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WHAT WE LEARN FROM THE AFTERGLOW OF GRB 021211

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ABSTRACT

The behavior of the afterglow (AG) of gamma-ray bursts (GRBs) directly provides, in the cannonball (CB) model, information about the environment of their progenitor stars. The well-observed early temporal decline of the AG of GRB 021211 is precisely the one predicted in the presence of a progenitor's "wind," which resulted in a density profile $\propto 1/r^2$ around the star. The subsequent fast fading—which makes this GRB "quasi-dark"—is the one anticipated if, farther away, the interstellar density is roughly constant and relatively high. The CB model fit to the AG clearly shows the presence of an associated supernova akin to SN 1998bw and allows even for the determination of the broadband spectrum of the host galaxy. GRB 990123 and GRB 021004, whose AGs were also measured very early, are also discussed.

Subject heading: gamma rays: bursts

On-line material: color figures

1. INTRODUCTION

Massive stars are observed to emit a dense stellar wind, continuously or in a sequence of eruptions, which presumably intensifies before their death as core-collapse supernovae (SNe). Indirect evidence for a large mass loss from the progenitor stars during their late-time evolution is provided by the absence of H lines (and He lines) in the spectra of SNe of Type Ib (Ic). In Type II SNe, direct evidence for a wind emitted shortly before the explosion is provided by the subsequent observations of emission by the circumburst material of narrow optical lines (see, e.g., Salamanca et al. 1998; Salamanca, Terlevich, & Tenorio-Tagle 2002; Fassia et al. 2001), radio waves, and X-rays (for a recent review, see Chevalier 2003). All these observations indicate that the circumstellar density profile is $\rho_w \propto r^{-2}$, as expected from a quasi-steady stellar wind.

Gamma-ray bursts (GRBs), in the cannonball (CB) model, are associated with the death of massive stars in core-collapse SN explosions (Dar & De Rújula 2000a, 2000b; Dado, Dar, & De Rújula 2002a, 2003a). Clear indications for this association are the effect of the progenitor's wind on their early-time afterglow (AG) and the presence of a supernova in their late-time AG. In a CB model analysis, there is very convincing evidence of a GRB-SN association (Dado et al. 2002a, 2002b, 2002c, 2002d, 2003b). The CB model fingerprints of the massive wind of the progenitor star have also been spotted in the AGs, but never before with unquestionable certainty.

In this paper we fit the broadband optical afterglow of GRB 021211 in the CB model and extract information about the circumburst density profile, the associated SN, and the host galaxy. We also rediscuss GRB 990123 and GRB 021004. In these three cases the AG was observed in the optical band early enough after the onset of the burst for the CBs to still be moving through the progenitor's wind. The observed early AG decline, roughly $t^{-1.6}$, is the CB model expectation[3] for a wind density profile $\propto r^{-2}$. In the well-measured early AG of GRB 021211, the agreement between the observations and the CB model prediction is extremely satisfactory.

In the CB model we assumed GRBs to be associated with SNe similar to SN 1998bw (Dar & De Rújula 2000a). In subsequent work (Dado et al. 2002a, 2002b, 2002c, 2002d, 2003b) we found that, indeed, in all cases of GRBs of known z in which such an SN was in practice visible (all cases with $z < 1.12$), the CB model fit to the corresponding AG disclosed its presence. GRB 021211, at $z = 1.006$, is one more example: the fit clearly requires such an SN contribution, tentatively reported by Fruchter et al. (2002) and Testa et al. (2003). The CB model has so few parameters that we could determine via our fits the unknown contribution of the host galaxy of GRB 021211 to the different optical bands. The resulting broadband spectrum snugly resembles that of other GRB host galaxies (see, e.g., Gorosabel et al. 2003) and star-forming galaxies at a similar z (Fruchter et al. 2002).

In the CB model "dark" GRBs without AGs are not expected. But the AGs' decline is expected to be often fairly fast, in particular if the interstellar medium (ISM) density is relatively high, making their detection difficult or, in the bygone days of slow GRB localization, nearly impossible; see Figure 6 of Dado et al. (2002a) and its discussion. With faster detectors, more of these faint, fast-declining, "quasi-dark" GRBs ought to be found, and GRB 021211 is an example. The detailed shape of the fast AG decline observed from 20 to 150 minutes, roughly as $1/t$, is well fitted with an ISM whose density, beyond the reaches of the wind, is relatively high and approximately constant.

