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DISCOVERY OF THE OPTICAL TRANSIENT OF GRB 990308

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ABSTRACT

The optical transient of the faint gamma-ray burst GRB 990308 was detected by the QUEST camera on the Venezuelan 1 m Schmidt telescope starting 3.28 hr after the burst. Our photometry gives $V = 18.32 \pm 0.07$, $R = 18.14 \pm 0.06$, $B = 18.65 \pm 0.23$, and $R = 18.22 \pm 0.05$ for times ranging from 3.28 to 3.47 hr after the burst. The colors correspond to a spectral slope of close to $f_\nu \propto \nu^{1/3}$. Within the standard synchrotron fireball model, this requires that the external medium be less dense than 10^4 cm^{-3}, the electrons contain more than 20% of the shock energy, and the magnetic field energy be less than 24% of the energy in the electrons for normal interstellar or circumstellar densities. We also report upper limits of $V > 12.0$ at 132 s (with LOTIS), $V > 13.4$ from 132 to 1029 s (with LOTIS), $V > 15.3$ at 28.2 minutes (with Super-LOTIS), and a 8.5 GHz flux of less than 114 μJy at 110 days (with the Very Large Array). Wisconsin-Indiana-Yale-NOAO 3.5 m and Keck 10 m telescopes reveal this location to be empty of any host galaxy to $R > 25.7$ and $K > 23.3$. The lack of a host galaxy likely implies that it is either substantially subluminous or more distant than a redshift of $\sim$1.2.

Subject heading: gamma rays: bursts

1. INTRODUCTION

The old dilemma of whether gamma-ray bursts (GRBs) are galactic or cosmological has been solved recently with the discovery of X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997), and radio transients (Frail et al. 1998). Four optical transients have measured redshifts of 0.835 (GRB 970508), 0.966 (GRB 980703), ≥1.600 (GRB 990123), and ≥1.619 (GRB 990510), thus proving that bursts are at cosmological distances.

After the burst is over, the expanding shell emits an afterglow which eventually fades to invisibility. Early detections of the afterglow include GRB 990510 at 3.52 hr (Harrison et al. 1999) and GRB 990123 during the burst by *ROTSE* (Akerlof et al. 1999). Theoretical models of synchrotron emission from a decelerating relativistic shell shocked by collision with an external medium are in good agreement with afterglow observations from X-ray to radio and from the earliest to the latest times of available observations (Galama et al. 1998, 1999).

The accurate optical/radio positions allow for very deep searches after the transient fades. For the 11 optical/radio transient positions searched to date, a very faint galaxy (typically with $R \sim 25$) appears within an arcsecond or so for nine of the positions. This result demonstrates that most GRBs reside inside distant host galaxies. Although the optical/radio transient positions are within the galaxies, they are significantly offset from the centers, demonstrating that the progenitors are neither associated with a giant central black hole nor are ejected from the galaxy. Bursts have been associated with active star formation (Totani 1997; Paczyński 1998), while the hosts have been shown to be significantly subluminous for normal galaxies in the majority of cases (Schaefer 1999). Three of the positionally coincident host galaxies have observed redshift values of 0.695 (GRB 970228), 3.418 (GRB 971214), and 1.097 (GRB

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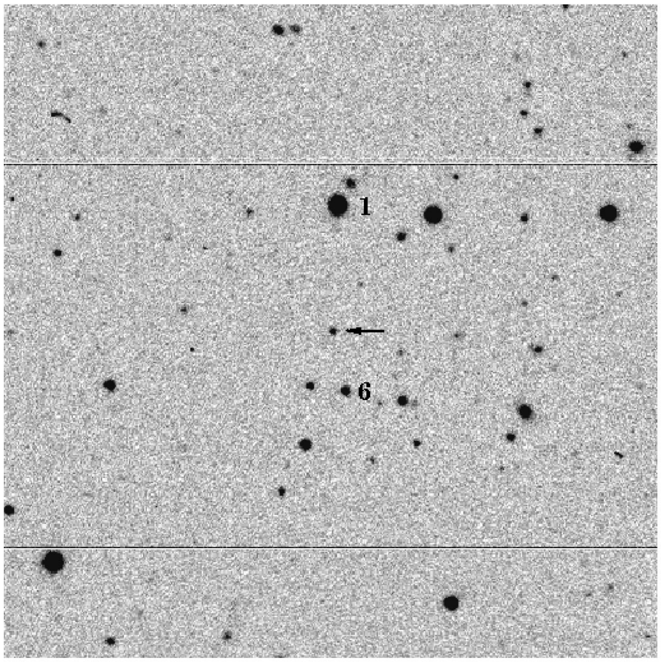

