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DETECTION OF A SUPERNOVA SIGNATURE ASSOCIATED WITH GRB 011121[1]

J. S. Bloom,[2] S. R. Kulkarni,[2] P. A. Price,[2,3] D. Reichart,[2] T. J. Galama,[2] B. P. Schmidt,[3] D. A. Frail,[2,4] E. Berger,[2] P. J. McCarthy,[5] R. A. Chevalier,[6] J. C. Wheeler,[7] J. P. Halpern,[8] D. W. Fox,[2] S. G. Djorgovski,[2] F. A. Harrison,[2] R. Sari,[9] T. S. Axelrod,[3] R. A. Kimble,[10] J. Holtzman,[11] K. Hurley,[12] F. Frontera,[13,14] L. Piro,[15] and E. Costa[15]

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ABSTRACT

Using observations from an extensive monitoring campaign with the *Hubble Space Telescope*, we present the detection of an intermediate-time flux excess that is redder in color relative to the afterglow of GRB 011121, currently distinguished as the gamma-ray burst with the lowest known redshift. The red “bump,” which exhibits a spectral rollover at ∼7200 Å, is well described by a redshifted Type Ic supernova that occurred approximately at the same time as the gamma-ray burst event. The inferred luminosity is about half that of the bright supernova SN 1998bw. These results serve as compelling evidence for a massive star origin of long-duration gamma-ray bursts. Models that posit a supernova explosion weeks to months preceding the gamma-ray burst event are excluded by these observations. Finally, we discuss the relationship between spherical core-collapse supernovae and gamma-ray bursts.

Subject headings: gamma rays: bursts — supernovae: general — supernovae: individual (SN 1998bw)

1. INTRODUCTION

Two broad classes of long-duration gamma-ray burst (GRB) progenitors have survived scrutiny in the afterglow era: the coalescence of compact binaries (see Fryer, Woosley, & Hartmann 1999 for review) and massive stars (Woosley 1993). More exotic explanations (e.g., Paczyński 1988; Carter 1992; Dermer 1996) fail to reproduce the observed redshift distribution, the detection of transient X-ray lines, and/or the distribution of GRBs about host galaxies.

In the latter viable scenario, the so-called collapsar model (Woosley 1993; MacFadyen & Woosley 1999; Hansen 1999), the core of a massive star collapses to a compact stellar object (such as a black hole or magnetar), which then powers the GRB while the rest of the star explodes. We expect to see two unique signatures in this scenario: a rich circumburst medium fed by the mass-loss wind of the progenitor (Chevalier & Li 1999) and an underlying supernova (SN). Despite extensive broadband modeling of afterglows, unambiguous signatures for a wind-stratified circumburst media have not been seen (e.g., Frail et al. 2000; Berger et al. 2001).

There has, however, been tantalizing evidence of an underlying SN. The first association of a cosmologically distant GRB with the death of a massive star was found for GRB 980326, where a clear excess of emission was observed, over and above the rapidly decaying afterglow component. This late-time “bump” was interpreted as arising from an underlying SN (Bloom et al. 1999) since, unlike the afterglow, the bump was very red (see below). GRB 970228, also with an intermediate-time bump and characteristic SN spectral rollover, is another good candidate (Reichart 1999; Galama et al. 2000).

Suggestions of intermediate-time bumps in GRB light curves have since been put forth for a number of other GRBs (Lazzati et al. 2001; Sahu et al. 2000; Fruchter et al. 2000; Björnsson et al. 2001; Castro-Tirado et al. 2001; Sokolov 2001; Dar & De Rújula 2000). Most of these results are tentative or suspect, with the SN inferences relying on a few mildly deviant photometric points in the afterglow light curve. Even if some of the bumps are real, a number of other explanations for the physical origin of such bumps have been advanced: for example, dust echoes (Esin & Blandford 2000; Reichart 2001), shock interaction with circumburst density discontinuities (e.g., Ramirez-Ruiz et al. 2001), and thermal reemission of the afterglow light (Waxman & Draine 2000). To definitively distinguish between the SN hypothesis and these alternatives, detailed spectroscopic and multicolor light-curve observations of intermediate-time bumps are required.

