IS THE AFTERGLOW OF GAMMA-RAY BURST GRB 021004 UNUSUAL?
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ABSTRACT
The afterglow (AG) of gamma-ray burst GRB 021004 has been claimed to be unusual. In the cannonball (CB) model of GRBs, that is not the case. The very early AG’s shape is, like for GRB 990123, a direct tracer of the expected circumburst density profile. The unprecedented precision of the data allows for the “resolution” of two CBs in the AG. These two CBs correspond to the two pulses in the GRB and to the two wide shoulders in the AG light curve. The smaller wiggles in the AG are, like for GRB 000301c and for GRB 970508, to be expected: they trace moderate deviations from a constant density interstellar medium. The observed evolution of the optical spectrum is that predicted in the CB model. The X-ray and radio emissions of GRB 021004 are also normal.

Subject heading: gamma rays: bursts

1. INTRODUCTION
The bright optical afterglow (AG) of the gamma-ray burst GRB 021004 (Shirasaki et al. 2002), which was discovered (Fox et al. 2002) 9 minutes after the burst, allowed precise measurements to be made of its temporal decline, polarization, and spectral evolution. The redshift of its host galaxy, \( z = 2.33 \), was first determined by Chornock & Filippenko (2002). Its optical AG, shown in Figures 1 and 2, deviates from the smooth decline observed in most optical AGs. There are also “unexpected” features in its spectrum (e.g., Salamanca et al. 2002) and in its evolution (e.g., Matheson et al. 2002). Its radio AG was also claimed to be “unusual” (Berger et al. 2002a, 2002b).

Here we show that in the cannonball (CB) model, the only uncommon feature of GRB 021004 is the precision of the measurements. Most of its “surprising” properties were anticipated, in the sense that there are, again in the CB model, precedents for all of them in past GRBs.

2. THE CB MODEL OF GRBs
In the CB model (Dar & De Rújula 2000, 2001; Dado, Dar, & De Rújula 2002a, 2002b, 2002c, 2002d; reviewed in De Rújula 2002a, 2002b), long-duration GRBs and their AGs are produced in core-collapse supernovae akin to SN 1998bw by the ejection of a jet of ordinary hydrogenic plasma clouds or “cannonballs” with high Lorentz factors (\( \gamma \approx 10^3 \)). A CB is emitted, as observed in \( \mu \)-quasars, when part of an accretion disk falls abruptly onto the newly born compact central object. Crossing the circumburst shells with a large \( \gamma \), the surface of a CB is collisionally heated to keV temperatures, and the thermal radiation it emits as it reaches the transparent outskirts of the shells—boosted and collimated by the CB’s motion—is a single \( \gamma \)-ray 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)

After becoming visible, a CB first cools by bremsstrahlung and expansion. When its temperature approaches \( \sim 1 \) eV (within a few observer minutes), its emissivity is dominated by synchrotron emission from the electrons that penetrate it as it propagates in the interstellar medium (ISM). Integrated over frequency, this synchrotron emissivity 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. In that frame, the electrons’ synchrotron emission (prior to attenuation corrections) has a spectral energy density (Dado et al. 2002b):

\[
F_{\text{CB}}(\nu, t) = f_0 \frac{(p - 2)\gamma^2 n_e m_e c^3 (\nu/\nu_\text{inj})^{-1/2}}{(p - 1)\nu_\text{inj}^{-1} + (\nu/\nu_p)^{-p-1}},
\]

where \( f_0 \) is a normalization constant, \( p \approx 2.2 \) is the spectral index of the Fermi-accelerated electrons prior to the inclusion of radiation losses, \( n_e \) is the ISM baryon density, \( \gamma \) is the Lorentz factor of the CBs, and \( \nu_p \) is the “injection bend” frequency in the CB’s rest frame. It reflects an injection bend in the electron spectrum at the energy \( E_p(\gamma) = \gamma(t_0) m_e c^2 \) with which the ISM electrons enter the CB in its decelerated motion (Dado et al. 2002b):

\[
\nu_p = 1.9 \times 10^4 [\gamma(t)]^{1/2} \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right)^{1/2} \text{ Hz}.
\]

