THE ASTROPHYSICAL JOURNAL, 470:L93–L96, 1996 October 20

A *JHK′* SURVEY OF THE ERROR BOX OF THE GAMMA-RAY BURST 790418

SYLVIO KLOSE[1] AND JOCHEN EISLÖFFEL[1]
Thüringer Landessternwarte Tautenburg, D-07778 Tautenburg, Germany

AND

STEFFEN RICHTER
Max Planck Society, Research Unit "Dust in Star-Forming Regions," Schillergäßchen 3, D-07745 Jena, Germany
Received 1996 June 6; accepted 1996 August 13

ABSTRACT

We performed a deep *JHK′* survey of the 2.9 arcmin^2 positional error box of the gamma-ray burst (GRB) 790418. At limiting magnitudes of $J \sim 21$, $H \sim 20$, and $K \sim 19$, we find about 20 objects within the box, galaxies as well as very red stars. A relatively bright galactic nucleus ($K = 16.3$), presumably the bulge of a spiral galaxy, is located about 5″ outside the 3 σ box given in Vrba, Hartmann, & Jennings, with its halo region possibly extending inside the box. Although this seems to match well into the framework of the cosmological model of GRBs, the assumption that this galaxy is physically related to GRB 790418 is not strongly supported by simple statistical arguments. No potential Galactic halo burst source could be selected from our data.

Subject headings: gamma rays: bursts — infrared: galaxies

1. INTRODUCTION

In spite of a tremendous observational effort (see, e.g., McNamara, Harrison, & Williams 1995), no source of a classical gamma-ray burst (GRB) has yet been identified. Deep counterpart searches for the bursters concentrate mainly on the bursts with positional error boxes of arcminute size. Among these is GRB 790418, which was detected by altogether seven experiments on board the *Prognoz 7*, *Venera 11*, and *Venera 12* spacecraft, the *Pioneer Venus Orbiter*, and the *International Sun-Earth Explorer* (Atteia et al. 1987). Due to this network localization, its positional error box at the 3 σ confidence level amounts to only 2.9 arcmin^2 (see Fig. 1*b* in Vrba, Hartmann, & Jennings 1995, hereafter VHJ95), making this box one of the smallest known. Over the years, it was the target of a number of surveys covering nearly the whole accessible wavelength range: the radio (Schaefer et al. 1989), the near- and far-infrared (Schaefer et al. 1987), the optical (Schaefer 1992; VHJ95), the X-ray band (Boer et al. 1991; Greiner et al. 1995), as well as the gamma-ray band (Horack & Emslie 1994). However, only the deep *UBVI* survey by VHJ95, in the *V* band down to a limiting magnitude of ∼24, revealed stellar objects in the error box. Schaefer (1990) searched nearly 2000 archival plates for optical transients in this box and found nothing, as in other cases.

Recently, Webber et al. (1995) investigated whether, in the 60 smallest GRB error boxes, any source population is known at optical or radio wavelengths (stars, bright galaxies, radio galaxies, active galactic nuclei, clusters of galaxies, or quasars) that is statistically overabundant with respect to the field. No evidence for such a population was found. However, very recently, Larson, McLean, & Becklin (1996) noted that in near-infrared surveys there is evidence for an excess of galaxies with magnitudes $K < 15.5$ in small GRB error boxes.

In this Letter, we report on the results of a deep *JHK′* survey of the GRB 790418 error box for the quiescent burst source down to a limiting magnitude of $J \sim 21$, $H \sim 20$, and $K \sim 19$. This is more than 5 mag deeper than in a previous near-infrared survey of this box by Schaefer et al. (1987).

2. OBSERVATIONS AND DATA REDUCTION

Observations were performed on 1995 November 13/14 at the 3.5 m telescope on Calar Alto, Spain, equipped with the near-infrared camera MAGIC (Herbst et al. 1993; Herbst & Rayner 1993). In the high-resolution mode, the camera has a 84″ field of view and an image scale of 0″.33 pixel^{-1}. The seeing was between 0″.8 and 1″ (FWHM). The error box of GRB 790418 was imaged repeatedly at four different positions that, put together as a complete mosaic, gave per pixel integration times of 10 minutes in *J* and *H*, and 14 minutes in *K′*.