It is against this background that we initiated a program with the *Hubble Space Telescope* (*HST*) to sample afterglow light curves at intermediate and late times. The principal attractions of *HST* are the photometric stability and high angular resolution. These are essential in separating afterglows from host galaxies and in reconstructing afterglow colors.

On theoretical grounds, if the collapsar picture is true, we should expect to see a Type Ib/Ic SN (Woosley 1993). In the first month, core-collapsed SN spectra are essentially charac-

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[2] Division of Physics, Mathematics and Astronomy, MS 105-24, California Institute of Technology, Pasadena, CA 91125.

[3] Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston Creek, Canberra, ACT 2611, Australia.

[4] National Radio Astronomy Observatory, P.O. Box O, 1003 Lopezville Road, Socorro, NM 87801.

[5] Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101.

[6] Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903-0818.

[7] Department of Astronomy, University of Texas at Austin, RLM 15.308, C-1400, Austin, TX 78712-1083.

[8] Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027.

[9] Theoretical Astrophysics, MS 130-33, California Institute of Technology, Pasadena, CA 91125.

[10] Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Code 681, Greenbelt, MD 20771

[11] Department of Astronomy, MSC 4500, New Mexico State University, P.O. Box 30001, Las Cruces, NM 88003.

[12] University of California at Berkeley, Space Sciences Laboratory, Grizzly Peak at Centennial Drive, Berkeley, CA 94720-7450.

[13] Istituto Astrofisica Spaziale and Fisica Cosmica, CNR, Via Gobetti, 101, 40129 Bologna, Italy.

[14] Physics Department, University of Ferrara, Via Paradiso, 12, 44100 Ferrara, Italy.

[15] Istituto Astrofisica Spaziale, CNR, Area di Tor Vergata, Via Fosso del Cavaliere, 100, 00133 Roma, Italy.

terized by a blackbody (with a spectral peak near ∼5000 Å) modified by broad metal-line absorption and a strong flux suppression blueward of ∼4000 Å in the rest frame. For GRBs with low redshifts, $z \lesssim 1$, the effect of this blue absorption blanketing is a source with an apparent red spectrum at observer-frame optical wavelengths; at higher redshifts, any SN signature is highly suppressed. For low-redshift GRBs, intermediate-time follow-ups are, then, amenable to observations with the Wide Field Planetary Camera 2 (WFPC2). In this Letter, we report on WFPC2 multicolor photometry of GRB 011121 ($z = 0.36$; Infante et al. 2001), and elsewhere we report on observations of GRB 010921 ($z = 0.451$; Price, Schmidt, & Kulkarni 2002b). In a companion paper (Price et al. 2002a, hereafter Paper II), we report a multiwavelength (radio, optical, and near-IR) modeling of the afterglow.

2. OBSERVATIONS AND REDUCTIONS

On 2001 November 21.7828 UT, the bright GRB 011121 was detected and localized by *BeppoSAX* to a 5′ radius uncertainty (Piro 2001). Subsequent observations of the error circle refined by the Interplanetary Network (IPN) and *BeppoSAX* (see Paper II) revealed a fading optical transient (OT; Wyrzykowski, Stanek, & Garnavich 2001; Stanek, Garnavich, & Wyrzykowski 2001). Spectroscopic observations with the Magellan 6.5 m telescope revealed redshifted emission lines at the OT position ($z = 0.36$), indicative of a bright, star-forming host galaxy of GRB 011121 (Infante et al. 2001).

