The Astrophysical Journal, 591:L13–L16, 2003 July 1

THE REDSHIFT AND THE HOST GALAXY OF GRB 980613: A GAMMA-RAY BURST FROM A MERGER-INDUCED STARBURST?[1]

S. G. Djorgovski, J. S. Bloom,[2] and S. R. Kulkarni
Palomar Observatory, MS 105-24, California Institute of Technology, Pasadena, CA 91125;
george@astro.caltech.edu, jsb@astro.caltech.edu, srk@astro.caltech.edu
Received 2003 May 2; accepted 2003 May 19; published 2003 June 2

ABSTRACT

We present the optical and near-IR identification and spectroscopy of the host galaxy of gamma-ray burst GRB 980613. The burst was apparently associated with the optically (rest-frame UV) brightest component of an apparent system of at least five galaxies or galaxy fragments, at least two of which are at a redshift of $z = 1.0969$. The component we identify as the host galaxy shows a moderately high unobscured star formation rate, SFR ~ 5 $M_\odot$ yr^{-1}, but a high SFR per unit mass, indicative of a starburst. The image components show a broad range of $(R-K)$ colors, with two of them being very red, possibly due to dust. The overall morphology of the system can be naturally interpreted as a strong tidal interaction of two or more galaxies, at a redshift where such events were much more common than now. Given the well-established causal link between galaxy mergers and starbursts, we propose that this is a strong case for a GRB originating from a merger-induced starburst system. This supports the proposed link between GRBs and massive star formation.

Subject headings: cosmology: miscellaneous — cosmology: observations — gamma rays: bursts

On-line material: color figure

1. INTRODUCTION

Studies of the cosmic gamma-ray bursts (GRBs) are currently one of the most active and exciting fields of astrophysics. The resolution of the long-standing puzzle of GRBs began with the discovery of long-lived X-ray afterglows by the *BeppoSAX* satellite (Costa et al. 1997). This was followed by the discovery of optical (van Paradijs et al. 1997) and radio afterglows (Frail et al. 1997), and then the first redshift measurement that demonstrated the cosmological nature of GRBs (Metzger et al. 1997). Studies of afterglows confirmed the synchrotron shock model (e.g., Wijers, Rees, & Mészáros 1997), and their physics now seems to be reasonably well understood (see, e.g., Mészáros 2002, Waxman 2003, and references therein). Other recent reviews include Kulkarni et al. (2000), van Paradijs, Kouveliotou, & Wijers (2000), Hurley, Sari, & Djorgovski (2003), and Djorgovski et al. (2002, 2003).

There is now a growing body of evidence that GRBs (at least the long-soft type, for which afterglows have been observed) are associated with explosions of massive stars; the chief competing class of models, mergers of neutron stars or other compact stellar remnants, now appears much less likely. The most important evidence favoring the former class of models includes the distribution of GRBs within their host galaxies (Bloom, Kulkarni, & Djorgovski 2002a) and the probable detection of supernovae associated with GRBs (Galama et al. 1998; Kulkarni et al. 1998; Bloom et al. 1999a; Reichart 1999; Galama et al. 2000; Lazzati et al. 2001; Bloom et al. 2002b; Garnavich et al. 2003; see Bloom 2003 for a review).

All models involving massive stars and their remnants suggest that GRBs should be closely related to the massive star formation in galaxies (Paczyński 1998). Study of GRB host galaxies can provide valuable clues that can constrain the models (e.g., the relation to the star formation), and redshifts are necessary in order to derive the physical parameters of the GRBs (e.g., the energy scales).

Here we present deep imaging and spectroscopic observations of the host galaxy of GRB 980613. GRB 980613 was detected and localized by *BeppoSAX* (Piro & Costa 1998; Piro 1998). An optical transient (OT) was discovered by Hjorth et al. (1998; see also Hjorth et al. 1999). The detection of the host galaxy was reported by Djorgovski et al. (1998b), and its redshift by Djorgovski et al. (1999); these results are described in more detail here, with additional data. An independent, extensive study of the system was also presented by Hjorth et al. (2002; see also Holland 2000). Piro et al. (1999) reported an upper limit on possible X-ray Fe lines from this burst.

