A&A 406, L63–L66 (2003)
DOI: 10.1051/0004-6361:20030931
© ESO 2003

Astronomy & Astrophysics

# On the Ly$\alpha$ emission from gamma-ray burst host galaxies: Evidence for low metallicities[⋆,⋆⋆]

J. P. U. Fynbo[1,2], P. Jakobsson[2], P. Møller[3], J. Hjorth[2], B. Thomsen[1], M. I. Andersen[4], A. S. Fruchter[5], J. Gorosabel[6,5], S. T. Holland[7], C. Ledoux[8], H. Pedersen[2], J. Rhoads[5], M. Weidinger[1], and R. A. M. J. Wijers[9]

[1] Department of Physics and Astronomy, University of Aarhus, Ny Munkegade, 8000 Århus C, Denmark
[2] Astronomical Observatory, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark
[3] European Southern Observatory, Karl Schwarzschild-Strasse 2, 85748 Garching, Germany
[4] Astrophysikalisches Institut, 14482 Potsdam, Germany
[5] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[6] Instituto de Astrofísica de Andalucía (IAA-CSIC), PO Box 03004, 18080 Granada, Spain
[7] Department of Physics, University of Notre Dame, Notre Dame, IN 46556-5670, USA
[8] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[9] University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

Received 30 April 2003 / Accepted 19 June 2003

**Abstract.** We report on the results of a search for Ly$\alpha$ emission from the host galaxy of the $z = 2.140$ GRB 011211 and other galaxies in its surrounding field. We detect Ly$\alpha$ emission from the host as well as from six other galaxies in the field. The restframe equivalent width of the Ly$\alpha$ line from the GRB 011211 host is about 21 Å. This is the fifth detection of Ly$\alpha$ emission out of five possible detections from GRB host galaxies, strongly indicating that GRB hosts, at least at high redshifts, are Ly$\alpha$ emitters. This is intriguing as only ~25% of the Lyman-Break selected galaxies at similar redshifts have Ly$\alpha$ emission lines with restframe equivalent width larger than 20 Å. Possible explanations are *i)* a preference for GRB progenitors to be metal-poor as expected in the collapsar model, *ii)* an optical afterglow selection bias against dusty hosts, and *iii)* a higher fraction of Ly$\alpha$ emitters at the faint end of the luminosity function for high-$z$ galaxies. Of these, the current evidence seems to favour *i)*.

**Key words.** gamma rays: bursts – galaxies: high redshift – techniques: photometric

## 1. Introduction

Since 1997, the precise positional information of Gamma-Ray Burst (GRB) afterglows has provided a new method by which to locate and study galaxies in the early universe – the host galaxies. Once an afterglow position has been determined detecting the host is only a matter of integrating on this position until the host emerges from the noise. The impact parameters of afterglows relative to their hosts are small enough, typically a fraction of an arcsec on the sky, that chance alignment is not a serious limitation (Bloom et al. 2002). So far this approach has led to the detection of a host galaxy for almost all of nearly 50 well localised GRBs.

An important aspect of GRB selection compared to other selection mechanisms is that it is not flux limited. This is obviously the case for most other selection methods; Lyman-Break selection (Shapley et al. 2003 and references therein) is continuum flux limited and Ly$\alpha$ selection (e.g. Møller & Warren 1993; Cowie & Hu 1998; Rhoads et al. 2000; Fynbo et al. 2001; Ouchi et al. 2003; Fynbo et al. 2003) is line flux limited. Therefore, GRB selection allows us to probe the faint end of the luminosity function currently inaccessible to other techniques. GRB selection is subject to other selection mechanisms, but these are not yet known in detail (e.g. a relation to the occurrence of star formation). The precise nature of the GRB selection mechanism provides hints about the nature of the GRB progenitors (e.g. Woosley 1993; Paczyński 1998; Hogg & Fruchter 1999).

Ly$\alpha$ imaging of GRB hosts is interesting as Ly$\alpha$ emitting galaxies (in the following we will use the acronym LEGOs – Ly$\alpha$ Emitting Galaxy-building Objects, Møller & Fynbo 2001) are starburst galaxies with little or no dust. Ly$\alpha$ imaging is therefore a probe of the star formation rate and of the dust content of GRB host galaxies. Both of these parameters are

---

*Send offprint requests to*: J. P. U. Fynbo,
e-mail: `jfynbo@phys.au.dk`

[⋆] Based on observations collected at the European Southern Observatory, in La Silla (Chile) under ESO programme ID 70.B-0233.

