

DISCOVERY OF THE LOW-REDSHIFT OPTICAL AFTERGLOW OF GRB 011121 AND ITS PROGENITOR SUPERNOVA SN 2001ke¹

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ABSTRACT

We present the discovery and follow-up observations of the afterglow of the gamma-ray burst GRB 011121 and its associated supernova SN 2001ke. Images were obtained with the Optical Gravitational Lensing Experiment 1.3 m telescope in *BVRI* passbands, starting 10.3 hr after the burst. The temporal analysis of our early data indicates a steep decay, independent of wavelength, with $F_\nu \propto t^{-1.72 \pm 0.05}$. There is no evidence for a break in the light curve earlier than 2.5 days after the burst. The spectral energy distribution determined from the early broadband photometry is a power law with $F_\nu \propto \nu^{-0.66 \pm 0.13}$ after correcting for a large reddening. Spectra obtained with the Magellan 6.5 m Baade telescope reveal narrow emission lines from the host galaxy that provide a redshift of $z = 0.362 \pm 0.001$ to the GRB. We also present late *R*- and *J*-band observations of the afterglow ~ 7 –17 days after the burst. The late-time photometry shows a large deviation from the initial decline, and our data combined with *Hubble Space Telescope* photometry provide strong evidence for a supernova peaking about 12 rest-frame days after the GRB. The first spectrum ever obtained of a GRB supernova at cosmological distance revealed a blue continuum. SN 2001ke was more blue near maximum than SN 1998bw and faded more quickly, which demonstrates that a range of properties are possible in supernovae that generate GRBs. The blue color is consistent with a supernova interacting with circumstellar gas, and this progenitor wind is also evident in the optical afterglow. This is the best evidence to date that classical, long GRBs are generated by core-collapse supernovae.

Subject headings: gamma rays: bursts — supernovae: general — supernovae: individual (SN 2001ke)

On-line material: color figures

1. INTRODUCTION

The origin of gamma-ray bursts (GRBs) has been a mystery since their discovery in the 1960s. It has only been since the *BeppoSAX* satellite (Boella et al. 1997) began providing rapid, accurate localization of several bursts per year

that it has been possible to study these events and their afterglows in detail. Optical observations of afterglows (e.g., GRB 970228; Groot et al. 1997) have allowed redshifts to be measured for a number of GRBs (e.g., GRB 970508; Metzger et al. 1997), providing definitive proof of their cosmological origin. The unusually faint GRB 980425 associated with supernova SN 1998bw was the first direct evidence that at least some GRBs result from the core collapse of massive stars (Galama et al. 1998). However, other

¹ Based on data from the Optical Gravitational Lensing Experiment 1.3 m and the Magellan 6.5 m Baade telescopes and the *Hubble Space Telescope*.

indirect evidence has come from studies of the location of GRBs in their host galaxies (e.g., Holland & Hjorth 1999; Holland et al. 2000; Fynbo et al. 2000; Bloom, Kulkarni, & Djorgovski 2002a; Fruchter et al. 2002; Hjorth et al. 2002) and the types of galaxies that GRBs prefer (e.g., Hogg & Fruchter 1999). A number of other GRBs have shown deviations from a power-law decline (e.g., GRB 980326; Bloom et al. 1999), but these were at high redshift, and any supernova component was difficult to study.

The very bright GRB 011121 was detected by *BeppoSAX* on 2001 November 21.78288 (UT) (Piro 2001a), and its position was quickly refined to a $2'$ error radius (Piro 2001b). We began the effort to optically monitor the error circle with the 1.3 m Optical Gravitational Lensing Experiment (OGLE) telescope starting 10.3 hr after the burst. A possible optical afterglow (OA) was quickly identified (Wyrzykowski, Stanek, & Garnavich 2001) as a fairly bright ($R \approx 19.1$) new object not present in the Digitized Sky Survey image at the position later determined by Price et al. (2001a): $\alpha = 11^{\text{h}}34^{\text{m}}29^{\text{s}}.67$, $\delta = -76^{\circ}01'41''.6$ (J2000.0). The source's rapid fading by ~ 0.5 mag during the first ~ 3 hr of observations (Stanek, Garnavich, & Wyrzykowski 2001; Infante et al. 2001) strengthened its likely association with the GRB. Spectra of the OA were obtained 12 hr after the burst with the Magellan 6.5 m Walter Baade telescope, and narrow emission lines from the host galaxy gave a redshift of $z = 0.36$ (Infante et al. 2001). Infante et al. went on to note that the rapidly fading OA and the relatively low redshift of the GRB made this burst an attractive target to search for a possible underlying supernova. The afterglow was also detected in the infrared (Price et al. 2001b) and radio (Subrahmanyan et al. 2001).

Late-time imaging and spectra obtained with the Magellan telescope 2 weeks after the GRB suggested a slowing in the initial rapid decline of the OA or contamination from the host galaxy of the GRB. *Hubble Space Telescope* (*HST*) images taken 2 weeks after the burst and reported in 2002 March appeared to show the burst continuing to fade at the initial power-law rate (Bloom 2002). However, Garnavich et al. (2002) analyzed these same images and found that the point source was 2 mag brighter than the extrapolation of the OA light curve and possessed colors inconsistent with a power-law spectrum, suggesting the presence of a supernova (SN 2001ke; Stanek et al. 2002). Later *HST* epochs confirmed the slow decline consistent with a supernova (Bloom et al. 2002b; Kulkarni et al. 2002).

Here we present our extensive data set on the OA and the associated supernova. GRB 011121 has also been discussed in recent papers by Bloom et al. (2002c), Dado, Dar, & De Rújula (2002), and Price et al. (2002).

