. The forthcoming launch of the SWIFT mission at the end of 2003 will provide a dramatic increase of the number of GRB-selected sources. A detailed study of the chemical composition of the gas within this sample of galaxies will thus allow us to further analyse the potential effect of metallicity in the formation of GRB events.

Key words. galaxies: starburst – galaxies: evolution – cosmology: observations – gamma rays: bursts –
1. Introduction

In the past few years, a variety of high redshift star-forming galaxies have been discovered, which are key to understanding the evolution of the universe. These objects, usually found in dense regions, are believed to have fueled the most powerful episodes of star formation such as the luminous starburst galaxies. The discovery of X-ray/optical/radio transient counterparts to long-duration GRBs, the "collapsar" model, linking these events to the cataclysmic destruction of massive stars has indeed received a strong support from a growing number of evidence. These include the presence of dust extinction in the X-ray and optical transients (e.g., Galama & Wijers 2001), the spectral energy distribution and morphology of GRB hosts consistent with compact, irregular or merger-driven starbursts (e.g., Bloom et al. 2002a; Sokolov et al. 2001; Djorgovski et al. 1998), and the GRB localizations within their hosts suggesting a population of disk-residing progenitors (Bloom et al. 2002a). Moreover, the iron emission lines detected in their X-ray afterglows (e.g., Piro et al. 2000) and the late-time brightenings observed in the light-curves of several GRB optical transients (e.g., Galama et al. 2000) have been interpreted as the signature for the presence of an underlying supernova occurring with the GRB explosion, and thus provided further clues for the "collapsar" scenario. Because of the short-lived nature of massive stars, and because gamma-rays do not suffer from significant extinction, GRBs could thus be used to sign-post the instantaneous star formation in the Universe independently of the effects of dust extinction.

In this perspective, it is especially crucial to establish whether GRB-selected galaxies are really representative of the star-forming sources in the field at similar redshifts (Schaefeli et al. 2000), or whether they may form a particular category of new objects or any sub-sample of an already-known population of galaxies. Physical properties of the circum-burst environment could play a crucial role in the formation of these cataclysmic events. For example, GRBs could be favoured in low-metallicity regions of star formation (MacFadyen & Woosley 1999), and we would expect to detect these phenomena preferentially in dwarf and sub-luminous galaxies. On the other hand, their association with the destruction of massive stars may imply that GRBs are mostly observed in environments experiencing powerful episodes of star formation such as the luminous starburst galaxies.

Here we report on our GRB host imaging program carried out in the near-infrared (NIR) at European Southern Observatory (ESO) and Gemini Observatory. This program complements the K-band data of GRB host galaxies at Mauna Kea (Hawaii) under Proposal GN-2001A-Q-58.
0′6 and 1′5 from one night to another. Individual frames were obtained as a co-addition of 12 single exposures of 10 seconds each. The series of acquisition for each object were then carried out in a jitter mode, with a dither of the frames following either a random pattern characterized by typical offsets ∼ 30″ on the sky for the ISAAC and SOFI images, or a regular grid with shifts of 5″ for the Hokupa’a data. For the ISAAC observations, we reached a total on-source integration time of 1 hour per object.

Data reduction was performed following the standard techniques of NIR image processing. To estimate the thermal background contribution of each frame, a “sky” map was generated using a median-average of the 9 jittered images directly preceding and following a given acquisition. The corresponding “sky” was then scaled to the mode of the object frame and subsequently subtracted. This method allowed us to remove in the meantime the contributions of the bias and dark current. Finally, the differential pixel-to-pixel response of the arrays was corrected using flat-field images taken as part of the instrument calibration plans. For the ISAAC and Hokupa’a data, these flat-fields were obtained by observing a blank-field of the sky during twilights, while a white screen within the dome of the NTT was used for the SOFI observations. For the latter, we noticed that the low spatial frequencies of the detector sensitivity were not properly taken into account with the dome images. They were therefore corrected using a low-order polynomial 2D-fit of the array response, a method often refered as the “illumination correction technique”. Photometric calibrations were performed using the NICMOS standard stars from Persson et al. (1998).

2.2. Photometry

Each galaxy was observed more than 150 days after the date of its hosted GRB event (see column 3 of Table 1). Assuming the least favourable case of a bright GRB optical transient (R mag ∼ 20 at GRB + 2 days) with a break in the light-curve occurring ∼ 2 days after the burst and a slow decay with time (temporal index β ∼ −1.5), we estimate that all GRB counterparts should have been fainter than R mag ∼ 35 at the time of the observations. Taking account of a power law spectrum $F_{\nu} \propto \nu^{-1}$ for the modelling of the afterglow emission, we set a lower limit $K$ mag $\approx 33$. In our data, the flux contribution of any extra light from the fading afterglows should therefore be completely negligible relative to the emission of the host galaxies.

Our final images are presented in Fig. 1. For each observation, the astrometry was performed using foreground stars of the USNO catalog, and the GRB hosts were identified within 1″ of the positions of the GRB transients. Among the ten sources of our sample, six host galaxies are clearly detected in our $K_s$-band data. Using the task phot in the IRAF package\(^1\), we measured their total magnitude in an aperture of 5″ in diameter centered on the source, with the exception of GRB990506 host which lies only ∼ 1.8″ from another extended object. Since this host galaxy has a very compact morphology at optical wavelengths (FWHM ∼ 0.14″), as revealed by the high resolution HST images (Holland et al. 2000c), we assumed that we get a good estimation of its overall emission within an aperture of ∼ 1.5″ in diameter, inside which ∼ 95%

\(^1\) http://iraf.noao.edu/iraf/web/

| Table 1. Summary of observations |
|---------------------------------|
| Source ¶ | GRB II | $T_{\text{obs}} - T_{\text{grb}}$ (days) | On-Source Time (s) | Seeing (″) |
|-------------------|-------------------|-------------------|-------------------|-------------------|
| **ISAAC observations** |
| GRB J115450.1–264035 | 990506 | 701 | 3600 | 1.05 |
| GRB J182304.6–505416 | 001011 | 173 | 3600 | 0.70 |
| GRB J122519.3+200611 | 000418 | 422 | 3600 | 1.50 |
| GRB J015915.5–403933 | 000210 | 509 | 3600 | 1.20 |
| GRB J232937.2–235554 | 981226 | 893 | 3600 | 0.85 |
| GRB J061331.1–515642 | 000131 | 599 | 3600 | 0.75 |
| GRB J133807.1–802948 | 990510 | 697 | 3600 | 1.05 |
| **SOFI observations** |
| GRB J223153.1–732429 | 990712 | 403 | 5520 | 0.60 |
| GRB J122311.4+064405 | 990308 | 362 | 4200 | 0.75 |
| **Hokupa’a/QUIRC observations** |
| GRB J070238.0+385044 | 980329 | 1000 | 4320 | 0.15‡ |

