A&A 393, L25–L28 (2002)
DOI: 10.1051/0004-6361:20021167

Astronomy & Astrophysics

Letter to the Editor

The supernova associated with GRB 020405

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Received 26 July 2002 / Accepted 11 August 2002

Abstract. We use the very simple and successful Cannonball (CB) model of gamma ray bursts (GRBs) and their afterglows (AGs) to analyze the observations of the mildly extinct optical AG of the relatively nearby GRB 020405. We show that GRB 020405 was associated with a 1998bw-like supernova (SN) at the GRB's redshift that appeared dimmer and redder than SN1998bw because of extinction in the host and our Galaxy. The case for the SN/GRB association – advocated in the CB model – is becoming indubitable. We discuss the extent to which the GRB/SN connection is model-dependent.

Key words. gamma rays: bursts – supernovae: general

1. Introduction

In the Cannonball Model of GRBs (Dar & De Rújula 2000, briefly reviewed in De Rújula 2002a,b) long duration GRBs are produced by highly relativistic jetted plasmoids (cannonballs) in core-collapse supernovae akin to SN1998bw (Dar & Plaga 1999; Dar 1999a; Dar & De Rújula 2000 and references therein). Possible evidence for an SN1998bw-like contribution to a GRB afterglow (Dar 1999a; Castro-Tirado & Gorosabel 1999) was first reported by Bloom et al. (1999) for GRB 980326, but its unknown redshift prevented a categorical conclusion. The AG of GRB 970228 (at a redshift $z = 0.695$) appears to be overtaken by a light curve akin to that of SN1998bw (at $z_{\rm bw} = 0.0085$), when properly scaled by their differing redshifts (Dar 1999b; Reichart 1999; Galama et al. 2000). Evidence of a similar associations was found for GRB 000418 (Dar & De Rújula 2000; Dado et al. 2002a), GRB 980703 (Holland et al. 2001), GRB 991208 (Castro-Tirado et al. 2001), GRB 990712 (Bjornsson et al. 2001), GRB 970508 (Sokolov et al. 2001), GRB 000911 (Lazzati et al. 2001; Dado et al. 2002b), GRB 010921 (Dado et al. 2002c) and GRB 011121 (Bloom et al. 2002a; Dado et al. 2002d). In the CB model, even the very nearby GRB 980425 and its associated SN (1998bw) are "normal": only the low redshift and relatively large viewing angle are unique (Dar & De Rújula 2000; Dado et al. 2002e).

Unlike supernovae of type Ia (SNe Ia), core-collapse supernovae (SNe II/Ib/Ic) are far from being standard candles. But if their ejecta 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 due to the varying angles from which we see their non-spherically expanding shells. Exploiting this possibility to its extreme, i.e., using SN1998bw as an ansatz standard candle, Dar & De Rújula (2000) and Dado et al. (2002a) have shown that the optical AG of *all* relatively nearby GRBs with known redshift (all GRBs with $z < 1.12$) contain evidence or clear hints for an SN1998bw-like contribution to their optical AG, suggesting that most – and perhaps all – of the long duration GRBs are associated with 1998bw-like supernovae (in the more distant GRBs, the ansatz standard candle could not be seen, and it was not seen). In several of the above cases, however, scarcity of data, lack of spectral information and multicolour photometry and the uncertain extinction in the host galaxy prevented a firm conclusion. Thus, every new instance is still interesting, it might take a few more clear cases to reach a generally accepted conclusion.