2. THE PHOTOMETRIC DATA

2.1. *UBVRI* Photometry²

The majority of our photometric data were collected at two telescopes: the OGLE (Udalski, Kubiak, & Szymański 1997) 1.3 m telescope at the Las Campanas Observatory and the Magellan 6.5 m Walter Baade telescope at Las Campanas. The OGLE telescope was equipped with the $8\text{k} \times 8\text{k}$

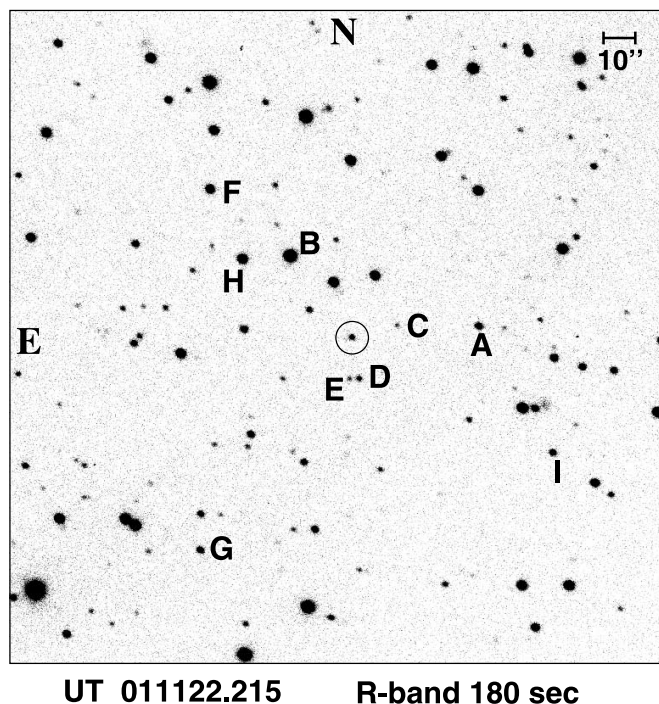


FIG. 1.—Discovery *R*-band image of the OA (circle) of GRB 011121, taken with the OGLE 1.3 m telescope. The size of the field is $200''$ on a side. Also marked are photometric comparison stars (see Table 1). [See the electronic edition of the *Journal* for a color version of this figure.]

OGLE-III CCD mosaic, which has a scale of $0''.26 \text{ pixel}^{-1}$. Most of the Magellan images were taken with the low-dispersion survey spectrograph (LDSS-2) in its imaging mode, with a scale of $0''.378 \text{ pixel}^{-1}$. Magellan images on 2001 November 24 and December 5 and 6 were taken with the Direct Cam imager with a scale of $0''.069 \text{ pixel}^{-1}$ (unbinned). Figure 1 shows the field containing the OA.

Photometry obtained with the Cerro Tololo Inter-American Observatory (CTIO) 0.9 m and 4 m telescopes on November 22 and 23 by Olsen et al. (2001) and Brown et al. (2001) were also added to our data set. The CCD images were kindly provided to us, and we measured the OA magnitudes using the same methods as applied to the OGLE and Magellan data.

During the night of 2001 November 22, the optical transient (OT) was observed with the MOSAIC-II camera (chip 2) on the CTIO 4 m telescope, using *UBRI* filters (Brown et al. 2001). That night three standard fields (Landolt 1992) were also observed in all four colors. There were between four and six standard stars on the chip, and we have made an independent calibration of the field stars around the GRB using this data. Aperture photometry was performed on the standard star frames. We determined the zero point for each color using average air mass terms for CTIO. We used DoPHOT (Schechter, Mateo, & Saha 1993) to extract the photometry of all stars on the frames containing the OT. We then determined an aperture correction for each frame using the same aperture as for the standard stars. These aperture magnitudes have been corrected for the zero point determined from the standard stars, accounting for the difference in air mass. Color terms between the CTIO filters and standard bandpasses were found to be small. We estimate that our calibration is accurate to ± 0.02 mag. Table 1

² The analysis presented here supersedes our GCN Circulars: Wyrzykowski et al. 2001; Stanek et al. 2001; Infante et al. 2001; Wyrzykowski & Stanek 2001; Stanek & Wyrzykowski 2001.

TABLE 1
LOCAL STANDARD STAR MAGNITUDES

| Star | <i>U</i> | <i>B</i> | <i>V</i> | <i>R</i> | <i>I</i> | <i>J</i> |
|--------|----------|----------|--------------------|----------|----------|----------|
| A..... | ... | 20.00 | 18.91 ^a | 18.20 | 17.58 | ... |
| B..... | 17.20 | ... | ... | ... | ... | ... |
| C..... | ... | 21.39 | ... | 20.00 | 19.45 | ... |
| D..... | ... | 21.03 | ... | 19.26 | 18.63 | 17.83 |
| E..... | ... | 21.87 | ... | 20.06 | 19.39 | 18.62 |
| F..... | 19.61 | 19.13 | ... | ... | 16.70 | ... |
| G..... | 20.32 | 20.09 | ... | 18.40 | 17.77 | ... |
| H..... | 18.39 | 18.21 | ... | ... | 16.22 | ... |
| I..... | 19.98 | 19.94 | ... | 18.42 | 17.83 | ... |

^a From Olsen et al. 2001.

gives the derived magnitudes for the secondary standard shown in Figure 1.

2.2. *HST* Photometry

The *HST* Wide-Field Planetary Camera 2 (WFPC2) observed the GRB 011121 field beginning 2 weeks after the burst (GO 9180; principal investigator, S. R. Kulkarni). Photometry was performed on objects in the field using a 2 pixel radius aperture. Corrections were made for charge-transfer efficiency using the Whitmore-Heyer prescription (Whitmore, Heyer & Casertano 1998) and for geometric distortion. Bright stars on the images were used to determine the correction to bring the measurement to an equivalent 0".5 aperture. All the data were then corrected to infinite aperture by subtracting 0.1 mag. Zero points in the Vega system were taken from the WFPC2 Data Handbook, and the resulting magnitudes in the flight system bands are shown in Table 2.

To compare with ground-based *R*-band photometry, the F702W magnitudes were converted to the standard *R* band using F555W–F702W color and the prescription of Dolphin (2000). Magellan *R*-band data obtained around the time of the first *HST* epoch are consistent with the converted F702W magnitude.

2.3. Near-Infrared Photometry³

We obtained deep *J*-band images during commissioning of the Classic Cam instrument on the 6.5 m Walter Baade Telescope. The instrument consists of a 256 × 256 pixel NICMOS3 array with an image scale of 0".094 pixel⁻¹. Images were obtained on 2001 November 29 and 30 and December 1 (UT) and were made up of 36, 64, and 72 individual 120 s exposures, respectively. Seeing on the first night was excellent and was estimated at 0".5, but this degraded to more than 0".6 for the final two nights. The average of the best seeing images from the three nights is shown in Figure 2. The host galaxy is clearly visible, as well as two stars just to the east of the host. We determined the location of the OA by transferring the coordinates from the *HST* WFPC2 F702W images taken on 2001 December 5 and noted that a faint source was present. Centroid determination on such a faint source results in unreliable photometry because the aperture tends to pick the brightest noise bump, so we fixed the position of the OA from the *HST* data and

³ The analysis presented here supersedes our GCN Circular: Phillips et al. 2001.

