IS THERE A 1998bw-LIKE SUPERNOVA IN THE AFTERGLOW OF GAMMA-RAY BURST 011121?

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ABSTRACT

We use the very simple and successful cannonball model of gamma-ray bursts (GRBs) and their afterglows (AGs) to analyze the observations of the strongly extinct optical AG of the relatively nearby GRB 011121; these observations were made with ground-based telescopes at early times and with the Hubble Space Telescope at later times. We show that GRB 011121 was indeed associated with a 1998bw-like supernova at the GRB’s redshift, as we had specifically predicted for this GRB before the supernova could be observed.

Subject headings: gamma rays: bursts — supernovae: general

1 INTRODUCTION

The identity of the progenitors of gamma-ray bursts (GRBs) is still unknown, but it is becoming clearer and clearer. It has been suggested that GRBs are produced by highly relativistic jets (e.g., Shaviv & Dar 1995; Dar 1998), mostly in core-collapse supernovae like SN 1998bw (Dar & Plaga 1999; Dar 1999a; Dar & De Rújula 2000 and references therein). Possible evidence of an SN 1998bw–like contribution to a contribution to an AG afterglow (AG; Dar 1999a; Castro-Tirado & Gorosabel 1999) was first found by Bloom et al. (1999) for GRB 980326, but its unknown redshift prevented a definite conclusion. The AG of GRB 970228 (located at redshift z = 0.695) appears to be overtaken by a light curve akin to that of SN 1998bw (located at z = 0.0085), when properly scaled by their differing redshifts (Dar 1999b; Reichart 1999; Galama et al. 2000). Evidence of a similar possible association was found for GRB 990703 (Björnsson et al. 2001), GRB 000418 (Dar & De Rújula 2000), GRB 991208 (Castro-Tirado et al. 2001), GRB 970508 (Sokolov 2001), GRB 000911 (Lazzati et al. 2001; S. Dado, A. Dar, & A. De Rújula 2002, in preparation), and GRB 010921 (Dado, Dar, & De Rújula 2002b).

Unlike Type Ia supernovae (SNe Ia), core-collapse supernovae (SNe II/ib/Ic) are far from being standard candles. But if their explosions are fairly asymmetric—as they would be if a fair fraction of them emit two opposite jets of cannonballs—much of the diversity could be a reflection of the varying angles from which we see their nonspherically expanding shells. Exploiting this possibility to its extreme, i.e., using SN 1998bw as an Ansatz standard candle, Dar & De Rújula (2000), Dado, Dar, & De Rújula (2002a and references therein) and the early-time R-band observations, recalibrated by the photometry of Olsen et al. (2001), to predict the late-time behavior of the AG in the BVRI bands and to demonstrate that “The inescapable conclusion is that the supernova associated with GRB 011121 will, at about day 20 after burst, tower in the BVRI bands above the proper GRB afterglow” (Dado, Dar, & De Rújula 2001), in spite of the strong extinction in the host galaxy and in ours.

Late-time ground-based optical observations were made with the 6.5 m Magellan telescope, and an extensive space-based monitoring campaign was made with the Hubble Telescope (HST). Indeed, from the first HST observations on 2001 December 4–5, Garnavich et al. (2002) concluded that the AG of GRB 011121 shows the anticipated SN 1998bw–like contribution, while Bloom et al. (2002a) had found before in the same data “no evidence of an intermediate-time light curve bump from an underlying supernova.” In following observations obtained on 2001 December 14–16 and 19–20, Bloom et al. (2002c) found a “bump” and concluded that “This curious bump is inconsistent with an underlying SN similar to SN 1998bw” one day; Kulkarni et al. (2002) concluded that “it appears that the case for an underlying SN in GRB 011121 is well established” the day after. As these authors caution, the conclusions (in the standard fireball paradigm) are affected by possible jet breaks (whose position and sharpness cannot be easily predicted).

In this Letter, we use the CB model to estimate the extinction in the host galaxy of GRB 011121 and to predict its late-time
optical AG. We show that the evidence is clear: this GRB was indeed associated with a standard-candle 1998bw-like supernova at \( z = 0.36 \), the GRB’s redshift.

2. THE CB MODEL

In the CB model, long-duration GRBs and their AGs are produced in core-collapse supernovae by jets of highly relativistic “cannonballs” that pierce through the supernova shell. The AG—the persistent radiation in the direction of an observed GRB—has three origins: the ejected CBs, the concomitant SN explosion, and the host galaxy. These components are usually unresolved in the measured “GRB afterglows,” so that the corresponding light curves and spectra are the cumulative energy flux density:

\[
F_{AG} = F_{CB} + F_{SN} + F_{WD}.
\]

The contribution of the candidate host galaxy depends on the angular aperture of the observations, and it is usually determined by late-time observations when the CB and SN contributions become negligible.