2. GRB 021211

The GRB 021211 was detected on 2002 December 11.471227 UT, with the *HETE* FREGATE, WXM, and

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[3] We have claimed before that this behavior ought to be $\sim t^{-2}$. In the case of GRB 990123, discussed in Dado et al. (2002a), that was due to our then-incomplete understanding of the AGs' broadband spectra, which we improved in Dado et al. (2003a). For GRB 021004, it was an error, which we correct here, although it is not relevant in practice (the early data on this AG are not sufficient to distinguish the two declines).

SXC instruments. It was a relatively long-duration ($\geq$5.7 s in the 8–40 keV band), single-pulse GRB with a peak flux of 8×10^{-7} ergs cm^{-2} s^{-1} and a fluence of $\sim 10^{-6}$ ergs cm^{-2} (Crew et al. 2002). Its early-time optical AG was detected by the robotic telescopes RAPTOR (Wozniak et al. 2002), KAIT (Li et al. 2003), and S-LOTIS (Park et al. 2002) 90, 108, and 143 s after the burst, respectively. A fit to the first nine KAIT data points, in the interval of 2.2–6.5 minutes after the burst, showed a temporal decay with a power-law index of -1.60 ± 0.02, and a fit to later data, taken 20–150 minutes after the GRB, gave a slope of -0.96 ± 0.04 (Chornock et al. 2002), consistent with the decay seen by Fox & Price (2002), who were the first to report the detection and the precise localization of the optical AG. Follow-up observations in the optical, near-IR (NIR), and radio bands were reported by Fox et al. (2003) and by other groups in the GCN. The redshift of the host galaxy, $z = 1.006 \pm 0.002$, was measured with the Very Large Telescope (VLT) by Vreeswijk et al. (2002) and confirmed by Della Valle et al. (2003). A flattening of the light curve due to the host galaxy and a possible contribution from an associated SN were observed with the *Hubble Space Telescope* 7 and 14 days after the burst in the *BVIH* bands (Fruchter et al. 2002) and with VLT-UT4 between days 30 and 35 in the *R* band (Testa et al. 2003). Well-sampled optical AG observations have been recently reported by Li et al. (2003). The published observational data on the broadband optical AG of GRB 021211 are shown in Figures 1 and 2.

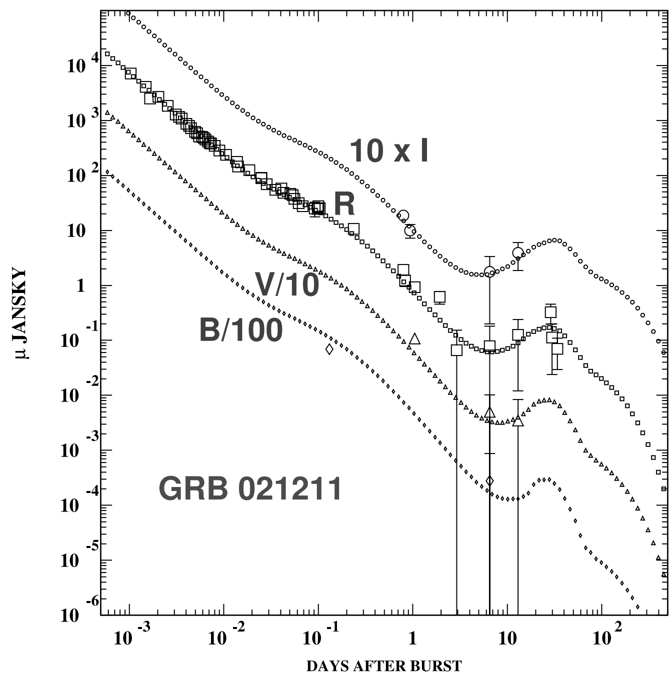

FIG. 2.—Broadband CB model fit to the optical and NIR observations for GRB 021211. For clarity, only the better sampled *I*, *R*, *V*, and *B* bands are shown, scaled by 10, 1, 1/10, and 1/100, respectively. The contribution of an SN 1998bw–like SN at the GRB position is discernible at late times. The host galaxy's contributions, which were fitted, are subtracted in this plot. [*See the electronic edition of the Journal for a color version of this figure.*]