[⋆⋆] Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Institute. STScI is operated by the association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555.

important for our understanding of GRB progenitors and of how the environment affects the propagation of afterglow emission out of host galaxies. Furthermore, Ly$\alpha$ narrow band imaging is an efficient way to probe if the host galaxy resides in an overdense environment such as a group or a proto-cluster. The first Ly$\alpha$ narrow band imaging of GRB host galaxies was presented in Fynbo et al. (2002) where we studied the fields of GRB 000301C and GRB 000926, both at redshift $z = 2.04$. That study resulted in the detection of Ly$\alpha$ emission from the host of GRB 000926 and 18 additional emitters in the two fields. The host galaxy of GRB 000301C was too faint, $R \approx 28$ (Bloom et al. 2002), to allow a detection even if it has a large Ly$\alpha$ equivalent width (*EW*). In this Letter we report on the results of a search for Ly$\alpha$ emission from the host galaxy of the $z = 2.140$ GRB 011211 and other galaxies in its surrounding field. The properties of the X-ray rich GRB 011211 and its afterglow are discussed in Holland et al. (2002) and Jakobsson et al. (2003a). The redshift was measured via absorption lines in the spectrum of the optical afterglow to be $z = 2.140$ (Fruchter et al. 2001; Holland et al. 2002). The host galaxy was detected with deep late time imaging to be a faint $R \approx 25$ galaxy (Burud et al. 2001; Fox et al. 2002; Jakobsson et al. 2003b).

## 2. Observations and data reduction

The observations were carried out during three nights in February 2003 at the 3.5-m New Technology Telescope on La Silla using the Superb Seeing Imager – 2 (SUSI2). The SUSI2 detector consists of two $2048 \times 4096$ thinned, anti-reflection coated EEV CCDs with a pixel scale of $0\farcs085$. The field of GRB 011211 was imaged in three filters: the standard $B$ and $R$ filters and a special narrow-band filter manufactured by Omega Optical. The narrow-band filter (OO3823/59) is tuned to Ly$\alpha$ at $z = 2.140$ and has a width of 59 Å (corresponding to a redshift width of $\Delta z = 0.049$ for Ly$\alpha$ or a Hubble flow depth of 4700 km s$^{-1}$). The total integration times were 15 hours (OO3823/59), 3.1 hours ($B$-band), and 1.9 hours ($R$-band). The individual exposures were bias-subtracted, flat-field corrected and combined using standard techniques. The full-width-at-half-maximum (*FWHM*) of point sources in the combined images are $1\farcs10$ ($R$-band), $1\farcs11$ ($B$-band) and $1\farcs22$ (OO3823/59).

The narrow-band observations were calibrated using observations of the spectrophotometric standard stars LTT3218, LTT7379, and GD108 (Stone 1996). The broad-band images were calibrated using the secondary standards from Jakobsson et al. (2003b) and brought onto the AB-system using the transformations given in Fukugita et al. (1995).

## 3. Results

We used the same methods for photometry and selection of LEGO candidates as those described in Fynbo et al. (2002).

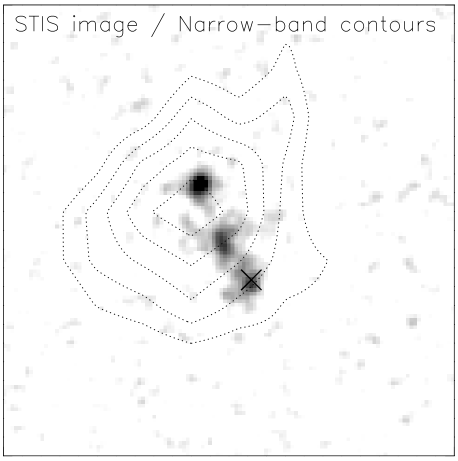

**Fig. 1.** A $3 \times 3$ arcsec$^2$ section of the STIS/CL image around the host galaxy of GRB 011211 (Jakobsson et al. 2003b). North is up and East is to the left. The GRB went off in the faint, southern part of the object (position marked with a cross). The contours show the Ly$\alpha$ emission based on our narrow band observations. The Ly$\alpha$ emission weighted centroid of the galaxy is close to the northern knot seen in the STIS image.