All individual frames were sky-subtracted, flat-fielded, and corrected for bad pixels. Photometry was done using DAOPHOT II (see also Stetson 1987) implemented in the MIDAS package (version 94). Calibration of the photometry was performed with the standard star FS 13 (Casali & Hawarden 1992). We used the analytic relation of Wainscoat & Cowie (1992), $K' - K \approx 0.20(H - K)$, to transform *K′* into *K* magnitudes for stars and galaxies (see Cowie et al. 1994, their Fig. 5, for quantitative differences between *K* and *K′* magnitudes for galaxies).

We observed the standard star at an air mass of $X^*_\lambda = 1.28$ in *J*, *H*, and *K′* but surveyed the GRB error box at mean air masses of $X_\lambda = 1.48$, 1.62, and 2.00, in *J*, *H*, and *K′*, respectively. Before transforming *K′* into *K* magnitudes, we corrected our data for atmospheric extinction by adding $a_\lambda(X^*_\lambda - X_\lambda)$ (cf. Kitchin 1991) to all *JHK′* magnitudes, where a_λ is the extinction coefficient in the considered photometric band. Because of the lack of available data, we made the approximation $a_{K'} = a_K$ (see Wainscoat & Cowie 1992 for a discussion of the atmospheric extinction in the *K′* band) and took a_J, a_H, $a_K = 0.11$, 0.07, 0.09 mag per air mass (Davis 1992) as extinction values, assuming that these values are also representative for the Calar Alto observing site. Because of these approximations, our final *JH* magnitudes may have a

[1] Visiting Astronomer, German-Spanish Astronomical Centre, Calar Alto, operated by the Max-Planck-Institut für Astronomie, Heidelberg, jointly with the Spanish National Commission for Astronomy.

systematic error on the order of 0.1 mag, whereas the systematic error in K may be twice as large.

To our knowledge, the line of sight to the GRB 790418 error box crosses no interstellar dust cloud. The error box lies at a Galactic latitude of $b \approx -16°$. At such latitudes, the expected interstellar extinction along the line of sight through the Galaxy is $A_J \sim 0.06$ mag, $A_H \sim 0.04$ mag, and $A_K \sim 0.02$ mag (see § 2 in Thuan et al. 1984 and Appendix B in Bessell & Brett 1988).

3. EXPECTATIONS AND OBSERVATIONAL RESULTS

The observational data of more than 1000 GRBs detected by the BATSE experiment on board the *Compton Gamma Ray Observatory* (Meegan et al. 1996) set strong constraints on GRB models (Briggs et al. 1996): briefly, the burst sources are located either in an extended Galactic halo or at cosmological distances (for recent reviews see Fishman & Meegan 1995; Hartmann 1995a, 1995b).

In the former case, it is generally assumed that neutron stars are the origin of the bursts (for a discussion see Hartmann & Narayan 1996). The current BATSE limit on a possible anisotropy in the distribution of the GRBs on the sky (Briggs et al. 1996) implies, however, that a possible GRB source population in the Galactic halo is at a distance on the order of 100 kpc (cf. Hakkila et al. 1994). In this case, even sources of strong bursts like GRB 790418 (fluence $\sim 6.5 \times 10^{-5}$ ergs cm^{-2}, $kT = 1150$ keV [Mazets et al. 1981]; peak flux $\sim 1.1 \times 10^{-4}$ ergs cm^{-2} s^{-1} [Schaefer 1990]) might not lie at distances smaller than, say, 10 kpc. Therefore, it seems reasonable to adopt the hypothesis that, within the framework of the Galactic halo model, the source of GRB 790418 should lie in the distance range from 10 to 100 kpc. Evidence for a stellar object at such distances could only be found on our frames if it formed a binary system together with an evolved bright star. Based on the absolute *BVJHK* magnitudes for stars of different spectral types given by Wainscoat et al. (1992; their Table 2), however, we do not expect to see any dwarf, giant, or supergiant star at the required distance that has not yet been detected in the deep V-band survey by VHJ95. Finally, a possible steady accretion disk around the potential Galactic halo neutron star may not be visible on our frames, neither for a standard α disk (see Schaefer et al. 1987) nor for a cool disk (cf. Epstein 1985; Melia 1988a, 1988b).