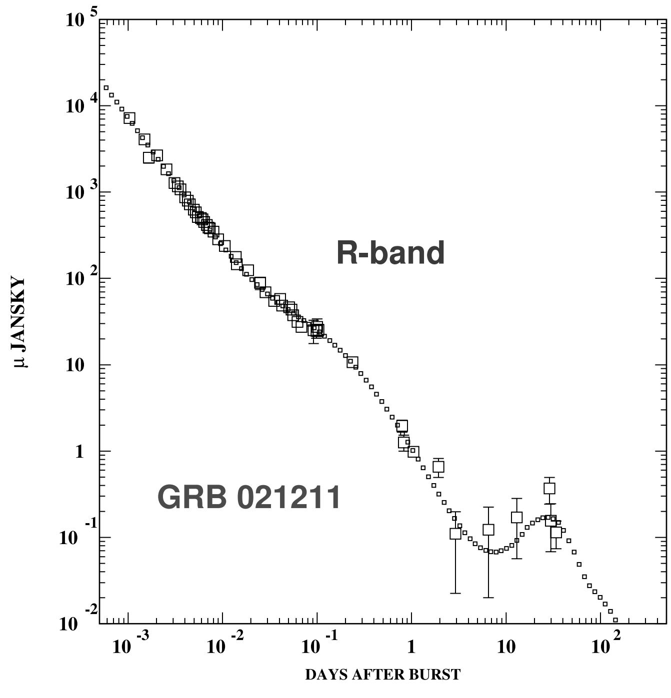

FIG. 1.—Optical observations of the *R*-band AG of GRB 021211 and their CB model fit. The ISM density is a constant plus a wind contribution decreasing as the inverse square of the distance. The two contributions are equal at $\bar{x} \simeq 1.2$ pc, a distance reached by the CBs in an observer's time, $\bar{t} \simeq 0.025$ days after the burst. The data are those reported to date, in the GCN notices quoted in § 2, in Fox et al. (2003), and in Li et al. (2003). The contribution of an SN 1998bw–like SN at the GRB position is discernible at late times. The host galaxy's contribution, which was fitted, is subtracted in this plot. [*See the electronic edition of the Journal for a color version of this figure.*]

3. THE CB MODEL

In the CB model bipolar jets of CBs are launched axially in core-collapse SNe, with initial Lorentz factors $\gamma_0 = \mathcal{O}(10^3)$. The CBs are assumed to be produced in an unstable accretion process, as in quasars and microquasars, and, as in SS 433, to be made of ordinary matter.[4] Crossing the SN shell and the progenitor's wind with a large γ, the front surface of a CB is collisionally heated to keV temperatures. The quasi-thermal radiation it emits, when no longer absorbed by the intervening matter and boosted and collimated by its relativistic 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 2000b; for recent reviews, see De Rújula 2003; Dar 2003). The ejected CBs, as observed in microquasars, are assumed to contain a tangled magnetic field. As they plough through matter, they gather and magnetically scatter its constituent protons. The reemitted protons exert an inward pressure on the CBs, which counters their expansion and makes them reach an asymptotic radius $R_{\rm CB}$ in minutes of the observer's time (Dado et al. 2002a). The electrons swept in by the CB in its voyage through the wind and ISM are Fermi-accelerated in the enclosed magnetic maze and cooled by synchrotron radiation. Shortly after the GRB, the optical radiation from the CB is dominated by synchrotron emission from these electrons. So far, the CB model has been very successful in

[4] Balmer H and He lines (see, e.g., Eikenberry et al. 2001) and the Kα line of Fe (Migliari, Fender, & Méndez 2002) were detected in the mildly relativistic CBs of this microquasar.

fitting the observed broadband AGs of all GRBs of known redshift (Dado et al. 2002a, 2002b, 2002c, 2002d, 2003b).