The CB’s radiation is Doppler-shifted and forward-collimated by its relativistic motion and redshifted by the cosmological expansion. A distant observer sees a spectral energy flux:

\[
F_{\text{obs}}(\nu, t) = \frac{(1 + z)^2 \delta(t)}{D_L^2} \frac{\nu}{\nu_p} F_{\text{CB}}(\nu', t'),
\]

where \( R \) is the radius of the CB (which, in the CB model, tends toward a calculable constant value \( R_{\text{max}} \) of \( (10^{14}) \) cm, in minutes of observer’s time), \( A(\nu, t) \) is the total extinction along the line of sight to the CB, \( D_L(z) \) is the luminosity distance [we adopt \( H_0 = 65 \) km (s Mpc)]\(^{-1}, \Omega_M = 0.3, \) and \( \Omega_L = 0.7 \), \( \nu' = (1 + z)\nu/\delta(t), \) \( t' = \delta(t)/(1 + z), \) and \( \delta(t) \approx 2\gamma(t)/(1 + \theta^2 \gamma(t)^2), \) with \( \theta \) being the angle between the CB’s direction of motion and the line of sight to the observer [the approximation to \( \delta(t) \) is valid for \( \gamma^2 \gg 1 \) and \( \theta^2 \ll 1 \), the domain of interest for GRBs]. The total AG is the sum over CBs (or large individual GRB pulses) of the flux of equation (3).
For an ISM of constant baryon density $n_p$, the deceleration of a CB results in a Lorentz factor, $\gamma(t)$, that satisfies (Dado et al. 2002a)

$$\frac{1}{\gamma} - \frac{1}{\gamma_0} + 3\beta^2 \left( \frac{1}{\gamma} - \frac{1}{\gamma_0} \right) = \frac{6ct}{(1+z)x_p}, \tag{4}$$

where $\gamma_0 = \gamma(0)$, and $x_p = N_{\text{CB}}/\pi R_{\text{max}}^2 n_p$ characterizes the CB's slowdown in terms of its baryon number $N_{\text{CB}}$ and its radius $R_{\text{max}}$.

The extinction, $A(\nu, t)$ in equation (3), can be estimated from the difference between the observed spectral index at very early times when the CBs are near the supernova and that expected in the absence of extinction ($F_{\text{obs}} \propto \nu^{-\alpha}$, for $\nu \ll \nu_c$). The CB model predicts, and the data seem to support, a gradual evolution of the AG’s optical spectral index in the host toward $\sim -1.1$, in all “late” AGs (Dado et al. 2002b) when the CBs are approaching the optically transparent halo of the host galaxy.

The comparison in Dado et al. (2002a, 2002b) of the predictions of equation (3) with the observations of optical, X-ray, and radio light curves and spectra for all GRBs of known redshift are very simple, satisfactory, and “parameter-thrifty.”

3. GRB 021004 IN THE CB MODEL

Five properties of AGs in the CB model are particularly relevant to GRB 021004: (1) The optical AG at very early times, when the CBs are still moving in a wind-generated density profile proportional to $1/r^2$, is proportional to the instantaneous swept-in electron density, implying an early $F_{\text{obs}} \propto 1/t^2$, as observed in GRB 990123 and GRB 021211 (Chornock et al. 2002). (2) The achromatic “bumps” in the AGs of GRB 970508 and GRB 000301c are explained (Dado et al. 2002a, 2002b) by inhomogeneities in the density along the CBs’ trajectory. (3) The data on past AGs were course enough or started late enough for the contributions of different CBs (which can often be resolved as individual pulses in the GRB phase) to coalesce into an AG describable by a single CB or a collection of similar ones. But individual CBs have different properties and may even be emitted at somewhat different angles because of the precession of the accretion disk, as observed in the microquasar SS 433 (Margon 1984). (4) The predicted AG spectra and their evolution, in particular the steepening at the time-varying frequency $\nu_c(t)$ of equation (2), are very well supported by the data (Dado et al. 2002b). (5) The excess polarization of AGs above that induced by the ISM in our Galaxy may be largely due to the host galaxy’s ISM. In that case, it should be correlated with the extinction in the host and should decline with time as the CBs move into the halo.

The $\gamma$-ray light curve of GRB 021004 shows two prominent pulses separated by $\sim 30$ s (Shirasaki et al. 2002).\(^3\) In the CB model, these correspond to two dominant CBs. The good quality of the optical data for GRB 021004—and its double-humped $\gamma$ burst—make irresistible the temptation to fit its broadband AG light curves with two CBs, emitted in the same direction\(^4\) but with otherwise free parameters (normalization, $\gamma_0$, and $x_p$). We fix the spectral index $\beta$ in equation (1) to the expected $\beta = 2.2$, assume a density profile of the form $n(r) = n_p [(r/r_p)^3 + 1]$, and fit simultaneously all the reported near-infrared (NIR), optical, and radio data.

\(^3\) See http://space.mit.edu/HETE/Bursts/GRB021004.