### 3.1. The host galaxy

The host galaxy of GRB 011211 is detected in all bands and is a Ly$\alpha$ emitter with a restframe *EW* of $21^{+11}_{-8}$ Å. Deep HST/STIS images of the host have been reported by Fox et al. (2002) and Jakobsson et al. (2003b). These images show that the host is a multi-component object extending over almost 1 arcsec or roughly 9 kpc at $z = 2.14$ (assuming $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$). In Fig. 1 we plot the contours of the Ly$\alpha$ emission on top of the HST/STIS image taken 59 days after the burst. The Ly$\alpha$ emission weighted centroid of the galaxy is close to the northern knot of the host, whereas the GRB occurred in the southern end of the host (Fox et al. 2002; Jakobsson et al. 2003b).

### 3.2. Other LEGO candidates in the field

In Fig. 2 we show the $n$(AB)$-B$(AB) versus $n$(AB)$-R$(AB) colour–colour diagram for synthetic galaxy spectra (left panel, see caption for details on the models) and for the detected objects in the field (middle and right panels). The full-drawn line indicates where objects with the same broad-band colour and with either absorption or emission in the narrow filter will fall. LEGOs will fall in the lower left corner of the diagram (due to excess emission in the narrow-filter). In the middle panel we show the colour-colour diagram for all objects detected in the field. We select as LEGO candidates objects detected at more than $5\sigma$ significance in the narrow band image and with a colour of $n$(AB)$-B$(AB) $< -0.60$. This criterion corresponds to an observed *EW* of about 60 Å, or 20 Å rest for Ly$\alpha$ at $z = 2.140$. The colours of the candidates are shown in the right panel of Fig. 2. We find seven candidates in the field including the host galaxy. In the following we will refer to these as S1211_1 through S1211_7. The host galaxy does not stand out as special compared to the other candidates.

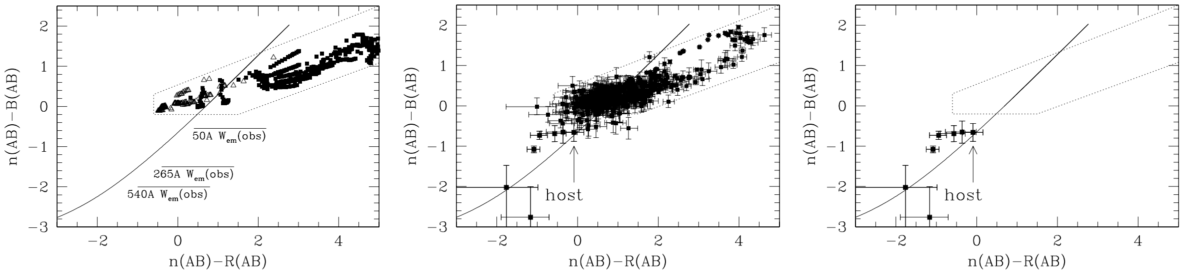

**Fig. 2.** *Left panel:* calculated colour–colour diagram based on Bruzual & Charlot (1993) model galaxy spectra. The filled squares are $0 < z < 0.6$ galaxies with ages from a few to 15 Gyr and the open triangles are $0.3 < z < 3.0$ galaxies with ages from a few Myr to 1 Gyr. The dotted box contains all these calculated galaxy colours. The full-drawn line corresponds to objects having the same broad-band colours, but various amounts of absorption (upper part) or emission (lower part) in the narrow-band filter. *Middle panel:* colour–colour diagram for all objects in the GRB field. The squares with error-bars indicate objects detected at $S/N > 5$ in the narrow-band image. As expected, most objects have colours consistent with being in the dotted box. However, a number of objects, including the GRB 011211 host, are seen in the lower left part of the diagram. *Right panel:* the colours of the seven LEGO candidates which are selected to have $n(\mathrm{AB})-B(\mathrm{AB}) < -0.60$.