For all the *HST* visits, the OT and its underlying host were placed near the serial readout register of WF chip 3 (position WFALL) to minimize the effect of charge transfer (in)efficiency (CTE). The *HST* imaging data were preprocessed with the best bias, dark, and flat-field calibrations available at the time of retrieval from the archive ("on-the-fly" calibration). We combined all of the images in each filter, dithered by subpixel offsets, using the standard IRAF/DITHER2 package to remove cosmic rays and produce a better-sampled final image in each filter. An image of the region surrounding the transient is shown in Figure 1. The point source was detected at better than 20 σ in epochs one, two, and three in all filters and better than 5 σ in epoch four.

Given the proximity of the OT to its host galaxy, the final *HST* images were photometered using point-spread function (PSF) fitting photometry (Stetson 1987). The PSF local to the OT was modeled with IRAF/PSTSELECT and PSF using at least 15 isolated stars detected in the WF chip 3 with an adaptive kernel to account for PSF variations across the image (VARORDER = 1). The resulting photometry, reported in Table 1, was obtained by finding the flux in an 0″.5 radius. We corrected the observed count rate using the formulation for CTE correction in Dolphin (2000) with the most up-to-date parameters;[16] such corrections, computed for each individual exposure, were never larger than 8% (typically 4%) for a final drizzled image. We estimated the uncertainty in the CTE correction, which is dependent on source flux, sky background, and chip position, by computing the scatter in the CTE corrections for each of the images that were used to produce the final image.

3. RESULTS

In Figure 2, we plot the measured fluxes from our four *HST* epochs in the F555W, F702W, F814W, and F850LP filters as well as measurements made at earlier times (0.5 days $< t <$ 3 days). The early-time magnitudes were converted to fluxes using the zero points of Fukugita, Shimasaku, & Ichikawa (1995) and plotted in the appropriate *HST* filters.

The estimated contribution from the afterglow is heavily weighted by the available data: our ground-based data (and those reported in the literature so far) are primarily at early times. Roughly, over the first week, the afterglow exhibits a simple power-law decay.

Garnavich et al. (2002) drew attention to an excess of flux (in the *R* band), at a time 13 days after the GRB, with respect to that expected from the power-law extrapolation of early-time afterglow emission; they suggested the excess to arise from an underlying SN. As can vividly be seen from our multicolor data, the excess is seen in all bands and over several epochs.

We used the light curve and spectra[17] of the well-studied Type Ic supernova SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999) to create a comparison template broadband light curve of a Type Ic SN at redshift $z = 0.36$. Specifically, the spectra of SN 1998bw were used to compute the *K*-corrections between observed photometric bands of 1998bw and *HST* bandpasses (following Kim, Goobar, & Perlmutter 1996 and Schmidt et al. 1998). A flat Λ cosmology with $H_0 = 65$ km s^{-1} Mpc^{-1} and $\Omega_M = 0.3$ was assumed, and we took the Galactic foreground extinction to SN 1998bw to be $A_V = 0.19$ mag (Galama et al. 1998).

Since dimmer Type Ic SNe tend to peak earlier and decay more quickly (see Fig. 1 of Iwamoto et al. 1998), much in the same way that Type Ia SNe do, we coupled the flux scaling