Notes:  
¶: host galaxies, named after their selection criteria (GRB) and their equatorial coordinates given in the standard equinox of J2000.0.  
II: official designation of the Gamma-Ray Burst which led to the selection of the corresponding host galaxy.  
†: number of days between the GRB event and the date of our observations of the host galaxy.  
‡: resulting from the Hokupa’a Adaptive Optics correction.
Fig. 1. Near-infrared images of the Gamma-Ray Burst host galaxies listed in Table 1. Observations were performed with a $K_s$ filter, except in the case of the GRB 980329 host for which a $K'$ filter was used. Each frame has a field of view of $45'' \times 45''$ and an orientation with the North to the top and the East to the left. From the top to the bottom and from the left to the right, they were tentatively ordered with increasing distance of the host from Earth. The GRB 981226 and GRB 001011 host galaxies have been assigned a plausible redshift range as described in Sect. 3.1, while references for the other redshifts are given in Table 2. In the last four images, the targets were not detected.
of the total flux would be included if the light profile is
gaussian. Given our typical uncertainty on the photometry
(∼0.2 mag) and taking account of the prescriptions men-
tioned in the ISAAC Data Reduction Guide\(^2\), we found
the \(K - K_s\) colour terms to be negligible in the final
conversions to \(K\) magnitudes.

The foreground Galactic extinctions in the direction
of our targets were derived from the DIRBE/IRAS dust
maps of Schlegel et al. (1998), assuming the \(R_V = 3.1\)
extinction curve of Cardelli et al. (1989). The final dered-
ddened magnitudes of our sources are given in Table 2,
together with their redshifts obtained from various papers of
the literature. To increase the size of our sample, we also
added in our analysis nine other GRB hosts with a de-
termined \(K\)-band photometry already published by other
authors (see caption of Table 2 for references). Including
our results, the number of GRB host galaxies detected in
the NIR by October 2002 thus amounts to 15 sources\(^3\)

\(^2\) http://www.eso.org/instruments/isaac/drg/html/drg.html

\(^3\) We did not consider the case of GRB980613. In spite of
the \(K\)-band detection of its complex host-environment by
Djorgovski et al. (2001), the \(K\) magnitude of its true host

| Source          | GRB          | \(z\) | Ref. | \(K\) mag | References | \(R - K\) colour \(\dagger\) | Abs. \(K\) mag. \(\ddagger\) |
|-----------------|--------------|------|------|----------|------------|--------------------------|--------------------------|
| GRB J225559.9+405553 | 010921      | 0.45 | 1    | 19.05 ± 0.1 | 1          | 2.40 ± 0.25               | -22.50                  |
| GRB J142121.5+330106 | 010222      | 1.48 | 2    | 23.5 ± 0.0\(\dagger\) | 3          | 2.20 ± 0.30               | -21.25                  |
| GRB J182304.6–505416 | 010011      |      |      | 21.45 ± 0.2 | this work  | 3.75 ± 0.45               |                         |
| GRB J122519.3+200611 | 000418      | 1.12 | 4    | 21.3 ± 0.2 | this work  | 2.50 ± 0.40               | -22.65                  |
| GRB J015915.5–403933 | 000210      | 0.85 | 5    | 20.95 ± 0.2 | this work  | 2.50 ± 0.30               | -22.25                  |
| GRB J061331.1–515642 | 000131      | 4.5  | 6    | ≥ 22.5     | this work  |                         |                         |
| GRB J163353.5+462721 | 991208      | 0.71 | 7    | 21.7 ± 0.2 | 8          | 2.60 ± 0.40               | -21.00                  |
| GRB J222153.1–732429 | 990712      | 0.43 | 9    | 20.05 ± 0.1 | this work  | 1.80 ± 0.30               | -21.40                  |
| GRB J133807.1–802948 | 990510      | 1.62 | 9    | ≥ 22.5     | this work  |                         |                         |
| GRB J115450.1–264035 | 990506      | 1.31 | 4    | 21.45 ± 0.2 | this work  | 4.05 ± 0.35               | -22.90                  |
| GRB J122311.4+604405 | 990308      |      |      | ≥ 21.5     | this work  |                         |                         |
| GRB J152530.3+444559 | 990123      | 1.60 | 10   | 21.9 ± 0.4 | 8, 11      | 2.40 ± 0.80               | -23.10                  |
| GRB J232937.2–235554 | 981226      |      |      | 21.1 ± 0.2 | this work  | 3.40 ± 0.50               |                         |
| GRB J235906.7+083507 | 980703      | 0.97 | 12   | 19.6 ± 0.1 | 8          | 2.80 ± 0.30               | -23.95                  |
| GRB J070238.3+385044 | 980329      |      |      | ≥ 23.0     | this work  |                         |                         |
| GRB J115626.4+651200 | 971214      | 3.42 | 13   | 22.4 ± 0.2 | 8          | 3.20 ± 0.40               | -24.45                  |
| GRB J180831.6+591851 | 970828      | 0.96 | 14   | 21.5 ± 0.3 | 14         | 3.60 ± 0.60               | -22.05                  |
| GRB J065349.4+791619 | 970508      | 0.83 | 15   | 22.7 ± 0.2 | 8          | 2.40 ± 0.40               | -20.45                  |
| GRB J050146.7+114654 | 970228      | 0.69 | 16   | 22.6 ± 0.3 | 8, 17      | 2.00 ± 0.50               | -20.05                  |

Notes:
\(\dagger\) : for all sources except the GRB981226 and GRB001011 hosts, the \(R - K\) colours were estimated using the \(R\) magnitudes
given in Table A.1 of Appendix A. The \(R\)-band photometry for the host galaxy of GRB981226 has been derived from
Saracco et al. (2001b), Frail et al. (1999) and Holland et al. (2000b), while that of the GRB001011 host is taken from
Gorosabel et al. (2002).

