

GRB 010921: Strong Limits on an Underlying Supernova from HST

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ABSTRACT

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GRB 010921 was the first HETE-2 GRB to be localized via its afterglow emission. The low-redshift of the host galaxy, $z = 0.451$, prompted us to undertake intensive multi-color observations with the *Hubble Space Telescope* with the goal of searching for an underlying supernova component. We do not detect any coincident supernova to a limit 1.34 mag fainter than SN 1998bw at 99.7% confidence, making this one of the most sensitive searches for an underlying SN. Analysis of the afterglow data allow us to infer that the GRB was situated behind a net extinction (Milky Way and the host galaxy) of $A_V \sim 1.8$ mag in the observer frame. Thus, had it not been for such heavy extinction our data would have allowed us to probe for an underlying SN with brightness approaching those of more typical Type Ib/c supernovae.

Subject headings: gamma rays: bursts

1. Introduction

Since the discovery of gamma-ray burst (GRB) afterglows there has been growing evidence linking GRBs to massive stars: the host galaxies of GRBs are star-forming galaxies and the position of GRBs appear to trace the blue light of young stars (Bloom, Kulkarni & Djorgovski 2002); some of the host galaxies appear to be dusty with star-formation rates comparable to ultra-luminous infrared galaxies (Berger, Kulkarni & Frail 2001; Frail *et al.* 2002). On smaller spatial scales, there is growing evidence tying GRBs to regions of high ambient density (Galama & Wijers 2001; Harrison *et al.* 2001) and the so-called dark GRBs arise in or behind regions of high extinction (Djorgovski *et al.* 2001; Piro *et al.* 2002).

However, the most direct evidence linking GRBs to massive stars comes from observations of underlying supernovae (SNe) and X-ray lines. The presence of X-ray lines would require a significant amount of matter on stellar scales (e.g. Piro *et al.* 2000), as may be expected in models involving the death of massive stars. However, to date, these detections (e.g. Piro *et al.* 2000; Reeves *et al.* 2002) have not been made with high significance.

If GRBs do arise from the death of massive stars, then it is reasonable to expect associated SNe. The GRB-SN link was observationally motivated by two discoveries: the association of GRB 980425 with the peculiar Type Ic SN 1998bw (Galama *et al.* 1998; Kulkarni *et al.* 1998) and an excess of red light superposed on the rapidly decaying afterglow of GRB 980326 (Bloom *et al.* 1999). However, these two discoveries were not conclusive. The SN association would require GRB 980425 to be extra-ordinarily under-energetic as compared to all other cosmologically located GRBs and the case for GRB 980326 is weakened

by the lack of a redshift for the GRB or the host galaxy.

Nonetheless, the two discoveries motivated searches for similar underlying SN components. As summarized in section 5, suggestions of similar red “bumps” in the light curves of various other GRB afterglows have been made (to varying degrees of confidence).

However, there is little dispute that the well-studied red bump in the afterglow of GRB 011121 is most easily explained by an underlying supernova (Bloom *et al.* 2002; Garnavich *et al.* 2002). Furthermore, from radio and IR observations of the afterglow (Price *et al.* 2002a), there is excellent evidence that the circumburst medium was inhomogeneous with ambient density $\rho \propto r^{-2}$, as expected from a massive star progenitor (Chevalier & Li 2000); here, r is the distance from the progenitor.

These developments are in accordance with the expectation of the “collapsar” model (Woosley 1993; MacFadyen & Woosley 1999). In this model, the core of a rotating massive star collapses to a black hole which then accretes matter and drives a relativistic jet. Internal shocks within this jet first cause bursts of γ -rays and then subsequently result in afterglow emission as the jet shocks the ambient medium.

It is important to appreciate that the SN light is primarily powered by radioactive decay of the freshly synthesized ^{56}Ni whereas the burst of γ -rays are powered by the activity of the central engine. In the current generation of collapsar models, there is sufficient flexibility to allow for a large dispersion of ^{56}Ni and the energy of the engine. Thus, the next phase of understanding the GRB-SN connection¹⁸ will benefit from (and require) observational measures of these parameters.

Motivated thus, we have an ongoing program of searches for SNe in GRB afterglows with the *Hubble Space Telescope* (HST). Here, we present a systematic search for a SN underlying GRB 010921. In §2 we present our observations and the details of photometry in §3. We fit afterglow models and constrain the brightness of an underlying SN in §4. We then present an overview of previous such efforts and conclude in §5.