FIG. 1.—QUEST image from 3.28 hr after the burst. This image was taken in the drift scan mode starting 3.28 hr after the burst, and is a combination of the two R-band images with a limiting magnitude of roughly $R = 22.1$ at the S/N = 3 level. North is up, east is to the left, and the image shows an area 8′ by 8′. The optical transient is indicated with an arrow, while the comparison stars 1 and 6 are labeled.

980613), in reasonable agreement with the redshifts from the optical transients.

The GRB explosion mechanism is still unknown, but a profitable line of study is to observe the burst afterglows over a wide range of time and frequency, with demographic arguments providing information on the progenitor and hence the explosion mechanism. Few afterglows have been observed to date, so further examples are important. This Letter reports the discovery of the afterglow of GRB 990308 with B, V, and R imagery starting 3.28 hr after the burst.

2. OBSERVATIONS

GRB 990308 triggered the *Compton Gamma-Ray Observatory* Burst and Transient Source Experiment (BATSE) on 1999 March 8, 05:15:07 UT. This burst has a peak flux (50–300 keV, 256 ms time bins) of 1.6 ± 0.1 photons $\mathrm{s^{-1}\,cm^{-2}}$, a fluence (>25 keV) of 2.2×10^{-5} ergs $\mathrm{cm^{-2}}$, and a T_{90} duration of 106 ± 12 s. GRB 990308 also triggered one camera of the *Rossi X-Ray Timing Explorer* (*RXTE*) All-Sky Monitor (Levine et al. 1996; Smith et al. 1999a). At 06:32 UT, a preliminary position had been determined and distributed as e-mail by the GRB Coordinate Network (GCN; Barthelmy et al. 1994). This position is a long thin error box which has since been updated (see below) to one with a 3 σ total width of close to 6′.8.

GRB 990308 was also detected, very weakly, by the *Ulysses* GRB detector (Hurley et al. 1992). A cross correlation of the light curves between *Ulysses* and BATSE (separated by 2066.004 lt-s) as part of the Interplanetary Network (IPN; Hurley et al. 1999) yields an annulus with 3 σ total width of 35′.9. The IPN/*RXTE* error boxes overlap at an angle of ~80° to form a 3 σ error box defined by four points with J2000 coordinates of $12^{\rm h}21^{\rm m}47^{\rm s}$, $+06°31'11''$; $12^{\rm h}22^{\rm m}00^{\rm s}$, $+06°25'00''$; $12^{\rm h}24^{\rm m}21^{\rm s}$, $+07°01'44''$; and $12^{\rm h}24^{\rm m}34^{\rm s}$, $+06°55'36''$.

The final error region was imaged with the LOTIS (Park et al. 1997) and Super- LOTIS (Park et al. 1998) wide-field fast response cameras located at the Lawrence Livermore National Laboratory. Both systems responded to a GCN notice of the preliminary BATSE coordinates, and the first images were taken 12.6 s after the trigger. An updated BATSE position from the GCN shifted the position, with the cameras responding quickly, such that the first LOTIS images that cover the error box are at 132 s after the BATSE trigger. This 10 s integration reached $V = 12.0$ (signal-to-noise ratio [S/N] = 3, no filter) with no indication of an optical transient. A sum of roughly 10 minutes of exposure from 132–1029 s after the BATSE trigger showed no optical transient to $V = 13.4$. Unfortunately, the night was somewhat foggy, so the limiting magnitude was dominated by the unusually bright sky background. The Super-LOTIS camera has a 0°.8 square field of view which took 30 s exposures in a spiral pattern around the center of the BATSE error region. The burst position was imaged starting 28.2 minutes after the burst to a depth of $V = 15.3$ (S/N = 3, no filter) with no evidence for an optical transient.