TABLE 2
GRB 011121/SN 2001ke PHOTOMETRY

| UT Date (2001) | Age (days) | Filter | Magnitude | Telescope |
|------------------|------------|----------|------------|-------------|
| Nov 22.2149..... | 0.4323 | <i>R</i> | 19.06 (03) | OGLE 1.3 m |
| Nov 22.2214..... | 0.4388 | <i>R</i> | 19.09 (03) | OGLE 1.3 m |
| Nov 22.2519..... | 0.4693 | <i>I</i> | 18.55 (03) | OGLE 1.3 m |
| Nov 22.2637..... | 0.4811 | <i>V</i> | 19.87 (03) | OGLE 1.3 m |
| Nov 22.2714..... | 0.4888 | <i>R</i> | 19.26 (04) | CTIO 0.9 m |
| Nov 22.2796..... | 0.4970 | <i>R</i> | 19.31 (03) | CTIO 0.9 m |
| Nov 22.2824..... | 0.4998 | <i>B</i> | 20.68 (08) | OGLE 1.3 m |
| Nov 22.2871..... | 0.5045 | <i>I</i> | 18.61 (03) | CTIO 0.9 m |
| Nov 22.2947..... | 0.5121 | <i>B</i> | 20.71 (06) | CTIO 0.9 m |
| Nov 22.3021..... | 0.5195 | <i>V</i> | 20.00 (04) | CTIO 0.9 m |
| Nov 22.3057..... | 0.5231 | <i>R</i> | 19.45 (03) | OGLE 1.3 m |
| Nov 22.3121..... | 0.5295 | <i>V</i> | 20.05 (05) | OGLE 1.3 m |
| Nov 22.3183..... | 0.5357 | <i>I</i> | 18.81 (03) | OGLE 1.3 m |
| Nov 22.3265..... | 0.5439 | <i>R</i> | 19.50 (03) | OGLE 1.3 m |
| Nov 22.3357..... | 0.5531 | <i>V</i> | 20.16 (04) | OGLE 1.3 m |
| Nov 22.3452..... | 0.5626 | <i>U</i> | 20.46 (15) | CTIO 0.9 m |
| Nov 22.3454..... | 0.5628 | <i>I</i> | 18.86 (03) | OGLE 1.3 m |
| Nov 22.3542..... | 0.5716 | <i>R</i> | 19.59 (03) | OGLE 1.3 m |
| Nov 23.2400..... | 1.4574 | <i>I</i> | 20.60 (10) | OGLE 1.3 m |
| Nov 23.2679..... | 1.4853 | <i>V</i> | 21.19 (10) | OGLE 1.3 m |
| Nov 23.3149..... | 1.5323 | <i>R</i> | 21.41 (05) | Baade 6.5 m |
| Nov 23.3177..... | 1.5351 | <i>R</i> | 21.43 (04) | CTIO 4 m |
| Nov 23.3201..... | 1.5375 | <i>R</i> | 21.40 (06) | Baade 6.5 m |
| Nov 23.3231..... | 1.5405 | <i>B</i> | 22.86 (06) | CTIO 4 m |
| Nov 23.3327..... | 1.5501 | <i>U</i> | 22.40 (20) | CTIO 4 m |
| Nov 23.3450..... | 1.5624 | <i>I</i> | 20.86 (03) | CTIO 4 m |
| Nov 24.361..... | 2.578 | <i>R</i> | 22.24 (12) | Baade 6.5 m |
| Nov 29.31..... | 7.53 | <i>J</i> | 22.31 (15) | Baade 6.5 m |
| Nov 30.30..... | 8.52 | <i>J</i> | 22.09 (15) | Baade 6.5 m |
| Dec 1.30..... | 9.52 | <i>J</i> | 22.11 (15) | Baade 6.5 m |
| Dec 4.33..... | 12.55 | <i>R</i> | 23.07 (15) | Baade 6.5 m |
| Dec 4.90..... | 13.12 | F450W | 24.67 (13) | <i>HST</i> |
| Dec 4.97..... | 13.19 | F555W | 23.87 (10) | <i>HST</i> |
| Dec 5.04..... | 13.26 | F702W | 23.14 (07) | <i>HST</i> |
| Dec 5.33..... | 13.55 | <i>R</i> | 23.11 (12) | Baade 6.5 m |
| Dec 5.83..... | 14.05 | F814W | 22.78 (08) | <i>HST</i> |
| Dec 5.94..... | 14.16 | F850LP | 22.78 (13) | <i>HST</i> |
| Dec 6.35..... | 14.57 | <i>R</i> | 23.23 (15) | Baade 6.5 m |
| Dec 7.31..... | 15.53 | <i>R</i> | 23.19 (15) | Baade 6.5 m |
| Dec 9.06..... | 17.28 | <i>R</i> | 23.10 (13) | Baade 6.5 m |
| Dec 14.82..... | 23.04 | F555W | 24.51 (11) | <i>HST</i> |
| Dec 14.88..... | 23.10 | F702W | 23.37 (08) | <i>HST</i> |
| Dec 16.64..... | 24.86 | F814W | 23.12 (10) | <i>HST</i> |
| Dec 16.75..... | 24.97 | F850LP | 22.73 (13) | <i>HST</i> |
| Dec 19.02..... | 27.24 | F555W | 25.02 (12) | <i>HST</i> |
| Dec 19.08..... | 27.30 | F702W | 23.66 (10) | <i>HST</i> |
| Dec 19.89..... | 28.11 | F814W | 23.21 (10) | <i>HST</i> |
| Dec 19.95..... | 28.17 | F850LP | 22.78 (13) | <i>HST</i> |

used DAOPHOT II (Stetson 1987) and ALLSTAR (Stetson 1992) to perform point-spread function (PSF) photometry on the OA.

Three infrared standard stars (Persson et al. 1998) were observed before and after the GRB and were used to calibrate the two bright stars south of the host galaxy (see Table 1). The Classic Cam used a *J_s* filter that is slightly narrower than the standard *J* band, but color corrections are expected to be small (Krisciunas et al. 2001).