¹⁸A class of models, known as “supranova” models, posit a supernova greatly in advance, many months, of the the GRB event (Vietri & Stella 1999). The long delay was physically motivated to explain the X-ray lines as arising from a large spatial region. The current data (e.g. GRB 011121) do not allow for such long delays.

2. Observations and Reductions

GRB 010921 was detected by the High Energy Transient Explorer (HETE-2) satellite at 2001 September 21.219 UT (Ricker *et al.* 2002) and the position was refined by the InterPlanetary Network error-box (Hurley *et al.* 2001). Using the 5-m Hale telescope and the Very Large Array we discovered the afterglow of this event as well as the redshift of the host galaxy (Price *et al.* 2002b).

The low redshift of this event, $z = 0.451$, made it a prime candidate for a search for an underlying SN. Accordingly, as a part of our large *Hubble Space Telescope* (HST) Cycle 9 program (GO-8867, P. I.: Kulkarni), we triggered a series of observations with the Wide Field Planetary Camera 2 (WFPC2) aboard HST. Owing to the lateness in identifying the afterglow candidate, the first observation was on day 35, slightly after the expected peak of the SN. At each of epochs 1–3 we obtained 4×400 s exposures in each of five filters (F450W, F555W, F702W, F814W and F850LP) with a single diagonal dither by 2.5 pixels to recover the under-sampled point-spread function (PSF). The fourth epoch was optimized for photometry of the host galaxy and, accordingly, we increased the exposure time to 4×1100 s.

We used “On-The-Fly” pre-processing to produce debiased, flattened images. The images were then drizzled (Fruchter & Hook 2002) onto an image with pixels smaller than the original by a factor of 0.7 using a `pixfrac` of 0.8. After rotation to a common orientation the images were registered to the first epoch images using the centroids of common objects in the field. The typical r.m.s. registration errors were less than 0.15 drizzled pixels.

3. Host Subtraction and Photometry

The host galaxy of GRB 010921 has an integrated magnitude of $R \sim 22$ mag or about $5 \mu\text{Jy}$ (Price *et al.* 2002b). Consequently great care has to be taken to properly photometer the fading afterglow. Below, we review various photometric techniques.

Total magnitudes: The simplest technique is to perform aperture photometry (e.g. Galama *et al.* 2000; Price *et al.* 2001). The afterglow flux is obtained by subtracting the host flux estimated from a very late time measurement. A major concern is that the host flux is dependent upon the choice of aperture (both center and size). Thus, if different images have different seeing then it is possible to obtain an artificial bump in the light curve.

Host subtraction: The above concern can be alleviated by subtracting a late-time image from the earlier images. The afterglow may then be easily photometered in the host-

subtracted images. This method has been used with considerable success by those observing SNe Ia (e.g. Schmidt *et al.* 1998).

$N \times (N - 1)/2$ **subtraction:** In this technique, each image is subtracted from every other image and the afterglow residual photometered. The flux at each epoch can be fit through least-squares, assuming the flux at the final epoch is zero (Novicki and Tonry, personal communication). This method makes use of the fact that the host galaxy has not been observed only once at late times, but at each epoch and thus better S/N can be obtained from the over-constrained system.

We employed the $N \times (N - 1)/2$ subtraction technique to photometer the GRB 010921 afterglow in our HST images. The images were subtracted using a modified version of ISIS (Alard 2000) and photometered using the analytic PSF-fitting routine within Vista (J. Tonry, personal communication). We used the `synphot` package within IRAF to calculate the response of the instrument and filter combination to a source with constant flux of 1 mJy; the resulting values are AB magnitudes (Fukugita *et al.* 1996), expressed as fluxes. Corrections were made for charge-transfer (in)efficiency (CTE) using the prescription of Dolphin (2000) and aperture-corrected to infinity.

We have also re-analyzed and photometered ground-based images (Price *et al.* 2002b; Park *et al.* 2002) of the afterglow, applying $N \times (N - 1)/2$ subtraction. Since this technique assumes that the flux of the afterglow in the final epoch is zero, which may not be correct for these images, we subtracted the appropriate fourth-epoch HST observation (which we have assumed contains no afterglow) from the final ground-based images, measured the flux of the afterglow and added this value to the fluxes derived from the $N \times (N - 1)/2$ subtraction.

