The case for late-time optical bumps in GRB afterglows as a supernova signature

J. S. Bloom

Harvard-Smithsonian Center for Astrophysics, MC 20, 60 Garden Street, Cambridge, MA 02138, USA

Abstract. Observations of late-time optical bumps have been reported for several GRBs. The timescale for such bumps, and colors of such when available, find a natural explanation as due to associated supernovae. Ground-based and HST observations of the afterglow and bump of GRB 011121, in particular, place the strongest constraints yet on the physical nature of the supernova and any alternative explanations, such as supranovae or dust echoes. I summarize the search for underlying bumps in other GRBs and make the case for the supernova hypothesis in light of observed bumps and bump non-detections (e.g., GRB 010921).

There is a good deal of theoretical motivation to expect to see bumps in GRB afterglow lightcurves¹. For massive star progenitors (Woosley 1993), a bump can arise either by reflection/reprocessing of the afterglow light by surrounding dust (Waxman & Draine 2000; Esin & Blandford 2000) or from a supernova that accompanies the GRB. A bump might also arise from delayed energy injection by the central source (Dai & Lu 1998). If the afterglow encounters a shell of material with higher density at \( \sim 10^{17} \) cm, then the afterglow could rebrighten. For compact binary mergers (e.g., double neutron star coalescence), a late-time bump is not a natural expectation since, a) mergers should occur in homogeneous regions of low density, b) explosive nucleosynthesis leading to a supernova is not expected around such systems, and c) the creation of a stable neutron star after merger that is capable of re-injecting energy after \( \sim 20 \) days seems implausible. D. Lazzati (this workshop) has given an excellent overview of various progenitor scenarios.

Thus the mere existence of bumps offer a strong discriminator between merger and massive star scenarios. Within the confines of the massive star progenitors model, the details of the bumps and accompanying afterglows should also offer insight into the specifics of the progenitors. For example, a bump from a supernova should have the spectral and temporal characteristics of other supernovae observed in the local universe; Woosley (1993) suggested that baryon contamination of the relativistic jets could be minimized if this supernova was of type Ic. A bump from thermal dust emission could have similar rise and fall.

¹For the purposes of this presentation, I define a bump as: an increase in flux above an extrapolated/interpolated light curve; extra source of emission, owing, as reckoned, to processes of a different physical mechanism. In Bloom et al. (1999) we referred to the optical bump in GRB 980326 as a rebrightening. Bumps have been seen on shorter timescales (e.g. a few days 970508) but here, we focus on the late-time bumps (\( \sim 20-40 \) day timescale).
timescales as a supernova, but the spectrum would be thermal and featureless, without any of the metal-line blanketing seen in supernovae. A bump from dust echoes could mimic supernovae timescales (Reichart 2001), but the bump should fade as a power-law rather than an exponential.

1. Bumps Associated With Cosmological GRBs

The first observational detection of a bump associated with a “cosmological” burst\(^2\) came with afterglow observations of GRB 980326 (Bloom et al. 1999). There, the early afterglow was seen to fade rapidly in the first few days \((f_\nu \propto t^{-2})\) with a fairly generic afterglow spectrum \((f_\nu \propto \nu^{-0.8})\). At day 22 and day 28, imaging and spectroscopic detections revealed a source that was about 60 times brighter than the early extrapolation and significantly more red \((f_\nu \propto \nu^{-2.3})\). By the next series of observations at 200 days, the bump had faded by at least a factor of ten. HST imaging observations later revealed a faint galaxy at the position of the transient (Fruchter et al. 2001).

What powered the bump in GRB 980326? The timescale for rise and decay are natural in the supernova interpretation. Moreover, the red color of the bump can be understood as due to metal line blanketing of a core-collapsed supernova redward of \(\sim 4000 \text{ Å}\) in the restframe. That the spectrum differed significantly from the early afterglow spectrum suggests a different physical emission process than in the afterglow. In other words, the bump in 980326 disfavors a synchrotron shock origin, such as might be expected from a more dense external medium or from delayed energy injection of a central source.