In order to determine if the detections of the OA in these images were real, we ran a series of artificial star tests on the images from each night. We added 10 artificial stars with magnitudes similar to that of the OA to each image. These

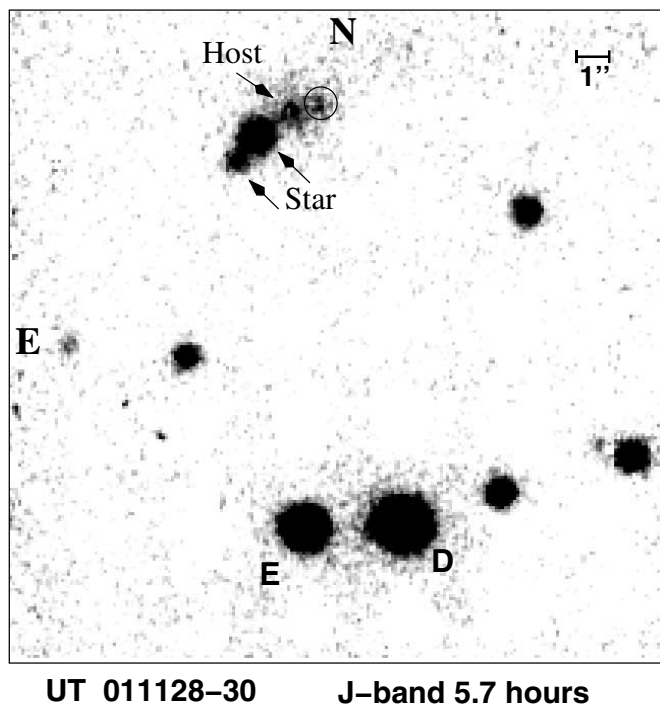


FIG. 2.—Infrared image of GRB 011121 taken with the Magellan Classic Cam. The field is $20''$ on a side, and the small circle that marks the OA/SN has a $0''.5$ radius. An infrared calibration of the two bright stars in the south are given in Table 1. [See the electronic edition of the *Journal* for a color version of this figure.]

stars were placed in regions where the background was similar to that of the OA. We then ran DAOPHOT II/ALLSTAR on these images in exactly the same way as we did for the original images and obtained magnitude estimates for each artificial star. This procedure was repeated for several sets of artificial stars with a range of input magnitudes. We derive a limiting magnitude of $J_{\text{lim}} \approx 22.4 \pm 0.2$ for the images. This suggests that the OA/SN was near the magnitude limit of the data.

We subtracted the stars and used aperture photometry to measure the brightness of the host. The host has $J = 19.8 \pm 0.3$ in an aperture with a radius of $4''$. We were unable to detect any light outside this aperture.

3. THE SPECTROSCOPIC DATA

Spectra of the OA were obtained with the Magellan 6.5 m Walter Baade telescope using the LDSS-2 imaging spectrograph on 2001 November 22.3 UT, ≈ 12 hr after the burst, and again on November 23.3, ≈ 36 hr postburst. We used a slit width of $1''$ rotated to the parallactic angle that provided a resolution of 12 \AA and coverage from 4000 to 9500 \AA . Each night of observation consisted of two 1200 s exposures on the OA as well as images of He-Ne comparison lamps and standard stars. The spectra were bias-subtracted and flat-field corrected using a normalized continuum lamp spectrum. The extracted spectra were then wavelength and flux calibrated. The spectrum taken on the first night showed a steep decline in flux toward the blue, which was not consistent with the second night's spectrum. By calibrating stars elsewhere on the long slit, we found that these too had a blue deficit that was not accounted for by the flux standards. We concluded that vignetting within the spectro-

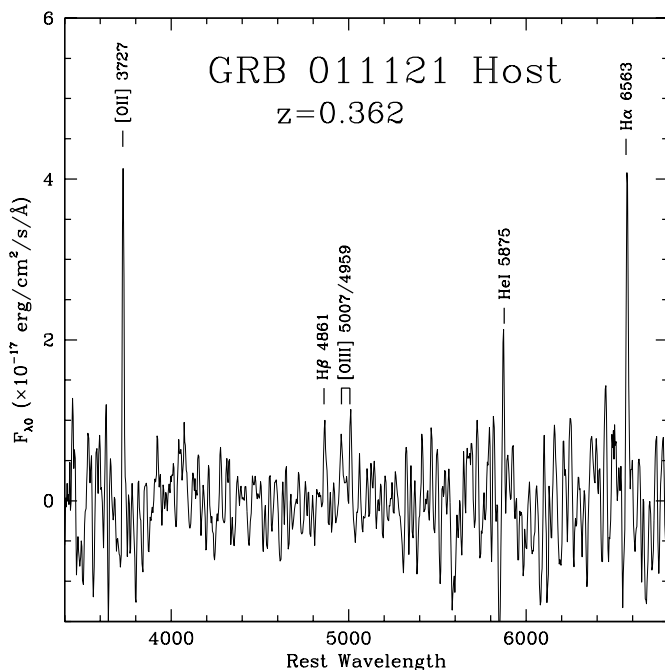


FIG. 3.—Spectrum of the GRB plus host galaxy obtained within the first 2 days of the burst. The continuum has been fitted with a polynomial and subtracted, leaving only emission lines from the host.

graph had partially blocked the shorter wavelengths and that the flux calibration of the GRB that first night was compromised.

Spectra of the OA taken on November 23 showed a smooth continuum with no strong features, as expected from a power-law source. Weak, narrow emission lines were detectable in spectra from both nights. Since the photometry showed little color change between the two nights, we used the November 23 spectrum to correct the vignetting in the November 22 data and combined all the spectra to maximize the signal-to-noise ratio. The resulting spectrum with the OA continuum removed is shown in Figure 3. Narrow emission features associated with H II regions in the host galaxy are clearly present, and they provide a redshift of $z = 0.362 \pm 0.001$. The line that we identify as He I $\lambda 5875$ is stronger than normally seen in typical H II regions.

Late-time spectra were again obtained with the Magellan LDSS-2 spectrograph on December 7.3, ≈ 15 days after the burst when the supernova light dominated over the OA flux. The $1''$ slit was rotated to include the faint star $2''.5$ to the southeast of the OA and the host galaxy (see Fig. 2). The spectra were obtained to confirm the redshift of the host galaxy, since the supernova had not been reported. Two 900 s exposures were taken and reduced in the same way as the early spectra. The seeing was good, and this permitted the two point sources to be extracted separately. Fortunately, the slit included the position of SN 2001ke, and the resulting spectrum is the first of a supernova associated with a cosmological GRB (Fig. 8).