4. THE FATE OF A CANNONBALL

Let n_p be the baryonic number density of the circumburst material or the ISM, both dominated by protons. A spherical CB of radius $R_{\rm CB}$ flying through this material sees, in its rest system, an incoming flux of protons entering it with a total momentum per unit time $\Pi \simeq n_p m_p c^2 \gamma^2 \pi R_{\rm CB}^2$, with $\gamma = \gamma(t)$ the diminishing CB's Lorentz factor. If the CB's enclosed magnetic field randomizes these protons so that they are reemitted isotropically, the CB's surface is subject to an inward pressure $P = \Pi/(4\pi R_{\rm CB}^2)$, which is independent of $R_{\rm CB}$. In Dado et al. (2002a) we have assumed that this pressure is sustained by the equal and opposite pressure $B^2/(8\pi)$ of the CB's enclosed magnetic field (which is thereby determined), resulting in an equilibrium situation for a CB of approximately constant $R_{\rm CB}$. We also assumed that $R_{\rm CB}$, for a CB originally expanding at a transverse velocity $\beta_0 c$, can be estimated as the maximum expansion radius attained as the pressure P opposes the expansion, that is, $R_{\rm CB} \sim [3N_{\rm CB}\beta_0^2/(2\pi n_p \gamma_0^2)]^{1/3}$, with $N_{\rm CB}$ the CB's baryon number.

To test the above bold assumptions, we have fitted the model to all broadband AGs of GRBs of known z, with satisfactory results. In Dado et al. (2002a) we have also tried a model with continuously expanding CBs and found it to be completely inadequate, supporting the *Ansatz* of CBs with constant radius. The estimated value of $B \sim 10$ G (for $n_p = 10^{-2}$ cm^{-3} and $\gamma_0 = 10^3$) is adequate for the description of the data, but our original guess, $R_{\rm CB} = \mathcal{O}(10^{14})$ cm, turned out to be an overestimate by at least 1 order of magnitude (Dado et al. 2003a). In this paper we subject the CB's defining property—that they reach an approximately constant radius—to a severe test, by studying in detail its consequences for very early AGs.

Let θ be the angle between the direction of a jet of CBs and the observer. The Doppler factor of the light the CB emits is well approximated by $\delta(t) \approx 2\gamma(t)/[1+\theta^2\gamma(t)^2]$ in the domain of interest for GRBs: large γ and small θ (typical values ensuing from our fits are $\gamma_0 \sim 1/\theta \sim 10^3$). The relation between time—as measured by the observer—and distance—as traveled by the CB—is

$$dx = \frac{\gamma\delta}{(1+z)}\, c\, dt\ . \tag{1}$$

The ambient protons that a CB scatters in the interval dx slow it down by an amount[5]

$$d\gamma = -\frac{\pi R_{\rm CB}^2 n_p \gamma^2}{N_{\rm CB}}\, dx\ , \tag{2}$$

where $N_{\rm CB}$ is the CB's baryon number, for which our reference value is 6×10^{50}. The function $\gamma(t)$ can be explicitly found by quadrature in the two cases of interest here: a density profile $n(x) = n_w (x_w/x)^2$ (for a "windy" neighborhood) and a constant density (an adequate approximation as the CBs get farther away into the ISM).

For an ISM of constant density, $\gamma(t)$ depends on θ, on the initial $\gamma = \gamma_0$ as a CB exits the denser wind domain, and on $x_\infty = N_{\rm CB}/(\pi n_p R_{\rm CB}^2)$, a deceleration parameter. The value of $\gamma(t)$ is the real root of the cubic:

$$\frac{1}{\gamma^3} - \frac{1}{\gamma_0^3} + 3\theta^2\left(\frac{1}{\gamma} - \frac{1}{\gamma_0}\right) = \frac{6ct}{(1+z)x_\infty}\ . \tag{3}$$

It takes a distance $x_{1/2} = x_\infty/\gamma_0$ for $\gamma(t)$ to descend to $\gamma_0/2$ (Dado et al. 2002a). Our fitted values of $x_{1/2}$ are in the range 0.1–1 kpc, corresponding to AGs that fade in the observed characteristic times of the order of $(1+z)x_{1/2}/(c\delta_0\gamma_0)$ $\sim$ days. This range may be affected by an observational bias: AGs with a smaller x_∞ (e.g., those with CBs moving in a relatively high density ISM) decay faster in time and are quasi-dark, harder to detect. GRB 021211 is one such case.

