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# Are the hosts of gamma-ray bursts sub-luminous and blue galaxies?$^{\star,\star\star,\star\star\star}$

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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 host 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

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$^{\star}$ Based on observations with the Very Large Telescope, obtained at the European Southern Observatory in Chile under proposal 67.B-0611(A).

$^{\star\star}$ Based on observations with the Gemini-North Telescope, obtained at Mauna Kea (Hawaii) under proposal GN-2001A-Q-58.

$^{\star\star\star}$ Appendix A is only available in electronic form at `http://www.edpsciences.org`

## 1. Introduction

In the past few years, a variety of high redshift star-forming sources such as the Lyman- and Balmer-break galaxies (e.g. Steidel et al. 1999) or the SCUBA and ISO dusty starbursts (Barger et al. 1998; Aussel et al. 1999; Elbaz et al. 1999) were discovered at different wavelengths from a broad range of observing techniques. However, each of these methods of detection strongly suffers from its own selection effects (e.g., dust extinction, flux limitation or colour selection at the observed wavelength), and the connection between the various populations of distant objects currently known is still poorly understood (e.g., Webb et al. 2003).

In the goal to trace the star-forming activity and the evolution of high redshift galaxies with reduced biases, an alternative approach using the cosmological gamma-ray bursts (GRBs) as probes of star formation was recently proposed (e.g., Wijers et al. 1998; Mirabel et al. 2000; Blain & Natarajan 2000). Since the discovery of X-ray/optical/radio transient counterparts to long-duration GRBs, the "collapsar" model (Woosley 1993; MacFadyen & Woosley 1999) 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., Hjorth et al. 2002; 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. 2002b). 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 occuring 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 intervening columns of gas and dust, 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 (Schaefer 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 already obtained in the northern hemisphere (e.g., Chary et al. 2002). Observations performed in the NIR present multiple interests. They first allow to probe the light emitted by the old star populations, which provides a good indication of the stellar mass of galaxies. For high redshift sources, the relative importance of the NIR versus optical emission can moreover be used to roughly estimate the level of dust obscuration. Finally, the selection of distant objects in the NIR is nearly insensitive to the spectral energy distribution (SED) of galaxies up to very high redshift ($z \sim 2$) because of an invariant k-correction along the Hubble sequence.

We describe our observations and data reduction in Sect. 2, and present our results in Sect. 3. We discuss these new data in Sect. 4 and finally conclude in Sect. 5. Additional information on the GRB host optical properties are mentioned in Appendix A (only available in electronic form at `http://www.edpsciences.org`).

## 2. Observations, reduction and analysis

Observations were performed using the ESO facilities in Chile and the Gemini-North telescope in Hawaii. Ten GRB host galaxies, most of them located in the southern hemisphere and selected for having had an optical and/or radio bright afterglow, were imaged at near-infrared wavelengths. Our sample of sources is listed in Table 1 together with a log of the observations.

### 2.1. Near-infrared observations

The NIR data were obtained with the Infrared Spectrometer And Array Camera (ISAAC) on the Very Large Telescope (VLT) at Paranal, the Son OF ISAAC (SOFI) installed on the New Technology Telescope (NTT) at La Silla, and with the Adaptive Optics Hokupa'a/QUIRC instrument on Gemini-North at Mauna Kea. Observations were carried out between March 2000 and September 2001 under photometric conditions. A $K_s$ filter (2.0–2.3 $\mu$m) was used for the ISAAC and SOFI data, while the observations on Gemini were performed with a $K'$ filter (1.9–2.3 $\mu$m). The focal lens configurations resulted in a respective pixel size of $0\farcs148$, $0\farcs297$ and $0\farcs02$ for the ISAAC, SOFI and Hokupa'a images. The seeing remained rather stable during the observations of one given source, though it varied between $0\farcs6$ and $1\farcs5$ 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 $\sim 30''$ 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

**Table 1.** Summary of observations.

| Source ¶ | GRB II | $T_{obs}$–$T_{grb}$ (†) (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.

