THE SUPERNova ASSOCIATED WITH GRB 030329

SHLOMO DADO,1 ARNON DAR,1 AND A. DE RÚJULA2
Received 2003 April 9; accepted 2003 July 24; published 2003 August 6

ABSTRACT

The relative proximity of the recent gamma-ray burst GRB 030329 resulted in a large gamma-ray fluence and in the brightest-ever afterglow (AG), hours after the burst, in the radio, optical, and X-ray bands, permitting precise AG measurements, sensitive tests of models, and an excellent occasion to investigate the association of gamma-ray bursts (GRBs) with supernovae (SNe). The Cannonball model provides a simple, and universal description of all AGs of GRBs of known redshift, so that it is straightforward to use it to predict what the expected SN signatures are. In the case of GRB 030329, 10 days after the burst, the AG should begin to reveal the light curve, spectrum, and polarization of an underlying SN—akin to SN 1998bw—which will peak in the optical band around day 15.

Subject heading: gamma rays: bursts
On-line material: color figures

1.INTRODUCTION

It is important to know what it is that makes gamma-ray bursts (GRBs). The evidence for an association of long-duration GRBs with supernovae (SNe) has been treated by observers with due care, since in only a few cases is the evidence very clear and model independent. Moreover, the only overwhelmingly clear association—that of GRB 980425 with SN 1998bw—does not fit at all in the generally accepted fireball models: the GRB is far too weak, and the SN is annoyingly peculiar. These, and the other suggestions for the physical origin of late bumps in optical afterglows (AGs) of GRBs, such as dust echoes (Esin & Blandford 2000; Reichart 2001), shock interactions with circumburst density discontinuities (Ramirez-Ruiz et al. 2001), and thermal reemission of the AG light (Waxman & Draine 2000), may have been the reasons that reviews of the subject, even very recent ones, did not consider the SN/GRB association to be an established fact (e.g., Waxman 2003).

In the cannonball (CB) model, long-duration GRBs are produced by jets ejected in core-collapse SNe (Dar & De Rújula 2000). In this model, there is nothing special about GRB 980425, which was observed farther off-axis than any other GRB of known redshift. Nor is SN 1998bw peculiar: it did not emit the observed puzzling radio and X-ray signals; the CB responsible for the GRB did it, as discussed in tiresome detail in Dado, Dar, & De Rújula (2003a). Since, in the CB model, the SNe associated with GRBs are observed from the same specific direction (near their “axis”), it is justifiable to use SN 1998bw as a putative standard candle for SNe associated with GRBs and could, in this sense, be anticipated. The early optical AG of GRB 030329 is, as for GRBs 990123, 021004, and 021121, a direct tracer of the expected 1/hr2 circumburst density profile generated by a pre-SN stellar wind (Dado et al. 2003c). Both GRB 030329 and 021004 have gamma-ray light curves dominated by two pulses or, in the CB model, two cannoneballs. Both AGs display two wide shoulders that, in the same model, correspond to the contributions of the two CBs. The superimposed variations in the predicted smooth AG light curve, ups and downs of ∼2 magnitude, are, as for GRBs 970508, 000301c (Dado et al. 2002a), and 021004 (Dado et al. 2003b), to be expected: they directly trace moderate deviations from a constant-density interstellar medium (ISM).

2. GRB 030329

The bright optical AG of this GRB (Vanderspek et al. 2003), first observed ∼1.25 hr after burst by Peterson & Price (2003) and by Torii (2003), is—at magnitude 0 ∼ 12.5—by far the brightest optical AG observed hours after burst. The X-ray AG, also very bright, was seen at time t ∼ 5 hr after burst with the Rossi X-Ray Timing Explorer by Marshall & Swank (2003). The bright radio AG was observed at t ∼ 14 hr by Berger et al. (2003). The redshift of the host galaxy was first determined by Greiner et al. (2003) to be z = 0.1685. The large luminosity of this AG has triggered a wide interest, reflected in a copious and enthusiastic release of GCN communications.