Bumps, attributed to SNe, have since been claimed in a number of other cosmological bursts. The bump in the afterglow of GRB 970228 was based on observations in at least three bandpasses (Reichart 1999; Galama et al. 2000). Moreover, the probable turn over in the spectrum at \(1 \mu\text{m}\) (Reichart 2001) could not be easily explained by thermal emission from dust or a dust echo. The peak of redshifted thermal emission should occur redward of \(\sim 2 \mu\text{m}\) and dust echo spectra should not exhibit a strong roll over. Optical/IR bumps discovered 20–30 days after GRBs 000911 (Lazzati et al. 2001), 990712 (Björnsson et al., 2001), 980703 (Holland et al. 2001) provided suggestive evidence of bumps—all of which the authors claimed found a reasonable explanation in the context of an added supernova component. For several bursts, however, no bump was detected to limits of comparable brightness to 1998bw (see Price et al. 2002 for a review). Note that due to severe line blanketing in the restframe UV, a bump from a supernovae is not expected to be seen at optical wavelengths for bursts beyond redshifts of \(z \sim 1.2\) whereas bumps from dust echoes could be seen to

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\(^2\)The detection of a low-redshift supernova, SN 1998bw, coincident with a GRB (980425) (Galama et al. 1998; E. Pian, this workshop) provided an observational link that until then had only been explored theoretically. However, since the burst must have been extraordinarily dim when compared to other well-studied bursts—rather than definitively prove that long-duration bursts arise in the core-collapse of a massive stars—it is now believed that GRB 980425 might simply represent a sub-class with a different bursting mechanism than the lion’s share of long-duration bursts (Bloom et al., 1998; Tan, Matzner, & McKee, 2001). Nevertheless, we might consider SN 1998bw as the ultimate bump associated with a GRB.
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Figure 1. (top) Peak bump magnitude versus host magnitude for those 12 bursts with $z < 1.2$ where a bump search has been conducted. Circles (squares) mark those bursts for which a bump was searched for using ground-based (HST) data. Color gradations are intended to show the relative significance of the detection. Note that the significance of ground detection is stronger for bumps brighter than the host and no bumps have been seen much fainter than the host. Bumps found with HST can probe significantly fainter. (bottom) The deepest non-detection of a bump with HST (adapted from Price et al. 2002). Though any bump must be fainter than 1998bw at the redshift of GRB 010921, it could still have been brighter than SN 1994I.
higher redshifts. Consistent with the SN hypothesis, no bumps were detected by our group in the afterglows of GRBs 010222 ($z = 2.09$) and 000926 ($z = 1.48$).

2. Using HST to overcome observational impediments

The ability to detect the bump in 980326 was aided by two important occurrences. First, the rapid fading of the early afterglow effectively removed any possible light contamination from the afterglow beyond a few days. Second, the host galaxy was exceedingly faint ($R = 29.4$ mag). Therefore, as we pointed out in Bloom et al. (1999), a bump in new GRBs could be easily outshone for bright host galaxies and/or by bright afterglows. The latter difficulty can be minimized by observing bursts with rapidly fading afterglow or with early temporal breaks (presumably due to jetting). Even for these, without an excellent multi-wavelength characterization of the early-time afterglow, which allows for accurate predictions of the flux at 10–40 days, bump detections will be more difficult to claim unambiguously. Overcoming the former host difficulty requires either an intrinsically faint galaxy (like 980326) or the ability to resolve the GRB afterglow from its host. To dig deeper into the bump luminosity function, observations with the Hubble Space Telescope, then, seemed the natural choice.

As of this workshop there have been 12 reported searches for bumps in GRB afterglows for bursts originating from $z < 1.2$. Of these, half utilized only ground-based observations, and half used both ground-based and HST photometry. GRB 020405 (Price, this workshop) and GRB 020331 (Soderberg, this workshop) are two new positive detections from our HST program. As illustrated in Figure 1, for the bursts where a bump was seen or an upper-limit found from ground-based observations alone, the host galaxy is a dominant contaminant. Interestingly, only three bumps appear brighter than their respective hosts at the same wavelengths.

HST observations have allowed us to probe nearly four magnitudes fainter than the total magnitude of the host (in the case of GRB 010921; $z = 0.45$). The non-detection of a bump in GRB 010921 is the deepest constraint on a bump: any bump must have been at least 70% fainter than 1998bw at the redshift of the burst. In other words, despite the added depth with HST photometry, we still have not been able to probe for bumps fainter than about $M_V = -18$ mag.

3. GRB 011121: The Best Case for a Bump

Given the low redshift of GRB 011121 and extensive ground-based observations at early times, we undertook a multi-epoch multi-wavelength program with HST to try to detect a bump and test our hypothesis that any detected bump could be due to a supernova. Garnavich et al. (2002) first pointed out that the $R$-band flux at day 14 was higher than the extrapolated light curve from earlier times. As described in more detail in Bloom et al. (2002), we detected a significant bump in four HST filters. In that paper we described how the light curve and spectra over the next 78 days appeared to resemble a supernova. In addition, afterglow models of 011121 provided the first clear-cut case of a wind-stratified medium around the burst. This, coupled with the SN interpretation, provides strong evidence for a massive star origin.
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Figure 2. A simulated SN spectrum at $R = 25.4$ mag and $z = 0.5$ as observed with the Advanced Camera for Surveys + WFC on HST. The template is SN 1994I (Type Ic), but dimmed to be 10 times fainter than 1998bw at a redshift of $z = 0.5$. Some broad core-collapsed SNe spectral features are detectable even at such faint magnitude levels. For nearer bursts or those with a brighter SN component (such as we have already observed with GRB 011121), the signal-to-noise could be high enough to measure an expansion velocity of the supernova.