\(\ddagger\) : defined as \(M_K + 5 \log_{10} h_{65}\) assuming a ΛCDM Universe with \(\Omega_m = 0.3\) and \(\Omega_k = 0.7\) (\(h_{65} = H_0 / (\text{km s}^{-1}\text{Mpc}^{-1}) / 65\)).

\(\dagger\) : estimated from an extrapolation of the afterglow \(K\)-band light curve (Frail et al. 2002).

References: (1) Price et al. 2002a; (2) Jha et al. 2001; (3) Frail et al. 2002; (4) Bloom et al. 2002a; (5) Piro et al. 2002; (6) Andersen et al. 2001; (7) Castro-Tirado et al. 2001; (8) Chary et al. 2002; (9) Vreeswijk et al. 2001; (10) Kulkarni et al. 1999; (11) Bloom et al. 1999a; (12) Djorgovski et al. 1998; (13) Kulkarni et al. 1998; (14) Djorgovski et al. 2001; (15) Bloom et al. 1998a; (16) Bloom et al. 2001; (17) Fruchter et al. 1999a.

The GRB host galaxies span a broad range of redshifts
(\(0.2 \text{–} 23.0\)) and taking account of the prescriptions men-
tioned in the ISAAC Data Reduction Guide\(^2\), we found
the \(K - K_s\) colour terms to be negligible in the final
conversions to \(K\) magnitudes.

3. Results

The GRB host galaxies span a broad range of redshifts
(see Table A.1 of Appendix A), but the current sample of
these GRB-selected sources is actually too small to study
the evolution of their characteristics with different look-
back times. On the other hand, it can be particularly in-
teresting to consider these objects as a whole sample of
high-z sources, and compare their properties with other
field galaxies selected by different observing techniques. In
this section, we compare the observed and absolute mag-
nitudes of the GRB host galaxies at different wavelengths
(e.g., \(B\), \(R\), \(K\)-band) as well as their \(R - K\) colours,
with those of high redshift sources detected in the optical,
NIR, mid-infrared and submillimeter deep surveys.

\(\text{component H, see Hjorth et al. 2002}\) has not been determined
so far.

(1) Price et al. 2002c; (2) Jha et al. 2001; (3) Frail et al. 2002; (4) Bloom et al. 2002a; (5) Piro et al. 2002; (6) Andersen et al. 2001; (7) Castro-Tirado et al. 2001; (8) Chary et al. 2002; (9) Vreeswijk et al. 2001; (10) Kulkarni et al. 1999; (11) Bloom et al. 1999a; (12) Djorgovski et al. 1998; (13) Kulkarni et al. 1998; (14) Djorgovski et al. 2001; (15) Bloom et al. 1998a; (16) Bloom et al. 2001; (17) Fruchter et al. 1999a.
3.1. “K – z” and “R – z” diagrams

The Hubble “K–z” diagram of the GRB host galaxies is illustrated in Fig. 2. The spectroscopic redshifts of the GRB981226 and GRB001011 hosts have not been so far determined. Based on their K magnitude and R – K colour (see Sect. 3.2), we estimate that these objects could be located in the 0.7 < z < 1.4 redshift range. To allow comparisons with other sources in the field, we overplotted the K magnitudes of galaxies reported from various surveys. Nearby sources were taken from the Hawaii K–band galaxy survey (z = 0.35, Cowie et al. 1994; Songaila et al. 1994), while galaxies at intermediate redshift (z = 0.8) were derived from the Hawaii Deep Surveys by Cowie et al. (1996). Those at higher z (z = 1.5) were taken from the catalog of photometric redshifts in the Hubble Deep Field (HDF, Fernández-Soto et al. 1999). We also indicated the K magnitudes of the ISO sources observed in the CFRS and HDF with flanking fields as given by Flores et al. (1999), Hogg et al. (2000) and Cohen et al. (2000), as well as those of the NIR counterparts to the SCUBA sources with confirmed spectroscopic redshifts, obtained by Smail et al. (2002a) and Dev et al. (1999). The K–band luminosities of these SCUBA galaxies were de-magnified from gravitational amplification for the lensed cases.

The comparison suggests that in the NIR, the GRB host galaxies do not particularly distinguish themselves from the field sources selected in optical/NIR deep surveys. No particular bias of detection toward the luminous sources is in fact apparent. There is however a significant contrast between their K magnitudes and those of the ISO and SCUBA sources which, like the GRB hosts, are birthplaces of massive star formation. These differences of magnitudes and the implications on their absolute luminosities will be more firmly established in Sect. 3.3 and discussed in Sect. 4.

To further address the nature of galaxies selected by GRBs relative to other field sources at high redshift, we also present in Fig. 3 the Hubble “R–z” diagram for the sample of GRB hosts detected at optical wavelengths. Their R magnitudes are given in Table A.1. They were obtained from various papers of the literature and homogenized following the method described in Appendix A. This sample is significantly larger than the one selected in the K–band. In addition to the hosts which have not been imaged in the NIR yet, there is indeed a number of GRB host galaxies which were both observed at optical and NIR wavelengths, but only detected in the visible. This can be explained from the fact that the GRB hosts display blue colours (see Sect. 3.2) and that, for the faintest sources at R ~ 26–29, optical deep observations are generally more...
sensitive than NIR images to detect blue objects. It is also the reason why the scatter in the optical magnitudes appears larger than in the K-band.

In this “R–z” diagram, we have also indicated the R magnitudes of optically-selected galaxies from the Caltech Faint Galaxy Redshift Survey (Hogg et al. 2000) and the Hubble Deep Field (Fernández-Soto et al. 1999). For the latter, the R-band photometry was derived from the V and I magnitudes of the catalog assuming a linear interpolation between the mean wavelengths of the V-band (F606 WFPC filter, 6031Å) and the I-band (F801 WFPC filter, 8011Å). The conversion from the standard AB magnitudes to the Vega system used throughout this paper was obtained using the calibrations of Fukugita et al. (1995) and Alcaino (2000).