Let the energy flux density of SN 1998bw at redshift \( z_{bw} = 0.0085 \) (Galama et al. 1998) be \( F_{bw}(\nu, t) \). For a similar SN placed at a redshift \( z \),

\[
F_{SN}(\nu, t) = \frac{1 + z}{1 + z_{bw}} \frac{D_L^2(z_{bw})}{D_L^2(z)} F_{bw}\left(\nu \frac{1 + z}{1 + z_{bw}}, \frac{1 + z_{bw}}{1 + z}\right) A(\nu, z),
\]

where \( D_L(z) \) is the luminosity distance\(^4\) and \( A(\nu, z) \) is the extinction along the line of sight.

The contribution of a jet of CBs to the GRB AG at “late” times \( (t > 1 \text{ day}) \) is given by (Dado et al. 2002a)

\[
F_{CB} = f[\gamma(t)]^{3a-1} |\delta(t)|^{3+\nu} \nu^{-\alpha},
\]

where \( f \) is a normalization constant (see Dado et al. 2002a for its theoretical estimate), \( \alpha \) is the spectral index of the electron synchrotron radiation, \( \gamma(t) \) is the Lorentz factor of the CB, and \( \delta(t) \) is its Doppler factor:

\[
\delta = \frac{1}{\gamma(1 - \beta \cos \theta)} = \frac{2\gamma}{(1 + \theta^2 \gamma^2)},
\]

whose approximate expression is valid for small observing angles \( \theta \ll 1 \) and \( \gamma \gg 1 \) (the domain of interest for GRBs). For an interstellar medium of constant baryon density \( n_p \), the Lorentz factor \( \gamma(t) \) is given by (Dado et al. 2002a)

\[
\gamma = \gamma(\gamma_0, \theta, x_r; t) = \frac{1}{B} \left( \beta^2 + C \theta^4 + \frac{1}{C} \right),
\]

\[
C \equiv \left( \frac{2}{B^2 + 2\theta^6 + B^2 + 4\theta^2} \right)^{1/3},
\]

\[
B \equiv \frac{1}{\gamma_0} \frac{3\theta}{\gamma_0} + \frac{6ct}{(1 + z)x_r},
\]

where \( \gamma_0 = \gamma(0) \) and

\[
x_r = \frac{N_{CB}}{\pi R_{max}^2 n_p}
\]

characterizes the CB’s slowdown in terms of its baryon number \( N_{CB} \) and its radius \( R_{max} \) (it takes a distance \( x_r/\gamma_0 \) for the CB to halve its original Lorentz factor).

The selective extinction, \( A(\nu, t) \) in equation (2), can be estimated from the difference between the observed spectral index and the one expected\(^3\) in the CB model (\( \alpha = 0.5 \) at \( t < 1 \text{ day} \), and \( \alpha = 1.1 \) after a couple of days). From the early-time relative intensities in the \( B \) and \( V \) bands of the AG of GRB 011121, we obtain a total selective extinction of \( E(B-V) = 0.615 \pm 0.07 \) mag along the line of sight to GRB 011121. Most of this extinction is due to dust in the Galaxy, \( E(B-V) = 0.50 \) mag (Schlegel, Finkbeiner, & Davis 1998) in the direction of GRB 011121. The total selective extinction yields an estimated attenuation factor \( A(\nu, z) = 0.18 \) in the \( V \) band \( [A_v \approx 3.05 \text{ and } E(B-V) = 1.87 \text{ mag}; \text{Whittet 1992, p. 65}]. \) From the early-time relative intensities in the \( I, R, V \), and \( B \) bands, we deduce the attenuation factors \( A(\nu, z) \sim 0.26, 0.22, 0.18, \) and 0.11, to be used in equation (2) to estimate the expected spectral energy densities of SN 1998bw at the position of GRB 011121.

We assume, for the late-time AG of GRB 011121, a spectral slope \( \alpha = 1.1 \), compatible with that of all other GRB AGs (Dado et al. 2002a). The rest of the fitted parameters are \( \gamma_0 = 1222, \theta = 0.104 \text{ mrad, and } x_r = 0.83 \text{ Mpc}. \) The resulting late-time \( R \)-band light curve is presented in Figure 1.