The results of the photometry are host-subtracted fluxes for the afterglow in each of the images, under the assumption that the afterglow flux in the final HST image (2001 Dec 21) is zero (or negligible). These values are presented in Tables 1 and 2. The values in Table 2 supersede the corresponding measurements presented in Price *et al.* (2002b) and Park *et al.* (2002). We plot the afterglow light curves in Figure 1. The light-curves are monotonically decreasing (i.e. do not level off), and hence we deduce that our assumption of negligible flux in the final HST image is justified.

4. Discussion

Temporal breaks in optical light-curves have been seen in many afterglows and are usually attributed to a “jet” geometry (see Frail *et al.* 2001). We adopt a standard optical afterglow model, consisting of a broken power-law temporal decay with power-law indices

α_1 and α_2 , and a power-law spectral index, β (Sari, Piran & Narayan 1998; Sari, Piran & Halpern 1999).

Each of these indices are functions of the electron energy distribution index, p , dependent upon the location of the cooling break relative to the optical bands, and so we consider two cases: the cooling break is redward of the optical (hereafter, case R); and the cooling break is blueward of the optical (case B). We consider, in addition to a constant circumburst medium, an inhomogeneous circumburst medium, $\rho \propto r^{-2}$ (see Chevalier & Li 2000 and Price *et al.* 2002a).

We apply the parametric extinction curves of Cardelli, Clayton & Mathis (1989) and Fitzpatrick & Massa (1988) using the interpolation calculated by Reichart (2001). These extinction curves are characterized by two values, the magnitude of the extinction in the rest-frame of the host galaxy, A_V^{host} , and the slope of the UV extinction curve, c_2 (see Reichart 2001). Following Price *et al.* (2002b), we adopt $c_2 = 4/3$, corresponding to an LMC-like extinction curve. Adopting other extinction curves (e.g. MW, SMC) yields similar, but more-constraining results (i.e. any underlying SN must be even fainter than the upper limit we derive below); see Price *et al.* (2002b).

The main purpose of this analysis is to determine whether the light curves contain an SN component. To this end, we use the observations of SN 1998bw for an SN template since it is one of the well observed bright Ib/c SNe which may be related to a GRB (Galama *et al.* 1998). Specifically, we used the *UBVRI* photometry of Galama *et al.* (1998) and derived the flux distribution of SN 1998bw, using the zero-points and filter curves of Bessell (1990). The resulting low resolution spectrum (consisting of 5 points at the effective wavelength of each broadband filter), is redshifted to $z = 0.451$ (Price *et al.* 2002b), assuming a flat lambda cosmology with $\Omega_M = 0.3$ and $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The redshifted spectrum, which represents what SN 1998bw would look like at cosmological distances, is integrated with the appropriate filter curve to derive the apparent brightness at this redshift.

SN 1998bw at $z = 0.451$ would peak in the rest-frame *I*-band at approximately $4 \mu\text{Jy}$. It is evident from Figure 1 that the afterglow is much fainter than this, and, further, that there is no clear bump in the afterglow light curve. We therefore allow the SN component to be scaled by δ magnitudes in our model. The SN is placed behind the same foreground (i.e. Milky Way) and host galaxy extinction as the afterglow (which can be inferred by demanding that the temporal and intrinsic spectral slopes, which both depend on the electron distribution index, p , be consistent; see e.g. Price *et al.* 2002a).

To calculate the SN detection limit of our observations, we fit the model by minimizing χ^2 . The afterglow was not detected in any of the F450W images, and so we exclude them

from our analysis. Subtracting the host F450W image from our ground-based g' image left a large residual at the position of the host galaxy (not of the OT). This poor subtraction is likely due to the filter mis-match, and so we do not include this point in our analysis.

Our analyses are summarized in Table 3. In short, we find no evidence for an underlying SN. In order to calculate the formal limits, we re-fit the data for a range of values of the SN brightness and computed the probability distribution from the resultant $\Delta\chi^2$. As can be seen from Table 4, the least constraining limit comes from the case where the afterglow evolves in a wind-stratified medium with the cooling break redward of the optical band, and even in this case, a SN brighter than $\delta = 1.40$ mag is excluded at 99.7% confidence, and a SN as bright as SN 1998bw ($\delta = 0$ mag) is ruled out at greater than 99.999% confidence.