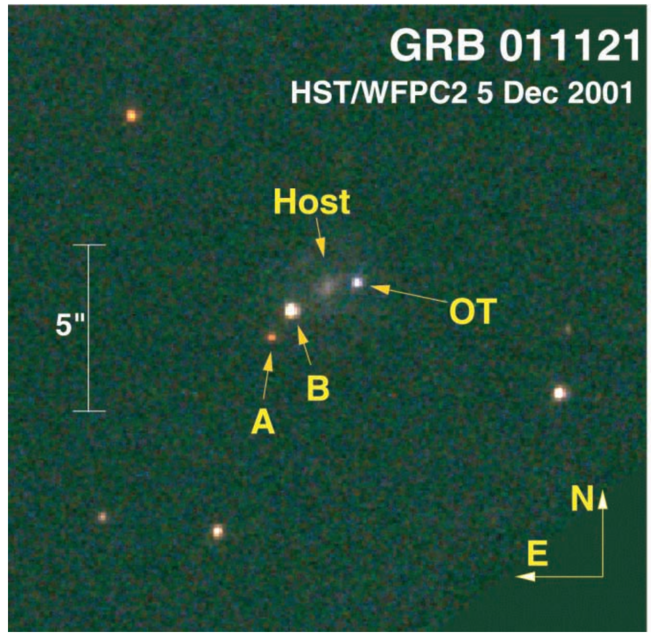

Fig. 1.—*HST* image of the field of GRB 011121 on 2001 December 4–6 UT. This false-color image was constructed by registering the final drizzled images in the F555W (*blue*), F702W (*green*), and F814W (*red*) filters. The OT is clearly resolved from the host galaxy and resides on the outskirts of the morphologically smooth host galaxy. Following the astrometric methodology outlined in Bloom, Kulkarni, & Djorgovski (2002), we find that the transient is offset from the host galaxy 883 ± 7 mas west, 86 ± 13 mas north. The projected offset is 4.805 ± 0.035 kpc, almost exactly at the host half-light radius. Sources "A" and "B" are nonvariable point sources that appear more red than the OT and are thus probably foreground stars.

[16] See http://www.noao.edu/staff/dolphin/wfpc2_calib.

[17] Spectra were obtained through the Online Supernova Spectrum Archive (SUSPECT) at http://tor.nhn.ou.edu/∼suspect/index.html.

TABLE 1
Log of *HST* Imaging and Photometry of the OT of GRB 011121

Filter	Δt[a] (days)	Integration Time (s)	λ_{eff} (Å)	$f_\nu(\lambda_{eff})$ (μJy)	Vega Magnitude[b] (mag)
			Epoch 1		
F450W	13.09	1600	4678.52	0.551 ± 0.037	B = 24.867 ± 0.073
F555W	13.16	1600	5560.05	0.996 ± 0.049	V = 23.871 ± 0.056
F702W	13.23	1600	7042.48	1.522 ± 0.072	R = 23.211 ± 0.054
F814W	14.02	1600	8110.44	1.793 ± 0.042	I = 22.772 ± 0.032
F850LP	14.15	1600	9159.21	1.975 ± 0.103	...
			Epoch 2		
F555W	23.03	1600	5630.50	0.647 ± 0.035	V = 24.400 ± 0.061
F702W	23.09	1600	7002.71	1.271 ± 0.051	R = 23.382 ± 0.048
F814W	24.83	1600	8105.05	1.495 ± 0.053	I = 22.982 ± 0.043
F850LP	24.96	1600	9166.39	1.708 ± 0.100	...
			Epoch 3		
F555W	27.24	1600	5711.00	0.378 ± 0.027	V = 25.071 ± 0.076
F702W	27.30	1600	7043.85	0.981 ± 0.036	R = 23.697 ± 0.044
F814W	28.10	1600	8164.90	1.301 ± 0.070	I = 23.157 ± 0.061
F850LP	28.16	1600	9188.39	1.635 ± 0.092	...
			Epoch 4		
F555W	77.33	2100	5604.61	0.123 ± 0.014	V = 26.173 ± 0.118
F702W	76.58	4100	7042.09	0.224 ± 0.019	R = 25.264 ± 0.092
F814W	77.25	2000	8149.18	0.294 ± 0.020	I = 24.762 ± 0.073