On 2002 April 5.028773 UT the long duration (~40 s) GRB 020405 was detected and localized by Ulysses, Mars Odyssey – HEND, and BeppoSAX (Hurley et al. 2002). Its optical AG was first detected in the *R*-band, 17.5 h after the burst (Price et al. 2002a) and its fading was followed in the *I*, *R*, *V* and *B* bands (Castro-Tirado et al. 2002; Palazzi et al. 2002; Hjorth et al. 2002a,b; Price et al. 2002b; Gal-Yam et al. 2002; Covino et al. 2002a,b,c; Bersier et al. 2002). Its redshift, $z = 0.69$, was determined (Masetti et al. 2002; Price et al. 2002c) from emission lines of its likely host galaxy. The optical AG was well fitted by a $t^{-1.72}$ power-law decay, but the late time *R*-band measurements with the Magellanic 6.5 m Baade telescope, on April 18th, and with the 100″ du Pont telescope at Las Campanas, on May 3rd, lie significantly above the power-law extrapolation (Bersier et al. 2002).

The late time AG of GRB 020405 was observed with HST at several epochs spanning 19–31 days after the GRB and, to remove the host contribution, two months after the GRB

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(Price et al. 2002d). An excess of flux was found in the HST images, compared to an extrapolation of the light-curve from early times and was identified as a SN associated with GRB 020405, redder than a SN1998bw displaced to $z = 0.69$, and dimmer than this ansatz by about one half magnitude (Price et al. 2002d).

In this letter we use the Cannonball Model to estimate the extinction in the host galaxy of GRB 020405, and to predict the late time optical AG. We show that the evidence from HST is clear: GRB 020405 was indeed associated with a standard-candle 1998bw-like supernova at $z = 0.69$, appearing somewhat dimmer and redder just because of the extinction in the host galaxy and in ours.

2. The CB model

In the CB model, long-duration GRBs and their AGs are produced in core collapse SNe by jets of highly relativistic "cannonballs" that pierce through the SN shell. Crossing this shell with a large Lorentz factor γ, the surface of a CB is collisionally heated to keV temperatures and the radiation it emits when it reaches the transparent outskirts of the shell – boosted and collimated by the CB's motion – is a single γ-ray pulse in a GRB. The cadence of pulses reflects the chaotic accretion processes and is not predictable, but the individual-pulse temporal and spectral properties are. A long list of general properties (Dar & De Rújula 2001) of GRB pulses is reproduced in the CB-model, in which, unlike in the standard "fireball" models (for a review, see, e.g. Ghisellini 2001) the GRBs' γ's have a thermal – as opposed to synchrotron – origin.

A CB exiting a SN shell soon becomes transparent to its own enclosed radiation. At that point, it is still expanding and cooling adiabatically and by bremsstrahlung. The bremss spectrum is hard and dominates the very early X-ray AG (for a minute or two) with a fluence of predictable magnitude decreasing with time as t^{-5} until synchrotron emission from the ISM electrons that enter the CB takes over. All X-ray AGs are compatible in magnitude and shape with this prediction (Dar & De Rújula 2002a) for the very early AG, for which, as far as we know, there is no standard (fireball-model) counterpart. The optical AGs for which the data also start very early after the GRB show an early decline $\propto t^{-2}$. This initial decline is produced when the CB is plowing through a $\sim r^{-2}$ density-profile of the "wind" from the SN progenitor (Dado et al. 2002a). In the fireball models, the absence of "windy" signatures is a problem: of the score of observed cases, only one has "clear evidence for a wind-fed circumburst medium" (Price et al. 2002).

In the CB model the AGs observed at later times have 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 $F_{\rm AG} = F_{\rm CBs} + F_{\rm SN} + F_{\rm HG}$. The contribution of the host galaxy (HG) is usually determined by late time observations when the CB and SN contributions become negligible.

Let the energy flux density of SN1998bw at redshift $z_{\rm bw} = 0.0085$ (Galama et al. 1998) be $F_{\rm bw}[\nu, t]$. For a similar SN placed at a redshift z:

$$F_{\rm SN}[\nu,t] = \frac{1+z}{1+z_{\rm bw}}\,\frac{D_{\rm L}^2(z_{\rm bw})}{D_{\rm L}^2(z)} \times F_{\rm bw}\left[\nu\,\frac{1+z}{1+z_{\rm bw}},\; t\,\frac{1+z_{\rm bw}}{1+z}\right] A(\nu,z)\,, \quad (1)$$

where $A(\nu, z)$ is the attenuation along the line of sight and $D_{\rm L}(z)$ is the luminosity distance (we use a cosmology with $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65$ km s^{-1} Mpc^{-1}).