The peak brightness and the time scales for SNe Ib/c are generally correlated such that fainter SNe may peak earlier (Iwamoto *et al.* 1998). It may be important to take this into account for our analysis, since the observations most sensitive to the presence of an underlying SN are all after the peak. To do this, we shifted the $UBVRI$ photometry of the (intrinsically-)fainter Type Ic SN 1994I (Richmond *et al.* 1996) to $z = 0.451$, and derived the transformation between the redshifted SN 1998bw and 1994I light curves using a similar method as Bloom *et al.* (2002). This method is analogous to the “stretch” method for SNe Ia (Perlmutter *et al.* 1999). If we use this transformation in our model to transform the redshifted SN 1998bw light curve to the light curve of a SN fainter than SN 1998bw by δ magnitudes, then our least-constraining limit on an underlying SN becomes $\delta = 1.34$ mag fainter than SN 1998bw (at 99.7% confidence). The agreement with the above limit indicates that the uncertainty in our knowledge of the the light-curve shape and luminosity scaling light-curve is not important for this analysis.

Leaving aside the SN issue, our fits provide a jet-break time of approximately 35 days. From the FREGATE 8 – 400 keV fluence of 1.5×10^{-5} erg cm $^{-2}$, we calculate the k -corrected isotropic-equivalent energy release (Bloom, Frail & Sari 2001) in the γ -ray band, $E_\gamma \sim (1.3 \pm 0.3) \times 10^{52}$ erg. Applying the geometric correction from our measurement of the jet break (using the formulation and normalization of Frail *et al.* 2001), we obtain a jet opening angle of 18° . Thus the true energy release is $(6.5 \pm 1.6) \times 10^{50}$ erg — consistent with the clustering of energy releases around 5×10^{50} erg (Frail *et al.* 2001).

5. Conclusions

Here we report the search for an underlying SN in the afterglow of GRB 010921. Thanks to the superb photometric stability of HST and the $N \times (N - 1)/2$ subtraction technique, we

have been able to trace the light curve of the afterglow of GRB 010921 over two months. The resulting photometry is unbiased by aperture effects that are so prevalent in simple aperture and PSF-fitting photometry. We report two results.

First, we find a jet break time of 35 days, using only optical data. Second, we find no evidence for an SN. A SN, if present, must be fainter than SN 1998bw by > 1.34 mag at 99.7% confidence. To our knowledge, to date, this is the most stringent limit for an underlying SN associated with a cosmologically located GRB.

As noted in §1, the collapsar model as currently understood has little power in predicting the dispersion in the amount of ^{56}Ni synthesized as compared to the energy in relativistic ejecta. Underlying SNe are directly powered by the former whereas the GRB is powered by the latter. Observations are needed to start mapping the distribution in these critical explosion parameters. Progress can be expected with such observational inputs accompanied by further refinements in the model. Motivated thus, we summarize in Table 5 the status of SN searches for all Table 5 all known GRBs with redshift¹⁹ less than 1.2.

The most secure case for an SN is that for GRB 011121 (Bloom *et al.* 2002; Garnavich *et al.* 2002). GRB 980326 shows a strong red excess at about a month but unfortunately a redshift is lacking. GRB 970228 shows a less clear excess but benefits from a known redshift. Stated conservatively, a SN as bright as that of SN 1998bw can be ruled out in GRB 000911. In all cases, save that of GRBs 980326 and 011121, the presence of a host with a magnitude comparable to the brightness of the peak of the SN, makes it difficult to identify an SN component. As noted in §3, “bumps” can arise from host contamination. Combining HST and ground based measurements (as is the case for GRB 970228) is prone to considerable errors (§3).

In summary, there is good evidence for an SN comparable in brightness to SN 1998bw in GRB 011121 (Bloom *et al.* 2002). For GRB 010921, using the HST observations reported here, we constrain any putative underlying SN to be 1.34 mag fainter than SN 1998bw. In the collapsar framework, this absence could be most readily attributed to the well known dispersion of the peak luminosity of Type Ib/c SNe.

An alternative possibility is that there may be more than one type of progenitor for long duration GRBs. Along these lines we note that Chevalier & Li (2000) claim that some afterglows (e.g. GRB 990123) are incompatible with a $\rho \propto r^{-2}$ inhomogeneous circumburst distribution whereas other afterglows (e.g. GRBs 970228 and 970508) are better explained

¹⁹Beyond a redshift of ~ 1.2 , the distinctive and strong absorption blueward of 4000\AA is redshifted out of the optical bands. The higher sensitivity of the optical bands thus favor searches for SNe below this redshift.

by invoking an inhomogeneous circumburst medium. Progress requires both searches for underlying SNe as well as characterizing the circumburst medium via modeling of the early-time afterglow (e.g. GRB 011121, see Price *et al.* 2002a).