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 Col. 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 occuring ~2 days after the burst and a slow decay with time (temporal index $\beta \sim -1.5$), 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* within the IRAF package[1], we measured their total magnitude in an aperture of 5$''$ in diameter centered on the source, with the exception of GRB 990506 host which lies only ~1.8$''$ from another extended object. Since this host galaxy has a very compact morphology at optical wavelengths ($FWHM \sim 0.14''$), 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% 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 mentioned 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 dereddened 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 determined $K$-band photometry already published by other authors (see caption of Table 2 for references). Including our results, the number of GRB host galaxies

[1] http://iraf.noao.edu/iraf/web/
[2] http://www.eso.org/instruments/isaac/drg/html/drg.html

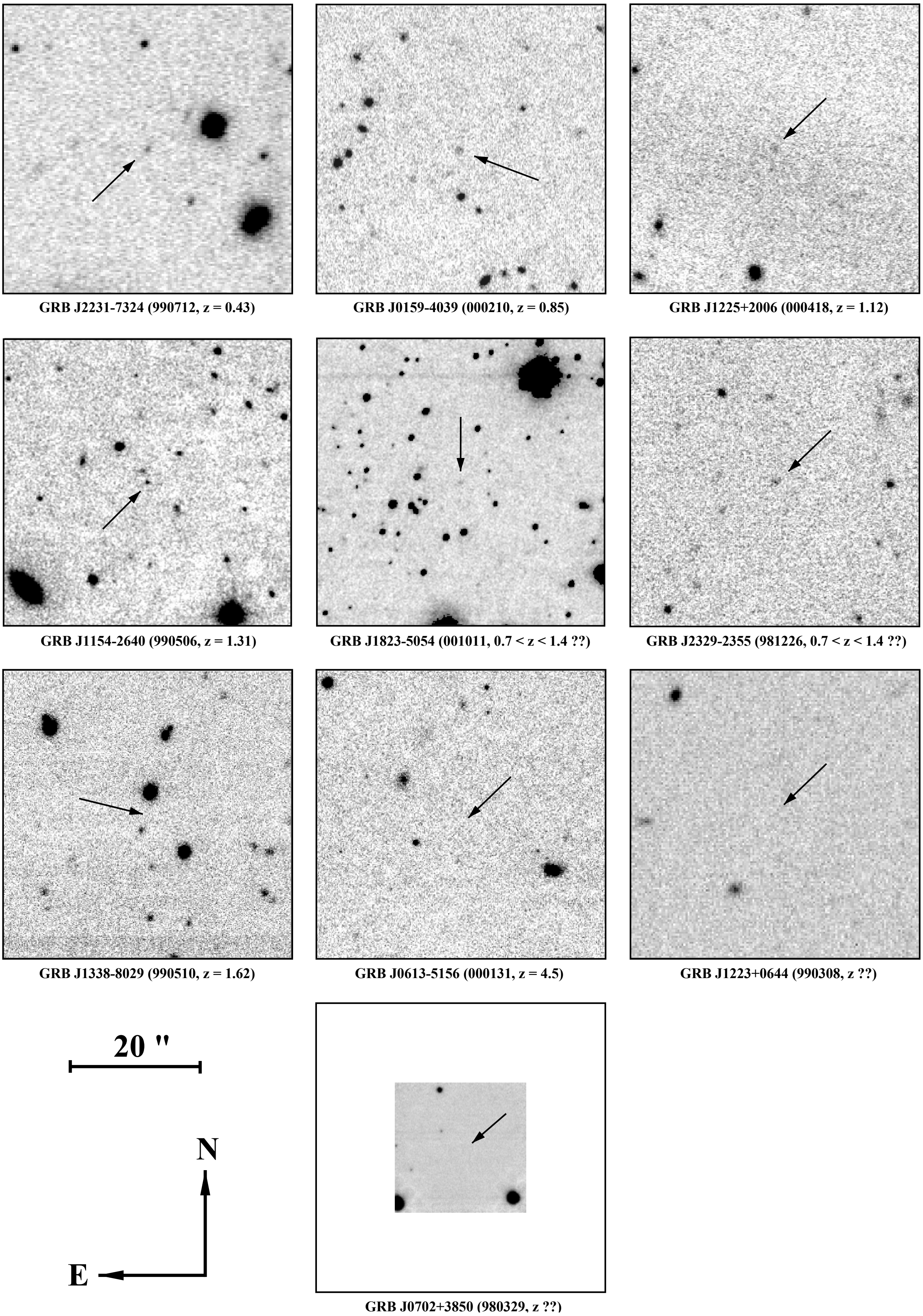


**Fig. 1.** Near-infrared images of the gamma-ray burst host galaxies listed in Table 1. Observations were performed with a $K_s$ filter, except in the case of the GRB 980329 host for which a $K'$ filter was used. Each frame has a field of view of $45'' \times 45''$ and an orientation with the North to the top and the East to the left. From the top to the bottom and 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.

**Table 2.** Properties of GRB host galaxies.

| Source | GRB | Redshift $z$ | Ref. | Photometry $K$ mag | References | $R-K$ colour ‡ | Abs. $K$ mag. ¶ |
|---|---|---|---|---|---|---|---|
| GRB J225559.9+405553 | 010921 | 0.45 | 1 | 19.05 ± 0.1 | 1 | 2.40 ± 0.25 | −22.50 |
| GRB J145212.5+430106 | 010222 | 1.48 | 2 | 23.5 ± 0.0† | 3 | 2.20 ± 0.30 | −21.25 |
| GRB J182304.6–505416 | 001011 | | | 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 J223153.1–732429 | 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+064405 | 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 J070238.0+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:**