With the QUEST camera on the 1.0 m Schmidt telescope of the Observatorio Nacional de Llano del Hato near Mérida, Venezuela, we started scans of the preliminary error box approximately 3 hr after the burst. The QUEST camera consists of 16 2048 × 2048 CCD detectors in a 4 × 4 array operating in a drift scan mode (Snyder 1998; Sabbey, Coppi, & Oemler 1998). At any instant the QUEST camera is viewing 5.4 deg^2 and in 1 hr will scan a 2°.3 × 15° region, which makes the camera ideal for rapid response to large preliminary GRB error boxes. Each row of detectors is covered with a different filter, so that the GRB 990308 error box was imaged four independent times with standard (Bessel 1990) V, R, B, and R bands in time order. The integration time for each image was 142 s, with a total time of 11.5 minutes separating the centers of first and last. The limiting magnitudes were $B = 19.2$, $V = 20.2$, and $R = 21.6$ to the S/N = 3 level with the 69% illuminated Moon 53° away. The pixel size is 1″.02, the FWHM seeing was 2″.6, and the entire IPN/*RXTE* box was covered.

The large size of the QUEST field of view is good for rapid imaging of large preliminary GRB positions, but it also means that rapid identification is difficult until a small error box is reported. For GRB 990308, the early error box was 8°.6 long until March 14 when the small IPN/*RXTE* region was produced (Smith et al. 1999b). The deep limiting magnitude of QUEST is good for catching faint optical transients, but it also means that the afterglow cannot be recognized if it is near or below the threshold of the Digital Sky Survey until deeper comparison images can be made. For GRB 990308 where our combined images go to $R = 22.1$ for S/N = 3 with no obvious transient brighter than $R = 18$, we had to await the acquisition of deep comparison images. These were made with the Yale 1 m telescope at Cerro Tololo (operated by the YALO consortium; Méndez, Depoy, & Bailyn 1998) in the R band on 1999 May 29 as a 14 element mosaic reaching $R = 22.9$ mag. A star-by-star comparison rapidly revealed an optical transient close to the center of the IPN/*RXTE* region (Fig. 1).

The transient appears with an S/N of 15.0, 17.1, 4.7, and 20.8 on the V, R, B, and R images, respectively. All four images show the transient with the shape and FWHM of our point-spread function. The astrometric position on all four images is identical to within an rms scatter of 0″.4, with the fitted motion during the 11.5 minutes of observation equal to 0″.03 ± 0″.28. We take the appearance of four independent and significant images with good stellar shapes as proof that the images are not artifacts of any kind. For the position near opposition, the lack of motion rules out all solar system objects, including Kuiper Belt objects. The source must have an amplitude of greater than 7.5 mag since the source position is empty to $R > 25.7$ in June (see below). The only known astrophysical objects outside our solar system with such amplitudes are dwarf novae, novae, supernovae, and GRBs. The transient cannot be a dwarf nova or nova since the $R = 18.14$ observed magnitude (see below) would imply a distance far outside any galaxy. The transient cannot be a supernova (with $M_R > -19.5$ for a distance modulus of <37.64) as our limit on any parent galaxy (which must have $R > 25.7$, see later) would then be $M_R > -11.94$. The transient is rather similar to GRBs seen previously (van Paradijs et al. 1997; Galama et al. 1998, 1999; Harrison et al. 1999). Thus we conclude that our optical transient is definitely the afterglow of GRB 990308.

We calibrated the *B*, *V*, and *R* magnitudes of nearby comparison stars with images taken on 1999 June 10 with the Yale 1 m telescope. This calibration was made by the observation of 22 standard stars (Landolt 1992) which was then applied to images of the GRB 990308 field. We then performed differential photometry on the QUEST images with respect to four nearby comparison stars of known magnitude. We find $V = 18.32 \pm 0.07$ at 196.8 minutes, $R = 18.14 \pm 0.06$ at 200.6 minutes, $B = 18.65 \pm 0.23$ at 204.5 minutes, and $R = 18.22 \pm 0.05$ at 208.3 minutes after the burst. The times are for the middle of the integrations relative to the BATSE trigger.