2. OBSERVATIONS AND DATA REDUCTIONS

In what follows, we assume the Galactic foreground extinction of $A_V = 0.27$ mag (Schlegel, Finkbeiner, & Davis 1998) and use the Galactic extinction curve from Cardelli, Clayton, & Mathis (1988) with $R = A_V/E_{B-V} = 3.1$. Our initial imaging data were obtained using the W. M. Keck Observatory 10 m telescope (Keck II) by H. Ebeling, on 1998 June 16.30 UT, in the R band, using the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995); two 300 s exposures were obtained. We reduced these images in the standard manner and confirmed that no cosmic rays affected the immediate area of the transient. After the transient had faded, we reobserved the field in the R (1998 November 29 UT; 900 s), I (1999 March 24 UT; 1000 s), and K bands (1999 February 7 UT; 2040 s). The final combined images in each filter are shown in Figure 1. The morphology of the system surrounding the GRB is complex. We label five distinct components in Figure 2. Table 1 provides their magnitudes and offsets relative to the position of the OT.

We referenced our R- and I-band magnitudes using star 2 (Halpern & Fesen 1998; Diercks et al. 1998). For each component, we used a circular aperture and performed an aperture correction using the curve of growth of star 2. The total mag-

[1] Partially based on the observations obtained at the W. M. Keck Observatory, which is operated by the California Association for Research in Astronomy, a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration.

[2] Present address: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

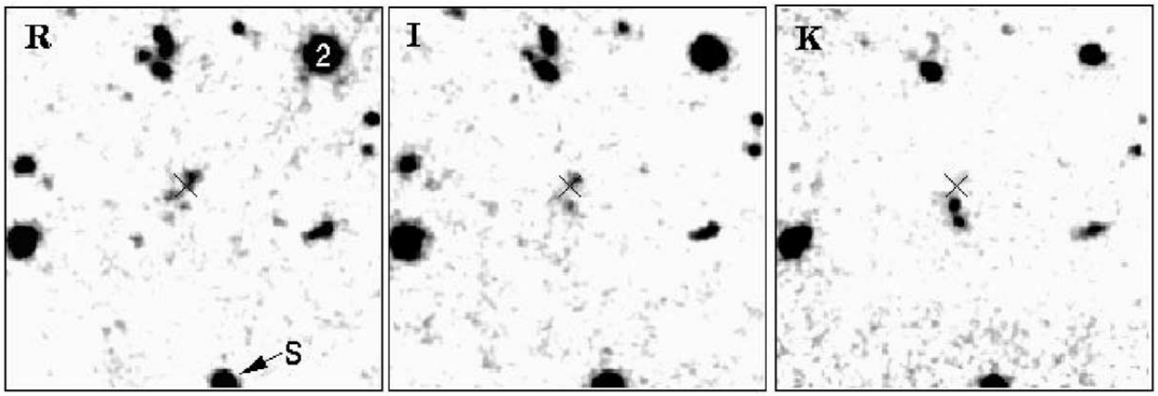

FIG. 1.—Late-time images of the field of GRB 980613 with the Keck telescopes in the *R* (*left*), *I* (*middle*), and *K* bands (*right*). The field size is 37″ × 37″, with north up and east to the left. The mult cross marks the location of the OT. The offset star used for our spectrosopic observations is labeled S (the OT was 21″.0 north and 3″.9 east from the star), as is the Halpern & Fesen (1998) star 2 used for the photometric zero pointing of our *R*- and *I*-band images.

nitude of system A+B+C is $R = 23.11 \pm 0.05$. We estimate the zero-point systematic uncertainty because of an uncertain color correction at 0.15 mag. The 2 σ upper limit to a point-source detection is 25.9 mag for *R* and 24.9 mag for *I*. Our *K*-band imaging was taken under photometric conditions, and we used SJ 9134 (Persson et al. 1998) to obtain a zero point for the night. The *K*-band aperture magnitudes of the five components are listed in Table 1.