Within the framework of the cosmological model of GRBs, the bursters are at typical redshifts $z \approx 1$ (cf. Wickramasinghe et al. 1993). Since GRB 790418 was a relatively strong burst, its host galaxy could lie relatively nearby. Fenimore et al. (1993) estimated its distance to only 390 Mpc ($z \approx 0.1$ for a Hubble constant of 75 km s^{-1} Mpc^{-1}). In the Hawaii K-band galaxy survey, the mean magnitude of a galaxy at a redshift of 0.1 is $K \sim 14$ (Songaila et al. 1994; their Fig. 8). Such a bright galaxy should be clearly visible on our frames. In particular, based on various galaxy counts in the K band (e.g., Cowie et al. 1990, 1994; Gardner, Cowie, & Wainscoat 1993; Chokshi et al. 1994; Glazebrook et al. 1994, 1995; Djorgovski et al. 1995; McLeod et al. 1995), we expect to see no galaxy brighter than $K \sim 15$ in the 2.9 arcmin^2 large error box (but about five to ten galaxies per arcmin^2 down to our detection limit).

Figure 1 (Plate L10) shows our final J-, H-, and K'-band images of the GRB 790418 error box, Figure 2 shows a contour plot of the J image. There are seven objects on our images within the GRB error box that seem to be stellar. One of them is relatively bright in the K band, and very red [at pixel coordinates (130, 385) in Fig. 2 with V, I, J, H, K = 22.25, 19.77, 18.2, 17.5, 17.2; V, I from VHJ95]. However, comparably red objects with $V - K > 5$ mag (altogether eight) are also found among the 26 stellar objects on our images outside the GRB error box. This holds true especially for the object labeled No. 158 in VHJ95 (their Fig. 1b), for which we measure J, H, K = 15.8, 15.2, 14.8 and for which VHJ95 give V, I = 20.32, 17.54. Our data confirm the conclusion of VHJ95 that it could be a late-type M star. Unfortunately, based on our photometry alone, we cannot distinguish (nearby) dwarfs from (faraway) giants. Although we can state that

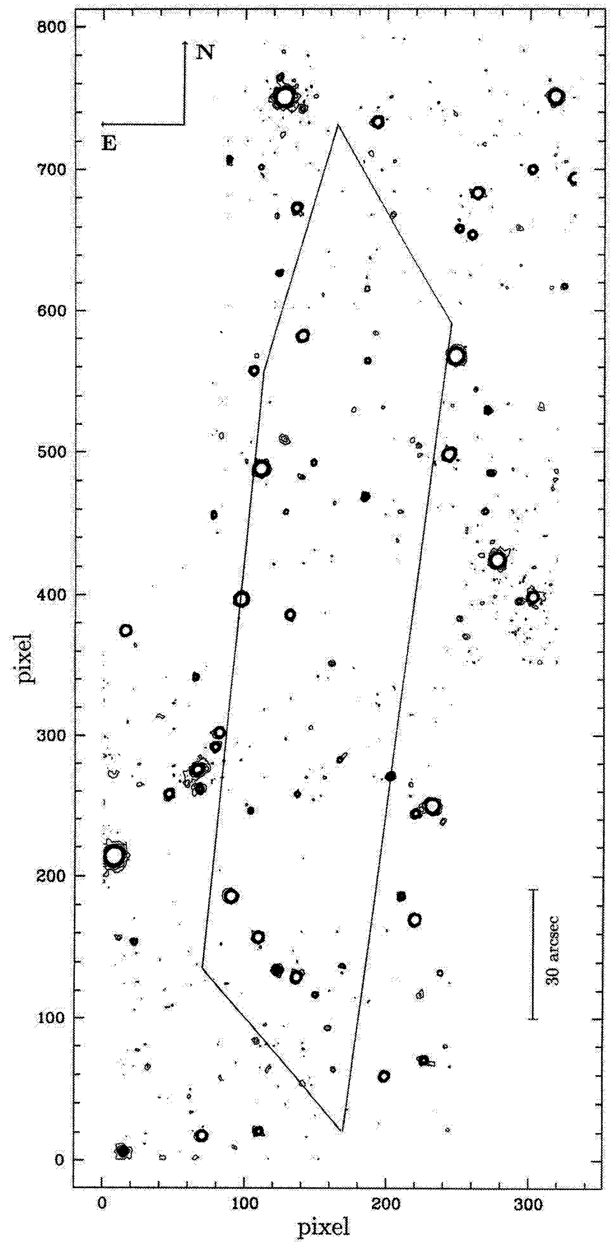

FIG. 2.—Contour plot of our J-band image. The error box of GRB 790418 is drawn according to Fig. 1b in VHJ95. The scale is 0".33 pixel^{-1}.