The position of the transient was measured for all four images with respect to stars in the USNO-A2.0 catalog[19] (Monet et al. 1998). The combined position is J2000 $12^{\mathrm{h}}23^{\mathrm{m}}11^{\mathrm{s}}.44 \pm 0^{\mathrm{s}}.02$, $+06°44'05''.10 \pm 0''.17$. For comparison purposes, our star 1 ($B = 14.75 \pm 0.01$, $V = 13.94 \pm 0.02$, $R = 13.50 \pm 0.03$) is at $12^{\mathrm{h}}23^{\mathrm{m}}11^{\mathrm{s}}.272$, $+06°45'38''.19$, while star 6 ($B = 18.40 \pm 0.07$, $V = 17.63 \pm 0.03$, $R = 17.16 \pm 0.03$) is at $12^{\mathrm{h}}23^{\mathrm{m}}10^{\mathrm{s}}.824$, $+06°43'20^{\mathrm{s}}.67$.

We observed this position with the Very Large Array telescope and found no significant radio sources to the 3 σ level of 258 μJy at 8.5 GHz on 1999 June 18, to 114 μJy at 8.5 GHz on 1999 June 26, and to 165 μJy at 1.4 GHz on 1999 July 4.

The transient had probably faded to invisibility by mid-March, but late time imaging was carried out to find the GRB host galaxy. The transient position is empty on the Palomar Sky Survey and our Yale 1 m images. We took deep *R*-band images with the Wisconsin-Indiana-Yale-NOAO (WIYN) 3.5 m telescope on Kitt Peak on 1999 June 12. Our six 15 minute exposures were processed and co-added by the normal procedures. The resulting picture shows no significant source within 6″ to a S/N = 3 limiting magnitude of $R = 25.4$.

We also obtained deep *K*- and *R*-band images of the optical transient position with the 10 m Keck I and II telescopes, respectively. The *R*-band image was obtained on 1999 June 19 as a combination of five 200 s exposures with the Low-Resolution Imaging Spectrometer (Oke et al. 1995). This reached an S/N = 3 limiting magnitude of $R = 25.7$. No star or galaxy appears to this limit within $6''.3$ of the optical transient position. The *K*-band images were obtained on 1999 June 23 and 24 as a combination of 12 s exposures totaling 71 and 72 minutes with the Near-Infrared Camera (Matthews & Soifer 1994). The nights were photometric, and we obtained standard star observations to calibrate the photometry. The fields are roughly $38''.4$ on a side with 0.15 pixels, reaching an S/N = 3 limiting magnitude of $K = 23.3$. The position of the optical transient was empty to this threshold.

3. ANALYSIS

Our observations can be used to constrain the decline rate of the afterglow. We will parameterize the decline with a power-law index δ, such that the flux varies as t^{δ} with t the time since the burst. The two QUEST *R*-band observations 7.7 minutes apart show a fading by 0.08 ± 0.08 mag which suggests that $\delta = -2 \pm 2$. The QUEST *V*-band measurements can be combined with each of the three limits from LOTIS and Super-LOTIS to give similar constraints that $\delta > -1.3$ for early times. The WIYN and Keck limits imply that $\delta < -1.1$ for late times. Taken together, all of our detections and limits are consistent with $\delta = -1.2 \pm 0.1$ for the assumption of a single power law over all time. As discussed below, the spectral slope gives reason to expect a more complicated time dependence with δ close to zero for early times.

The QUEST *B*, *V*, and *R* magnitudes can yield a spectral slope. The first step is to correct for the known galactic extinction of $E(B-V) = 0.023$ (Schlegel, Finkbeiner, & Davis 1998). The second step is to deduce the magnitudes and colors at one instant of time, which we take as the time of our first image. If $\delta = -1$ then the colors are $B-V = 0.26 \pm 0.24$ and $V-R = 0.17 \pm 0.08$, while if $\delta = 0$ then the colors are $B-V = 0.30 \pm 0.24$ and $V-R = 0.13 \pm 0.08$. The third step is to convert these magnitudes into flux units in janskys, f_{ν}. The fourth step is to fit the three fluxes to a presumed power law with $f_{\nu} \propto \nu^{\alpha}$. We find $\alpha = 0.38 \pm 0.25$ for $\delta = -1$ and $\alpha = 0.49 \pm 0.26$ for $\delta = 0$.