Note.—In the fourth column, the effective wavelength of the filter is based on the observed SFD of the transient at the given epoch. In the fifth column, the flux is given at this effective wavelength in a 0″.5 radius. The observed count rate, corrected for CTE effects, was converted to flux using the IRAF/SYNPHOT package. An input spectrum with f_ν = constant was first assumed. Then approximate spectral indices between each filter were computed and then used to recompute the flux and the effective wavelength of the filters. This bootstrapping converged after a few iterations. The *HST* photometry contains an unknown but small contribution from the host galaxy at the OT location. We attempted to estimate the contamination of the host at the transient position by measuring the host flux in several apertures at approximate isophotal levels to the OT position. We estimate the contribution of the host galaxy to be f_ν(F450W) = 0.098 ± 0.039 μJy, f_ν(F555W) = 0.087 ± 0.027 μJy, f_ν(F702W) = 0.127 ± 0.026 μJy, f_ν(F814W) = 0.209 ± 0.059 μJy, and f_ν(F850LP) = 0.444 ± 0.103 μJy. To correct these numbers to "infinite aperture," multiply the fluxes by 1.096 (Holtzman et al. 1995). These fluxes have not been corrected for Galactic or host extinction.

[a] Mean time since GRB trigger on 21.7828 November 2001 UT.

[b] Tabulated brightnesses in the Vega magnitude system (B_{Vega} = 0.02 mag, V_{Vega} = 0.03 mag, R_{Vega} = 0.039 mag, and I_{Vega} = 0.035 mag; Holtzman et al. 1995). Subtract 0.1 mag from these values to get the infinite aperture brightness. These magnitudes have not been corrected for Galactic or host extinction.

of SN 1998bw with time scaling in a method analogous to the "stretch" method for Type Ia SN distances (Perlmutter et al. 1997). To do so, we fitted an empirical relation between 1998bw and 1994I to determine the flux-time scaling. We estimate that a 1998bw-like SN that is dimmed by 55% (see below) would peak and decay about 17% faster than 1998bw itself. Some deviations from our simple one-parameter template are apparent, particularly in the F555W band and at late times.

In Figure 3, we plot the spectral flux distributions (SFDs) of the intermediate-time bump at the four *HST* epochs. A clear turnover in the spectra in the first three epochs is seen at about 7200 Å. The solid curve is the SFD of SN 1998bw transformed as described above with the associated 2 σ errors. Bearing in mind that there are large systematic uncertainties in the template (i.e., the relative distance moduli between SN 1998bw and GRB 011121) and in the reconstruction of the red bump itself (i.e., the Galactic extinction toward GRB 011121 and the contribution from the afterglow in the early epochs), the consistency between the measurements and the crude SN template is impressive. We consider the differences, particularly the bluer bands in epoch one, to be relatively minor compared with the overall agreement of the light-curve and broadband spectral evolution. This statement is made in light of the large observed time and spectral diversity of Type Ib/Ic SNe (see, e.g., Fig. 1 of Mazzali et al. 2002; see also § 4).

4. DISCUSSION AND CONCLUSIONS

We have presented unambiguous evidence of a red, transient excess above the extrapolated light curve of the afterglow of GRB 011121. We suggest that the light curve and SFD of this excess appear to be well represented by a bright SN. While we have not yet explicitly compared the observations with the expectations of alternative suggestions for the source of emission (dust echoes, thermal reemission from dust, etc.), the simplicity of the SN interpretation—requiring only a (physically motivated) adjustment in brightness—is a compelling (i.e., Occam's razor) argument to accept our hypothesis. Given that the red bump detections in a number of other GRBs occur on a similar timescale as in GRB 011121, any model for these red bumps should have a natural timescale for peak of ~20(1 + z) days; in our opinion, the other known possibilities do not have such a natural timescale as compared with the SN hypothesis. Indeed, if our SN hypothesis is correct, then the flux should decline as an exponential from epoch four onward. The ultimate confirmation of the SN hypothesis is a spectrum that