4. PROPERTIES OF THE OPTICAL AFTERGLOW

4.1. The GRB Temporal Behavior

We plot the GRB 011121 *UBVRI* light curves in Figure 4. The majority of these data come from this paper, with addi-

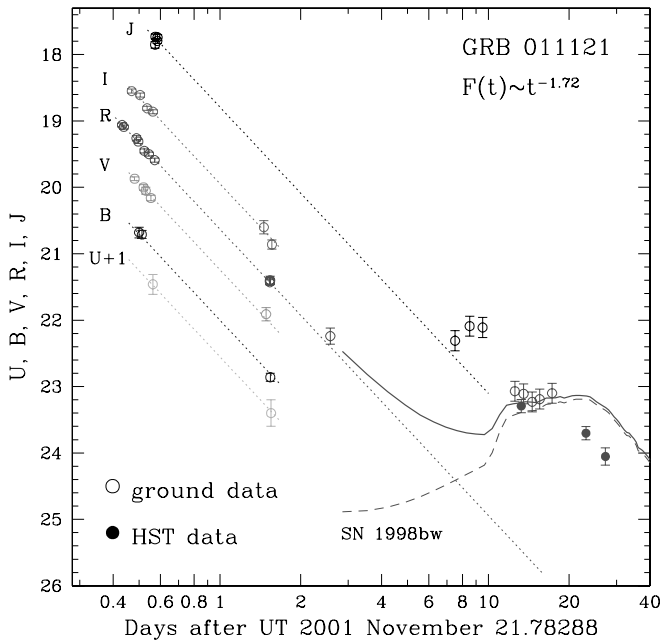


FIG. 4.—*UBVR* light curves of GRB 011121. A majority of these data derive from this paper, with additional *UBVR* data from Olsen et al. (2001) and Brown et al. (2001) (see Table 2) and early *J*-band data from Price et al. (2002). Also shown are three *HST* F702W epochs converted to the standard *R* band. Dotted lines show the OA power-law decay, and the dashed line shows the light curve of SN 1998bw redshifted to $z = 0.36$, converted to the *R* band, corrected for extinction, and scaled by 0.1 mag. The solid line shows the combination of the OA and SN 1998bw. [See the electronic edition of the *Journal* for a color version of this figure.]

tional *UBVR* data from Olsen et al. (2001) and Brown et al. (2001), which we reduced independently to be consistent with our other photometry (see Table 2). In order to assess the importance of our late *J*-band data, we also show some early *J*-band data from Price et al. (2002). Also shown are three *HST* F702W epochs converted to the standard *R* band.

The OT decays relatively quickly in early time, without a clear break (unlike many GRBs observed since GRB 990510; Stanek et al. 1999) or other deviations from smooth decay, such as observed in GRB 000301C (e.g., Garnavich, Loeb, & Stanek 2000) or GRB 011211 (Holland et al. 2002). To determine the early temporal behavior of the OA, we have decided to fit only the data taken earlier than 2 days after the burst. There are 26 such *UBVR* points, and as can be seen in Figure 4, a single power-law $t^{-1.72 \pm 0.05}$ fit to these early data is excellent, with the resulting $\chi^2/\text{dof} = 0.6$.

4.2. The GRB Broadband Spectral Energy Distribution

GRB 011121 is located at Galactic coordinates of $l = 298^\circ 23' 23''$, $b = -13^\circ 8' 63''$ in a heavily reddened direction, according to the map of Schlegel, Finkbeiner, & Davis (1998, hereafter SFD98). The SFD98 Galactic reddening toward the burst is large, $E(B-V) = 0.50$, and such large reddenings tend to be overestimated in the SFD98 maps (e.g., Stanek 1998).

To make an independent estimate of the extinction, we assume that the intrinsic energy distribution of the OA is a power law and find the extinction that gives the best match to a single power-law index. We first synthesize the *UBVR* spectrum from our data by interpolating the magnitudes to

a common time. As discussed in § 4.1, the optical colors of the GRB 011121 counterpart do not show significant variation during the first day. We therefore select the epoch of November 22.283 UT (12.0 hr after the burst) for the color analysis. We convert the *UBVR* magnitudes to fluxes using the effective frequencies and normalizations of Fukugita, Shimasaku, & Ichikawa (1995). These conversions are accurate to about 3%–4%, so to account for the calibration and interpolation errors, we assign to each flux a 5% error (7% for the *B* band and 10% for the *U* band). To get further leverage on the reddening, we add the *J* and *K* observations of Price et al. (2002) scaled to the fiducial time and converted to fluxes using the effective wavelengths and normalizations of Megessier (1995). We then determine how well a single power law fits the dereddened fluxes using the χ^2 parameter and varying the total extinction assuming the standard reddening curve of Cardelli, Clayton, & Mathis (1989), as tabulated by SFD98 (their Table 6). We find a best-fit power law at $E(B-V) = 0.43 \pm 0.07$ (1 σ) and adopt this as the reddening to the OA. This technique lumps together Galactic and host-galaxy extinction; however, our adopted value is 1 σ lower than the SFD98 extinction, which implies that Galactic reddening strongly dominates over the host contribution. Our value is slightly higher than that obtained by Price et al. (2002), most likely because of the somewhat different calibration of the optical data.

Under the assumption that the OA spectrum is a single power law, the best-fit spectrum is $\nu^{-0.66 \pm 0.13}$. The observed and corrected broadband spectra are presented in Figure 5.

5. LATE-TIME PHOTOMETRY

We searched for a late-time recrudescence in the OA by *R*-band imaging with Magellan between 12 and 17 days

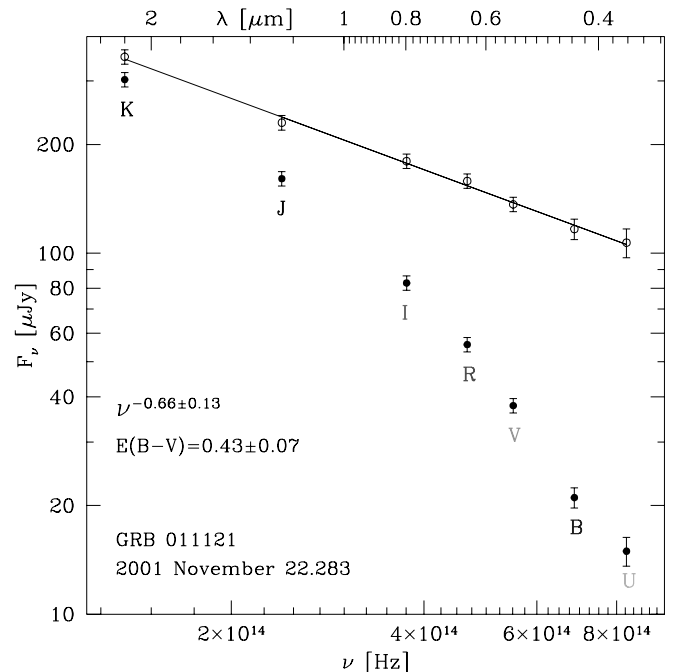


FIG. 5.—Synthetic broadband spectrum of GRB 011121 12 hr after the burst, constructed using the analytical fits shown in Fig. 4. The open symbols show the best-fit power law, which occurs for $E(B-V) = 0.43$. [See the electronic edition of the *Journal* for a color version of this figure.]