We registered the images from 1998 June 16 and November 29 *R*-band images using seven unsaturated stellar objects common to both images within 30″ from the host galaxy. We used the optimum-filter technique in the IRAF package CENTER to position the astrometric tie objects. We determined the rotation, shift, and relative scale of the two images using GEOMAP and then registered the early-time image to the late-time image. The peaks of the OT and the putative host were then estimated. Including the peak center errors and the registration uncertainty, we find that the OT was offset from the brightest *R*-band peak (A) by 0″.52 ± 0″.13 east and 0″.83 ± 0″.14 south. This amounts to a radial angular projected offset of 0″.98 ± 0″.14, and we interpret component A as the most likely host galaxy of the GRB. The *I*- and *K*-band images of the host were also registered to the late-time *R*-band image. Figure 2 shows a color composite 15″.3 × 15″.3 region around the GRB and its host using the late-time *R*-, *I*-, and *K*-band images. The ellipse is a 3 σ error contour about the position of the GRB.

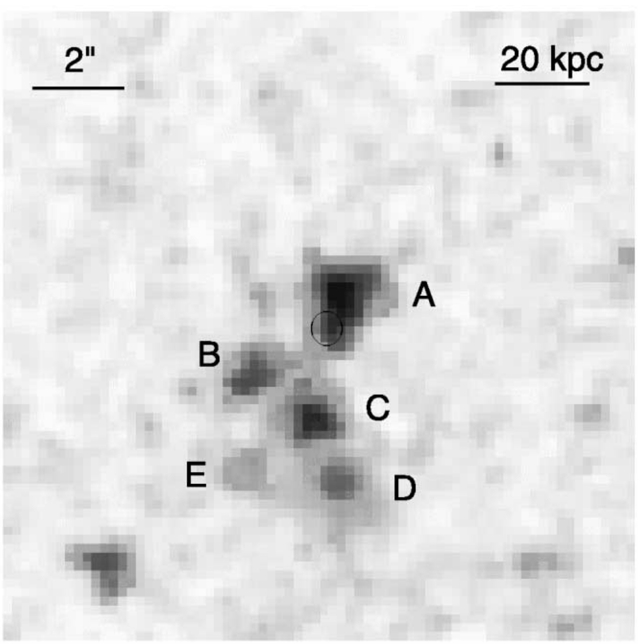

FIG. 2.—Color-composite 15″.3 × 15″.3 region around the GRB and its host. We have used the late-time *R*-, *I*-, and *K*-band images for the red, green, and blue channels, respectively. Before combining, we subtracted the mode-determined sky level and scaled each image by the rms noise of the background. The ellipse is a 3 σ error contour about the position of the GRB. The five distinct components A–E are labeled. The physical scale was computed by assuming that all objects are in a redshift sheet at $z = 1.096$. As discussed in the text, the GRB appears within the light of component A, which we interpret as the host galaxy. [*See the electronic edition of the Journal for a color version of this figure.*]

Spectra of the host galaxy were obtained using LRIS on 1998 December 11, 1999 January 14, and 1999 February 16 UT, all in good observing conditions. We used a 1″.5 wide long slit, always at a position angle close to the parallactic. On December 14, we used a 300 line mm^{-1} grating, giving an effective instrumental resolution of FWHM ≈ 16 Å and an approximate wavelength coverage of 3950–8950 Å, and we obtained six exposures totaling 8300 s. On January 14 and February 16, we used a 600 line mm^{-1} grating, giving an effective instrumental resolution of FWHM ≈ 8 Å and an approximate wavelength coverage of 5970–8540 and 5700–8270 Å, respectively; three exposures of 1800 s were obtained on each night. The object was dithered on the spectrograph slit by several arcseconds between the exposures. Exposures of an internal flat-field lamp and of arc lamps were obtained at comparable telescope pointings immediately following the target observations. Exposures of standard stars from Oke & Gunn (1983) and Massey et al. (1998) were obtained and used to measure the instrument response curve. We estimate the net flux zero-point uncertainty, including the slit losses, to be about 10%–20%.