In its rest frame the optical AG of a CB is given by:

$$F_{\rm CB}[\nu,t] = \frac{f\,[\gamma(t)]^2}{\nu_{\rm b}}\,\frac{[\nu/\nu_{\rm b}]^{-1/2}}{\sqrt{1+[\nu/\nu_{\rm b}]^{(p-1)}}}\,, \quad (2)$$

where f is a normalization constant (see Dado et al. 2002e 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 $\nu_{\rm b}$ is the "injection bend" frequency. For an interstellar density $n_{\rm p}$:

$$\nu_{\rm b} \simeq 1.87\times10^3\,[\gamma(t)]^3\left[\frac{n_{\rm p}}{10^{-3}\ {\rm cm}^3}\right]^{1/2}\ {\rm Hz}. \quad (3)$$

The theoretical motivation, as well as the excellent observational support for this "bend", are discussed in Dado et al. (2002e). 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:

$$\delta(t) \equiv \frac{1}{\gamma(t)\,(1-\beta(t)\cos\theta)} \simeq \frac{2\,\gamma(t)}{1+\theta^2\gamma(t)^2}\,, \quad (4)$$

where the approximation is valid in the domain of interest for GRBs: large γ and small θ. The cannonballs' AG spectral energy density $F_{\rm CB}^{\rm obs}$ seen by a cosmological observer at a redshift z (Dar & De Rújula 2000), is:

$$F_{\rm CB}^{\rm obs}[\nu,t] \simeq \frac{A(\nu,z)\,(1+z)\,\delta(t)^3}{4\,\pi\,D_{\rm L}^2}\,F_{\rm CB}\left[\frac{(1+z)\,\nu}{\delta(t)},\,\frac{\delta(t)\,t}{1+z}\right]. \quad (5)$$

For an interstellar medium of constant baryon density $n_{\rm p}$, the Lorentz factor $\gamma(t)$ is given by (Dado et al. 2002a):

$$\gamma = \gamma(\gamma_0,\theta,x_\infty;t) = B^{-1}\left[\theta^2 + C\,\theta^4 + 1/C\right]$$
$$C \equiv \left[2/\left(B^2 + 2\,\theta^6 + B\,\sqrt{B^2+4\,\theta^6}\right)\right]^{1/3}$$
$$B \equiv 1/\gamma_0^3 + 3\,\theta^2/\gamma_0 + 6\,c\,t/\left[(1+z)\,x_\infty\right] \quad (6)$$

where $\gamma_0 = \gamma(0)$, and $x_\infty \equiv N_{\rm CB}/(\pi\,R_{\rm max}^2\,n_{\rm p})$ characterizes the CB's slow-down in terms of $N_{\rm CB}$: its baryon number, and $R_{\rm max}$: its radius (it takes a distance x_∞/γ_0 for the CB to half its original Lorentz factor).

The selective extinction, $A(\nu, t)$ in Eq. (1), 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. Indeed, the CB model predicts – and the data confirm with precision – the gradual evolution of the effective optical spectral index towards the constant value ≈−1.1 observed in all "late" AGs (Dado et al. 2002a). 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 of the predictions of Eq. (5) with the observations of optical and X-ray AG light curves and of broad-band spectra is discussed in Dado et al. (2002a and 2002e, respectively). The results – for *all* GRBs of known redshift – involve a total of only five parameters, and are very satisfactory. The CB-model results concerning X-ray lines in GRB AGs are also exceptionally predictive, simple and encouraging (Dado et al. 2002f).