Again, the GRB hosts in the visible appear just typical of the other optically-selected galaxies at high redshift (see Fig.3). Yet, it is worth mentioning a particular feature of the GRB host sample, which is clearly apparent in this “R–z” diagram. Whereas most of field sources at Rmag > 25 have a redshift only determined with photometric techniques, the GRB hosts have an accurate spectroscopic redshift identification. These redshifts were derived using the emission and/or absorption features detected in the X-ray/optical spectra of GRBs and their afterglows. Such a method is independent of the GRB host luminosities, and only depends on the possibility to rapidly perform spectroscopy of the GRB transient before it has begun to fade. This advantage of GRBs for the selection of high-z sources lies in stark opposition with the deep survey approach. Note that it is particularly apparent in the “R–z” diagram, but it is not that exceptional at NIR wavelengths (see Fig.2). As mentioned previously, it is due to the blue colours of GRB hosts, which thus allow the faintest of these hosts detected in the K-band to be spectroscopically observed in the visible.

3.2. Colours

So far, the various works related to the understanding of the high redshift Universe have made an extensive use of the integrated R–K colours of galaxies as an indicator of their nature. These colours provide indeed a crucial information on the importance of the old stellar populations — as traced by the NIR emission — relative to the contribution of young stars dominating the optical light. For example, unobscured star-forming galaxies are typically blue objects (R − K ∼ 2–3) while old elliptical sources at z ≥ 1 exhibit extremely red colours (R − K ≥ 5). Furthermore, large R − K colours in distant sources can also suggest dust obscuration, and may thus signal post-powerful dust-enshrouded starburst galaxies.

In Table2, we indicate the observed R − K colours for the K–selected sub-sample of GRB host galaxies. The corresponding diagram showing these colours versus redshift is presented in Fig.4. As in the “K–z” relation displayed in Fig.2, we also plotted the R − K colours of optically-selected sources taken from the HDF (Fernández-Soto et al. 1999), and those of the ISO and SCUBA sources already considered in the previous section. The R magnitudes of the ISO galaxies from the CFRS were derived using an interpolation between the V and I magnitudes of Flores et al. (1999). Those of the HDF ISO detections and SCUBA sources were taken from the papers mentioned in Sect. 3.1.

In this diagram, we also indicate the hypothetical colours of typical present-day galaxies if they were moved to higher redshift assuming no evolution of their physical properties. These galactic templates were chosen to be mostly representative of the local Hubble sequence, and include both early-type (E/Sc) and late-type (Scd/Irr) sources. To compute the evolution of their R − K colours with redshift, we used the optical/NIR templates of Manucci et al. (2001) for the E and Sc types, and the optical Scd and Irr SEDs of Coleman et al. (1980). For the latter, the extrapolation to the near-infrared was derived using the NIR portion of the Manucci et al. Sc template. This decision was justified from the prescriptions of Pozzetti et al. (1996), which show that the NIR continuum emission of dust-free galaxies longward of 1μm always appears dominated by the same stellar populations, and therefore does not vary much from one type to another.

As it can be seen in Fig.3, the GRB hosts exhibit rather blue colours that are typical of the faint blue galaxy population in the field at z ∼ 1. Besides, we note that most of them appear even bluer than the colours predicted from the SED of local irregular galaxies. This is similar to what has been already noticed for a large fraction of blue sources detected in the optical deep surveys (Volonteri et al. 2000). Such blue colours originate from the redshifted blue continuum of the OB stars found in HII regions. They are characteristic of unobscured star-forming galaxies, which is not surprising in the scenario linking GRBs to massive star formation. It is moreover in full agreement with the results of Sokolov et al. (2001) who found that the optical SEDs of the GRB host galaxies are consistent with those of the blue starbursts observed in the nearby Universe.

3.3. Absolute K magnitudes

We computed the absolute K magnitudes for the sample listed in Table2 using the optical and NIR galaxy templates described in Sect. 3.2 to derive the k-corrections. For all but two sources, the latter were obtained assuming an SED typical of Irr-type objects as suggested by their blue R − K colours (see Sect. 3.2). In the case of the GRB990506 and GRB970828 hosts, we rather used an Scd-type template as indicated by their redder SEDs (see Fig.3). Luminosity distances were computed assuming a ΛCDM Universe with Ωm = 0.3 and Ωλ = 0.7. We parametrized the Hubble constant using h_{65} = H_0 (km s^{-1} Mpc^{-1}) / 65.
The absolute $K$ magnitudes are reported in Table 2 and illustrated in the Hubble diagram of Fig. 5. Again, we also compared the GRB host galaxies with other field sources quoted from the catalogs mentioned in Sect. 3.1. For the galaxies of the HDF, the k-corrections used to compute these magnitudes were derived assuming the best spectral type estimations of Fernández-Soto et al. (1999). Solid curves indicate the observed colours of local E, Sc, Scd and Irr galaxies if they were moved back to increasing redshifts (see text for explanations). We also indicated the colours of the ISO sources from the HDF (open squares) and those of SCUBA galaxies with confirmed redshifts (filled squares). See Sect. 3.2 for references.

We also indicated the absolute magnitudes of galaxies with luminosities of $0.1 L_\odot$ ($M = -22.5$), $L_\odot$ ($M = -25$) and $3L_\odot$ ($M = -26.2$), assuming $M_\odot = -25$. This value was roughly estimated from the Schechter parametrizations of the $K$-band luminosity function for high redshift galaxies, taken from Cowie et al. (1996) and Kashikawa et al. (2003). Both were determined assuming a matter-dominated Universe with $\Omega_m = 1$.

$$M_\odot = -25 + 5 \log_{10} \left[ H_0 (\text{km s}^{-1} \text{Mpc}^{-1}) / 50 \right] \alpha = -1.3$$

$$M_\odot = -25.9 + 5 \log_{10} \left[ H_0 (\text{km s}^{-1} \text{Mpc}^{-1}) / 50 \right] \alpha = -1.35$$

Nevertheless, the differences in comoving distance between a Universe with $H_0 = 50; \Omega_m = 1$ and one characterized by $H_0 = 65; \Omega_m = 0.3; \Omega_\Lambda = 0.7$ imply absolute magnitude variations of only $\Delta m = 0.4$ on the $0.7 \lesssim z \lesssim 3$ redshift range. Therefore, it should not significantly affect our qualitative comparison.

With a median–averaged $M_K = -22.25$ (corresponding to $T \sim 0.08 L_\odot$), the GRB host galaxies are significantly sub-luminous in the $K$-band. We also note a large difference with the luminosities of massive starbursts probed with ISO and SCUBA, as it was already noticed in Sect. 3.1. Since the NIR emission of galaxies gives a good indication on their mass, the low $K$-band luminosities of GRB hosts indicate that GRBs, so far, were not observed toward massive objects.