Wavelength solutions were obtained from arc lamps in the

TABLE 1
PHOTOMETRY AND OFFSETS OF COMPONENTS NEAR GRB 980613

Component	Offset with respect to OT (arcsec)	*R* (mag)	*I* (mag)	*K* (mag)
A	0.52 W, 0.83 N	23.81 ± 0.06	23.42 ± 0.10	21.65 ± 0.22
B	1.58 E, 1.18 S	24.95 ± 0.17	24.12 ± 0.16	>22.3
C	0.25 E, 2.26 S	24.45 ± 0.10	23.81 ± 0.12	20.08 ± 0.06
D	0.47 W, 3.84 S	>25.9	>24.9	20.12 ± 0.06
E	1.72 E, 3.44 S	25.2 ± 0.3	24.66 ± 0.28	>22.3

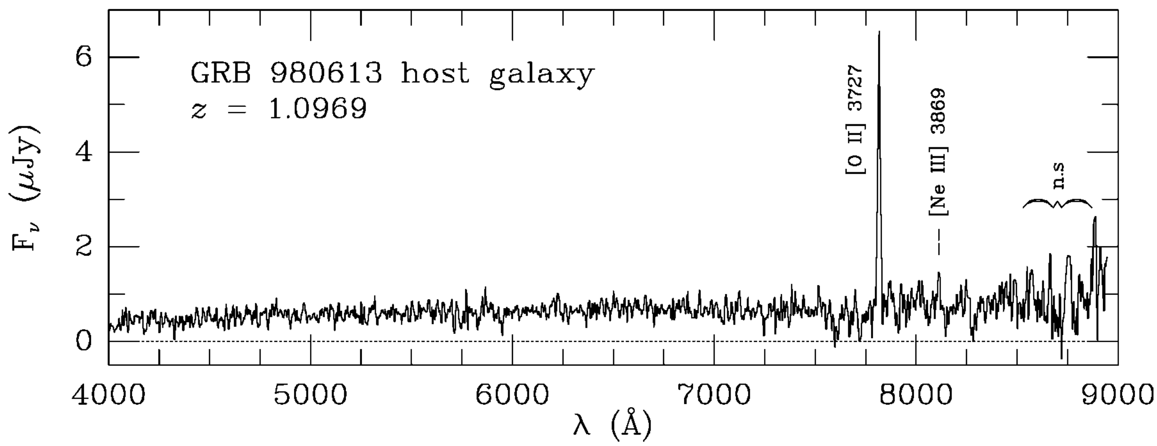

FIG. 3.—Weighted average spectrum of the host galaxy of GRB 980613 (component A in Fig. 2), obtained at the Keck II telescope. Emission lines [O II] λ3727 and [Ne III] λ3869 are labeled; "n.s." refers to noise spikes from a poor subtraction of strong night-sky lines.

standard manner, and then a second-order correction was determined from the wavelengths of isolated strong night-sky lines and was applied to the wavelength solutions. This procedure largely eliminates systematic errors due to the instrument flexure and is necessary in order to combine the data obtained during separate nights. The final wavelength calibrations have an rms ~ 0.2–0.5 Å, as determined from the scatter of the night-sky line centers. All spectra were then rebinned to a common wavelength scale with a sampling of 2.5 Å using a Gaussian with a $\sigma = 2.5$ Å as the interpolating/weighting function. This is effectively a very conservative smoothing of the spectrum since it is smaller than the instrumental resolution. Individual spectra were extracted and combined using a statistical weighting based on the signal-to-noise ratio determined from the data themselves (rather than by the exposure time).