\(^4\) We have also made fits with two different values of the emission angles $\theta$. They do not improve $\gamma$ significantly and yield similar parameters: two different emission angles are not really necessary.
NIR-optical AG.—In Figure 1, we show the CB model’s fit to the data for the NIR-optical light curves. We have corrected for selective Galactic extinction in the direction of GRB 021004 (Schlegel, Finkbeiner, & Davis 1998): \( E(B-V) = 0.06 \) (attenuation magnitudes \( A_V = 0.33, A_R = 0.26, A_V = 0.20, A_R = 0.16, A_I = 0.12, A_J = 0.08, A_{160} = 0.04, \) and \( A_{24} = 0.01 \) in the various bands) and for absorption in intergalactic space and in the host galaxy in the \( B \) and \( U \) bands, \( A_B = 0.25 \) and \( A_U = 0.50 \) mag, estimated from the reported spectra of GRB 021004 (Moller et al. 2002; Matheson et al. 2002; Bersier et al. 2002; Holland et al. 2002). The contribution from the host galaxy normalized to \( B \)-Sersic et al. 2002; Holland et al. 2002). The contribution from the host galaxy normalized to \( B \)-Sersic et al. 2002; Holland et al. 2002). The contribution from the host galaxy normalized to 0.66 ± 0.33 \( \mu \)Jy in the \( R \) band (Holland et al. 2002) was subtracted. The results are very satisfactory, although, as befits a rough approximation to a non-doubt very complex system, they are not perfect (\( \chi^2 \) per degree of freedom for 465 data points, if all reported errors <0.05 mag are fixed to 0.05 mag, to account for uncertainties in calibration and in the conversion from magnitudes to janskys). The broadband fitted parameters are \( \theta = 1.47 \) mrad, \( \gamma_0 = 1403, \gamma_0(2) = 1259 \) [implying \( \delta(1) = 542 \) and \( \delta(2) = 576], x_0 = 25 \) kpc, and \( x_0 = 620 \) kpc. To demonstrate the “early” quality of the fit, we have blown up the \( R \)-band results in Figure 2. In the region between \( \sim 0.5 \) and \( \sim 5 \) days, the data “wiggle” by as much as 20% around the theoretical curve. It would be easy to correct for this by assuming similar deviations of the ISM density relative to the constant value adopted at large distances, clearly a moot exercise.

Optical polarization.—The polarization of the optical AG of GRB 021004, which is consistent with that induced by the ISM in our Galaxy (Covino et al. 2002a, 2002b; Rol et al. 2002; Wang et al. 2002), implies that the polarization induced by the host’s ISM is small; i.e., the attenuation of the AG in the host must be small, consistent with our fit to the AG.

X-ray AG.—The Chandra observations by Sako et al. (2002) in the 2–10 keV domain, from 0.867 to 1.874 days after burst, result in a spectrum \( d\nu dE \propto E^{-2.5 \pm 0.1} \), and a decline \( d\nu dt \propto \nu^{-1.0 \pm 0.2} \) both consistent with the optical data and with the CB model’s expectations: \( d\nu dE \propto E^{-2.1} \) and, except at earlier times, an achromatic light curve. In this GRB, as in most others, the temporal and spectral behaviors are similar in the optical and X-ray bands, but synchrotron emission understimates the X-ray fluence. The CB model explanation is that in the X-ray domain, Compton upscattering and line emission also contribute to the flux (Dado et al. 2002a, 2002b). The X-ray data for GRB 021004 are not exceptional.

Radio and submillimeter AG.—Figure 3 is the CB model’s broadband fit to these data. Unlike the X-ray and optical AGs, the radio AGs are sensitive to self-absorption in the CBs, parameterized by a single absorption frequency \( \nu_a \) (Dado et al. 2002b). The fit value for the CB that dominates the “late” radio AG is \( \nu_a(2) = 0.98 \) GHz, similar to those of other GRBs (Dado et al. 2002b). The fit in Figure 3 is very satisfactory, in particular in view of expected scintillations in the radio data. The CB model is seen to correctly predict the early temporal increase (to be followed by a later turnover due to self-absorption) and the spectral behavior \( (F \nu \sim \nu^{-1.3 \pm 0.1} \) between 1.43 and 86 GHz, observed around 5 days after the burst), again akin to those of other GRBs such as 991208, 000926 and 000301c.