3. GRB 020405 in the CB model

We have first fitted the CB-model predictions to the *B*, *V*, *R* and *I* light curves of the AG of GRB 020405, as observed during the first 5 days after burst. In using Eq. (2), we assumed an electron spectral index $p = 2.2$, compatible with that of all other GRB AGs (Dado et al. 2002a). The fitted parameters are: $\gamma_0 = 645$, $\theta = 0.42$ mrad, and $x_\infty = 0.31$ Mpc. After correcting for selective extinction in our Galaxy ($E(B-V) = 0.054$ mag towards GRB 020405; Schlegel et al. 1998), Bersier et al. (2002) found that the broad band *BVRI* spectrum of the AG, 1.3 days after the burst, had a spectral shape $F_{\rm obs} \sim \nu^{-1.43\pm0.08}$. In the CB model, the unextinct spectral index in optical and nearby frequencies evolves from ∼−0.5 to ∼−1.1, as the injection bend frequency of Eq. (3) diminishes with time. At the time of these observations, our fit to the AG time-evolution results in a predicted index -0.8 ± 0.1. If the difference with the observed index is due to selective extinction in the host galaxy, then $E(B-V) = 0.24 \pm 0.05$ and the attenuation factors in the *I*, *R*, *V* and *B* bands (e.g., Whittet 1992) are, respectively, $A(\nu, z) \sim 0.58, 0.50, 0.42$ and 0.34. These attenuations, together with the Galactic extinction, were used to dim the contribution to the AG of a SN1998bw-like supernova at the redshift of GRB 020405. The resulting late-time *I*, *R*, *V* and *B* light curves are presented in Fig. 1.

The agreement between theory and observations in Fig. 1 is surprisingly good, in view of the large observational uncertainties and the theoretical approximations. The presence of an SN1998bw-like signal is completely convincing. With our consistent estimate of extinction in the host galaxy, the underlying SN is indistinguishable, within errors, from a standard candle SN1998bw.

4. The GRB/SN association in various models

In the CB model, GRBs are associated with SNe. The model is so simple and predictive that it allowed us to use, in the case of GRB 011121, the first 2 days of *R*-band data to fit the parameters describing the CBs' contribution to the AG. These fitted parameters were used to predict explicitly the AG evolution and that *the SN will tower in all bands over the CB's declining light curve at day ∼30 after burst* (Dado et al. 2001). The comparison with the data, gathered later, vindicated the presence of a SN1998bw-like signal (Dado et al. 2002d), as in GRB 020405 and all the other cases for which the SN was, in practice, detectable (Dado et al. 2002a). To what extent is the GRB/SN association model-dependent?