We do not report the function $\gamma(t)$ for the small values of t corresponding to the CBs crossing the parent stellar wind, since, for typical parameters, the fractional energy loss $\Delta\gamma/\gamma$ is negligible in that interval. The "canonical" stellar wind of a very massive star has a rate $\dot M_w \sim 10^{-4}\ M_\odot$ yr^{-1} and a velocity $v_w \sim 100$ km s^{-1}, so that $\rho(x) \approx \rho_w (x_w/x)^2$, with $\rho_w x_w^2 \approx \dot M_w/(4\pi v_w) \sim 5.1 \times 10^{13}$ g cm^{-1}, or $n_w x_w^2 \sim 3 \times 10^{37}$ cm^{-1}. The actual observations of $\dot M_w$ and v_w span an order of magnitude around these canonical values. It follows from equation (2) that the condition $\Delta\gamma/\gamma \ll 1$, for a wind profile extending from x_i to $x_f \gg x_i$, is $R_{\rm CB}^2 \ll N_{\rm CB} x_i/(\pi n_w x_w^2 \gamma)$. For observations starting at $\Delta t = 100$ s after the burst, $z = 1$ and typical $\gamma = \delta = 10^3$, $x_i = c\gamma\delta\Delta t/(1+z) = 0.5$ pc, and the constraint is $R_{\rm CB} < 10^{14}$ cm, which we have found to be amply satisfied (Dado et al. 2003a).

The fact that $\Delta\gamma/\gamma$ is typically small as the wind is crossed has, as we shall see anon, an important consequence: *the shape of the early optical AG locally and directly reflects the shape of the circumburst density profile*.

5. THE GRB AFTERGLOW IN THE CB MODEL

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 (HG). These components are usually unresolved in the observed "GRB afterglows," so that the light curves and spectra are measures of the corresponding cumulative energy flux density: $F_{\rm AG} = F_{\rm CBs} + F_{\rm SN} + F_{\rm HG}$. In all observed cases but one (GRB 021004, discussed in Dado et al. 2003b), it is sufficient to approximate the ensemble of CBs in the AG phase as a single (or dominant) CB.

The contribution $F_{\rm SN}$ of the SNe is approximated by that of SN 1998bw (Galama et al. 1998), displaced to the GRB's redshift.[6] In the CB model the pair GRB 980425 and SN 1998bw is in no way exceptional (but for the accidentally small z and large θ of the GRB). Thus, the use of SN 1998bw as a candidate GRB-associated standard candle makes sense.

The optical AG of a CB is dominated by synchrotron radiation from the ISM electrons that penetrate in it. We argued in Dado et al. (2003a) that these electrons are Fermi-accelerated in the CB-enclosed magnetic maze and cooled by synchrotron radiation to a distribution (in the CB's rest system) $dn_e/dE \propto E^{-2}$ below the *injection bend* energy at which they enter the CB [$E_b = \gamma(t) m_e c^2$], and to a distribution $dn_e/dE \propto E^{-(p+1)}$ above E_b, with $p = 2$ in analytical

[5] We call x and not r the distance from the progenitor, to not insinuate a hypothesis of spherical symmetry.

[6] The cosmological parameters we use are $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

approximations and $p = 2.2$ in numerical simulations. The emitted synchrotron radiation has a corresponding double power-law form $\nu\, dn_\gamma/d\nu \propto \nu^{-\alpha}$, with a power-law index $\alpha_l \approx 0.5$ well below a *bend frequency* ν_b and $\alpha_h = p/2 \approx 1.1$ well above it. Broadband fits to the data on the AGs of all GRBs of known z result in $\alpha_l \approx 0.6 \pm 0.1$, $\alpha_h \approx 1.1 \pm 0.1$. In practice α_l is less well determined than α_h, the CB model fits being good even for a fixed $\alpha_h = 1.1$. We attribute this to the fact that the extracted α_h is sensitive to the AG light curve at relatively late times, when CBs are typically hundreds of parsecs away from the progenitor and the absorption in the host, which is hard to ascertain, may be minimal.