Within the framework of afterglow models for the synchrotron emission from external shocks (Sari, Piran, & Narayan 1998), the spectral slope is either in an $\alpha = 1/3$ regime or in regimes with $\alpha \leq -0.5$. Our measured spectral slope is easily consistent with the $\alpha = 1/3$ regime, yet is inconsistent with the $\alpha \leq -0.5$ regime at the 5×10^{-4} probability level. Thus we conclude that the afterglow was in the $\nu^{1/3}$ regime at a time 3.28 hr after the burst.

Synchrotron models require that any afterglow in the $\nu^{1/3}$ regime have $-1/3 \leq \delta \leq 1/2$ (Sari et al. 1998), which is to say that the afterglow is not fast fading and may even be brightening. GRB 970508 provides a precedent for an afterglow brightening for the first 2 days, during which time the spectral slope is positive and consistent with $\nu^{1/3}$ (Castro-Tirado et al. 1998). A $\delta \sim 0$ light curve for GRB 990308 would explain the absence of a detection by LOTIS and Super-LOTIS, yet is not significantly inconsistent with our observed decline by 0.08 ± 0.08 mag in 7.7 minutes.

Within the standard synchrotron fireball model, we can place interesting constraints on the burst energetics. For the GRB 990308 optical light to be in the $\nu^{1/3}$ regime, the characteristic times t_c and t_m (Sari et al. 1998, eqs. [15] and [16]) must both be greater than 3.28 hr. For the case of adiabatic evolution, this requires $E_{52} > 0.0023\epsilon_B^{-1}\epsilon_e^{-4}$ and $E_{52} < 0.0002\epsilon_B^{-3}n^{-2}$, where E_{52} is the energy in the spherical shock in units of 10^{52} ergs, n is the number density in the external medium in units of cm^{-3}, while ϵ_e and ϵ_B are the fractions of the shock energy in the electrons and magnetic field. These two constraints limit the allowed values to a small sliver of $E_{52} - \epsilon_B$ parameter space, centered roughly on the $40\epsilon_B = E_{52}^{-0.5}$ line. With $n \geq 1$ and the required $\epsilon_e \leq 1$, then $\epsilon_B \leq 0.25$ and $E_{52} > 0.01$. Since for reasonable models and beaming factors we have $E_{52} < 100$ and $n > 1$, we derive $\epsilon_e > 0.2$. Similarly, for $E_{52} < 100$ and $\epsilon_e \leq 1$,

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[19] Available at http://www.nofs.navy.mil/projects/pmm/catalogs.html.

we find that $n < 10^4$, which might be a problem for models in which the burster sits in a massive wind from a massive supernova precursor or in dense star-forming regions. For the case of equipartition of energy, there is no acceptable solution other than in the case that $n < 0.1$. For the cases of $n = 1$ and $n = 1000$, ϵ_B must be less than 24% and 0.03% of ϵ_e, respectively, with both t_c and t_m pushed to 3.28 hr. Similar conclusions are reached in the radiative case with the Lorentz factor of the shocked material is greater than 10. So, with GRB 990308 being in the $\nu^{1/3}$ regime at 3.28 hr after the burst for standard fireball models with $n > 0.1$, we argue that the external medium has $n < 10^4$, that the fraction of the shock energy in electrons must be greater than 20%, that the fraction of the shock energy in the magnetic field must be less than 25%, and that the electrons not be in equipartition with the magnetic field.

It is generally thought that GRBs were born in distant host galaxies, so the absence of any possible host galaxy to $R = 25.7$ is problematic. A possible solution to the lack of a visible host galaxy is that the burster was ejected from its home galaxy long ago. The possibility of ejection is natural in some models, such as neutron star collision scenarios, where the progenitor binary system may receive large velocity kicks during neutron star formation. This solution might be implausible since all other optical/radio transients with exact positions and associated hosts are within the visible galaxies, so at least these bursters have not been ejected. For the specific case of GRB 990308, the nearest galaxy is one with $R = 24.7$ at $6''.3$ angular distance, which implies a transverse separation of ~50 kpc or more for a plausible host and luminosity. Such a transverse separation is unlikely within current models (Bloom, Sigurdsson, & Pols 1999), so we consider ejection improbable.