\(^4\) The cosmological parameters that we use are \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}, \) \( \Omega_m = 0.3, \) and \( \Omega_{\Lambda} = 0.7. \)

\(^3\) The time dependence of \( \alpha \) is analyzed in detail in Dado, Dar, & De Rújula (2002c). The CB model predicts, and the data confirm with precision, the predicted gradual evolution of \( \alpha(t) \) in the first day or two to the constant value of \( \approx 1.1 \) observed in all late AGs (Dado et al. 2002a).
The contribution of the host galaxy has been subtracted. This contribution—$F_{\text{host}} \approx 2 \, \mu\text{Jy} (R_{\text{host}} \approx 23)$ to the early-time measurement and $0.127 \pm 0.026 \, \mu\text{Jy}$ to the late-time $HST$ measurements—is a rough estimate; its true value depends, respectively, on the angular aperture of the observations and on the unknown extinction of the host galaxy’s light within this aperture.

In Figures 2, 3, and 4, we present the CB model’s predictions for the light curves of the AG in the $IVB$ bands, with the host galaxy’s contribution subtracted with use of its magnitudes in these bands, as estimated by Bloom et al. (2002b), which correspond to $0.209 \pm 0.059$, $0.087 \pm 0.027$, and $0.098 \pm 0.039 \, \mu\text{Jy}$, respectively. The theoretical contribution of an unextinct SN 1998bw at redshift 0.36 to the $BVRI$ bands was dimmed by the attenuation factors $A(\nu, z) = 0.11$, 0.18, 0.22, and 0.26 because of extinction by dust in the host galaxy and in ours, as estimated above.

The agreement between theory and observations in Figures 1–4 is almost surprisingly good, in view of the large observational uncertainties and the theoretical approximations. A similarly strong correspondence between predictions and observations is shown in Figure 5, where we compare the predicted late-time spectral energy distribution, which is to a large extent dominated by the SN 1998bw–like contribution, with the $HST$ observations (Bloom et al. 2002b) on days 13–14, 23–24, 27–28, and 76–77 after burst.

3. CONCLUSION

In Dado et al. (2001), we used the early AG data for GRB 011121 to predict the later AG, in particular the presence of an SN 1998bw–like supernova transported to the GRB’s redshift, which at the earlier time was still unobservable. All we have done in this Letter is update and refine these expectations.
Fig. 5.—From top to bottom: Spectral energy density of the AG of GRB 011121 on days 13–14, 23–24, 27–28, and 76–77 at which the SN contribution is clearly there in all of the light curves at different frequencies and in all of the spectra at different times.

In Dar & De Rújula (2000), we argued that all long-duration GRBs may be associated with 1998bw-like supernovae and that the apparent variability of core-collapse SNe may be due to a spread of viewing angles, relative to the CB-emission axis. In Dado et al. (2002b), we showed how the 1998bw-like contribution, properly redshifted in its time and frequency dependence and dimmed by extinction, all as in eq. (2). For clarity, the experimental data points and the theoretical predictions for days 23–24, 27–28, and 76–77 were multiplied by a factor of 1/10, 1/100, and 1/1000, respectively.

with the use of the improved observational constraints on absorption in the host galaxy and compare the prognosis with the early and late AG data. The 1998bw-like contribution is clearly there in all of the light curves at different frequencies and in all of the spectra at different times.

In Dar & De Rújula (2000), we argued that all long-duration GRBs may be associated with 1998bw-like supernovae and that the apparent variability of core-collapse SNe may be due to a spread of viewing angles, relative to the CB-emission axis. In Dado et al. (2002b), we showed how surprisingly successful the Ansatz of an associated supernova identical to 1998bw was, when confronted with the observations for optical and X-ray AGs. The AGs of some GRBs discovered after these quoted works—that of GRB 000911, discussed in S. Dado, A. Dar, & A. De Rújula (2002, in preparation), that of GRB 010921, discussed in Dado et al. (2002b), and that of GRB 011121, discussed here—strengthen the conclusion that, so far, in all AGs in which an SN like 1998bw was visible (in practice, in all cases with redshifts \( z < 1.2 \)), the supernova was seen. And it was compatible in magnitude and color with an SN 1998bw standard candle! It goes without saying that there are no standard candles. It is just that the current data are not precise enough to detect significant variations in this particular one. But the important fact is that the supernovae allegedly associated with all long-duration GRBs (Dado et al. 2002a and references therein) are indeed there.

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