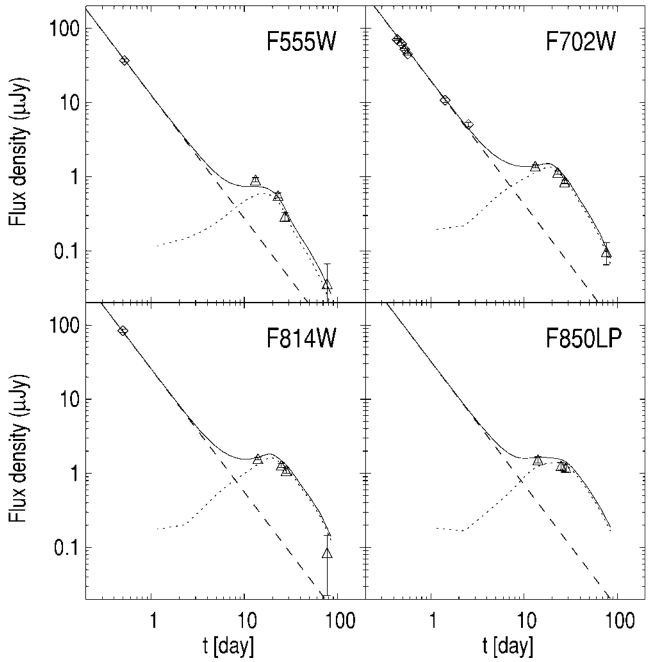

FIG. 2.—Light curves of the afterglow and the intermediate-time red bump of GRB 011121. The triangles represent our *HST* photometry in the F555W, F702W, F814W, and F850LP filters (all corrected for the estimated contribution from the host galaxy), and the diamonds represent ground-based measurements from the literature (Olsen et al. 2001; Stanek & Wyrzykowski 2001). The dashed line is our fit to the optical afterglow (see Paper II), the dotted line is the expected flux from the template SN at the redshift of GRB 011121, with foreground extinction applied and dimmed by 55% to approximately fit the data, and the solid line is the sum of the afterglow and SN components. Corrections for color effects between the ground-based filters and the *HST* filters were taken to be negligible for the purpose of this exercise.

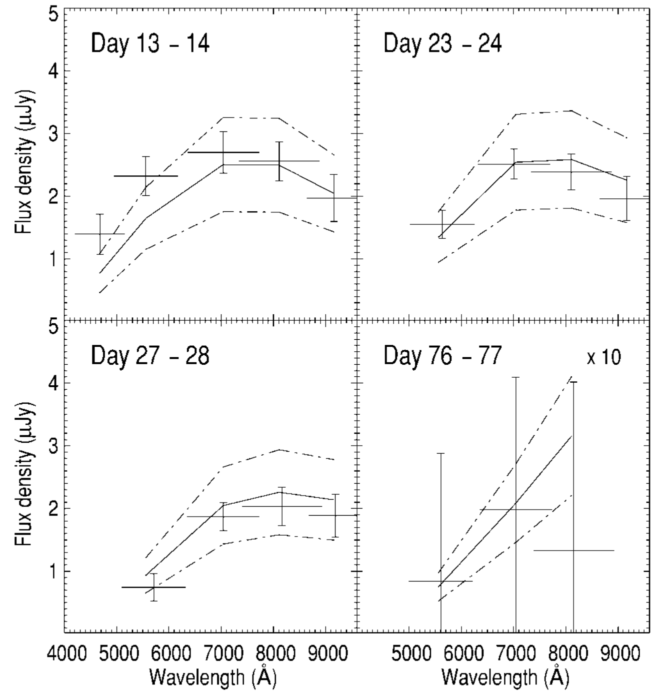

FIG. 3.—SFDs of the red bump at the time of the four *HST* epochs. The fluxes are dereddened using $A_V = 1.16$ mag. Spectral evolution and, more important, a turnover in the spectra of the first three epochs are clearly seen. The peak of the turnover (around 7200 Å) corresponds to a peak in the red bump spectrum at ∼5300 Å. For comparison, we show a template broadband SN spectra (a dimmed version of SN 1998bw; *solid curve*) as it would appear at the redshift of GRB 011121 and the associated 2 σ errors (see text). The vertical error bars on the red bump reflect the 1 σ statistical uncertainty flux from only the red bump. There are large (∼1 mag) systematic uncertainties (e.g., Galactic reddening, relative distance moduli between SN 1998bw and GRB 011121) in both the data and the model; these are suppressed for clarity.

should show characteristic broad metal-line absorption of the expanding ejecta (from, e.g., Ca II, Ti II, and Fe II).