The second possible solution to the lack of a visible host is that the galaxy is substantially subluminous. This case has already been demonstrated for the majority of the very brightest bursts irrespective of the breadth of the GRB luminosity function (Schaefer 1999), while several of the hosts associated with optical transients with redshifts are in the lower few percent of the luminosity-weighted Schechter luminosity function (GRB 970228, GRB 970508, GRB 990510). Indeed, if GRB 990308 has the average luminosity associated with the no-evolution fits to the $\log N$–$\log P$ curve (10^{57} photons s^{-1} or 6×10^{50} ergs s^{-1}; Fenimore et al. 1993), then the host galaxy would be at $z = 0.50$ with an absolute magnitude fainter than -17.2, which is in the faintest ~2% of galaxies.

The third possible solution to the lack of a visible host is that the burst can be at a high redshift. For an average galaxy, say one in the middle of the luminosity-weighted luminosity function with an absolute R magnitude of -20.8, the burst must have $z > 1.2$ for us to not detect the host to $R = 25.7$. Here and throughout this Letter, we have adopted a Hubble constant of 65 km s^{-1} Mpc^{-1}, $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, the galaxy K-corrections for Sb galaxies of Rocca-Volmerange & Guideroni (1988), and the GRB K-corrections of Fenimore et al. (1992) with spectral slope -1.5. With this approximate limit based on an assumption that the host is average in brightness, the deduced burst luminosity must be greater than 6×10^{57} photons s^{-1}. Pushing GRB 990308 to $z > 1.2$ is plausible.

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REFERENCES

Akerlof, C., et al. 1999, Nature, 398, 400
Barthelmy, S., et al. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts, ed. G. Fishman, J. Brainerd, & K. Hurley (New York: AIP), 643
Bessel, M. S. 1990, PASP, 102, 1181
Bloom, J. S., Sigurdsson, S., & Pols, O. R. 1999, MNRAS, 305, 763
Castro-Tirado, A. J., et al. 1998, Science, 279, 1011
Costa, E., et al. 1997, Nature, 387, 783
Fenimore, E., Epstein, R., Ho, C., Klebesadel, R., & Laros, J. 1992, Nature, 357, 140
Fenimore, E. E., et al. 1993, Nature, 366, 40
Frail, D., et al. 1998, Nature, 395, 663
Galama, T. J., et al. 1998, ApJ, 500, L97
———. 1999, Nature, 398, 394
Harrison, F. A., et al. 1999, ApJL, in press (astro-ph/9905306)
Hurley, K., et al. 1992, A&AS, 92, 401
———. 1999, ApJS, 120, 399
Landolt, A. 1992, AJ, 104, 340
Levine, A., Bradt, H., Cui, W., Jernigan, J., Morgan, E., Remillard, R., Shirey, R., & Smith, D. 1996, ApJ, 469, L33
Matthews, W., & Soifer, B. 1994, in Infrared Astronomy with Arrays, ed. I. McLean (Dordrecht: Kluwer), 239
Méndez, R., Depoy, D., & Bailyn, C. 1998, NOAO Newsl., 55, 17
Monet, D. et al. 1998, USNO-A2.0 Catalog (Washington DC: USNO)
Oke, B., et al. 1995, PASP, 107, 375
Paczyński, B. 1998, ApJ, 494, L45
Park, H.-S., et al. 1997, ApJ, 490, L21
———. 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts, ed. C. Meegan, R. Preece, & T. Koshut (New York: AIP), 842
Rocca-Volmerange, B., & Guideroni, G. 1988, A&AS, 75, 93
Sabbey, C. N., Coppi, P., & Oemler, A. 1998, PASP, 110, 1067
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Schaefer, B. E. 1999, ApJ, 511, L79
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Smith, D. A., et al. 1999a, ApJ, submitted
———. 1999b, GCN Circ. 275 (http://gcn.gsfc.nasa.gov/gcn/gcn3/275.gcn3)
Snyder, J. A. 1998, Proc. SPIE, 3355, 635
Totani, T. 1997, ApJ, 486, L71
van Paradijs, J., et al. 1997, Nature, 386, 686