3. THE CANNONBALL MODEL OF GRBS

In the CB model (Dar & De Rújula 2000, 2001; Dado et al. 2002a, 2003a) reviewed in De Rújula 2002 & Dar (2003), long-duration GRBs and their AGs are produced in core-collapse SNe akin to SN 1998bw by the ejection of bipolar jets of ordinary matter: hydrogenic plasma clouds or CBs with high Lorentz factors (γo ∼ 103). Crossing the circumburst shells with a large γo, the surface of a CB is collisionally heated to keV tempera-

1 Physics Department and Space Research Institute, Technion, Haifa 32000, Israel; dado@hep3.technion.ac.il, arnon@physics.technion.ac.il, dar@cern.ch.
2 Theory Division, CERN, CH-1211 Geneva 23, Switzerland; alvaro .derujula@cern.ch.
tures, and the thermal radiation it emits as it reaches the transparent outskirts of the shells and the SN light it scatters—boosted and collimated by the CB’s motion—constitute a single gammaray pulse in a GRB. The cadence of pulses reflects the chaotic accretion and is not predictable, but the individual pulse temporal and spectral properties are (Dar & De Rújula 2001; Dar 2003). In practice, GRBs are observable only if the angle θ subtended by the CB’s velocity vector and the line of sight to the observer is small: 0 = O(1/ρo).

After becoming visible, a CB first cools by bremsstrahlung and expansion. Afterward, its emissivity is dominated by synchrotron emission from the electrons that enter it as it propagates in the ISM. The total AG fluence is proportional to the energy deposition rate of the ISM electrons in the CB. These electrons are Fermi-accelerated in the CB’s tangled magnetic maze to a broken power-law energy distribution with a “bend” energy equal to their incident energy in the CB’s rest frame. Their synchrotron radiation—the AG—is also collimated and Doppler-boosted by the relativistic motion of the CBs. The radiation is also redshifted by the cosmological expansion and attenuated on its way to an earthly observer, during its passage through the CB itself, the host galaxy, the intergalactic space, and our own Galaxy.

4. NIR-OPTICAL AFTERGLOW

In the CB model, the observed AGs have three origins: the ejected CBs, the concomitant SN explosion, and the host galaxy. These components are usually unresolved in the measured “GRB afterglow,” so that the corresponding light curves and spectra are the cumulative energy flux density FAG = FCB + FSN + FIC

The contribution of the host galaxy, FIC, is usually extracted from “very” late time observations, when the CB and SN contributions become negligible, or is best-fitted if such data are not available. Let the energy flux density of SN 1998bw at redshift zb = 0.0085 (Galama et al. 1998) be FSN (r, t). For a similar SN placed at a redshift z (Dar & De Rújula 2000),

F(r, t) = \frac{1 + z}{1 + zb} \frac{D_L(z)}{D_L(z)} F\left(\bar{r}, \bar{t}, \frac{A_{SN}(r, z)}{A_{BN}(\bar{r}, zb)}\right),

where \(\bar{r} = \frac{r}{1 + zb}/(1 + zb), \bar{t} = t/(1 + zb)/(1 + z), A_{SN}(r, z)\) is the attenuation along the line of sight, and \(D_L(z)\) is the luminosity distance (we use a cosmology with Ωm = 0.3, Ωλ = 0.7, and H0 = 65 km s−1 Mpc−1).

In a CB’s rest frame, an observer would see an optical AG,

F_{CB}(r, t) = f[\gamma(t)]^{3/2} \frac{\rho_t}{\nu_b} \frac{(\rho_t/\rho_w)^{-1/2}}{\sqrt{1 + (\rho_t/\rho_w)^{0.62}}},

where f is a normalization constant (see Dado et al. 2003a for its theoretical estimate), \(\gamma(t)\) is the Lorentz factor of the CB, \(p \approx 2.2\) is the spectral index of the radiating electrons in the CB, and \(\nu_b\) is the “injection bend” frequency for an interstellar density \(n_t:\)

\nu_b = 1.87 \times 10^{3}[\gamma(t)]^{1/2} \left(\frac{n_t}{10^{-3} \text{cm}^{-3}}\right)^{1/2} \text{Hz.}

The theoretical motivation, as well as the excellent observational support for this bend, are discussed in Dado et al. (2003a). An observer in the GRB progenitor’s rest system, viewing a CB at an angle θ, sees its radiation Doppler-boosted by a factor δ,

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

where the approximation is valid in the domain of interest for GRBs: large γ and small θ. The CBs’ AG spectral energy density at redshift z seen by a local observer is