The final combined spectrum of the galaxy is shown in Figure 3. A strong [O II] λ3727 line emission is present, and a weaker [Ne III] λ3869 line is also seen. The weighted mean redshift is $z = 1.0969 \pm 0.0002$. The observed continuum is moderately blue, with the spectrophotometric colors $(B-V) \approx 0.45$ and $(V-R) \approx 0.35$ mag.

The corrected [O II] λ3727 line flux is $(5.25 \pm 0.15) \times 10^{-17}$ ergs cm^{-2} s^{-1} Hz^{-1}, and its observed equivalent width is $W_\lambda = 125 \pm 5$ Å, i.e., 60 ± 2.4 Å in the rest frame, which is on a high side for field galaxies at comparable redshifts but not extraordinary (Hogg et al. 1998). The [Ne III] λ3869 line has a flux of about 10% of the [O II] λ3727 line. The continuum flux at $\lambda_{\rm obs} = 5871$ Å, corresponding to $\lambda_{\rm rest} = 2800$ Å, is $F_\nu = 0.84$ μJy, which has an uncertainty of a few percent (statistical). An additional spectrophotometric flux zero-point uncertainty is estimated to be ~10%–20%. The continuum flux from our direct photometry in the I band, which corresponds roughly to the rest-frame B band, is $F_\nu = 1.15$ μJy, which has an uncertainty of ~10%.

3. DISCUSSION

We will assume a flat cosmology with $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Lambda_0 = 0.7$. For $z = 1.0969$, the luminosity distance is 2.461×10^{28} cm, and 1″ corresponds to 8.8 proper kpc in projection.

The gamma-ray fluence from this burst was $(1.71 \pm 0.25) \times 10^{-6}$ ergs cm^{-2} (Woods, Kippen, & Connaughton 1998). The corresponding isotropic gamma-ray energy is $E_{\gamma,\rm iso} = 6.2 \times 10^{51}$ ergs.

From the [O II] 3727 line flux, we derive the line luminosity $L_{3727} = 4.0 \times 10^{41}$ ergs s^{-1}. Using the star formation rate (SFR) estimator from Kennicutt (1998), we derive an SFR $\approx 5.6\ M_\odot$ yr^{-1}. From the UV continuum luminosity at $\lambda_{\rm rest} = 2800$ Å, following Madau, Pozzetti, & Dickinson (1998), we derive an SFR $\approx 3.1\ M_\odot$ yr^{-1}. The difference may be due to the internal reddening within the host galaxy, but we also note that the [O II] line estimator is more sensitive to the current or recent massive star formation than the UV continuum estimator is. This is consistent with the presence of the [Ne III] λ3869 line, also seen in spectra of some other GRB hosts (Bloom et al. 1998; Bloom, Djorgovski, & Kulkarni 2001) that may be indicative of a recent, very massive star formation. We are completely insensitive to any fully obscured star formation component, so that these numbers represent lower limits. The only GRB host galaxy with a higher unobscured SFR measured to date is the host of GRB 980703 (Djorgovski et al. 1998a).

From the observed continuum flux in the rest-frame B band, we derive $M_B \approx -19.85$ mag, which is about 1 mag fainter than the present-day L_* galaxy. Considering that an average galaxy at this redshift may be ~0.5–1 mag brighter than today because of normal evolution effects, we conclude that this galaxy (A) is moderately underluminous. The SFR per unit mass is thus fairly high, consistent with the large equivalent width of the [O II] line. The [Ne III] line must be produced by massive, and thus short-lived, stars. We therefore conclude that this galaxy is undergoing at least a mild starburst.

However, the most interesting feature may be the morphology of the entire system (components A–E), which is highly suggestive of an interaction or early stages of a merger of at least two galaxies, some of which may be partly obscured. Redshifts of all vie components are necessary to really test this interpretation; we note, however, that we detect a weak [O II] line emission coincident with component C in our long-slit spectra, at the same redshift (within the joint measurement errors, $\Delta z \lesssim 0.002$) as component A. Another possibility is that we are seeing a chance superposition of galaxies at very different redshifts, e.g., that the IR-bright components C and D may be unrelated to component A (and perhaps also to components B and E), and if they are in the foreground, some gravitational lensing may be involved. However, we consider this less likely than the interaction/merger hypothesis.