4. Discussion

Our analysis described in Sect. 3 indicates that the GRB host galaxies are characterized by rather blue colours (see Fig. 4), sub-$L_\odot$ luminosities (see Fig. 4) and low masses (see Fig. 5). Their morphology is moreover consistent with that of compact, irregular or merging systems (Bloom et al. 2002). Their spectra clearly exhibit prominent emission lines such as [OII], [NeIII] and the Balmer hydrogen lines (e.g., Djorgovski et al. 1998; Le Floc'h et al. 2002), and their optical SED is similar to that of starburst galaxies observed in the local Universe.
shown that a significant fraction of the Extremely Red Background (CIRB, Elbaz et al. 2002) produced at this epoch roughly originate from two distinct populations of star-forming sources, namely the faint blue galaxies and the luminous dusty starbursts (e.g., Rigopoulou et al. 2002). Given that the CIRB and the OEB are more or less equivalent in terms of bolometric luminosity (e.g., Hauser & Dwek 2001), and taking into account the contribution of the ISO sources to the CIRB, we found that approximately 25% of the GRB host galaxies should belong to the class of infrared dusty starbursts such as those detected with ISO. Within the sub-sample of GRB hosts observed in the $K$-band and located at $0.5 \leq z \leq 1.5$, 5–6 sources would thus be expected to exhibit $K$ luminosities greater than the estimates from UV–selected galaxies at $z \sim 1$ (Smail et al. 2002b). With a similar argument as aforementioned, we would expect to find several EROs among the GRB host sample, while all of the GRB host galaxies display $R - K$ colours bluer than $\sim 4$.

This lack of luminous ($L > L_\odot$) and red ($R - K > 4$) galaxies among the GRB hosts could be explained by the existence of the so-called “dark” bursts. Lacking counterparts at optical/NIR wavelengths in spite of a rapid and deep search of afterglows during the few hours following their detection at high energy, a fraction of these bursts could be hidden behind optically-thick columns of dust and gas, and thus would be obscured in the visible. Indeed, the spatial scale of dust-enshrouded regions of star formation in luminous infrared galaxies can easily reach $\sim 1$ kpc (Soifer et al. 2001). Even if the beamed emission of GRBs can destroy dust grains on distances up to $\sim 100$ pc from the burst location (Fruchter et al. 2001b), the resulting column density on the GRB line of sight would still be high enough to prevent the production of a detectable afterglow in the visible. Such GRBs could thus only be observed via the emission of their afterglows in the X-rays and, possibly, through their synchrotron emission at radio wavelengths. Since most of the currently known GRB hosts were selected using GRB optical transients, it may therefore indicate that the sample is likely biased toward galaxies harbouring unobscured star-forming activity.

In this hypothesis, we would have the rough picture in which most of GRBs with detectable optical transients mainly probe the dust-free starbursts hosted in sub-luminous blue galaxies, while the bursts occurring within the most dusty sources appear optically dark. Naturally, intermediate cases should also exist, as illustrated by the VLA detection of the GRB 980703 host galaxy (Berger et al. 2001b). Assuming that the radio/far-infrared correlation still holds for high redshift sources, this host pinpointed by an optical transient of a GRB occurring at $z = 0.97$ could be indeed a dusty galaxy luminous in the infrared. In fact, we note that its $R - K$ colour $\sim 2.8$ and its absolute $K$ magnitude $\sim 24.0$ would be consistent with this source being similar to the NIR counterparts of the ISO dusty starbursts (see Figs. 4 and 5). Other intermediate examples of dusty galaxies probed with optically bright GRB afterglows were also reported from the faint detections of the GRB 000418 and GRB 010222 hosts at submillimeter wavelengths (Berger et al. 2001a, Frail et al. 2002).

A possible method to reliably probe the dusty star formation with GRBs could be the use of optically-dark bursts yet harbouring detectable afterglows at radio wavelengths. However, the observations of four sources pinpointed with such optically-dark and radio-bright GRBs by Barnard et al. 2003 have not revealed these galaxies to be especially bright in the submillimeter. These particular bursts do not seem therefore to preferentially select obscured sources. This indicates that GRBs occurring within dust-enshrouded star-forming regions could probably be dark at both optical/NIR and radio wavelengths,
which might be understood if GRB radio transients can not be easily generated within the densest environments of dusty galaxies (Barnard et al. 2003).

It is therefore likely that the census of dust-enshrouded star formation with GRBs will require a follow-up of the bursts characterized by both optically- and radio-dark transients. The use of their X-ray afterglows will thus be needed to correctly localize these GRBs on the sky. To this purpose, the forthcoming GRB-dedicated SWIFT mission will enable to derive the positions of hundreds of GRBs with a sub-arcsecond error box from the sole detections of their afterglows in the X-rays. This should ultimately provide a statistically-significant sample of star-forming galaxies selected from high energy transients of GRBs, thus less affected by dust extinction than the current sample of GRB hosts. The study of these sources with the Space InfraRed Telescope Facility (SIRTF) will moreover allow to characterize their dust content by directly observing the thermal emission of these galaxies in the mid-infrared. Since the SIRTF instruments will be able to detect the rest-frame infrared emission of dusty starbursts up to $z \sim 2.5$, the parallel use of SWIFT and SIRTF will therefore open new perspectives to use GRBs as probes of the dusty star formation at high redshift.

On the other hand, we note that this apparent selection effect toward blue and sub-luminous sources may simply reflect an intrinsic property of the GRB host galaxies themselves. For example, GRBs could be preferentially produced within young systems experiencing their first episode of massive star formation, thus explaining the low mass of their underlying stellar populations and their apparent blue colors. A larger statistics and a better understanding of the possible observational bias associated with the GRB selection, as previously mentioned, will be however required to further investigate this hypothesis.

4.2. Are GRB hosts representative of the faint blue galaxy population at high redshift?

In the previous section, we have argued that the current sample of GRB hosts could be biased toward unobscured star-forming galaxies, and that such a bias could be related to the existence of the dark bursts. Since the long-duration GRBs are believed to trace the star-forming activity at high redshift, this sample of dust-free GRB-selected sources should be therefore more or less representative of the population of faint blue galaxies which were discovered in the optical deep surveys.