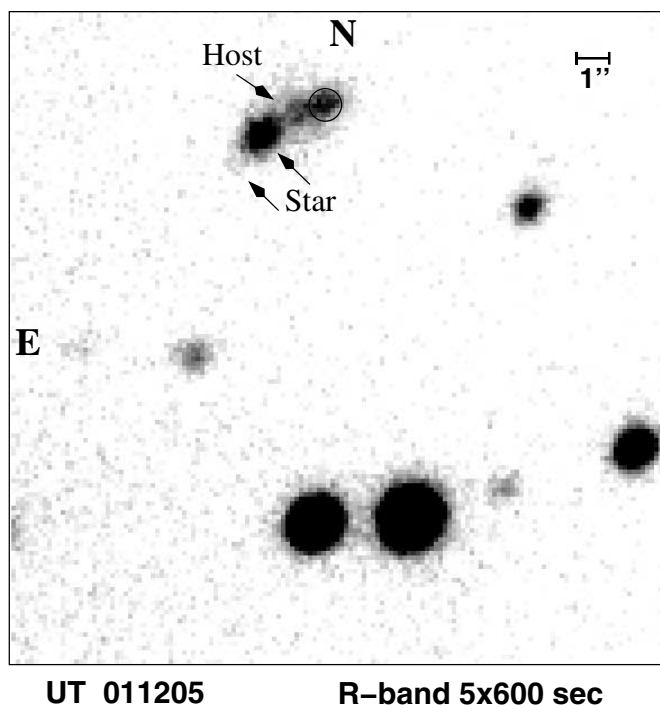


FIG. 6.— R -band image of GRB 011121 on 2001 December 5 taken with Magellan and Direct Cam. The circle marks the position of the OA/SN. [See the electronic edition of the *Journal* for a color version of this figure.]

after the burst (see Fig. 6). Subtracting these images from each other revealed no significant variation at the location of the OA, suggesting that the host galaxy dominated the emission. When the *HST* data were publicly released, it was clear that a point source was present (see Fig. 7) that was 2 mag brighter than the extrapolated light curve of the OA

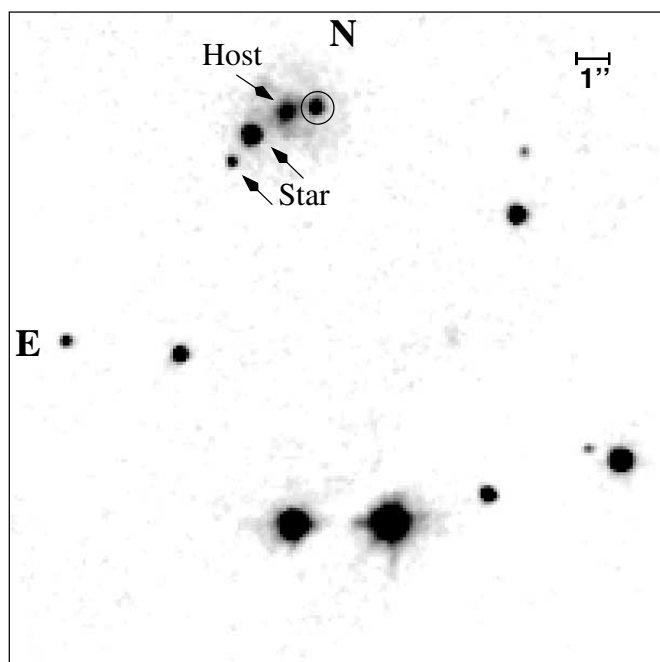


FIG. 7.—Average of F555W, F702W, and F814W *HST* images from all the available epochs. The extent of the host galaxy is shown, as well as a hint of spiral structure. [See the electronic edition of the *Journal* for a color version of this figure.]

(Garnavich et al. 2002). The position of the source was determined from seven USNO-A2.0 stars on the WFPC2 chips and was found to be $\alpha = 11^{\text{h}}34^{\text{m}}29^{\text{s}}.64$, $\delta = -76^{\circ}01'41''.51$ (J2000.0), with an error of $0''.2$ (Stanek et al. 2002). This is consistent with the position of the OA determined by Price et al. (2001a), based on the same astrometric catalog.

To remove host-galaxy contamination in the late-time Magellan images, we used the *HST* data as a template. After drizzling each epoch of F702W imaging, we employed DAOPHOT II (Stetson 1987) to subtract the PSF of the source. The three epochs were then combined, smoothed, and rebinned to create a high signal-to-noise ratio template image. Each Magellan image was then shifted to the coordinates of the template and the template convolved to match the PSF of the ground-based image. The difference between the image and the template then gave the uncontaminated brightness of the OA. The derived magnitudes are given in Table 2 and plotted in Figure 4.

6. DISCUSSION

6.1. GRB Properties

For a redshift of $z = 0.36$ and assuming a flat cosmology with $\Omega_m = 0.3$ and $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the GRB was at a luminosity distance of 2.07 Gpc. This is the nearest OA with a determined redshift. The GRB 980425 associated with SN 1998bw was at a redshift of $z = 0.009$ but did not have a detected OA. The fluence of GRB 011121 in the 25–100 keV band of *Ulysses* was $2 \times 10^{-5} \text{ ergs cm}^{-2}$ (Hurley et al. 2001), which corresponds to an isotropic energy output of $2.7 \times 10^{52} \text{ ergs}$ after correction to a rest-frame 20–2000 keV energy band (Bloom, Frail, & Sari 2001). This is at the low end of the isotropic energies listed in the compilation by Frail et al. (2001) but is not at all unusual.

The R -band light curve of the OA shows no evidence for a break from the time of discovery to 2.5 days after the burst. If a break occurred later than 2.5 days, then the low isotropic energy implies a jet opening angle of $\theta > 6^\circ$. Radio observations reported by Price et al. (2002) appear to support a late break. Correcting for the beaming fraction, this burst would then have a total energy similar to the “standard energy” for a GRB of $5 \times 10^{50} \text{ ergs}$ suggested by Frail et al. (2001).