The rate of galaxy interactions and mergers increases sharply with redshift (see, e.g., Le Fèvre et al. 2000), and finding a strongly interacting system at $z \sim 1.1$ is not surprising. The projected separations of components A–E (see Fig. 2) are typical of intergalactic separations, in which dark halos are overlapping and in which the tidal friction inevitably leads to a merger.

The very red colors of components C and D, $(R-K) \approx 4.4$ and $(R-K) > 5.8$, respectively, are naturally explained as being due to obscuration by dust, which is consistent with the merger hypothesis. Alternatively, they could be passively evolving elliptical galaxies that formed at a very high redshift, which requires some fine-tuning of model parameters. The data presented here have been used by Sokolov et al. (2001) in their modeling study.

It is now well established that mergers of gas-rich galaxies lead to bursts of star formation, some of which could be partly or entirely obscured by dust. This may be the strongest case so far for a GRB from such a system. Another case showing morphology consistent with a mild tidal interaction is the host galaxy of GRB 990123 (e.g., Bloom et al. 1999b; Fruchter et al. 1999; Holland & Hjorth 1999). Additional cases of GRBs from obscured starburst galaxies have been discussed by Berger, Kulkarni, & Frail (2001), Chary, Becklin, & Armus (2002), Frail et al. (2002), and Berger et al. (2003). These observations provide growing support for the connection of GRBs to massive star formation.

We want to thank the staff of the W. M. Keck Observatory for their expert assistance and Harald Ebeling for obtaining the early images of the field. We thank Dana Sadava for help in the *K*-band imaging reductions and Titus Galama for comments. J. S. B. gratefully acknowledges the fellowship from the Fannie and John Hertz Foundation. S. G. D. acknowledges partial funding from the Ajax Foundation. This work was supported in part by grants from the NSF and NASA to S. R. K.