The value of E_b and the estimate of the CB's magnetic field described in the previous section allow us to estimate the bend frequency of the synchrotron radiation spectrum:

$$\nu_b(t) \simeq \frac{1.87 \times 10^3 [\gamma(t)]^3 \delta(t)}{1+z} \left[\frac{n_p(x)}{10^{-3}\ \mathrm{cm}^{-3}}\right]^{1/2} \mathrm{Hz}\ . \quad (4)$$

In the observer frame, this radiation is Doppler-boosted, collimated by the relativistic motion of the CB, and redshifted by the cosmic expansion. Its explicit form, extending from radio to X-ray frequencies, is given in equations (4), (6), and (8) of Dado et al. 2003a; here we only report its behavior near the optical domain, which is simple above and below the injection bend. Let $\alpha = (\alpha_l, \alpha_h) = (0.5, 1.1)$ be the predicted power indices at $\nu \ll \nu_b$ and $\nu \gg \nu_b$, respectively. The time and frequency dependence of the energy fluence in these limits is

$$F_\nu \propto A'(\nu, t) n_e^{(1+\alpha)/2} [\gamma(t)]^{3\alpha-1} [\delta(t)]^{3+\alpha} \nu^{-\alpha}\ , \quad (5)$$

where $n_e = n_e(x) \simeq n_p(x)$ is the electron density along the CBs' trajectory and $A'(\nu, t)$ corrects for absorption, in the host galaxy and in ours, its possible time dependence originating in the kiloparsec length of the CBs' trajectory in the host galaxy. Self-absorption in the CB is irrelevant at the optical and NIR wavelengths. In the CB model the early AG is dominated by the last significant pulse (or CB) of the GRB, so that t in equation (5) is the time after that pulse. The nuance may be significant at very small t.

In deriving equation (5) we have assumed that a fixed fraction of the energy deposition rate by ISM electrons in a CB ($\pi R_{\mathrm{CB}}^2 n_e m_e c^3 \gamma^2$, in the CB's system) is reemitted as the AG. The AG spectrum is a function of ν and ν_b, so that at fixed ν it depends on $n_e = n_p$ via ν_b, as in equation (4), thus a result that is not linear in n_e and peculiar at first sight.

In our fits we assume as the circumburst density profile a constant plus a windy term:

$$n(x) = n_0 + n_w (x_w/x)^2 \equiv n_0[1 + (\bar{x}/x)^2]\ . \quad (6)$$

6. THE VERY EARLY OPTICAL AG

For typical parameters, the first few parsecs of a CB's voyage—as it crosses the "wind" material emitted by the progenitor star—are seen by an observer in the first few minutes of the AG. During that "early" time, the ambient density is high enough for ν_b, as in equation (4), to be comfortably above the optical frequencies, so that $\alpha = \alpha_l = 0.5$ in equation (5). We have seen that, at early times, a CB has its Lorentz factor insignificantly changed by collisions with the wind material, so that the observer's time and the CB's traveled distance, as in equation (1), are strictly proportional. Thus, equations (5) and (6) reduce to

$$F_\nu \simeq n_e^{(1+\alpha)/2} \propto [1 + (\bar{t}/t)^2]^{3/4}\ . \quad (7)$$

Had we used the observed $\alpha_l = 0.6 \pm 0.1$, as opposed to the naive theoretical $\alpha_l = 0.5$, we would have obtained $F_\nu \simeq t^{-1.6}$ at very early times, in close agreement with the fit by Chornock et al. (2002) for GRB 021211 and the observations of Akerlof et al. (1999) for GRB 990123 and Fox et al. (2002) for GRB 021004. But we shall see that equation (7) provides an excellent fit to the data. The observed deviations relative to the smooth curve of equation (7) reflect the variations of the wind that generated the profile. In the case of GRB 021211, these variations are at the ~10% level (Li et al. 2003).

7. THE OVERALL AG OF GRB 021211 IN THE CB MODEL

The copious early data on GRB 021211 obtained by Li et al. (2003), along with all other data communicated in the GCN notices quoted in § 2 and in Fox et al. 2003, are shown in Figure 1 for the R band and in Figure 2 for the broadband optical ($IRVB$) and NIR (HKJ) passbands. In fitting these results we neglect the unknown extinction in the host, because of the lack of relevant spectral information.[7] For this GRB the R-band data are relatively so copious that it is useful to perform separate R-band and broadband fits.