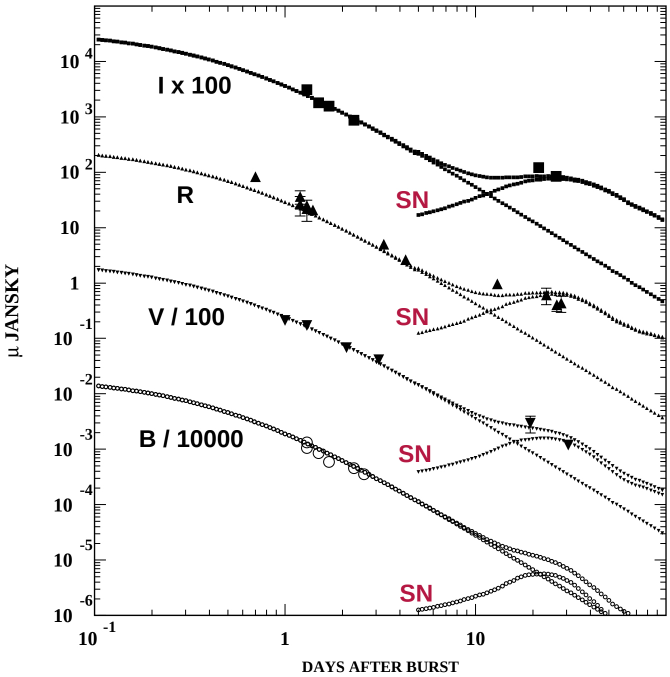

Fig. 1. CB model fit to the measured *I*, *R*, *V*, and *B*-band AG of GRB 020405, multiplied by 100, 1, 1/100, 1/10000, respectively. The observations are not corrected to eliminate the effect of extinction, thus the theoretical contribution from a SN1998bw-like supernova, Eq. (1), was dimmed by the known extinction in the Galaxy and our consistently estimated extinction in the host. The contribution of the host galaxy, subtracted from the data by the HST observers, is not included in the fit.

There are other models that link long-duration GRBs with SN explosions: the hypernova model (Paczynski 1998), the collapsar model (Woosley 1993) the supranova model (Vietri & Stella 1998) and the currently favoured conical jet models (see, e.g. Rossi et al. 2002; Zhang & Meszaros 2002; Salmonson & Galama 2002; Granot et al. 2002), in which the authors depart from the earlier view that it is a good approximation (Rhoades 1999) to consider conical jets of various *opening* angles, pointing exactly to the observer, and having a uniform Lorentz factor (in the CB model the *viewing* angle is the *only one* that matters, and there is no need to introduce "jet profiles" of varying rapidity). A common feature of all these models is that they are not sufficiently specific to repeat the CB-model exercise of the previous paragraph. In the jetted models, for instance, the AGs (unlike the smoothly-varying data) have "breaks". The early data on GRB 011121 do not tell where the break "is": they cannot be extrapolated.

In the CB model, the exceptionally close-by GRB 980425 ($z = 0.0085$) and its associated SN1998bw are not intrinsically exceptional. Because it was viewed at an exceptionally large angle (∼8 mrad), the GRB's γ-ray fluence was comparable to that of more distant ones, viewed at $\theta \sim 1$ mrad. That is why its optical AG was dominated by the SN, except, perhaps, for the last measured point (Dar & De Rújula 2000). The X-ray AG is also of "normal" magnitude, it is not emitted by the SN; its fitted parameters allowed us to predict successfully the magnitude of the cited last optical point (Dado et al. 2002a). The normalization, time and frequency dependence of the radio AG of this GRB are also "normal", and due to the CB, not the SN (Dado et al. 2002e). SN1998bw, deprived of its "abnormal" X-ray and radio emissions (which it did not emit!), loses most of its "peculiarity". Given that GRB 980425 and SN 1998bw are not exceptional, the use of this SN as a standard candle to look for in other AGs (Dar 1999b) is, in the CB model, entirely natural. The surprise is how well this ansatz works (Dado et al. 2002a).

In the hypernova and collapsar models the parent star is supposed to be exceptionally massive. In the supranova model, it must have exploded months before the GRB emission. Moreover, in these models, and in the currently favoured jetted models, GRB 980425 stands in a class by itself. Thus, there is every reason not to expect its associated SN (1998bw) to be similar to the SNe associated with other GRBs. In the CB model – and in the data – the opposite is true.

5. Conclusion

In Dar & De Rújula (2000) we argued that long-duration GRBs may all be associated with 1998bw-like supernovae, and that the apparent variability of core-collapse SNe may to a large extent be due to a spread of viewing angles, relative to the CB-emission axis. In Dado et al. (2002a) 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 – GRB 000911 (Dado et al. 2002b), GRB 010921 (Dado et al. 2002c), GRB 011121 (Dado et al. 2002d) and GRB 020405, discussed here – strengthen the conclusion: so far, in all AGs in which a SN like SN1998bw could be seen (in practice, in the cases with redshift $z < 1.12$), it was seen, and it was compatible in magnitude and colour with an SN1998bw 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 deviations. But the important fact is that the SN1998bw-like supernovae allegedly associated with all long-duration GRBs (Dado et al. 2002a, and references therein) happen to be there.