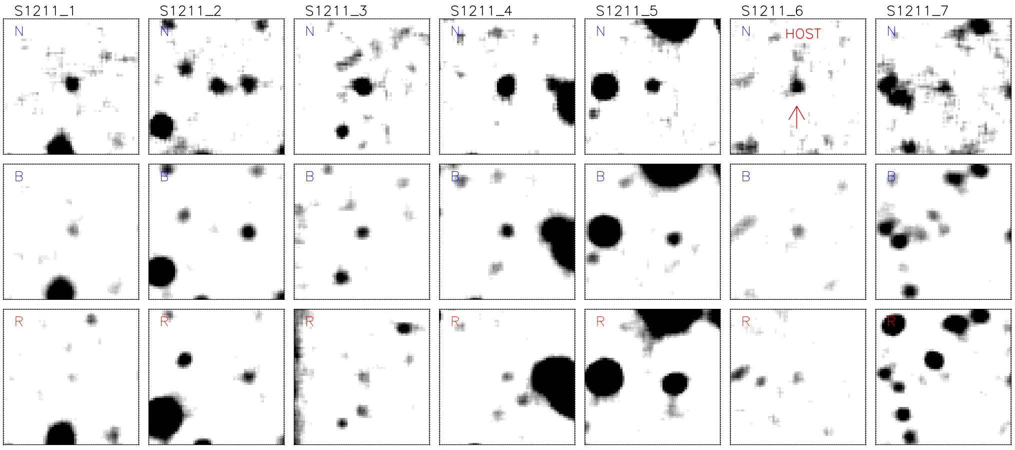

**Fig. 3.** $10 \times 10$ arcsec$^2$ sections around each of the seven LEGO candidates from the narrow band (top row), *B*-band (middle row) and *R*-band (bottom row). North is up and East is to the left. The host galaxy is number six named S1211_6.

It ranks sixth in brightness. Images of the candidates are shown in Fig. 3 and their photometric properties based on the total magnitudes (`mag_auto`) from SExtractor (Bertin & Arnouts 1996) are given in Table 1. We also derive Star Formation Rates (*SFR*s) for the LEGO candidates from the Ly$\alpha$ luminosities as described in Fynbo et al. (2002). The seven candidates are distributed uniformly over the field with no obvious structure such as the $z = 3.04$ filament reported by Møller & Fynbo (2001), but this does not exclude underlying structure. The filter used in the present study is about three times wider than in the Møller & Fynbo study and therefore any underlying structure would easily be washed out in the 2d image.

**Table 1.** Photometric properties of the seven LEGO candidates, including the host galaxy, in the field of GRB 011211. Upper limits are $2\sigma$. S1211_6 is the host galaxy of GRB 011211.

| Object | $B$(AB) | $R$(AB) | $f$(Ly$\alpha$) $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ | $SFR_{\mathrm{Ly}\alpha}$ $M_\odot$ yr$^{-1}$ |
|---|---|---|---|---|
| S1211_1 | $25.54^{+0.22}_{-0.18}$ | $25.55^{+0.55}_{-0.36}$ | 3.1 ± 0.7 | 0.8 ± 0.2 |
| S1211_2 | >26.5 | >26.0 | 5.1 ± 0.6 | 1.4 ± 0.2 |
| S1211_3 | $25.14^{+0.14}_{-0.13}$ | $24.71^{+0.21}_{-0.18}$ | 5.8 ± 0.8 | 1.5 ± 0.2 |
| S1211_4 | $24.89^{+0.10}_{-0.09}$ | $25.00^{+0.26}_{-0.21}$ | 10.6 ± 0.7 | 2.8 ± 0.2 |
| S1211_5 | >26.5 | >26.0 | 5.7 ± 0.8 | 1.5 ± 0.2 |
| S1211_6 | $25.31^{+0.19}_{-0.16}$ | $24.90^{+0.30}_{-0.23}$ | 2.8 ± 0.8 | 0.8 ± 0.2 |
| S1211_7 | $25.71^{+0.19}_{-0.16}$ | $25.28^{+0.23}_{-0.19}$ | 1.7 ± 0.6 | 0.5 ± 0.2 |

