A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
06; 19.63.1

ASTRONOMY AND ASTROPHYSICS
July 25, 2002

The supernova associated with GRB 020405

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the date of receipt and acceptance should be inserted later

Abstract. We used 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, first made with ground-based telescopes, and with the HST at later times. We show that GRB 020405 was associated with a 1998bw-like supernova (SN) at the GRB's redshift which appeared dimmer and red relative to 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.

Key words: gamma rays: bursts—supernovae: general

1. Introduction

In the Cannonball Model of GRBs (Dar and 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 and Plaga 1999; Dar 1999a; Dar and 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 and De Rújula 2000; Dado et al. 2002a), GRB 980703 (Holland et al. 2000), 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 and 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 and 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 hours after the burst (Price et al. 2002a) and its fading behaviour was followed in the I, R, V and B bands (Castro-Tirado et al. 2002; Palazzi et al. 1328; Hjorth et al. 2002a; Price et al. 2002b; Gal-Yam et al. 2002; Hjorth 2002b; Covino et al. 2002a; Covino et al. 2002b; Covino et al. 2002c; 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 temporal decay of its optical AG was well fitted by a $t^{-1.72}$ power-law, but the late time R-band measurements with the Magellanic 6.5m Baade telescope, on April 18th, and with the 100" du Pont telescope at Las Campanas, on May 3rd, appear to be significantly above the power-law extrapolation from early times (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 (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 supernovae by jets of highly relativistic "cannonballs" that pierce through the supernova shell. The AG 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 $F_{AG} = F_{CBs} + F_{SN} + F_{HG}$. 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 $z_{bw} = 0.0085$ (Galama et al. 1998) be $F_{bw}[\nu, t]$. For a similar SN placed at a redshift z:

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

where $A(\nu, z)$ is the attenuation along the line of sight and $D_L(z)$ is the luminosity distance (we use a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65$ km/s/Mpc).

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

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

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 ν_b is the "injection bend" frequency (Dado et al. 2002e). For an interstellar density n_p:

$$\nu_b \simeq 1.87\times10^3\,[\gamma(t)]^3\,\left[\frac{n_p}{10^{-3}\,\mathrm{cm}^3}\right]^{1/2}\,\mathrm{Hz}. \qquad (3)$$

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:

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

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

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

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

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

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

The selective extinction, $A(\nu, z)$ 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.

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 rest of 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 along the line of sight to 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 $F_{obs} \sim \nu^{-1.43\pm0.08}$. In the CB model, the unextinct spectral index in optical and neighbouring frequencies is expected to evolve from ∼ 0.5 to ∼ 1.1, as the injection bend frequency of Eq. (3) diminishes with time. At the time of the quoted observations, our CB-model fit to the AG time-dependence 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 $E(B-V) = 0.20 \pm 0.05$. Together with the Galactic extinction the corresponding attenuation factors in the I, R, V and B bands (e.g., Whittet 1992) are, respectively,

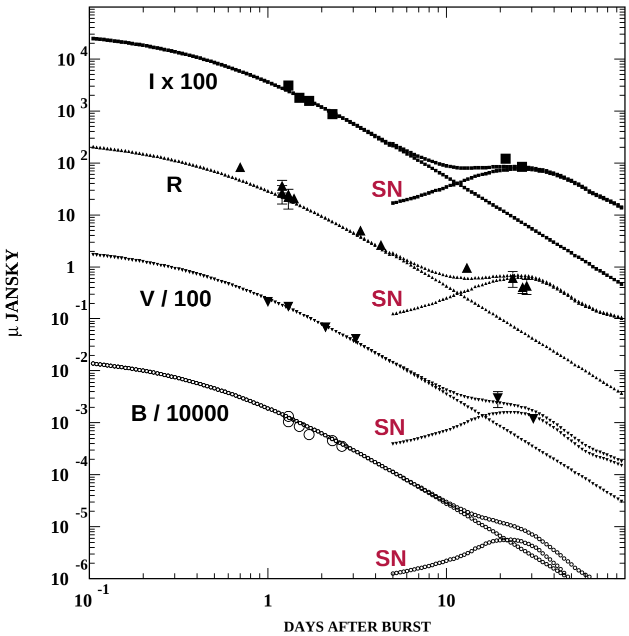

Fig. 1. CB model fit to the measured I, R, V, and B-band AG of GRB 020405, multiplied by 100, 1, 1/100, 1/10000, respectively. The observations are not corrected to eliminate the effect of extinction, thus the theoretical contribution from a SN1998bw-like supernova, Eq. (1), was dimmed by the known extinction 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.

$A(\nu, z) \sim 0.57\,, 0.50\,, 0.45$ and 0.39. These attenuation factors, were used to dim the expected 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. Conclusion

In Dar and 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 optical AGs of the 4 GRBs with $z < 1$ 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**.

Acknowledgment: This research was supported in part by the Helen Asher Space Research Fund and by the VPR fund for research at the Technion.

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