The GRB proper.—In the CB model (Dar & De Rújula 2000), the rest-frame fluence of a CB viewed at a small \( \theta \) is amplified by a huge factor, \( \delta_0 \), because of the Doppler boost and relativistic beaming of the radiation (Shaviv & Dar 1995). In Dado et al. (2002a), we deduced that the GRB photons of the GRBs of known redshift correspond to a total energy release in the CBs’ rest system that is in a surprisingly narrow interval,\(^5\) \( 10^{44} \pm 0.3 \) ergs, and that the spread in the “equivalent spherical energies” \( E \), around their mean, \( E \approx 4 \times 10^{43} \) ergs, is mainly due to the spread of their Doppler factors (deduced from the fits to their AGs) around their mean: \( \delta_0 \approx 1100 \). For GRB 021004, \( \delta_0 \approx 550 \), and the CB model expectation is \( E \approx E_0(\delta_0/\delta_0) \approx 5 \times 10^{43} \) ergs, in agreement with that observed, \( 4 \times 10^{42} \) ergs (we have corrected the value of Lamb et al. 2002 to a redshift \( z = 2.335 \), from their adopted \( z = 1.6 \)). The GRB of GRB 021004 is also entirely normal.

Spectral variability.—The optical spectra of GRBs typically steepen in the first few days, as the bend frequency in the observer’s frame \( \nu_b^{obs}(t) = \nu_b(t)/(1+z) \) “crosses” the optical band (Dado et al. 2002b). Let \( \lambda_b^{obs}(t) = c/\nu_b^{obs}(t) \). Given the parameters of our fit to the optical AG, we can predict, by use of equation (1), the spectral energy density \( F_b \) as a function of the ISM density \( n_p \). The two CBs of GRB 021004 have similar \( \gamma_0 \) and \( \delta_0 \) but different \( x_c \): their time evolution and injection bends are different. The AG is dominated before and after \( \sim 0.5 \) days by one or the other CB, whose properties determine the “early” or “late” spectral evolution. The predictions for the spectral ratio at the “late” times \( (t = 0.756 \) days and \( t_2 = 2.786 \) days) measured by Matheson et al. (2002) are shown in Figure 4. The upper panel is for \( n_p = 0.0018 \) cm\(^{-3} \), the density predicted from \( x_c(2) \) using the CB model reference values \((N_b = 6 \times 10^{16} \) and \( R_{max} = 2 \times 10^{14} \) cm; Dado et al. 2000a, 2000b). For this \( n_p = \lambda_b^{obs}(t_1) = 3140 \) Å, and \( \lambda_b^{obs}(t_2) = 8940 \) Å.

The spectral transition from \( \nu \ll \nu_b \rightarrow \nu_b \gg \nu_b \) could be more abrupt than in equation (1). In the lower panel of Figure 4, we illustrate the result for a sharp transition, for which, with

\(^5\) GRBs in the CB model are much better standard candles than in the standard model (Frail et al. 2001).
The smooth line in the upper panel is the smoothing procedure; the error in the plotted magnitude difference is estimated. The wiggles on the curve extracted from observations are artifacts of the smoothing process, with the ISM density extracted from the observed $x(2)$. The smooth line in the lower panel illustrates an abrupt injection bend at $A_\lambda \sim 5500$ Å.

4. CONCLUSIONS

The CB model’s interpretation of the light curves and wideband spectrum of GRB 021004 is quite simple and very successful. The main novelty is that, relative to other GRB AGs, the optical data start very early and are so copious that a single CB would not fare well in explaining the light curves. Two large pulses are observed in the GRB’s γ-ray light curve, enticing one to fit the AG with two CB contributions. The results are excellent and do not require ad hoc assumptions about the circumburst ISM density: GRB 021004 fits naturally along all other GRBs of known redshift.

The standard explanations of the AG of GRB 021004 (Lazzati et al. 2002; Nakar, Piran, & Granot 2002; Heyl & Perna 2002) require model-dependent inversions of the observed light curves to obtain the ISM-density or energy-supply profile and the extinction in the host in order to “predict” the light curves at different frequencies. The various quoted authors, using the same model, extract very different input functions.

For a nonconstant ISM density, short-time spectral variations and AG features are expected in the CB model because of the local instantaneous dependence of $F$ and $v_b$ on the density (see eqs. [1] and [2]). These would explain the $\Omega(20%)$ oscillations of the data around our two-CB fit and the much larger abrupt rise of fluence observed in GRB 970508. An abrupt achronic dip would be unexplainable in the standard models.

The CB model is very modest in the adjectives that refer to GRBs. None of them are exceptional, not even the very energetic GRB 990123, nor GRB 970508 with its peculiar AG shape, nor the extraordinarily close-by GRB 980425. They are all associated with supernovae, seen when they are visible, not seen when they are not (Dado et al. 2002a). The explosions that generate GRBs are not “the biggest after the Big Bang.” The mechanism that begets GRBs is common: it takes place in quasars and microquasars as well. The model works very well and is very predictive, thus falsifiable.

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