‡ For all sources except the GRB 981226 and GRB 001011 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 GRB 981226 has been derived from Saracco et al. (2001b), Frail et al. (1999) and Holland et al. (2000b), while that of the GRB 001011 host is taken from Gorosabel et al. (2002).

¶ Defined as $M_K + 5\log_{10} h_{65}$ assuming a ΛCDM Universe with $\Omega_m = 0.3$ and $\Omega_\lambda = 0.7$ ($h_{65} = H_0\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})/65$).

† Estimated from an extrapolation of the afterglow $K$-band light curve (Frail et al. 2002).

**References:** (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. (2000); (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. (1999); (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).

detected in the NIR by October 2002 thus amounts to 15 sources[3] out of the ∼35 GRBs which were so far localized with a sub-arcsecond error box (Greiner 2002).

## 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 lookback times. On the other hand, it can be particularly interesting 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 magnitudes 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.

[3] We did not consider the case of GRB 980613. In spite of the $K$-band detection of its complex host-environment by Djorgovski et al. (2000), the $K$ magnitude of its true host (component H, see Hjorth et al. 2002) has not been determined so far.

### 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 GRB 981226 and GRB 001011 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 $0.7 \lesssim z \lesssim 1.4$ 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 ($\bar{z} = 0.35$, Cowie et al. 1994; Songaila et al. 1994), while galaxies at intermediate redshift ($\bar{z} = 0.8$) were derived from the Hawaii Deep Surveys by Cowie et al. (1996). Those at higher $z$ ($\bar{z} = 1.5$) 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),