In our fit, the density is that of equation (6) and the limiting exponents in the synchrotron spectrum $\propto \nu^{-\alpha}$ are set to their theoretical values $(\alpha_l, \alpha_h) = (0.5, 1.1)$. The fit is made with the complete analytical broadband prediction equations (4), (6), and (8) of Dado et al. 2003a, their equation (5) describes the limiting behavior and their equation (3) is the deceleration law. The best-fitted parameters for the R-band fit shown in Figure 1 are $\gamma_0 = 262$, $\theta = 1.76$ mrad (i.e., $\delta_0 = 431$), and $x_\infty = 4.7$ kpc, with 51 degrees of freedom (dof) and $\chi^2/\mathrm{dof} = 0.97$ if the outlying point at $t \sim 2$ days is eliminated. The constant contribution of the host galaxy was left as a free parameter, for which the fit returned $F_{\mathrm{HG}} = 0.34\ \mu$Jy. The contribution of a standard candle SN 1998bw at the GRB position is discernible in Figure 1, in which F_{HG} has been subtracted.

We have also tried a fit with an arbitrary power a in the windy term: $n_w(x_w/x)^a$, resulting in a best-fitted $a = 1.92 \pm 0.03$, close to the canonical expectation $a = 2$. Thus, the agreement of the fits with the canonical windy power is not a consequence of the scarcity of data. Also, at early times, the fit is totally insensitive to the other parameters (γ_0, θ, and x_∞). Thus, the result for a is robust: the signature of a wind is there.

The overall normalization of the AG is also a free parameter in our fits; it is proportional to the ambient density $n(x)$, to the CBs' cross sections, to their number, and to the unknown fraction of the energy of the gathered ISM electrons that is reemitted as the AG. Thus, extracting a value of $n(x)$ from the fit normalization requires extra assumptions. Yet the value of $n(x)$ at some reference distance (e.g., n_0, its limiting value at large distance) can be extracted from the fact that we use it as a free parameter in the expression

[7] An unabsorbed SN 1998bw–like contribution fits the late-time broadband data, indicating that host extinction is not large.

of equation (4) for ν_b. The fitted result is $n_0 = 2.97 \pm 0.22$ cm^{-3}. Combined with the fitted value $\bar{x} = 1.2$ pc in equation (6), this yields $\rho_w x_w^2 = m_p n_w x_w^2 = (6.8 \pm 0.5) \times 10^{13}$ g cm^{-1}, compatible with the expectation, quoted in § 4, for a canonical wind: 5.1×10^{13} g cm^{-1}.

The broadband fit is shown in Figure 2; it has essentially the same fit parameters as the *R*-band fit. The contributions $F_{\rm HG}$ of the host galaxy in the different bands, resulting from the fit, are 0.50, 0.34, 0.23, and 0.23 μJy for the *IRV* and *B* bands. This extracted spectrum, and in particular its flattening above the *V* frequencies, is compatible with that of other GRB hosts (see, e.g., Gorosabel et al. 2003) and star-forming galaxies at $z \sim 1$ (see, e.g., Fruchter et al. 2002).

The comparison we have described between the CB model expectations and the data for GRB 021211 is simply spectacular. The fits are good, particularly that to the shape of the *R*-band light curves. The agreement between the expected and extracted ambient density profiles is eerie. A word of caution, however, is necessary. The number of parameters in our fits is high: the "ambient" parameters describing the host galaxy ($F_{\rm HG}$) and the density profile (n_0 and $\bar{x}$), the observer's viewing angle θ, and the three quantities that are specific to the CBs: the overall AG normalization, γ_0, and x_∞. Even if the fitted ambient parameters turn out to have the expected values, a model with this many parameters has to be very wrong not to describe a very simple surface: the fluence as a function of frequency and time.[8] Moreover, the data are not cross-calibrated, their systematic errors are unknown, the model is no doubt a simplification of a very complicated phenomenon, and the parameters are not uncorrelated (except at the early times of particular interest here). As a consequence of all this, the "formal errors" of the parameters (as given by the standard program MINUIT) are no doubt underestimated, whence our habit of not always making the errors explicit.