F_{CB}^{obs}(r, t) = \frac{A(r, z, t)(1 + z)\delta(t)}{4\pi D_L^2} F_{CB}(\nu', t'),

where \(\nu' = \nu(1 + z)/\delta(t), t' = t/\delta(t)/(1 + z), A(r, z, t)\) is the correction for the total extinction of the CB’s radiation. For an ISM of constant baryon density \(n_b\), the Lorentz factor γ(t) is given by

γ = γ(0, x_r, t); t = B^{-1}(\gamma^2 + C\theta^4 + 1/C),

where x_r = \gamma(0)/C, and \(A_{CB} = (\pi R_{max}^2 n_b)\) characterizes the CB’s slowdown in terms of \(R_{max}\): its baryon number and \(R_{max}\): its asymptotic radius (it takes a distance \(x_r/\gamma_0\) for the CB to halve its original Lorentz factor).

For AGs that are observed very early (those of the GRBs 021211, 990123, 021004, and 030329), the approximation of a constant ISM density, adopted above, is not good, since the CBs are first observed while traveling in the progenitor star’s wind. The total wind grammage is insufficient to make γ(t) deviate from γ0 during the CB’s traversal of the wind. Thus, the only modification is that the constant ISM density \(n_t\) in equations (2) and (3) is replaced by \(n(r) = n_t(1 + r^2/\bar{r}^2)\). These fits have two extra parameters (\(n_t\), which was previously embedded in \(f\) or played a very marginal role via eq. [3], and \(r_0\)). At very early time, \(r \approx c\gamma_0\delta_0/(1 + z) \approx r_0\) and the above circumburst wind profile yields \(F_\nu \propto (1 + \alpha t)^{-\alpha/2}\) (Dado et al. 2003c), where \(\alpha\) is the observer time when \(r = r_0\). This very simple and predictive expression fits very well the data on the early-time behavior of the AGs of GRBs 990123, 021004, 021211, and 030329.

The contribution to \(A(r, z, t)\) in equation (5) from extinction in the host galaxy and in the intergalactic medium can be estimated from the difference between the observed spectral index at very early time, when the CBs are still near the SN, and that expected in the absence of extinction (at early times \(A(r, z, t)\) in eq. [5] equals \(A_{SN}(r, z)\) of eq. [1]). Indeed, the CB model predicts—and the data confirm with precision—the gradual evolution of the effective optical spectral index toward the constant value \(\approx 1\) observed in all “late” AGs (Dado et al. 2002a, 2003a). The late index is independent of the attenuation in the host galaxy, since at \(t > 1\) (observer’s) days after the explosion, the CBs are typically already moving in the low column density, optically transparent halo of the host galaxy.

The comparison in Dado et al. (2002a, 2002b, 2002c, 2003a, 2003b, 2003c) of the predictions of equation (5) with the observations of optical, X-ray, and radio light curves and spectra for all GRBs of known redshift is very simple, satisfactory, and parameter-thrifty.
5. GRB 030329 IN THE CB MODEL

The NIR/optical afterglow.—The gamma-ray light curve of GRB 030329, like that of GRB 021004, shows two prominent pulses (Vanderspek et al. 2003). In the CB model, these two gamma-ray pulses correspond to two dominant CBs. We fit the broadband AG light curves with the additive contributions of two CBs, emitted almost in the same direction but with otherwise independent parameters. We fixed the spectral index $p$ in equation (2) to the theoretically expected $p = 2.2$ (Dado et al. 2003a), assumed a density profile $n(r) = n_0(1 + r^2/r_0^2)$, and fitted simultaneously all the reported NIR, optical, and radio data.

The $R$-band magnitude of an SN akin to 1998bw, displaced to $z = 0.1685$, is $R \sim 20.2$ at peak brightness. Thus, in our fits, we neglect the smaller contribution of the host galaxy, $R > 23.1$ at 2σ confidence level (Blake & Bloom 2003). We have corrected for extinction in our galaxy (Schlegel, Finkbeiner, & Davis 1998): $E(B-V) = 0.025$ in the direction of GRB 030329 and for extinction in the host galaxy as inferred from the early-time AG spectrum, using the extinction curves of Cardelli, Clayton, & Mathis (1989). The resulting attenuation coefficients for the SN contribution are $A(J) = 0.93$, $A(I) = 0.88$, $A(R) = 0.82$, $A(V) = 0.75$, $A(B) = 0.57$, and $A(U) = 0.42$.