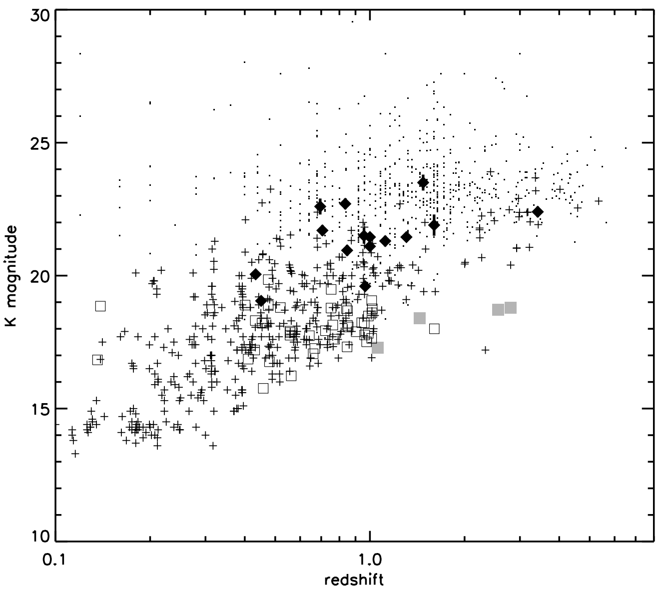


**Fig. 2.** Observed $K$ magnitudes of the GRB host galaxies versus redshift (*filled diamonds*) derived from Table 2. The GRB 001011 and GRB 981226 hosts are indicated assuming an arbitrary redshift $z = 1$. Photometric uncertainties are reported with vertical solid lines. The $K$ magnitudes of NIR-selected field sources with spectroscopic (*crosses*) and photometric (*dots*) redshifts are given for comparison (see Sect. 3.1 for references). We also indicate the $K$-band photometry of the NIR counterparts to high redshift ISO galaxies (*open squares*) and SCUBA sources with determined spectroscopic redshifts (*filled squares*).

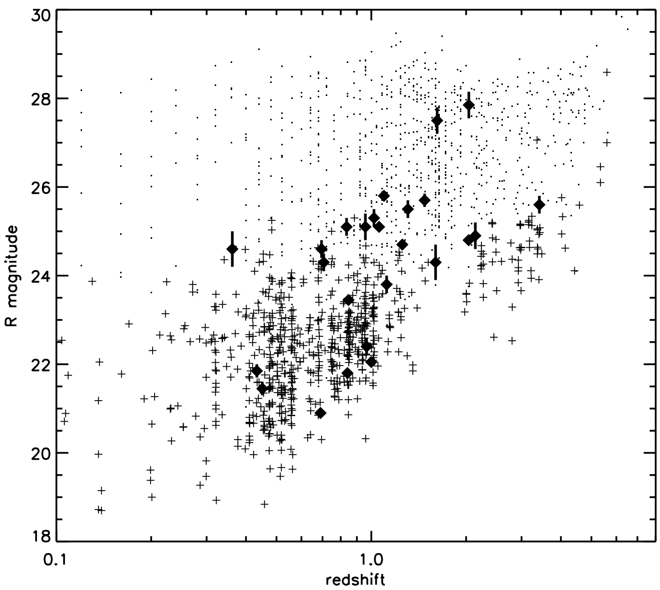


**Fig. 3.** Observed $R$ magnitudes of the GRB host galaxies versus redshift (*filled diamonds*) derived from Table A.1. The uncertainties are indicated with vertical solid lines. The largest ones reflect, for a given object, the scatter of the various magnitudes given in the literature (see Appendix A). The $R$ magnitudes of optically-selected field sources with spectroscopic (*crosses*) and photometric (*dots*) redshifts are given for comparison (see Sect. 3.1 for references).

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 Dey 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 $R \sim 26$–$29$, 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, 6031 Å) and the $I$-band (F801 WFPC filter, 8011 Å). 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 Allen (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 $R$ mag $\gtrsim 25$ 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 ($R-K \sim 2$–3) while old elliptical sources at $z \gtrsim 1$ exhibit extremely red colours ($R-K \gtrsim 5$). Furthermore, large $R-K$ colours in distant sources can also suggest dust obscuration, and may thus sign-post powerful dust-enshrouded starburst galaxies.