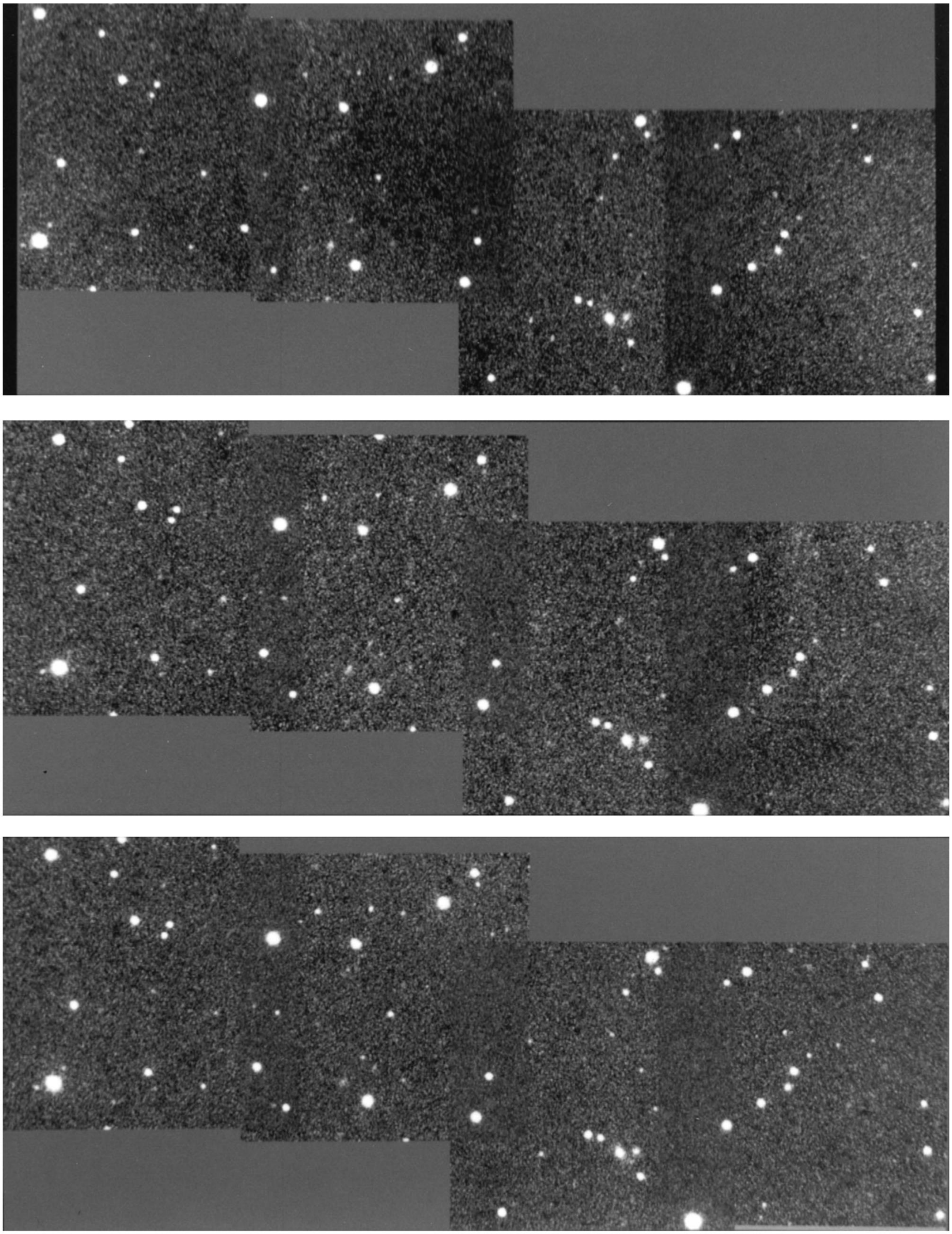

FIG. 1.—*J*-, *H*-, and *K*′- band images (*from left to right*) of the error box of GRB 790418. The faintest visible objects have $J \sim 21$, $H \sim 20$, and $K \sim 19$, respectively.