The index of the optical light curve power-law decay was high compared to most prebreak indexes but is typical for postbreak decay rates. The observed $\alpha = 1.72$ and $\beta = 0.66$ are best fitted by a jet shocking a uniform-density interstellar medium (ISM) and are a poor fit to an isotropic shock into the ISM (Sari, Piran, & Halpern 1999). Placing GRB 011121 on Figure 3 of Stanek et al. (2001) suggests that this OA was observed postbreak and implies that the index change occurred earlier than 10 hr after the burst. An early break means a smaller opening angle of $\theta < 3^\circ$ and an energy more than 10 times lower than a standard burst.

The very low redshift burst associated with SN 1998bw had an isotropic energy well below the “standard” energy proposed by Frail et al. (2001), and GRB 980326, the other cosmological burst with a well-established association with a supernova, was also underluminous compared to the standard energy (Frail et al. 2001), but the number of events directly associated with supernovae are too small to link them with subluminal GRBs.

If the break occurred after 2.5 days, then the steep light curve decay and flat spectral indexes observed in the GRB 011121 OA are better matched to a burst into a stratified medium instead of a uniform density gas (Chevalier & Li 2000). For a circumstellar density falling as r^{-2} , the observed $\beta = 0.66$ should result in a steep light curve index of $\alpha \approx 1.5$ in the slow-cooling regime. The ISM case predicts a more shallow $\alpha \approx 1.0$. The possibility of a circumstellar wind has been noted by Price et al. (2002). The presence of a supernova at late times appears to bolster the picture of a stratified circumburst environment produced by a stellar wind.

6.2. SN 2001ke: A Supernova of a Different Color

The late-time photometry shown in Figure 4 clearly shows a deviation from the OA power-law decay. A similar bump was detected in GRB 980326 (Bloom et al. 1999) and attributed to a supernova, although a light echo has also been proposed to explain these deviations (Esin & Blandford 2000). The combination of the fading OA and slowly rising supernova resulted in a nearly constant brightness for the combined light during our December imaging. The uncertainty in the brightness distribution of the host galaxy along with the nearly constant magnitude prevented us from detecting the supernova until the *HST* data became available to the public.

The first-epoch *HST* photometry of the supernova was surprising for having a F555W–F702W color that was very blue. The initial supernova color was, in fact, similar to the OA color, and this comparison is independent of the assumed reddening. This blue color is inconsistent with a thermal dust echo (Reichart 2001). A Type Ic supernova, even an unusually energetic one such as SN 1998bw, is fairly red compared to the power-law spectrum of most OAs. Our spectrum, shown in Figure 8, confirms the large UV flux when compared to SN 1998bw. The “red bump” thought to be characteristic of a supernova is really blue in the case of GRB 011121. It is only in the later *HST* photometry that the supernova turns red, as is characteristic of supernovae past maximum.

The colors of SN 2001ke are more typical of Type II_n supernova events, which interact with circumstellar gas and have narrow- and intermediate-width hydrogen emission lines in their spectra (Schlegel 1990). As an example, we compare the spectral energy distribution (SED) of SN 2001ke with the nearby Type II_n SN 1998S in Figure 9. Clearly, the first *HST* epoch is similar to the SN 1998S SED near maximum, and both supernovae redden within a few days. Note that the infrared varies little over the observation period, since the maxima are very broad in the infrared. SN 1998S showed Wolf-Rayet features in the early spectra and was likely the core collapse of a very massive star (Lentz et al. 2001). We do not claim that SN 1998S is identical to the GRB 011121 supernova, only that the color histories of these two events are similar and suggest that circumstellar material was present. This is consistent with the OA behavior, which implied a stratified circumstellar gas distribution.

The light curve of SN 1998S evolves much more slowly than that of SN 2001ke, and this is true for most Type II supernova events with large hydrogen envelopes. However, we also note, in contrast to Bloom et al. (2002c), that the light curve of SN 1998bw is a poor match to SN 2001ke. After correcting for the time dilation at $z = 0.362$, SN

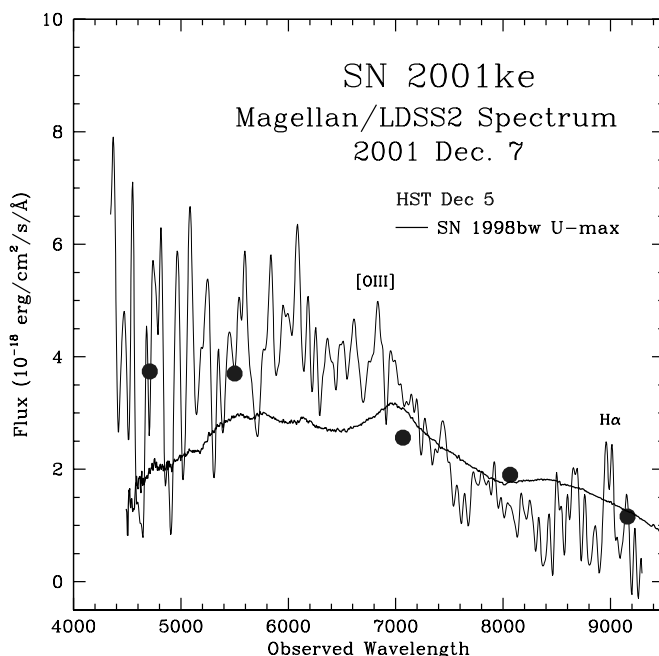


FIG. 8.—Spectrum of SN 2001ke taken December 7 (UT) with the LDSS-2 spectrograph on Magellan. The spectrum has been smoothed with a 30 Å FWHM Gaussian kernel and corrected for extinction. For comparison, the *HST* broadband flux measurements from December 5, also corrected for extinction, are shown as large circles. There are no obvious supernova features in the spectrum, but a comparison with SN 1998bw at the time of *U*-band maximum light (Galama et al. 1998) and corrected for $A_V = 0.2$ mag suggests that supernova features would be difficult to detect given the signal-to-noise ratio of the data. [See the electronic edition of the *Journal* for a color version of this figure.]