In Table 2, 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 Mannucci 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 Mannucci 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 1 $\mu$m 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. 4, the GRB hosts exhibit rather blue colours that are typical of the faint blue galaxy population in the field at $z \sim 1$. 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.

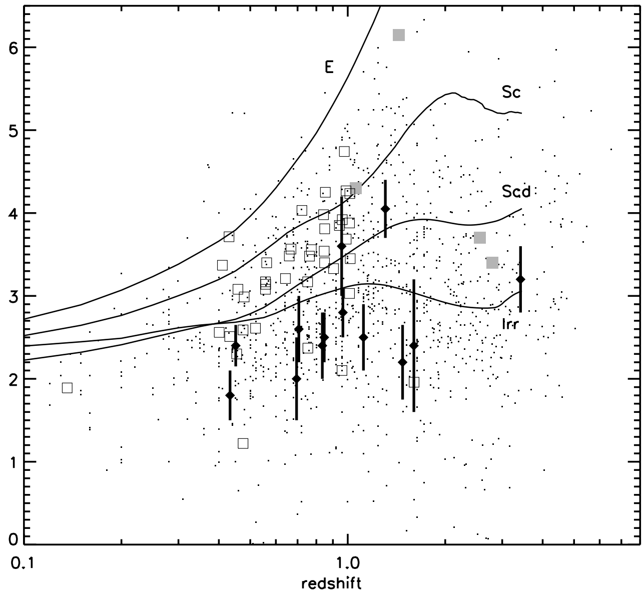


**Fig. 4.** Observed $R-K$ colours versus redshift for the sample of GRB host galaxies listed in Table 2 (*filled diamonds*). The estimated uncertainties are indicated with vertical solid lines. The colours and redshifts for optically-selected field sources (*dots*) were derived from the HDF source catalog 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.

### 3.3. Absolute K magnitudes

We computed the absolute $K$ magnitudes for the sample listed in Table 2, 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 GRB 990506 and GRB 970828 hosts, we rather used an Scd-type template as indicated by their redder SEDs (see Fig. 4). Luminosity distances were computed assuming a $\Lambda$CDM Universe with $\Omega_m = 0.3$ and $\Omega_\lambda = 0.7$. We parametrized the Hubble constant using $h_{65} = H_0\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})\,/\,65$.

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). For the lower-redshift samples taken from the NIR Hawaii Surveys and for the ISO sources, we arbitrarily assumed an Irr galaxy template relying on the fact that k-corrections are hardly type-dependent up to $z \sim 1.5$

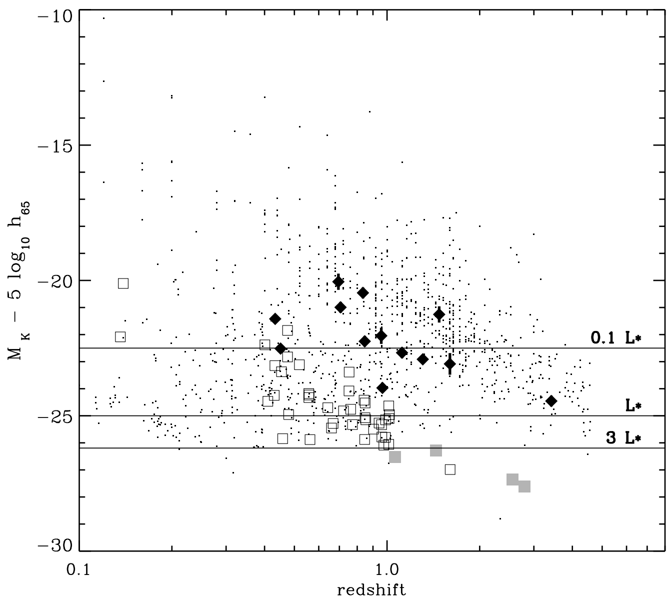


**Fig. 5.** Absolute $K$ magnitudes of the GRB host galaxies listed in Table 2, compared to optically/NIR-selected field sources and ISO/SCUBA galaxies in a ΛCDM Universe ($\Omega_m = 0.3$ and $\Omega_\lambda = 0.7$). Legend, photometry and redshift catalogs are similar to those used for Fig. 2, except for the NIR-selected objects with *spectroscopic* redshifts which are also indicated by dots in this plot. Horizontal lines indicate the magnitudes of $0.1\,L_*$, $L_*$ and $3\,L_*$ galaxies assuming $M_* = -25$.