In Figure 1, we show the CB model’s fit to data for the NIR-optical light curves reported in the GCN (and referenced explicitly in Dado, Dar, & De Rújula, 2003d). All the observational data were recalibrated to the field photometry of Henden et al. (2003). The individual CBs’ contributions are given by equation (5), which implicitly uses all equations from (2) to (6). The broadband fitted parameters of the two CBs are $\theta(1) = 2.00$ mrad, a nearly identical

$\theta(2) = 1.95$ mrad for the second CB’s direction, $\gamma_0(1) = 1477$, $\gamma_0(2) = 976$ (implying $\delta_0(1) = 306$, $\delta_0(2) = 423$), $x_c(2) = 476$ kpc, and $x_c(2) = 36$ kpc. The density and “wind” parameters are $n_c = 0.86 \times 10^{-2}$ cm$^{-3}$ and $r_0 = 26$ pc, which yield $p_r = 9.3 \times 10^{-13}$ g cm$^{-2}$ for the progenitor wind’s gram-mage, similar to the canonical value for the winds of the parent massive stars of core-collapse SNe (Dado et al. 2003c and references therein). The fact that $\theta(1) = \theta(2)$ strongly supports the CB model: the parameters of one or the other CB are determined by separate data (before and after $\sim 1$ day). The spread of $\theta$ values for other data sets (other GRBs) is much larger.

To demonstrate the real quality of the fit, we have blown up the $R$-band results in Figure 2. In the region between $t \sim 1$ and $\sim 5$ days, the data “wiggle” by as much as 30% around the smoother theoretical curve. It would be easy to correct for this by assuming similar deviations of the ISM density relative to a smooth profile, clearly a moot exercise.

An SN 1998bw–like contribution, as can be seen in Figures 1 and 2, will be observable. Since the contribution of the second CB is still considerable near the peak brightness of the SN (at $t \sim 15$ days) the SN contribution appears as a shoulder in the light curves. Its presence could be established by the change of spectrum from the broadband $F_r \sim r^{-1.1}$ behavior of the CBs’ emission toward the SN 1998bw spectrum (Patat et al. 2001).

Optical polarization.—In the CB model, the intrinsic AG polarization is the weighted sum of the polarizations of the CB’s light and the SN light. Both are small. The polarization of the optical AG is due mainly to the host and Galactic ISMs.

3 See http://space.mit.edu/HETE/Bursts/GRB030329.
It is therefore correlated with the extinction in the host along the line of sight to the moving CBs. As they move at an apparently superluminal speed from the star formation region into the host’s halo, the host contribution disappears in a few observer hours. We estimate it to be of the order of 1%–2% \( [E(B-V) = 0.08 \text{ from the initial spectrum of this AG}] \). The polarization and position angle of the AG’s light then tend to the values measured in the GRB’s direction for the most distant stars in our Galaxy [about 0.3% polarization, since \( E(B-V) = 0.025 \) in this GRB’s direction]. The polarization measured by Patat et al. (2001) for SN 1998bw is \( \sim 0.7\% \), slightly evolving in time, color, and position angle. Modified by its host’s contribution, the polarization of the AG of GRB 030319 should be the same when its SN dominates: after 10–12 days. These predictions differ from the standard ones (Ghisellini & Lazzati 1999; Sari 1999).

6. THE GRB ITSELF

In the CB model, the Doppler-boosting and relativistic collimation of the radiation from a GRB viewed at a small \( \theta \) amplify its fluence by a huge factor \( \delta_0^\gamma \) (Dar & De Rújula 2000):  
\[
F_{\text{GRB}} = (1+z)E_\gamma \delta_0^\gamma / (4\pi D_L^2),
\]
where \( E_\gamma \) is the total energy in photons emitted by the CBs in their rest system. The total “equivalent spherical,” or would-be isotropic energy, \( E^{\text{iso}}_\gamma \), inferred from the observed fluence, is a factor \( (\delta_0^\gamma)^3 \) larger than \( E_\gamma \). In Dado et al. (2002a), we deduced that the \( E_\gamma \) values of the GRBs of known \( z \) span the surprisingly narrow interval, \( 10^{44\pm3} \) ergs, the spread in \( F_{\text{GRB}} \) being due mainly to the spread in their values of \( \delta_0 \) (deduced from the fits to their AGs). For GRB 030329, the CB model fit to its broadband AG yields \( \delta_0^\gamma(1) = 2.86 \times 10^7 \) and \( \delta_0^\gamma(2) = 7.56 \times 10^7 \). The CB model expectation from the fitted AG is \( E^{\text{iso}}_\gamma \approx [\delta_0^\gamma(1)]^3 + [\delta_0^\gamma(2)]^3 E_\gamma \approx 1.04 \times 10^{52\pm3} \) ergs, in agreement with the observed \( E^{\text{iso}}_\gamma \approx 1.1 \times 10^{52} \) ergs, deduced from its measured redshift, \( z = 0.168 \), and fluence in the 30–400 keV band \( \sim 10^{-4} \) ergs cm\(^{-2}\).