Finally, we note that the afterglow of GRB 010921 (and any coincident SN) was extinguished by $A_V^{\text{MW}} \approx 0.5$ mag of dust in the foreground, and $A_V^{\text{host}} \approx 1$ mag of dust in the host galaxy (Table 3). Thus, in the future, using ACS aboard HST it should be possible to extend SN searches to at least 3 mag fainter than SN 1998bw, at which point it will be possible to detect more typical SNe Ib/c coincident with GRBs.

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REFERENCES

- Alard, C. 2000, A&AS, 144, 363.
- Berger, E. *et al.* 2001, ApJ, 556, 556.
- Berger, E., Kulkarni, S. R., and Frail, D. A. 2001, apj, 560, 652.
- Bessell, M. S. 1990, PASP, 102, 1181.
- Björnsson, G., Hjorth, J., Jakobsson, P., Christensen, L., and Holland, S. 2001, ApJ, 552, L121.
- Bloom, J. S., Frail, D. A., and Sari, R. 2001, AJ, 121, 2879.
- Bloom, J. S., Kulkarni, S. R., and Djorgovski, S. G. 2002, AJ, 123, 1111.
- Bloom, J. S. *et al.* 1999, Nature, 401, 453.
- Bloom, J. S. *et al.* 2002, ApJ, 572, L45.
- Cardelli, J. A., Clayton, G. C., and Mathis, J. S. 1989, ApJ, 345, 245.

- Castro-Tirado, A. J. *et al.* 2001, A&A, 370, 398.
- Chevalier, R. A. and Li, Z. 2000, ApJ, 536, 195.
- Djorgovski, S. G., Frail, D. A., Kulkarni, S. R., Bloom, J. S., Odewahn, S. C., and Diercks, A. 2001a, ApJ, 562, 654.
- Djorgovski, S. G. *et al.* 2001b, in Gamma-Ray Bursts in the Afterglow Era, Proceedings of the International workshop held in Rome, CNR headquarters, 17-20 October, 2000. Edited by Enrico Costa, Filippo Frontera, and Jens Hjorth. Berlin Heidelberg: Springer, 218+.
- Dolphin, A. E. 2000, PASP, 112, 1397.
- Fitzpatrick, E. L. and Massa, D. 1988, ApJ, 328, 734.
- Frail, D. A. *et al.* 2002, apj, 565, 829.
- Frail, D. A. *et al.* 2001, ApJ, 562, L55.
- Fruchter, A. S. and Hook, R. N. 2002, PASP, 114, 144.
- Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., and Schneider, D. P. 1996, AJ, 111, 1748.
- Galama, T. J. *et al.* 2000, ApJ, 536, 185.
- Galama, T. J. *et al.* 1998, Nature, 395, 670.
- Galama, T. J. and Wijers, R. A. M. J. 2001, ApJ, 549, L209.
- Garnavich, P. *et al.* 2002, ApJ (submitted), astro-ph/0204234.
- Garnavich, P. M., Jha, S., Pahre, M. A., Stanek, K. Z., Kirshner, R. P., Garcia, M. R., Szentgyorgyi, A. H., and Tonry, J. L. 2000, ApJ, 543, 61.
- Halpern, J. P. *et al.* 2000, ApJ, 543, 697.
- Harrison, F. A. *et al.* 2001, ApJ, 559, 123.
- Henden, A. 2001, GCN Circular 1100.
- Hjorth, J., Pedersen, H., Jaunsen, A. O., and Andersen, M. I. 1999, A&AS, 138, 461.
- Holland, S. *et al.* 2001, A&A, 371, 52.