in $K$. The absolute $K$ magnitudes of the SCUBA galaxies were determined assuming the SED suggested by their $R - K$ colour (see Fig. 4).

We also indicated the absolute magnitudes of galaxies with luminosities of $0.1\,L_*$ ($M = -22.5$), $L_*$ ($M = -25$) and $3\,L_*$ ($M = -26.2$), assuming $M_* = -25$. 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)[4] and Kashikawa et al. (2003)[5]. Both were determined assuming a *matter-dominated* Universe with $\Omega_m = 1$. 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 $0.7 \leq z \leq 3$ redshift range. Therefore, it should not significantly affect our qualitative comparison.

With a median–averaged $\overline{M_K} = -22.25$ (corresponding to $\overline{L} \sim 0.08\,L_*$), 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] $M_* = -25 + 5\log_{10}[H_0\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})/50]$, $\alpha = -1.3$.
[5] $M_* = -25.9 + 5\log_{10}[H_0\,(\mathrm{km\,s^{-1}\,Mpc^{-1}})/50]$, $\alpha = -1.35$.

## 4. Discussion

Our analysis described in Sect. 3 indicates that the GRB host galaxies are characterized by rather blue colours (see Fig. 4), sub-$L_*$ luminosities in the $K$ band and low masses (see Fig. 5). Their morphology is moreover consistent with that of compact, irregular or merging systems (Bloom et al. 2002b). 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 (Sokolov et al. 2001). All together, our results and those already published in the literature are therefore in agreement with GRBs tracing star-forming sources at cosmological distances.

We may now wonder whether the GRB-selected objects are actually representative of the *whole ensemble* of starburst galaxies at high redshift, or in other words, whether GRBs can really be used as unbiased probes of star formation.

### 4.1. Is there any bias in the current sample of GRB hosts?

Our results indicate that the GRB host galaxies significantly differ from the luminous and dusty starbursts which were discovered in the infrared and submillimeter deep surveys with ISO and SCUBA. This is clearly illustrated in Fig. 5 which shows that, contrary to the GRB hosts, these dusty star-forming objects are also luminous at optical and NIR wavelengths. As can be seen in Fig. 4, they moreover appear statistically much redder, indicating either the presence of underlying old stellar populations or an evidence for dust obscuration. Is this distinction between these galaxies and the GRB hosts simply due to the limited size of our sample, or does it reveal other biases affecting the GRB-selection?

The ISO starbursts have been shown to resolve ∼50% of the total energy produced by the Cosmic Infrared Background (CIRB, Elbaz et al. 2002). They trace therefore a significant fraction of the global activity of star formation which occured in the Universe. Within the $0.5 \lesssim z \lesssim 1.5$ redshift range where the ISO sources and most of the GRB host galaxies are located, we estimated the fraction of GRBs which should be observed toward these dusty galaxies assuming GRBs trace the star formation. To this purpose, we assumed that the respective contributions to the CIRB and the Optical Extragalactic Background (OEB) 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 $0.5 \lesssim z \lesssim 1.5$, ∼5–6 sources would thus be expected to exhibit $K$ luminosities $\gtrsim 0.5\,L_*$, while none of them actually satisfies this criterion.