## 4. Discussion

The host galaxy of GRB 011211 has been found to be a Ly$\alpha$ emitter with a restframe *EW* of $21^{+11}_{-8}$ Å. This is somewhat smaller than for GRB 000926 ($71^{+20}_{-15}$ Å) and suggests the presence of more dust. Although uncertain, the UV continuum of GRB 011211 host is also redder than that of the GRB 000926 host. The observed $B(\mathrm{AB})-R(\mathrm{AB})$ colour corresponds to $\beta \approx -1.2 \pm 0.5$, whereas Fynbo et al. (2002) found $\beta = -2.4 \pm 0.3$ and $\beta = -1.4 \pm 0.2$ for the two main components of the GRB 000926 host galaxy. Ly$\alpha$ emission has also been detected from the host galaxies of GRB 971214 at $z = 3.42$ (Kulkarni et al. 1998; Ahn 2000), GRB 021004 at $z = 2.33$ (e.g. Møller et al. 2002 and references therein), and GRB 030323 at $z = 3.37$ (Vreeswijk et al., in preparation). For GRB 021004 and GRB 030323 the Ly$\alpha$ emission line is detected superimposed on the afterglow spectrum. All current evidence is consistent with the conjecture that the host galaxies of GRBs, at least at high redshifts, are Ly$\alpha$ emitters. In contrast, only $\sim$25% and $\sim$33% of the Lyman-Break selected galaxies at similar redshifts are Ly$\alpha$ emitters with a restframe *EW* larger than 20 Å and 10 Å respectively (Shapley et al. 2003). The median restframe *EW* of the Ly$\alpha$ line for Lyman-Break galaxies (LBGs) is $\sim$0 Å (about half of the LBGs have Ly$\alpha$ in absorption). The restframe *EW* of the Ly$\alpha$ emission line from the GRB 021004 host is constrained to be higher than 50 Å (Møller et al. 2002). The restframe *EW* for the host galaxy of GRB 971214 is measured spectroscopically to be 14 Å (Ahn, private communication), whereas it is unknown for GRB 030323 as its host is still undetected. If we conservatively assume that the restframe *EW* is above 10 Å for three hosts (971214, 011211, 030323) and above 20 Å for two hosts (000926, 021004) then GRB host galaxies are inconsistent with being drawn randomly from the same Ly$\alpha$ *EW* distribution as the LBGs at the $1 - 0.33^3 \times 0.25^2 \approx 99.8\%$ level.

This remarkable fact can be explained by a preference for GRB progenitors to be metal-poor. Ly$\alpha$ emission with *EW* larger than 20 Å is locally only found in starforming galaxies with $[\mathrm{O/H}] \lesssim -0.5$ (Charlot & Fall 1993, their Fig. 8; Kunth et al. 1998; Kudritzki et al. 2000). Furthermore, Shapley et al. (2003) find that the collisionally excited UV nebular emission lines of C III] and [O III] are stronger than average for the quartile of the their sample with Ly$\alpha$ $EW > 20$ Å. By analogy with local starbursts this also implies low metallicity (Heckman et al. 1998). In the collapsar model (Woosley 1993) a strong stellar wind, which is the consequence of a high metallicity, makes it difficult to produce a GRB due to mass loss and loss of angular momentum (MacFadyen & Woosley 1999). Therefore, a preference for GRB hosts to be metal poor is a clear prediction of the collapsar model. Alternatively, the explanation could be an optical afterglow selection bias against dusty hosts. For 60–70% of the searches for optical afterglows since 1997 no detection was made – the dark burst problem (Fynbo et al. 2001; Berger et al. 2002). Thus, the bursts for which a bright optical afterglow is detected, including all the bursts with detected Ly$\alpha$ emission from their hosts, are biased against very dusty host galaxies (Fynbo et al. 2001; Lazzati et al. 2002; Ramirez-Ruiz et al. 2002). This is important as even small amounts of dust will preferentially destroy Ly$\alpha$ photons due to resonant scattering (e.g. Ferland & Netzer 1979). However, it remains to be shown that the majority of dark bursts indeed are dust obscured. In fact, several bursts have been found to be optically dim without significant extinction (Hjorth et al. 2002; Berger et al. 2002; Fox et al. 2003; Hjorth et al. 2003). The dark bursts are also generally fainter in X-rays (De Pasquale et al. 2003) again implying that they are intrinsically dim or very distant. Finally, the fraction of Ly$\alpha$ emitters could be larger at the faint end of the high-z luminosity function, where most GRB hosts are found, than the fraction found for the bright LBGs. Shapley et al. (2003) find that among the LBGs with Ly$\alpha$ $EW > 20$ Å the *EW*s are largest for the faintest galaxies, but argue that a constant fraction of Ly$\alpha$ emitters down to $R = 25.5$ is consistent with the data when selection effects are taken into account. Furthermore, a higher fraction of Ly$\alpha$ emitters at the faint end of the luminosity function would also imply a lower metallicity and this is therefore not in conflict with a low metallicity preference for GRB hosts. In conclusion, a lower metallicity of GRB hosts compared to LBGs in general seems to be well established.