We used a simplistic empirical brightness–time stretch relation to transform 1998bw, showing good agreement with the red bump. If we neglect the time stretching and only dim the 1998bw template, then the data also appear to match the template reasonably well; however, the discrepancies in the bluer bands become somewhat larger, and the flux ratios between epochs are slightly more mismatched. The agreement improves if we shift the time of the SN to be about ∼3–5 days (rest frame) before the GRB time. Occurrence times more than about 10 days (rest frame) before the GRB can be ruled out. This observation, then, excludes the original "supranova" idea (Vietri & Stella 1998) that posited that a SN would precede a GRB by several years (see eq. [1] of Vietri & Stella 1998). Modified SN scenarios that would allow for any time delay between the GRB and the accompanying SN, albeit ad hoc, are still consistent with the data presented herein.[18]

Regardless of the timing between the SN explosion and the GRB event (constrained to be less than about 10 days apart), the bigger picture we advocate is that GRB 011121 resulted from an explosive death of a massive star. This conclusion is independently supported by the inference, from afterglow observations of GRB 011121 (Paper II), of a wind-stratified circumburst medium.

The next phase of inquiry is to understand the details of the explosion and also to pin down the progenitor population. A large diversity in any accompanying SN component of GRBs is expected from both a consideration of SNe themselves and the explosion mechanism. The three main physical parameters of a Type Ib/Ic SN are the total explosive energy, the mass of the ejecta, and the amount of nickel synthesized by the explosion ($M_{\rm Ni}$). The peak luminosity and time to peak are roughly determined by the first two, whereas the exponential tail is related to $M_{\rm Ni}$. Ordinary Type Ib/Ic SNe appear to show a wide dispersion in the peak luminosity (Iwamoto et al. 1998). There is little ab initio understanding of this diversity (other than shifting the blame to dispersion in the three parameters discussed above).

It is now generally accepted that GRBs are jetted (e.g., Frail et al. 2001), with opening angles ranging from less than a degree to 30°. Given such strong collimation, we must be prepared to accept that any accompanying SN explosion is extremely asymmetric, leading to a richer diversity in the light curves. Indeed, there has been a significant discussion as to the degree to which the central engine in GRBs will affect the overall explosion of the star (Woosley 1993; Khokhlov et al. 1999; MacFadyen & Woosley 1999; Höflich, Wheeler, & Wang 1999; MacFadyen, Woosley, & Heger 2001). These models have focused primarily on the hydrodynamics and lack the radiative modeling necessary to compare observations with the models.

Clearly, the observational next step is to obtain spectroscopy (and perhaps even spectropolarimetry) and to use observations

[18] The explosion date of even very well studied SNe, such as SN 1998bw, cannot be determined via light curves to better than about 3 days (e.g., Iwamoto et al. 1998). This implies that future photometric studies might not be equipped to distinguish between contemporaneous SN/GRB events and small delay scenarios.

to obtain a rough measure of the three-dimensional velocity field and geometry of the debris. As shown by GRB 011121, the SN component may sometimes be bright enough to undertake observations with the largest ground-based telescopes.

We end by noting the following curious point. The total energy yield of a GRB is usually estimated from the gamma-ray fluence and an estimate of the opening angles (see Frail et al. 2001). Alternatively, the energy in the afterglow is used (e.g., Piran et al. 2001). However, for GRB 011121, the energy in the SN component (scaling from the well-studied SN 1998bw) is likely to be comparable to or even larger than that seen in the burst or the afterglow. In view of this, the apparent constancy of the gamma-ray energy release is even more mysterious.

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