Acknowledgements. This research was supported in part by the Helen Asher Space Research Fund and by the VPR fund for research at the Technion. We thank the referee Brian McBreen for useful suggestions.

References

Bersier, D., et al. 2002 [astro-ph/0206465]
Bjornsson, G., et al. 2001, ApJ, 552, 121L
Bloom, J. S., et al. 1999, Nature, 401, 452
Bloom, J. S., et al. 2002, ApJ, 572, L45
Castro-Tirado, A. J., & Gorosabel, J. 1999, A&AS, 138(3), 449
Castro-Tirado, A. J., et al. 2002, GCN. Circ., 1327
Covino, S., et al. 2002a, GCN. Circ., 1337
Covino, S., et al. 2002b, GCN. Circ., 1345
Covino, S., et al. 2002c, GCN. Circ., 1431
Dado, S., Dar, A., & De Rújula, A. 2001 [astro-ph/0111468]
Dado, S., Dar, A., & De Rújula, A. 2002a, A&A, 388, 1079
Dado, S., Dar, A., & De Rújula, A. 2002b, in preparation
Dado, S., Dar, A., & De Rújula, A. 2002c [astro-ph/0203315]
Dado, S., Dar, A., & De Rújula, A. 2002d, ApJ, 572, L143
Dado S., Dar, A., & De Rújula, A. 2002e [astro-ph/0204474]
Dado, S., Dar, A., & De Rújula, A. 2002f [astro-ph/0207015]
Dar, A. 1999a, A&AS, 138, 505
Dar, A. 1999b, GCN Circ., 346
Dar, A., & De Rújula, A. 2000 [astro-ph/0008474]
Dar, A., & De Rújula, A. 2001 [astro-ph/0012227]
Dar, A., & Plaga, R. 1999, A&A, 349, 259
De Rújula, A. 2002a [astro-ph/0201210]
De Rújula, A. 2002b [astro-ph/0207033]
Gal-Yam, A., et al. 2002, GCN Circ., 1335
Galama, T. J., et al. 1998, Nature, 395, 670
Galama, T. J., et al. 2000, ApJ, 536 185
Ghisellini, G. 2001 [astro-ph/0111584]
Granot, J., et al. 2002, ApJ, 570, L61
Hjorth, J., et al. 2002a, GCN Circ., 1329
Hjorth, J., et al. 2002b, GCN Circ., 1336
Holland, S., et al. 2001, A&A, 371, 52
Hurley, K., et al. 2002, GCN Circ., 1325
Lazzati, D., et al. 2001, A&A, 378, 996
Masetti, N., et al. 2002, GCN Circ., 1330
Palazzi, E., et al. 2002, GCN Circ., 1328
Paczynski, B. 1998, ApJ, 494, L45
Price, P. A. et al. 2002 [astro-ph/0203467]
Price, P. A., et al. 2002a, GCN Circ., 1326
Price, P. A., et al. 2002b, GCN Circ., 1333
Price, P. A., et al. 2002c, GCN Circ., 1340
Price, P. A., et al. 2002d, GCN Circ., 1458
Reichart, D. E. 1999, ApJ, 521, L111
Rhoades, J. E. 1999, ApJ, 525, 737
Rossi, E., Lazzati, D., & Rees, M. J. 2002, MNRAS, 332, 945
Salmonson, J. D., & Galama, T. J. [astro-ph/0112298]
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sokolov, V. V., et al. 2001a [astro-ph/0102492]
Vietri, M., & Stella, L. 1998, ApJ, 507, L45
Whittet, D. C. B. 1992, Dust in the Galactic Environment, IOP Pub. Ltd 1992, 65
Woosley, S. E. 1993, ApJ, 405, 273
Zhang, B., & Meszaros, P. 2002, ApJ, 571, 876