These faint blue sources in the field are indeed believed to produce the bulk of the OEB (Madan & Pozzetti 2000) and to be responsible for most of the unobscured star formation in the early Universe. Since the $B$–band emission is a good tracer of star-forming activity in dust-free sources, the absolute $B$ magnitude histogram of the GRB host sample, in this case, should closely follow the function of the $B$–band luminosity weighted by luminosity for blue galaxies at high redshift. The latter may indicate indeed, for a given bin of magnitude, the relative fraction of total star formation to which galaxies in this range of luminosity contributed as a whole. It should be therefore proportional to the fraction of GRB occurrence emerging from such galaxies.

Such a comparison is shown in Fig. 8. We computed the absolute magnitudes of the GRB host galaxies in the rest-frame $B$–band following the method described in Appendix A. To estimate the contribution of distant sources to the overall star-forming activity at similar redshifts, we used the results of the COMBO-17 Survey by Wolf et al. (2002), who derived the Schechter-parametrized luminosity functions for various types of galaxies up to $z \sim 1.2$, in a $\Lambda$CDM Universe with $\Omega_m=0.3$ and $\Omega_{\Lambda}=0.7$. We also used the observations of Kashikawa et al. (2003) from the Subaru Deep Survey who constrained the global function of the $B$–band luminosity for sources up to $z \sim 3.5$, in a flat Universe with $\Omega_m=1$. As explained in Sect. 3.3, the comoving distance variations between the two different cosmologies do not affect that much our comparisons. Assuming $M_{B,5} \sim -21+5 \log_{10} h_{65}$ for the blue galaxies at $z \sim 1$ (Wolf et al. 2002), it is clear that the GRB host galaxies are sub-luminous sources in the $B$–band. There is however an apparent and surprising trend for the GRB hosts to be, on average, even less luminous than the blue galaxies which mostly contributed to the energy density in the rest-frame $B$–band at $z \sim 1$. This apparent shift is unlikely due to the weak constraint which has been obtained so far on the faint end slope (usually referred as the parameter $\alpha$ in the Schechter parametrization) of the $B$–band luminosity function at high redshift. There are indeed noticeable discrepancies in this slope between the results of Kashikawa et al. ($-1.2 \lesssim \alpha \lesssim -0.9$) and those by Wolf et al. ($-1.5 \lesssim \alpha \lesssim -1.3$), but the implied variations on the $B$–band luminosity function weighted by luminosity are not that significant (see Fig. 8). To quantify the observed shift, we performed a Kolmogorov-Smirnov test on the data sets of GRB hosts and high redshift sources bluer than Sbc type objects. We obtained only a rather small probability ($\sim 17\%$) that the two distributions originate from the same population of galaxies. Could this shift be due to intrinsic properties of GRB host galaxies, and reveal that only particular environments favour the formation of GRB events?

In the “collapsar” scenario, GRBs are produced by the accretion of a helium core onto a black hole resulting from the collapse of a rapidly-rotating iron core. Since a low metallicity in the stellar envelope reduces the mass loss and inhibits the loss of angular momentum by the star, the formation of GRBs could be favoured in metal-poor environments (MacFadyen & Woosley 1999). As such, we could expect GRBs to be preferentially observed toward starbursts with very low luminosities. Interestingly, evidence for a low-metallicity host galaxy has been in fact recently reported toward the X-Ray Flash XRF 020903 (Chornock & Filippenko 2002). The influence of such intrinsic parameters could therefore not only explain the trend observed in Fig. 8, but it would also provide further
arguments for the lack of GRB host detections toward luminous reddened starbursts as discussed in the previous section.

Of course, one must remain very cautious regarding this interpretation, because of the small size of our sample. Moreover, the influence of metallicity in the formation of a GRB should be only localized in the close vicinity of the burst, whereas important gradients in the chemical composition of galaxies are commonly observed. However, we note that such gradients of metallicity are not present in local dwarfs (see Hidalgo-Gáméz et al. 2001 and references therein), which suggests that the average metallicity observed toward the sub-luminous GRB hosts should give a good estimation of the chemical properties characterizing the environments where the GRBs occurred. A detailed investigation of the gas metallicity within GRB host galaxies compared to other optically-selected sources has never been performed so far. Such a study will be definitely required to better address this issue.

5. Conclusions

Using our $K$-band observations of GRB host galaxies in combination with other optical and NIR data of the literature, we conclude that:

1) Most of the GRB hosts discovered so far belong to the population of faint and blue star-forming galaxies at high redshift. They have low masses as suggested by their faint luminosity in the near-infrared. They are also sub-luminous sources at optical wavelengths. Most of them are characterized by intrinsic $R-K$ colours even bluer than those displayed by the starburst galaxies observed in the nearby Universe.

2) The lack of GRB detection toward luminous starbursts and/or reddened sources such as those observed in the infrared and submillimeter deep surveys seems to indicate a possible bias of the currently-known GRB host sample against this type of objects. This could be explained by the fact that the selection of GRB host galaxies, so far, had to rely on the identification of optical GRB afterglows likely probing unobscured star-forming galaxies. The follow-up of optically-dark and radio-dark GRBs, and the use of their X-ray afterglows to obtain their localization with a sub-arcsecond error box will be likely necessary to probe dust-enshrouded star-forming galaxies in the early Universe with these particular phenomena. On the other hand, the hypothesis that such a bias of selection is purely intrinsic to the GRB host properties can not be rejected, assuming that GRBs preferentially occur within young and blue starbursts.

3) The observed GRB host galaxies seem to be statistically less luminous than the faint blue sources which mostly contributed to the $B$-band light emitted at high redshift. This could reveal an intrinsic bias of the GRB selection toward star-forming regions with very low luminosities, and might be explained taking account of particular environmental properties (e.g., metallicity) favouring the formation of Gamma-Ray Burst events. In this context, this could also indicate that GRBs can not be used as unbiased probes of star formation. A larger statistics of the GRB host absolute $B$ magnitudes and a detailed study of the chemical composition of the gas within GRB host galaxies will be however required to further confirm this result.