- Hurley, K., Cline, T., Frontera, F., Montanari, E., Guidorzi, C., Feroci, M., and the HETE Science Team 2001, GCN Circular 1097.
- Iwamoto, K. *et al.* 1998, *Nature*, 395, 672.
- Kulkarni, S. R. *et al.* 1998, *Nature*, 395, 663.
- Lazzati, D. *et al.* 2001, *A&A*, 378, 996.
- MacFadyen, A. I. and Woosley, S. E. 1999, *ApJ*, 524, 262.
- Park, H. S. *et al.* 2002, *ApJ*, 571, L131.
- Perlmutter, S. *et al.* 1999, *ApJ*, 517, 565.
- Piro, L. *et al.* 2002, *ApJ* (in press), astro-ph/0201282.
- Piro, L. *et al.* 2000, *Science*, 290, 955.
- Price, P. A. *et al.* 2002a, *ApJ*, 572, L51.
- Price, P. A. *et al.* 2001, *ApJ*, 549, L7.
- Price, P. A. *et al.* 2002b, *ApJ*, 571, L121.
- Reeves, J. N. *et al.* 2002, *Nature*, 416, 512.
- Reichart, D. E. 1999, *ApJ*, 521, L111.
- Reichart, D. E. 2001, *ApJ*, 553, 235.
- Richmond, M. W. *et al.* 1996, *AJ*, 111, 327.
- Ricker, G. *et al.* 2002, *ApJ*, 571, L127.
- Sari, R., Piran, T., and Halpern, J. P. 1999, *ApJ*, 519, L17.
- Sari, R., Piran, T., and Narayan, R. 1998, *ApJ*, 497, L17.
- Schmidt, B. P. *et al.* 1998, *ApJ*, 507, 46.
- Sokolov, V. V. 2001, in *Gamma-Ray Bursts in the Afterglow Era*, Proceedings of the International workshop held in Rome, CNR headquarters, 17-20 October, 2000. Edited by Enrico Costa, Filippo Frontera, and Jens Hjorth. Berlin Heidelberg: Springer, 136.
- Vietri, M. and Stella, L. 1999, *ApJ*, 527, L43.

Woosley, S. E. 1993, ApJ, 405, 273.

Table 1. HST+WFPC2 observations of GRB 010921

Date (2001, UT)	Filter	Flux (μJy)
Oct 26.731	F450W	-0.031 ± 0.022
Nov 06.956	F450W	0.001 ± 0.028
Nov 24.990	F450W	0.067 ± 0.029
Oct 26.791	F555W	0.157 ± 0.015
Nov 07.015	F555W	0.087 ± 0.017
Nov 25.121	F555W	0.063 ± 0.018
Oct 26.859	F702W	0.231 ± 0.013
Nov 07.149	F702W	0.096 ± 0.015
Nov 25.203	F702W	0.045 ± 0.015
Oct 26.932	F814W	0.433 ± 0.024
Nov 08.359	F814W	0.209 ± 0.024
Nov 25.621	F814W	-0.003 ± 0.025
Oct 26.992	F850LP	0.471 ± 0.092
Nov 08.418	F850LP	0.207 ± 0.088
Nov 25.687	F850LP	0.030 ± 0.096

Note. — These host-subtracted measurements have not been corrected for Galactic extinction, and are all made under the assumption that the flux of the OT on 2001 Dec 21 is zero or negligible, $\ll 0.01\mu\text{Jy}$.

Table 2. Re-analysis of ground-based observations of GRB 010921

Date (2001, UT)	Filter	Flux (μJy)	Telescope
Oct 19.178	g'	0.671 ± 0.097	P200
Sep 22.144	r'	46.104 ± 0.722	P200
Sep 22.148	r'	44.995 ± 0.661	P200
Sep 27.354	r'	2.13 ± 1.223	P200
Oct 17.145	r'	0.086 ± 0.379	P200
Oct 18.088	r'	0.189 ± 0.382	P200
Oct 19.109	r'	0.256 ± 0.285	P200
Oct 17.165	i'	0.560 ± 0.197	P200
Oct 18.110	i'	0.523 ± 0.191	P200
Oct 19.130	i'	0.649 ± 0.153	P200
Oct 19.149	z'	1.293 ± 4.273	P200
Sep 22.3038	B	11.319 ± 0.981	NOFS1.0
Oct 19.253	B	0.623 ± 0.675	P60
Sep 22.2976	V	24.727 ± 1.078	NOFS1.0
Oct 19.206	V	0.229 ± 0.720	P60
Sep 22.2930	R	39.116 ± 5.072	NOFS1.0
Sep 22.3210	R	36.135 ± 4.486	NOFS1.0
Oct 19.272	R	0.916 ± 4.284	P60
Nov 17.151	R	0.470 ± 4.238	NOFS1.0
Sep 22.2893	I	84.688 ± 5.778	NOFS1.0
Sep 22.795	I	40.277 ± 3.950	TS
Sep 22.825	I	47.281 ± 7.230	TS
Sep 22.878	I	50.926 ± 3.671	TS
Sep 22.954	I	41.321 ± 3.636	TS
Nov 17.093	I	1.229 ± 1.057	NOFS1.0