Further evidence supporting the lack of GRB-detections in reddened dusty starbursts is suggested by the very blue colours of GRB hosts. It has been recently shown that a significant fraction of the Extremely Red Objects (EROs, $R - K \gtrsim 5$) should be composed of dust-reddened sources responsible for a star formation density 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 ~4.

This lack of luminous ($L \gtrsim L_*$) and red ($R - K \gtrsim 4$) 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 ~1 kpc (Soifer et al. 2001). Even if the beamed emission of GRBs can destroy dust grains on distances up to ~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 occuring 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 occuring at $z = 0.97$ could be indeed a dusty galaxy luminous in the infrared. In fact, we note that its $R - K$ colour ~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 occuring 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 (Madau & 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

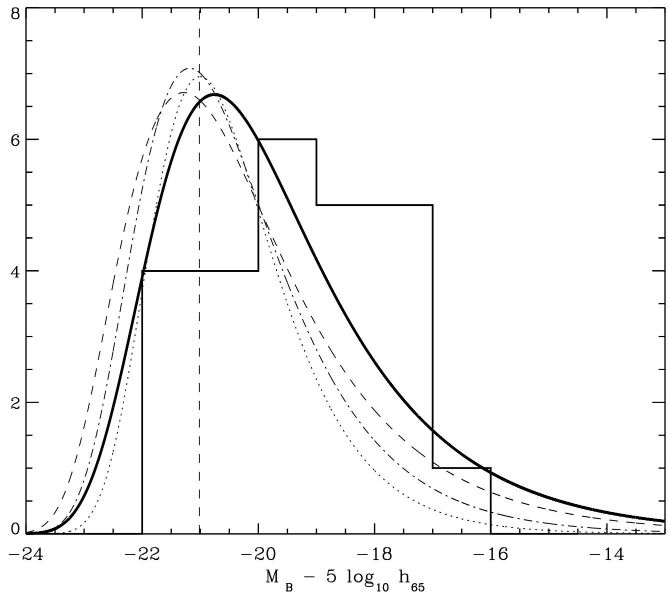


**Fig. 6.** Histogram of the absolute $B$ magnitudes for the sample of GRB host galaxies, estimated following the method described in Appendix A and assuming a ΛCDM Universe with $\Omega_m = 0.3$ and $\Omega_\lambda = 0.7$. Various functions of the $B$-band luminosity *weighted by luminosity* at high redshift have been overplotted in arbitrary units for comparison. They were taken from Wolf et al. (2003) for the $0.8 \lesssim z \lesssim 1.2$ redshift range (*dashed line*), and Kashikawa et al. (2003) for sources at $1 \lesssim z \lesssim 1.5$ (*dotted line*) and $1.5 \lesssim z \lesssim 2$ (*dashed-dotted line*). The thick solid line is also taken from Wolf et al. (2003) but restricted to galaxies bluer than Sbc type objects. The vertical dashed line depicts the $M_*$ parameter of this last Schechter parametrization.

proportional to the fraction of GRB occurence emerging from such galaxies.

Such a comparison is shown in Fig. 6. 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. (2003), who derived the Schechter-parametrized luminosity functions for various types of galaxies up to $z \sim 1.2$, in a ΛCDM 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 $M_{B*} \sim -21 + 5\log_{10} h_{65}$ for the blue galaxies at $z \sim 1$ (Wolf et al. 2003), 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 refered to 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. 6). 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 (~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 enveloppe 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. 6, 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-Gámez 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 occured. 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.

*Note added in proof:* A mistake in Table A.1 of Appendix A has been brought to our attention regarding the $R$ magnitude quoted for the host galaxy of GRB 011121. The value in our table does not reflect the total emission of this source, but its contribution to the flux measured in a small aperture of $1''$ in diameter centered on the position of the optical transient. The correct magnitude of the galaxy should be revised to $R = 18.95$ mag (dereddened from foreground Galactic extinction, Greiner et al. 2003, A&A, submitted). We found that this new value does not modify the general conclusions of our work.

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