As both we and Garnavich et al. (2003) described, the behavior of the bump of 011121 did not follow a simple redshifted 1998bw: this rise time appeared to be quicker (17% more rapid) and the peak flux lower (55% fainter). A few explanations could be possible. The supernova could be of a different type than 1998bw (e.g., type IIn; Garnavich et al., 2003). Instead, the supernova could be a type Ic but with an energy and ejecta mass between that of 1998bw and 1994I (see Figure 1). Alternatively, the supernova could be a dimmed version of 1998bw but with an explosion date that preceded the GRB by $-6 \pm 5$ days ($\chi^2$/dof < 1; Zeh et al., this workshop).

Accepting the supernova interpretation, the Zeh analysis is an important one because it places constraints on the relative timing of the supernova and the GRB. In a “supranova”, a supramassive neutron star is created as the massive star explodes to produce a supernova (Vietri & Stella 1998). When this neutron star spins down (via magnetic breaking or gravitational radiation) — losing centrifugal support — it collapses to form a black hole producing the GRB. Thus a supernova could precede a GRB in time. Unfortunately, the time offset is not a strong prediction of the supranova hypothesis—in fact, we point out
that the original incarnation of the model suggested a 10 year offset, which is clearly ruled out by the 011121 observations.

4. Conclusions

The short time-offset in 011121 (consistent with contemporaneous GRB and supernova explosions) underscores one of the more fundamental observational limits in understanding the origin of bumps and GRB progenitors. Since the explosion time of even the best studied supernovae cannot be dated to better than about ±2 days, we may never be able to infer the true time offset for short-delay supernovae. That is, we may never be able to distinguish between the collapsar model (zero delay) and short-delay supernova scenarios based upon optical observations alone (neutrino arrival times would help!).

Clearly not all bumps can be fit with redshifted versions of 1998bw, suggesting an intrinsic diversity in the properties of bumps (even without appealing to a supernova interpretation). If these bumps are due to supernovae then this diversity is unsurprising: local examples of core-collapsed supernovae are anything but standard. Mazzili et al. (2002) compiled spectra and light curves of a few well-observed core-collapse supernovae and emphasized the large scatter in peak fluxes ($M_V(\text{peak}) \approx -15$ to $-20$ mag) and broad range of colors at peak. Since the best non-detection of a bump reaches only $\approx -18$ mag, I suggest that we may be only detecting the tip of the iceberg of supernovae associated with GRBs.

There are several points to take away from the existing sample:

1. **Late-time bumps are real and common.** Bumps have been detected with high significance in at least five GRB afterglows (980326, 970228, 020405, 011121, 020331) with several other proposed bump identifications (e.g., 000911, 990712, 980703). The non-detections or ambiguity in the significance of bumps have been largely due to contaminating light from the host galaxies. HST observations have allowed us to push bump sensitivity almost four magnitudes fainter than the integrated host magnitude. Still, the best non-detection reaches only to $M_V \approx -18$ mag.

2. **The best case suggests a supernova origin.** GRB 011121 is the best case for a bump and has a spectrum and light curve similar to a type Ic or IIn supernova. This is also the best example of a burst that occurred in a wind-stratified medium.

3. **Limits on supranovae.** The original supranova hypothesis, which posited an offset in time between the GRB and the associated supernova of 10 years, is clearly ruled out. Modified-supranovae (with time offsets of less than a ~one week) are still allowed but may be indistinguishable from collapsar models using bump observations alone.

With such a small number of intensive bump searches, we know very little about the frequency of occurrence of GRB bumps. In a supernova-centric interpretation, the current non-detections of bumps at redshifts $z < 1.2$ may be due to a lack of sensitivity and intrinsic supernovae diversity. Despite the concordance
of a number of detected bumps with simplistic \textit{a priori} supernovae models, a spectrum of a bump — showing either the absence or presence of metal lines — would be most convincing one way or another. (Somewhat lost in the various disagreements over the specifics of the bump emission and timescales is: most viable alternatives put forth thus far to explain bumps require a massive star progenitor rather than merger products.) In the future, to more accurately characterize the nature of bumps, we hope to undertake HST spectroscopy of a bump (see Figure 2) and determine if bump decay rates are indeed exponential.

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