Note. — These host-subtracted measurements have not been corrected for Galactic or host extinction, and are all made under the assumption that the flux of the OT on 2001 Dec 21 is zero or negligible. Zero-points were set from the star at coordinates R.A. = $22^{\text{h}}56^{\text{m}}00^{\text{s}}.21$ Dec = $40^{\circ}54'58''.0$ with $B = 21.248$ mag, $V = 20.230$ mag, $R = 19.699$ mag and $I = 19.132$ mag, accurate to better than 3 percent (Henden 2001). Telescopes are: P200 — Hale Palomar 200-inch; NOFS1.0 — USNO Flagstaff Station 1.0-metre; P60 — Palomar 60-inch; TS — Tautenburg Schmidt. NOFS1.0 observations of Sep 22, and

Table 3. Best-fit afterglow models

Model	p	$t_{\text{jet}}/\text{days}$	$A_V^{\text{host}}/\text{mag}$	χ^2
ISM/Wind,B	2.67 ± 0.06	33.0 ± 6.5	0.95 ± 0.08	19.9
ISM,R	3.03 ± 0.04	37.5 ± 4.9	1.16 ± 0.07	19.2
Wind,R	2.33 ± 0.10	30.3 ± 9.5	1.35 ± 0.08	23.1

Note. — The best-fit afterglow parameters from fitting a standard afterglow model with host extinction and no SN. Each fit had 32 degrees of freedom. ISM models refer to afterglow evolution in an homogeneous ISM. Wind models refer to afterglow evolution in a wind-stratified (r^{-2}) medium. R and B refer to the location of the cooling break relative to the optical bands (redward and blueward, respectively). If the cooling break is blueward of the optical bands, then the ISM and wind models both have the same form.

Table 4. Maximum Allowed Brightness of a SN underlying GRB 010921

Significance	ISM/Wind,B	ISM,R	Wind,R
1σ (68.3%)	3.17 (2.89)	2.76 (2.61)	1.80 (2.39)
2σ (95.4%)	2.29 (2.17)	1.98 (1.94)	1.55 (1.70)
3σ (99.7%)	1.80 (1.73)	1.87 (1.57)	1.40 (1.34)

Note. — For each model and significance level, we list the magnitude relative to SN 1998bw of the faintest SN detectable by the observations. In brackets, we include the magnitude relative to SN 1998bw of a ‘generic SN’. Model descriptions are the same as in Table 3.

Table 5. Other GRB-SNe

GRB	z	Band	SN (mag)	Host (mag)	Ground/HST?	Comments, ref
970228	0.695	<i>R</i>	25.5	25.2	Both	Plausible but aperture, color effects with HST. (1)
970508	0.835	<i>I</i>	23.6	24.0	Ground	Aperture effects. (2)
980326	???	<i>R</i>	25	< 27	Ground	Plausible. (3)
980613	1.096	<i>R</i>	...	24.0	Ground	Faint afterglow, no search. (4)
980703	0.966	<i>R</i>	24	22.6	Ground	Consistent with no SN. (5)
990705	0.840	<i>R</i>	...	22.8	Ground	No search.
990712	0.433	<i>V</i>	23.8	21.2	Ground	Aperture effects? (6)
991208	0.706	<i>R</i>	23.9	24.4	Ground	Bad afterglow fit. (7)
991216	1.020	<i>R</i>	...	24.85	Ground	No search, consistent with no SN. (8)
000418	1.119	<i>R</i>	...	23.8	Ground	Consistent with no SN. (9)
000911	1.058	<i>I</i>	24.7	24.4	Ground	2σ detection, $SN \sim 0.9 \pm 0.3 \times SN_{1998bw}$. (10)
011121	0.365	<i>R</i>	23	26	HST	Secure. (11)

Note. — All GRBs with optical afterglows at $z < 1.2$, excepting GRB 980425 (SN 1998bw) and GRB 010921 (this study). References: 1: Reichart (1999); Galama *et al.* (2000); 2: Sokolov (2001); 3: Bloom *et al.* (1999); 4: Hjorth *et al.* (1999); 5: Holland *et al.* (2001); 6: Björnsson *et al.* (2001); 7: Castro-Tirado *et al.* (2001); 8: Garnavich *et al.* (2000); Halpern *et al.* (2000); 9: Berger *et al.* (2001); 10: Lazzati *et al.* (2001); 11: Bloom *et al.* (2002). Host magnitudes and redshifts were also compiled from Djorgovski *et al.* (2001).