*Acknowledgements.* We thank our anonymous referee for a very constructive report that helped us improve the paper on several important points. We also thank Stan Woosley for helpful comments and the La Silla staff for excellent support during our run. JPUF acknowledges support from the Carlsberg Foundation. PJ acknowledges support from The Icelandic Research Fund for Graduate Students, and from a special grant from the Icelandic Research Council. STH acknowledges support from the NASA LTSA grant NAG5–9364. We acknowledge benefits from collaboration within the EU FP5 Research Training Network "Gamma-Ray Bursts: An Enigma and a Tool". This work is supported by the Danish Natural Science Research Council (SNF).

## References

Ahn, S. H. 2000, ApJ, 520, L9
Berger, E., Kulkarni, S. R., Bloom, J. S., et al. 2002, ApJ, 581, 981
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bloom, J. S., Kulkarni, S. R. & Djorgovski, S. G. 2002, AJ, 123, 1111
Bruzual, A. G., & Charlot, S. 1993, ApJ, 405, 538
Burud, I., Rhoads, J., Fruchter, A., & Hjorth, J. 2001, GCN#1213
Charlot, S., & Fall, S. M. 1993, ApJ, 415, 580
Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319
De Pasquale, M., Piro, L., Perna, R., et al. 2003, ApJ, preprint doi: 10.1086/375854
Ferland, G., & Netzer, H. 1979, ApJ, 229, 274
Fox, D. W., Bloom, J. S., & Kulkarni, S. R. 2002, GCN#1311
Fox, D. W., Price, P. A., Soderberg, A. M., et al. 2003, ApJ, 586, L5
Fruchter, A., Vreeswijk, P., Rhoads, J., & Burud, I. 2001, GCN#1200
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Fynbo, J. P. U., Møller, P., & Thomsen, B. 2001, A&A, 374, 343
Fynbo, J. P. U., Jensen, B. L., Gorosabel, J., et al. 2001, A&A, 369, 373
Fynbo, J. P. U., Møller, P., Thomsen, B., et al. 2002, A&A, 388, 425
Fynbo, J. P. U., Ledoux, C., Møller, P., Thomsen, B., & Burud, I. 2003, A&A, in press
Heckman, T. M., Carmelle, R., Leitherer, C., Garnett, D. R., & van der Rydt, F. 1998, ApJ, 503, 646
Hjorth, J., Thomsen, B., Nielsen, S. R., et al. 2002, ApJ, 576, 113
Hjorth, J., Møller, P., Gorosabel, J., et al. 2003, ApJ, submitted
Hogg, D. W., & Fruchter, A. S. 1999, ApJ, 520, 54
Holland, S., Soszyński, I., Gladders, M., et al. 2002, AJ, 124, 639
Jakobsson, P., Hjorth, J., Ramirezruiz, E., et al. 2003a, ApJL, submitted
Jakobsson, P., Hjorth, J., Fynbo, J. P. U., et al. 2003b, A&A, in press
Kudritzki, R., Méndez, R. H., Feldmeier, J. J., et al. 2000, ApJ, 536, 19
Kulkarni, S. R., Djorgoski, S. G., Ramaprakash, A. N., et al. 1998, Nature, 393, 35
Kunth, D., Mas-Hesse, J. M., Terlevich, E., et al. 1998, A&A, 334, 11
Lazzati, D., Covino, S., & Ghisellini, G. 2002, MNRAS, 330, 583
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Møller, P., & Warren, S. J. 1993, A&A, 270, 43
Møller, P., & Fynbo, J. U. 2001, A&A, 372, L57
Møller, P., Fynbo, J. P. U., Hjorth, J., et al. 2002, A&A, 396, L21
Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2003, ApJ, 582, 600
Paczyński, B. 1998, ApJ, 494, L45
Ramirez-Ruiz, E., Trentham, N., & Blain, A. W. 2002, MNRAS, 329, 465
Rhoads, J. E., Malhotra, S., Dey, A., et al. 2000, ApJ, 545, L85
Shapley, A. E., Steidel, C. C., Pettini, M., et al. 2003, ApJ, 588, 65
Stone, R. P. S. 1996, ApJS, 107, 423
Woosley, S. E. 1993, ApJ, 405, 273