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References

Allen, C. W. 2000, “Allen’s Astrophysical Quantities”, 4th edition 2000, ed. A. N. Cox

Andersen, M. I., Hjorth, J., Pedersen, H., et al. 2000, A&A, 364, L54

Aussel, H., Cesarsky, C. J., Elbaz, D., & Starck, J. L. 1999, A&A, 342, 313

Barger, A. J., Cowie, L. L., Sanders, D. B., et al. 1998, Nature, 394, 248

Barnard, V. E., Blain, A. W., Tanvir, N. R., et al. 2003, MNRAS, 338, 1

Berger, E., Cowie, L., Aussel, H., et al. 2001a, GRB Circular Network, 1182

Berger, E., Kulkarni, S. R., & Bloom, J. S. 2001b, ApJ, 560, 652

Blain, A. W. & Natarajan, P. 2000, MNRAS, 312, L35

Bloom, J. S., Berger, E., Kulkarni, S. R., Djorgovski, S. G., & Frail, D. A. 2002a, ApJ, in press [astro-ph/0212123]

Bloom, J. S., Djorgovski, S. G., & Kulkarni, S. R. 2001, ApJ, 554, 678

Bloom, J. S., Djorgovski, S. G., Kulkarni, S. R., & Frail, D. A. 1999, ApJ, 518, L1

Burud, I., Rhoads, J., Fruchter, A., & Hjorth, J. 2001, GRB Circular Network, 1213

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

Castro, S., Galama, T., Harrison, F., et al. 2002, [astro-ph/0110560]

Castro-Tirado, A. J., Sokolov, V. V., Gorosabel, J., et al. 2001, A&A, 370, 398

Chary, R., Becklin, E. E., & Armus, L. 2002, ApJ, 566, 229

Chornock, R. & Filippenko, A. V. 2002, GRB Circular Network, 1609

Cohen, J. G., Hogg, D. W., Blandford, R., et al. 2000, ApJ, 538, 29

Coleman, G. D., Wu, C.-C., & Weedman, D. W. 1980, ApJS, 43, 393

Cowie, L. L., Gardner, J. P., Hu, E. M., et al. 1994, ApJ, 434, 114

Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839

Dey, A., Graham, J. R., Ivison, R. J., et al. 1999, ApJ, 519, 610

Djorgovski, S. G., Frail, D. A., Kulkarni, S. R., et al. 2001, ApJ, 562, 654

Djorgovski, S. G., Kulkarni, S. R., & Bloom, J. S. 2000, [astro-ph/0008029]

Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., et al. 1998, ApJ, 508, L17

Dutra, C. M., Bica, E., Clariá, J. J., Piatti, A. E., & Ahumada, A. V. 2001, A&A, 371, 895

Elbaz, D., Cesarsky, C. J., Chauhan, P., et al. 2002, A&A, 384, 848

Elbaz, D., Cesarsky, C. J., Fadda, D., et al. 1999, A&A, 351, L37

Fernández-Soto, A., Lanzetta, K. M., & Yahlil, A. 1999, ApJ, 513, 34

Flores, H., Hammer, F., Désert, F. X., et al. 1999, A&A, 343, 389

Fox, D. W., Kulkarni, S. R., & Weisssman, W. P. 2002, GRB Circular Network, 1427

Frail, D. A., Bertoldi, F., Moriarty-Schieven, G. H., et al. 2002, ApJ, 565, 829

Frail, D. A., Kulkarni, S. R., Bloom, J. S., et al. 1999, ApJ, 525, L81

Fruchter, A., Burud, I., Rhoads, J., & Levan, A. 2001a, GRB Circular Network, 1087

Fruchter, A., Hook, R., & Pian, E. 2000a, GRB Circular Network, 757

Fruchter, A., Krolik, J. H., & Rhoads, J. E. 2001b, ApJ, 563, 597

Fruchter, A. & Vreeswijk, P. 2001, GRB Circular Network, 1063

Fruchter, A., Vreeswijk, P., Hook, R., & Pian, E. 2000b, GRB Circular Network, 752

Fruchter, A. S., Pian, E., Gibbons, R., et al. 2000c, ApJ, 545, 664

Fruchter, A. S., Pian, E., Thorsett, S. E., et al. 1999a, ApJ, 516, 683

Fruchter, A. S., Thorsett, S. E., Metzger, M. R., et al. 1999b, ApJ, 519, L13

Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945

Galama, T. J., Tanvir, N., Vreeswijk, P. M., et al. 2000, ApJ, 536, 185

Galama, T. J. & Wijers, R. A. M. J. 2001, ApJ, 549, L209

Garnavich, P., Stanek, K., Wyzykowski, L., et al. 2002, [astro-ph/0204234]

Gorosabel, J., Fynbo, J. U., Hjorth, J., et al. 2002, A&A, 384, 11

Greiner, J. 2002, “Well-localized GRB web site”, http://www.mpe.mpg.de/~jcg/grb.html

Hauser, M. G. & Dwek, E. 2001, ARA&A, 39, 249

Hidalgo-Gámez, A. M., Olofsson, K., & Masegosa, J. 2001, A&A, 367, 388

Hjorth, J., Holland, S., Courbin, F., et al. 2000, ApJ, 534, L147

Hjorth, J., Thomsen, B., Nielsen, S. R., et al. 2002, ApJ, 576, 113

Hogg, D. W., Pahre, M. A., Adelberger, K. L., et al. 2000, ApJS, 127, 1

Holland, S., Andersen, M., Hjorth, J., et al. 2000a, GRB Circular Network, 753
Appendix A: Absolute B magnitudes of GRB host galaxies

The dereddened $R$ magnitudes of the GRB host galaxies with determined redshifts are given in Table A.1. They were estimated in the Vega system taking account of most of the published papers and GRB Coordinates Network circulars directly or indirectly reporting on optical observations of fading GRB afterglows and their hosts. When several $R$ magnitudes of a given source were available in the literature, the various measurements were weighted according to their photometric uncertainty, and subsequently averaged to get a final homogenized value. In some cases, we also relied on the host contribution derived from the fit of the $R$-band optical transient light-curve when the latter was clearly well constrained. The $R$ magnitude of the GRB990506 host galaxy was measured from an $R$-band image that we obtained using the EFOSC2 instrument on the ESO 3.6-m telescope at La Silla.
The redshifts given in Table A.1 have also been taken from the literature. In most cases, they were determined from emission lines directly observed in the spectra of the hosts. For the other sources, they were derived as the redshifts of the furthest absorbing medium observed in absorption within the spectra of the GRB optical transients. We made the assumption that the first interstellar medium illuminated by the background afterglow is indeed that of its host galaxy itself. We note that this hypothesis has been confirmed in several cases where the derived redshift could have been confirmed with emission lines from the host.