KLOSE, EISLÖFFEL, & RICHTER (see 470, L94)

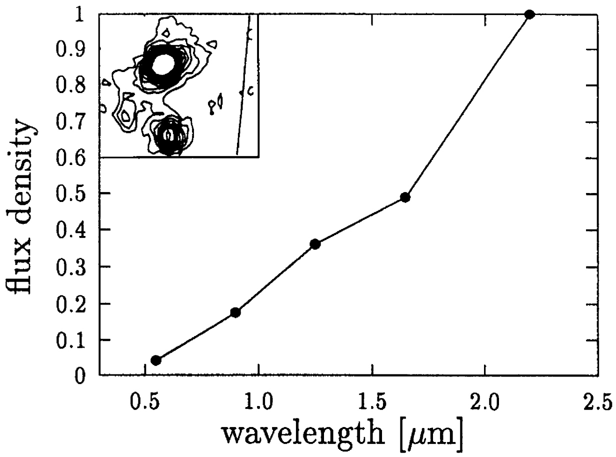

FIG. 3.—The spectral energy distribution of the bright galactic nucleus at the border of the 3 σ error box of GRB 790418. V and I magnitudes were taken from VHJ95. The flux density is normalized relative to the K band. The inset is an enlargement of this galaxy from Fig. 2.

the GRB error box contains faint Galactic late-type stars, we cannot select a potential burst source among them.

At a given apparent magnitude, the surface density of galaxies in the K band is a factor of $\sim$100 higher than in the optical B band (cf. Fig. 1 in Broadhurst, Ellis, & Glazebrook 1992). It is therefore not surprising that our JHK' survey reveals a number of extragalactic objects within the GRB error box, whereas Schaefer (1992) found nothing at a limiting magnitude of $B \sim 20$. Based on their visual appearance, about 14 objects within the GRB error box might be galaxies, a number in qualitative agreement with the expectations. Not all of these galaxies, however, have an accurate photometry. Among the galaxies are notably red objects with $V - K > 4$ mag. One of them is clearly extended (at pixel coordinates [125, 510] in Fig. 2) and seems to be a member of a cluster of galaxies. As we have noted, within the cosmological model of GRBs, we should clearly see the host galaxy of GRB 790418. Indeed, a relatively bright galactic nucleus (J, H, K = 18.4, 17.6, 16.3) is visible on our images [at pixel coordinates (65, 275)]. It has the reddest $H - K$ color (1.3 mag; Fig. 3) of all objects for which photometry in H and K was possible, and it seems to be the bulge of a spiral galaxy that has a nearby companion. Such a color is not unusual for, e.g., Seyfert galaxies (cf. Glass & Moorwood 1985). According to its K magnitude, as well as its $I - K$ color (V, I = 21.60, 19.51; VHJ95), this galaxy could indeed lie at the required redshift of $z \sim 0.1$ (see Fig. 9*a* in Songaila et al. 1994). It lies, however, about 5″ *outside* the 3 σ error box reported by VHJ95, although one cannot exclude that its outer halo regions do lie within the error box. On the other hand, the second brightest (in the K band) galaxy (J, H, K = 19.1, 18.3, 17.6; V, I = 22.19, 20.25 according to VHJ95) on our images lies at pixel coordinates (125, 135), well within the 3 σ GRB error box. At such K magnitudes, however, the probability of finding such a galaxy in a 2.9 arcmin^2 field approaches 1.0.

4. SUMMARY AND CONCLUSION

We find seven apparently stellar objects within the GRB error box, among them very red stars, but we were not able to select a potential Galactic halo burst source among them. In other words, our observations do not strongly constrain Galactic halo models of GRBs.

Within the framework of the cosmological model of GRBs, a relatively bright galaxy could be visible within the error box of GRB 790418. There is indeed a galaxy with $K \sim 16$ just outside the error box, with its halo region possibly extending inside the box. The mean surface density of galaxies with $K \sim 16$ is $\sim$500–1000 deg^{-2} mag^{-1} (for references see § 3), i.e., $\sim$0.15–0.3 arcmin^{-2} mag^{-1}. In other words, simple statistical arguments do not strongly support the assumption of a physical relation of this galaxy with the burst. It is an open question, however, whether this statement would change if more special properties of galaxies would be considered.

Deep near-infrared surveys seem to be a powerful tool for searching for potential extragalactic burst sources in GRB error boxes. This holds at least for strong GRBs with small error boxes, where the potential GRB host galaxy is expected to lie relatively nearby and therefore could be relatively bright.

The authors thank an anonymous referee for valuable comments to the original manuscript. This study has made use of a GRB bibliographic catalog by K. Hurley (1995, private communication).