REFERENCES

Berger, E., Cowie, L. L., Kulkarni, S. R., Frail, D. A., Aussel, H., & Barger, A. J. 2003, ApJ, 588, 99
Berger, E., Kulkarni, S. R., & Frail, D. A. 2001, ApJ, 560, 652
Bloom, J. S. 2003, in Gamma-Ray Bursts in the Afterglow Era: Third Meeting, ed. L. Piro & M. Feroci (San Francisco: ASP), in press
Bloom, J. S., Diercks, A., Kulkarni, S. R., Djorgovski, S. G., Scoville, N. Z., & Frayer, D. T. 1999a, GCN Circ. 480 (http://gcn.gsfc.nasa.gov/gcn/gcn3/480.gcn3)
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. 1998, ApJ, 507, L25
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002a, AJ, 123, 1111
Bloom, J. S., et al. 2002b, ApJ, 572, L45
———. 1999b, ApJ, 518, L1
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1988, ApJ, 329, L33
Chary, R., Becklin, E., & Armus, L. 2002, ApJ, 566, 229
Costa, E., et al. 1997, Nature, 387, 783
Diercks, A., Deutsch, E. W., Stubbs, C., Vreeswijk, P. M., Galama, T. J., van Paradijs, J., Robinson, C., & Kouveliotou, C. 1998, GCN Circ. 108 (http://gcn.gsfc.nasa.gov/gcn/gcn3/108.gcn3)
Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., Frail, D., Chaffee, F., & Goodrich, R. 1999, GCN Circ. 189 (http://gcn.gsfc.nasa.gov/gcn/gcn3/189.gcn3)
Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., Goodrich, R., Frail, D. A., Piro, L., & Palazzi, E. 1998a, ApJ, 508, L17
Djorgovski, S. G., Kulkarni, S. R., Odewahn, S. C., & Ebeling, H. 1998b, GCN Circ. 117 (http://gcn.gsfc.nasa.gov/gcn/gcn3/117.gcn3)
Djorgovski, S. G., et al. 2002, in Proc. Ninth Marcel Grossmann Meeting, ed. V. Gurzadyan, R. Jantzen, & R. Ruffini (Singapore: World Scientific), 315
———. 2003, Proc. SPIE, in press
Frail, D. A., et al. 2002, ApJ, 565, 829
Frail, D. A., Kulkarni, S. R., Nicastro, S. R., Feroci, M., & Taylor, G. B. 1997, Nature, 389, 261
Fruchter, A. S., et al. 1999, ApJ, 519, L13
Galama, T. J., et al. 2000, ApJ, 536, 185
———. 1998, Nature, 395, 670
Garnavich, P. M., et al. 2003, ApJ, 582, 924
Halpern, J. P., & Fesen, R. 1998, GCN Circ. 134 (http://gcn.gsfc.nasa.gov/gcn/gcn3/134.gcn3)
Hjorth, J., Andersen, M. I., Pedersen, H., Jaunsen, A. O., Costa, E., & Palazzi, E. 1998, GCN Circ. 109 (http://gcn.gsfc.nasa.gov/gcn/gcn3/109.gcn3)
Hjorth, J., Pedersen, H., Jaunsen, A. O., & Andersen, M. I. 1999, A&AS, 138, 461
Hjorth, J., et al. 2002, ApJ, 576, 113
Hogg, D. W., Cohen, J. G., Blandford, R., & Pahre, M. A. 1998, ApJ, 504, 622
Holland, S. 2000, GCN Circ. 777 (http://gcn.gsfc.nasa.gov/gcn/gcn3/777.gcn3)
Holland, S., & Hjorth, J. 1999, A&A, 344, L67
Hurley, K., Sari, R., & Djorgovski, S. G. 2003, in Compact Stellar X-Ray Sources, eds. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kulkarni, S. R., et al. 1998, Nature, 395, 663
———. 2000, Proc. SPIE, 4005, 9
Lazzati, D., et al. 2001, A&A, 378, 996
Le Fèvre, O., et al. 2000, MNRAS, 311, 565
Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106
Massey, P., Strobel, K., Barnes, J. V., & Anderson, E. 1988, ApJ, 328, 315
Mészáros, P. 2002, ARA&A, 40, 137
Metzger, M., Djorgovski, S. G., Kulkarni, S. R., Steidel, C., Adelberger, K., Costa, E., & Frontera, F. 1997, Nature, 387, 878
Oke, J. B., et al. 1995, PASP, 107, 375
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Paczyński, B. 1998, ApJ, 494, L45
Persson, S. E., Murphy, D., Krzeminski, W., Roth, M., & Rieke, M. 1998, AJ, 116, 2475
Piro, L. 1998, GCN Circ. 104 (http://gcn.gsfc.nasa.gov/gcn/gcn3/104.gcn3)
Piro, L., & Costa, E. 1998, GCN Circ. 99 (http://gcn.gsfc.nasa.gov/gcn/gcn3/99.gcn3)
Piro, L., et al. 1999, A&AS, 138, 431
Reichart, D. E. 1999, ApJ, 521, L111
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sokolov, V., et al. 2001, A&A, 372, 438
van Paradijs, J., et al. 1997, Nature, 386, 686
van Paradijs, J., Kouveliotou, C., & Wijers, R. 2000, ARA&A, 38, 379
Waxman, E. 2003, in Supernovae and Gamma-Ray Bursters, ed. K. Weiler (Berlin: Springer), in press
Wijers, R. A. M. J., Rees, M. J., & Mészáros, P. 1997, MNRAS, 288, L51
Woods, P., Kippen, R. M., & Connaughton, V. 1998, GCN Circ. 112 (http://gcn.gsfc.nasa.gov/gcn/gcn3/112.gcn3)