7. CONCLUSIONS

SN 2003dh was convincingly detected in the AG spectrum of GRB 030329, with the large (6.5 m) Magellan and Multiple Mirror Telescopes (Stanek et al. 2003) on April 8.13: very close to 10 days after burst, as we have predicted (see Dado et al. 2003d). The (local) spectrum and luminosity of this SN are remarkably similar to those of SN 1998bw, as expected in the CB model. This establishes our advocated association between long-duration GRBs and 1998bw-like standard-candle SNe. Thus, long GRBs can be used to provide the sky position and redshift of cosmological standard-candle core-collapse SNe. Powerful telescopes can then be used to search for the contribution of these SNe to GRB AGs and to measure their intensity and spectrum around peak time. This may add these SNe to the complementary Type Ib standard-candle SNe that have proved to be so useful in cosmology.

This research was supported in part by the Helen Asher Space Research Fund at the Technion. Arnon Dar thanks the Theory Division at CERN for its hospitality.

REFERENCES

Berger, E., et al. 2003, GCN Circ. 2014 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2014.gcn3)
Blake, C., & Bloom, J. S. 2003, GCN Circ. 2011 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2011.gcn3)
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Dado, S., Dar, A., & De Rújula, A. 2002a, A&A, 388, 1079
——.—. 2002b, ApJ, 572, L143
——.—. 2002c, A&A, 393, L25
——.—. 2003a, A&A, 401, 243
——.—. 2003b, ApJ, 585, L15
——.—. 2003c, ApJ, in press (astro-ph/0302429)
——.—. 2003d, preprint (astro-ph/0304106)
Dar, A. 2003, preprint (astro-ph/0301389)
Dar, A., & De Rújula, A. 2000, preprint (astro-ph/0008474)
——.—. 2001, A&A, submitted (astro-ph/0012227)
De Rújula, A. 2002, in New Views on Microquasars, ed. Ph. Durouchoux, Y. Fuchs, & J. Rodriguez (Kolkata: Center for Space Physics), 177
Esin, A. A., & Blandford, R. 2000, ApJ, 534, L151
Galama, T. J., et al. 1998, Nature, 395, 670
Ghisellini, G., & Lazzati, D. 1999, MNRAS, 309, L7
Greiner, J., et al. 2003, GCN Circ. 2020 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2020.gcn3)
Henden, A. A., et al. 2003, GCN Circ. 2082 (http://gcn.gsfc.nasa.gov/gcn/gcn3/2082.gcn3)
Marshall, F. E., & Swank, J. H. 2003, GCN Circ. 1996 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1996.gcn3)
Patat, F., et al. 2001, ApJ, 555, 900
Peterson, B. A., & Price, P. A. 2003, GCN Circ. 1985 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1985.gcn3)
Ramirez-Ruiz, E., Dray, L. M., Madau, P., & Tout, C. A. 2001, MNRAS, 327, 829
Reichart, D. E. 2001, ApJ, 554, 643
Sari, R. 1999, ApJ, 524, L43
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Torii, K. 2003, GCN Circ. 1968 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1968.gcn3)
Vanderspek, V., et al. 2003, GCN Circ. 1997 (http://gcn.gsfc.nasa.gov/gcn/gcn3/1997.gcn3)
Waxman, E. 2003, in Supernovae and Gamma Ray Bursters, ed. K. W. Weiler (Berlin: Springer), 393
Waxman, E., & Draine, B. T. 2000, ApJ, 537, 796