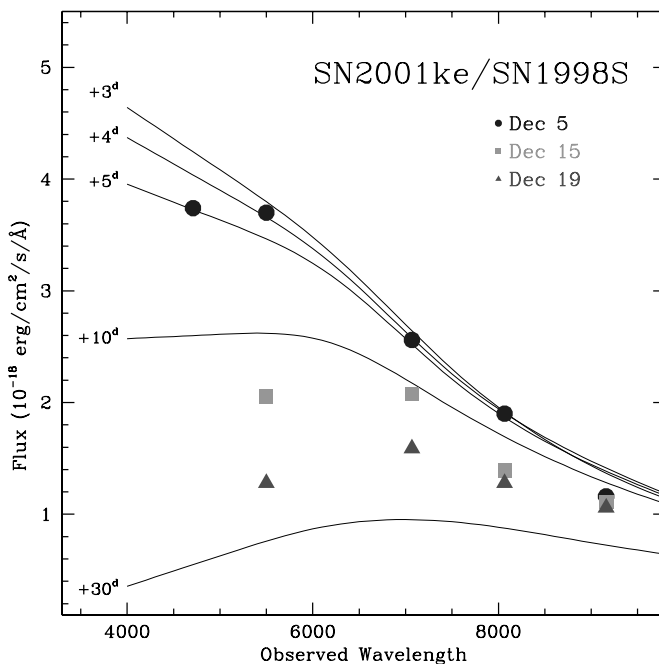


FIG. 9.—*HST* photometric measurements of SN 2001ke compared with early observations of SN 1998S. The *HST* fluxes (circles) have been corrected for our adopted extinction. The fluxes for SN 1998S (lines) have been corrected for $A_V = 0.12$ mag, redshifted to $z = 0.36$, and then scaled to approximately match the early *HST* photometry. The times given for SN 1998S are in rest-frame days after *V*-band maximum light. [See the electronic edition of the *Journal* for a color version of this figure.]

2001ke evolves 40% faster around 5000 Å than SN 1998bw (see Fig. 4), assuming the clock started for both at the time of the GRB.

There is a wide range of Type II_n supernova behavior. For example, the blue color of the Type II_b SN 1993J lasted for only a few days because of its unique distribution of circumstellar material (Garnavich & Ann 1994). Certainly, SN 2001ke could have been a Type Ib/c supernova that was dominated by circumstellar emission early on. SN 1997cy (Germany et al. 2000) was a Type II_n supernova event that also may have been associated with a GRB (GRB 970514).

The apparent rapid fading of SN 2001ke when compared to SN 1998bw could be explained if the light curves were identical, but we remove the assumption that the GRB occurred at core collapse. There is some evidence from X-ray spectra that metal-rich material surrounds some GRBs (e.g., Antonelli et al. 2000), which seems to imply that the associated supernovae exploded weeks to months before the gamma-ray emission. For a delay of a month, the supernova would have faded before the GRB was seen, and this may explain why supernovae are not detected after every GRB. In the case of GRB 011121, the time delay between core collapse and the burst of gamma rays would only need to be on the order of days to match the SN 1998bw light curve.

Converting the SN 1998bw light curve to the *R* band at $z = 0.362$ gives a peak brightness 1.3 mag less than the SN 2001ke observations. Our adopted extinction of 1.13 ± 0.18 in the *R* band suggests that SN 2001ke was similar in absolute brightness to SN 1998bw, which had $M_V = -19.35$ (Galama et al. 1998). We estimate an absolute brightness of SN 2001ke near maximum of $M_V = -19.2 \pm 0.2$, with most of the uncertainty due to the large extinction correction.

From the *HST* images, the host appears as a face-on spiral galaxy with the GRB/SN offset 0".88 or 4.8 kpc from the center in a low- Ω_m flat cosmology. The [O II] flux is a good indicator of the star formation rate. After correction for Galactic extinction and using the Balmer lines to correct for an average host extinction, we find a [O II] luminosity of 2.0×10^{41} ergs s⁻¹. We convert this to a star formation rate using the relation given by Kennicutt (1998). The slit did not cover the entire galaxy, so the total flux is uncertain but roughly corresponds to a star formation rate between 3 and $6 M_\odot$ yr⁻¹.

7. CONCLUSIONS

We have identified the OA associated with GRB 011121 and have found that its light curve is well fitted by a single power-law decay with an index of $\alpha = 1.72 \pm 0.05$ between 10 hr and 2.5 days after the burst. The broadband spectrum of the OA over this time period is well matched by a single power law with index $\beta = 0.66 \pm 0.13$ from 0.35 to 2.2 μm. We find that the reddening in the direction of the OA is large: $E(B-V) = 0.43 \pm 0.07$. Our early spectra reveal emission lines from the GRB host galaxy that provide a redshift of $z = 0.362 \pm 0.001$. Except for the unusual GRB 980425, this is the nearest GRB with a well-determined redshift.

Our observations 2 weeks after the GRB reveal a source 2 mag brighter than expected from the OA decline. We show that this light is likely from a supernova that was the pro-

genitor of GRB 011121. We obtained the first spectrum of a supernova associated with a cosmological GRB. The spectrum combined with colors from *HST* photometry show this emission to be intrinsically blue but becoming more red as the supernova fades. The colors are not consistent with a typical Type Ic supernova and are too blue for the “hypernova” SN 1998bw. However, the color can be explained by the supernova interacting with its circumstellar environment, as was the case in SN 1998S, and suggests that the supernova classification may be II_n. The presence of circumstellar gas at the time of the supernova implies that the GRB was not isotropic and must have left circumstellar material for later interaction with the supernova.

The light curve of SN 2001ke appears to have peaked 10–12 rest-frame days after the GRB, while SN 1998bw reached maximum some 2 weeks after GRB 980425. The time evolution of SN 1998bw does not fit the 2001ke light curve well. Another Type Ic hypernova, SN 2002ap (Mazzali et al. 2002), appeared to evolve more quickly than SN 1998bw; however, there was no associated GRB to set the time of explosion, and it appeared to be significantly less luminous than either SN 1998bw or 2001ke.

This early maximum combined with a blue color is surprising. Type II supernovae rise quickly, but their hydrogen envelope traps energy and makes them fade more slowly than observed for SN 2001ke. Possibly, the hydrogen envelope was small or nonexistent and the circumstellar phase relatively short, as was the case for SN 1993J. Of course, the supernova may have exploded days before the GRB detection, as has been proposed to explain metal absorption lines in X-ray spectra of some GRBs. Supernova 1998bw would fit *R*/F702W data well if it went off ~7 rest-frame days before the GRB. Assuming that the GRB may not signal core collapse, we still conclude that SN 2001ke was not identical to SN 1998bw and that a range of supernova types can produce GRBs.

GRB 011121 is an exciting new link connecting the fields of GRBs and supernovae, but it also represents something of a missed opportunity to study this link in detail. Prompt and reliable reduction of the *HST* data for this burst (taken when the supernova component was relatively bright) would have most likely enabled the astronomical community to obtain significantly more information about the supernova, including better spectroscopy and perhaps polarimetry. Given that this was the lowest redshift GRB and afterglow discovered to date (over more than 4 years of intense efforts), the community should take care that similar data are reported rapidly and accurately in the future.

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