These redshifts and $R$ magnitudes were subsequently used to derive the absolute $B$ magnitudes given in Column (1) of Table A.1 assuming a ΛCDM Universe with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$. For each host, the k-correction for the $R$-filter and rest-frame $B-R$ colour used for this computation were estimated taking account of the type of SED suggested by its $R-K$ and/or optical colours when available (see Table 2 and Fig. 1), otherwise assuming a blue continuum with a spectral slope $F_\nu \propto \nu^{-1}$.

To better establish the validity of our results, we also estimated, for most of the hosts, the absolute $B$ magnitudes from the observed flux density at the redshifted $B$-band wavelength. For each case, this flux density was derived interpolating the various broad-band filter magnitudes given in the literature (see Table A.1 for references) including the $K$ magnitudes given in Table 2. The final results are indicated in Column (2) of Table A.1. To compare the two methods, we computed the difference between the estimations given in the two columns, and found a mean value $\langle M_B^{(1)} - M_B^{(2)} \rangle = 0.07$ and a dispersion $\sigma (M_B^{(1)} - M_B^{(2)}) = 0.18$. 
### Table A.1. Optical (R and B-band) properties of GRB host galaxies

| Source          | GRB     | Redshift | Photometry | $M_B + 5 \log_{10} h_{65}$ (¶) |
|-----------------|---------|----------|------------|--------------------------------|
|                 |         |          | $E(B-V)$† | $R$ mag | References | (1) | (2) |
| GRB J194641.9–193605 | 020813  | 1.25     | 0.109      | 24.70 ± 0.20       | 2   | -19.30 |
| GRB J151455.8–192454 | 020531  | 1.00     | 0.140      | 22.05 ± 0.20       | 4   | -21.35 |
| GRB J135803.1–312222 | 020405  | 0.69     | 0.050      | 20.90 ± 0.20       | 5   | -21.50 |
| GRB J111151.0–215656 | 011211  | 2.14     | 0.036      | 24.90 ± 0.30       | 7   | -20.55 |
| GRB J113429.6–760141 | 011121  | 0.36     | 0.508      | 24.60 ± 0.40       | 9   | -16.15 |
| GRB J225559.9+405553 | 010921  | 0.45     | 0.145      | 21.45 ± 0.15       | 10, 11 | -19.75 |
| GRB J145212.5+330106 | 010222  | 1.48     | 0.023      | 25.70 ± 0.15       | 13, 14 | -18.75 |
| GRB J170409.7+514711 | 000926  | 2.04     | 0.024      | 24.80 ± 0.10       | 15  | -20.50 |
| GRB J021834.5+074429 | 000911  | 1.06     | 0.120      | 25.10 ± 0.10       | 16  | -18.80 |
| GRB J113407.1–802948 | 990705  | 0.85     | 0.017      | 23.45 ± 0.10       | 17  | -19.50 |
| GRB J115450.1–264035 | 000721  | 0.71     | 0.016      | 24.30 ± 0.20       | 18, 19 | -19.90 |
| GRB J152530.3+444559 | 990705  | 0.43     | 0.023      | 27.85 ± 0.30       | 20  | -17.45 |
| GRB J050931.3+111707 | 991216  | 1.02     | 0.633      | 25.30 ± 0.20       | 21  | -18.15 |
| GRB J163353.5+462721 | 991208  | 0.71     | 0.016      | 24.30 ± 0.20       | 22  | -18.30 |
| GRB J125626.4+651200 | 990703  | 0.97     | 0.032      | 21.85 ± 0.15       | 23  | -19.35 |
| GRB J180931.6+591851 | 990613  | 1.10     | 0.090      | 25.80 ± 0.10       | 24  | -17.85 |
| GRB J115626.4+651200 | 990703  | 0.97     | 0.032      | 21.85 ± 0.15       | 25  | -19.35 |
| GRB J050146.7+114654 | 902828  | 0.85     | 0.049      | 21.50 ± 0.20       | 26, 27 | -17.85 |

**Notes:**

†: foreground Galactic extinction. For all cases excepted GRB 990705, it has been estimated from the DIRBE/IRAS dust maps of Schlegel et al. (1998). For GRB 990705 which occurred behind the Large Magellanic Cloud, we used the results of Dutra et al. (2001).

‡: derived from the $V$ magnitude of Fruchter et al. (2000a) assuming a spectral slope $F_\nu \propto \nu^{-1}$.

¶: the absolute $B$ magnitudes were derived assuming a LCDM Universe with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Column (1) gives the estimations which were obtained by applying proper k-corrections and $B - R$ colours to the observed $R$ magnitudes. The results given in Column (2) were derived from the observed flux density at the redshifted $B$-band wavelength.

**References:**

(1) Price et al. 2002b; (2) Levan et al. 2002; (3) Kulkarni et al. 2002; (4) Fox et al. 2002; (5) Price et al. 2002; (6) Holland et al. 2002; (7) Burud et al. 2001; (8) Garnavich et al. 2002; (9) Bloom et al. 2002; (10) Price et al. 2002; (11) Park et al. 2002; (12) Jha et al. 2001; (13) Frail et al. 2002; (14) Fruchter et al. 2001; (15) Castro et al. 2002; (16) Price et al. 2002; (17) Bloom et al. 2002; (18) Metzger et al. 2000; (19) Klose et al. 2000; (20) Jensen et al. 2001; (21) Fruchter & Vreeswijk 2001; (22) Piro et al. 2002; (23) Vreeswijk et al. 1999; (24) Vreeswijk et al. 2000; (25) Castro-Tirado et al. 2001; (26) Sokolov et al. 2001; (27) Vreeswijk et al. 2001; (28) Fruchter et al. 2000; (29) Hjorth et al. 2000; (30) Sahu et al. 2000; (31) Le Floc'h et al. 2002; (32) Saracco et al. 2001; (33) Holland et al. 2000a; (34) Fruchter et al. 2000; (35) Kulkarni et al. 1999; (36) Fruchter et al. 1999; (37) Holland & Hjorth 1999; (38) Bloom et al. 1999; (39) Dierickx et al. 1998; (40) Bloom et al. 1998; (41) Holland et al. 2001; (42) Vreeswijk et al. 1999; (43) Dierickx et al. 2000; (44) Hjorth et al. 2002; (45) Kulkarni et al. 1998; (46) Odewahn et al. 1998; (47) Dierickx et al. 2001; (48) Bloom et al. 1998a; (49) Fruchter et al. 2000b; (50) Bloom et al. 2001; (51) Fruchter et al. 1999c; (52) Galama et al. 2000.