REFERENCES

Atteia, J.-L., et al. 1987, ApJS, 64, 305
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Boer, M., Hurley, K., Pizzichini, G., & Gottardi, M. 1991, A&A, 249, 118
Briggs, M. S., et al. 1996, ApJ, 459, 40
Broadhurst, T. J., Ellis, R. S., & Glazebrook, K. 1992, Nature, 355, 55
Casali, M., & Hawarden, T. 1992, JCMT-UKIRT Newsletter, 4, 33
Chokshi, A., Lonsdale, C. J., Mazzei, P., & de Zotti, G., 1994, ApJ, 424, 578
Cowie, L. L., Gardner, J. P., Lilly, S. J., & McLean, I. 1990, ApJ, 360, L1
Cowie, L. L., et al. 1994, ApJ, 434, 114
Davis, J. K. 1992, UKIRT Observer's Manual (Edinburgh: Royal Obs.)
Djorgovski, S., et al. 1995, ApJ, 438, L13
Epstein, R. I. 1985, ApJ, 291, 822
Fenimore, E. E., et al. 1993, Nature, 366, 40
Fishman, G. J., & Meegan, C. A. 1995, ARA&A, 33, 415
Gardner, J. P., Cowie, L. L., & Wainscoat, R. J. 1993, ApJ, 415, L9
Glass, I. S., & Moorwood, A. F. M. 1985, MNRAS, 214, 429
Glazebrook, K., Peacock, J. A., Collins, C. A., & Miller, L. 1994, MNRAS, 266, 65
Glazebrook, K., Peacock, J. A., Miller, L., & Collins, C. A. 1995, MNRAS, 275, 169
Greiner, J., et al. 1995, in NATO ASI Ser. 450, The Lives of Neutron Stars, ed. M. A. Alpar, Ü. Kiziloğlu, & J. van Paradijs (Dordrecht: Kluwer), 519
Hakkila, J., et al. 1994, ApJ, 422, 659
Hartmann, D. H. 1995a, in NATO ASI Ser. 450, The Lives of Neutron Stars, ed. M. A. Alpar, Ü. Kiziloğlu, & J. van Paradijs (Dordrecht: Kluwer), 495
———. 1995b, A&A Rev., 6, 225
Hartmann, D. H., & Narayan, R. 1996, ApJ, 464, 226
Herbst, T. M., et al. 1993, Proc. SPIE, 1946, 605
Herbst, T. M., & Rayner, J. T. 1993, in Infrared Astronomy with Arrays, ed. I. S. McLean (Dordrecht: Kluwer), 515
Horack, J. M., & Emslie, A. G. 1994, ApJ, 425, 776
Kitchin, C. R. 1991, Astrophysical Techniques. Adam Hilger Ltd., § 3.2
Larson, S. B., McLean, I. S., & Becklin, E. E. 1996, ApJ, 460, L95
Mazets, E. P., et al. 1981, Nature, 290, 378
McLeod, B. A., et al. 1995, ApJS, 96, 117
McNamara, B. J., Harrison, T. E., & Williams, C. L. 1995, ApJ, 452, L25
Meegan, C. A., et al. 1996, ApJS, 106, 65
Melia, F. 1988a, ApJ, 324, L21
———. 1988b, ApJ, 334, L9
Schaefer, B. E. 1990, ApJ, 364, 590
———. 1992, in Gamma-Ray Bursts, Observations, Analyses and Theories, ed. C. Ho, R. I. Epstein, & E. E. Fenimore (Cambridge: Cambridge Univ. Press), 107
Schaefer, B. E., et al. 1987, ApJ, 313, 226

Schaefer, B. E., et al. 1989, ApJ, 340, 455
Songaila, A., Cowie, L. L., Hu, E. M., & Gardner, J. P. 1994, ApJS, 94, 461
Stetson, P. B. 1987, PASP, 99, 191
Thuan, T. X., et al. 1984, ApJ, 285, 515
Vrba, F. J., Hartmann, D. H., & Jennings, M. C. 1995, ApJ, 446, 115 (AAS CD-ROM Series, Volume 5) (VHJ95)
Wainscoat, R. J., & Cowie, L. L. 1992, AJ, 103, 332
Wainscoat, R. J., et al. 1992, ApJS, 83, 111
Webber, W. R., Harrison, T. E., McNamara, B. J., & Lopez, A. 1995, AJ, 110, 733
Wickramasinghe, W. A. D. T., et al. 1993, ApJ, 411, L55