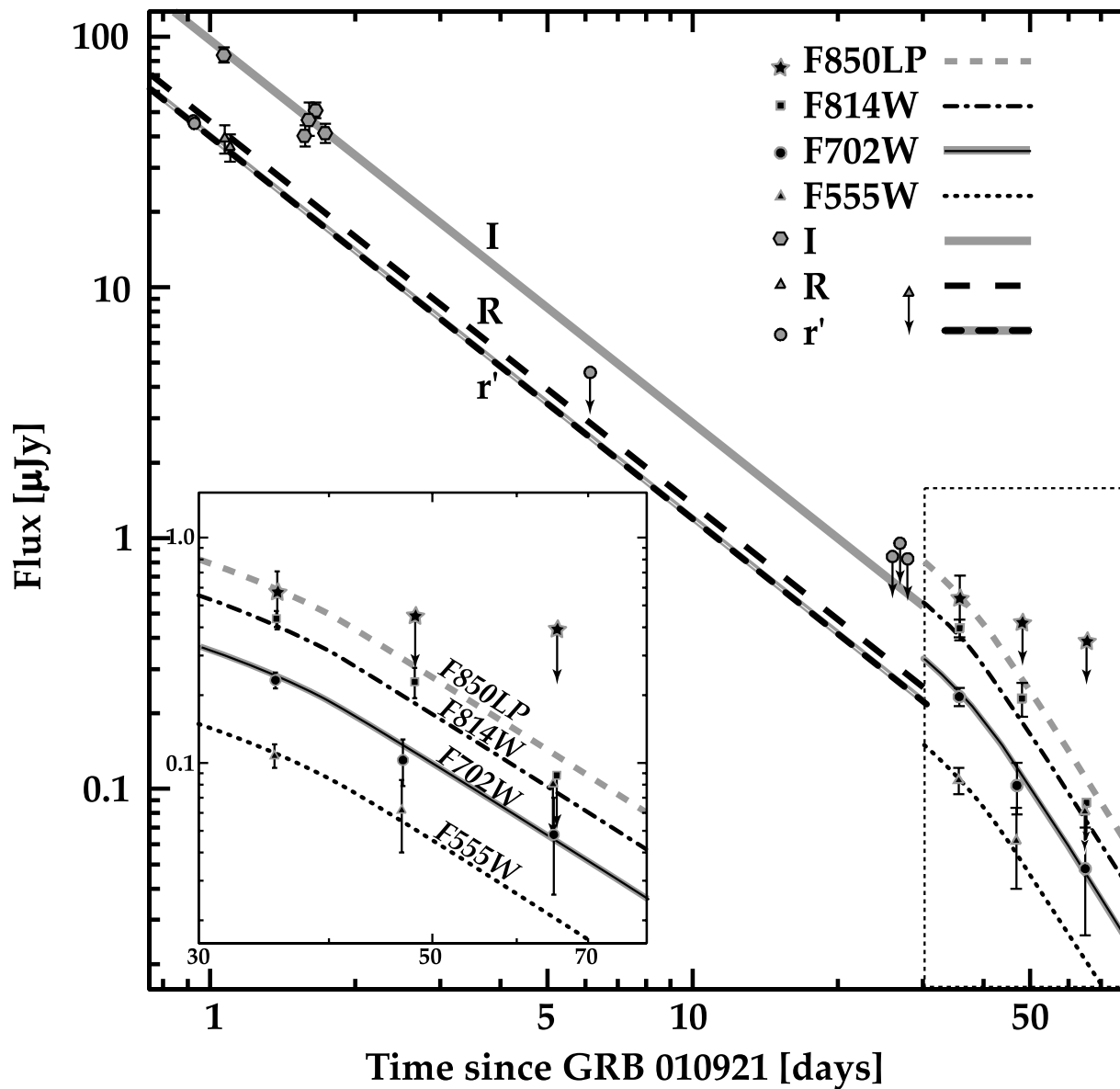


Fig. 1.— The optical light curve of the afterglow of GRB 010921. Each data point contains pure afterglow (no contribution from the host galaxy), and have not been corrected for foreground extinction. Downward arrows indicate 2σ upper limits. The fit is a standard broken power-law afterglow model (§4).