8. THE RADIO AG OF GRB 021211

In the CB model the radio AG at early time is suppressed because of limb darkening and the finite time it takes the electrons gathered by a CB to cool radiatively and reach an energy at which they emit synchrotron radiation of a given typical frequency (Dado et al. 2003a). At later times the radio emission, like the optical and X-ray emission, becomes proportional to a high power of the Lorentz factor. In the case of the radio AG of GRB 021211, only upper limits (or perhaps marginal detections) have been reported by Hoge et al. (2002) and Fox et al. (2002). The later authors, who analyze the AG in detail, consider the absence of a stronger radio signal to be a problem. In the CB model, it is not.

In the CB model the broadband spectrum of AGs is very simple. Its only feature—besides the bend frequency that we have discussed—is due to self-absorption in the CB, and it is described by a single parameter ν_a (Dado et al. 2003a). In the case of GRB 021211 we cannot fix this parameter, having no single secure radio signal. The best we can do is to show, by way of example, what the radio signal would be if

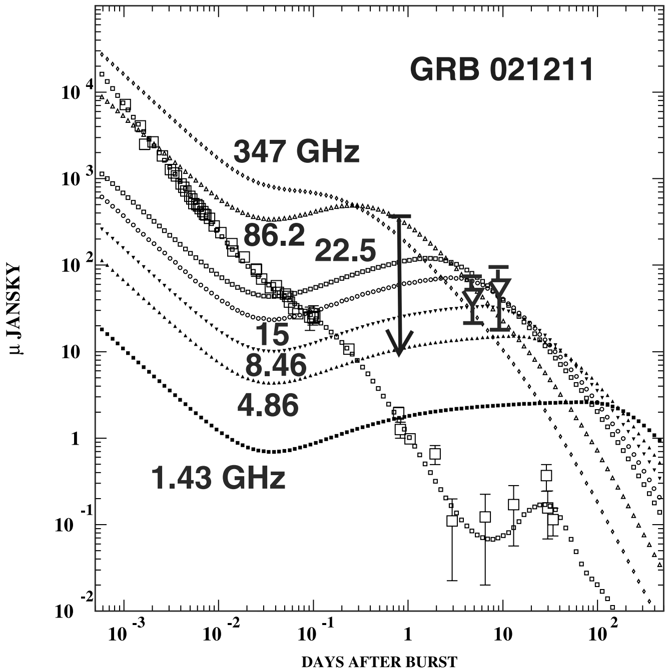

FIG. 3.—Optical *R*-band AG of GRB 021211, superposed on the predictions for the radio AG at the various labeled frequencies, for an assumed $\nu_a = 1$ GHz. The data points centered on inverted triangles are for the observations by Fox et al. (2002) at 8.46 GHz, and the arrow is for the upper limit of Hoge et al. (2002) at 347 GHz. [*See the electronic edition of the Journal for a color version of this figure.*]

the value of ν_a was similar to the average for other radio AGs ($\bar{\nu}_a \sim 1$ GHz) or to the value for GRB 021004 (0.98 GHz), which is otherwise akin to GRB 021211 and is very well described by the CB model (Dado et al. 2003b). The result of this exercise is shown in Figure 3, and it is compatible with the observational limits or marginal detections: the largest "signals" reported in Fox et al. (2002) are 45 ± 23 and 60 ± 38 μJy, at $t \sim 5$ and 10 days, respectively, both at 8.46 GHz, while Hoge et al. (2002) obtain a 3 σ upper limit of 7.5 mJy at 347 GHz, on day $t \sim 1$.

9. THE GRB ITSELF

In the CB model, the gamma-ray fluence F from a GRB viewed at a small θ is amplified by a huge factor δ_0^3, because of Doppler boosting and relativistic collimation (Dar & De Rújula 2000a, 2000b):

$$F = \frac{(1+z)\delta_0^3}{4\pi D_L^2} E_\gamma \, , \tag{8}$$

where E_γ is the total energy in photons emitted by CBs in their rest system. The total "equivalent spherical," or would-be isotropic energy, $E^{\rm iso}$, inferred from the observed fluence, is a factor of $(\delta_0)^3$ larger than E_γ. In Dado et al. (2002a) we deduced that the E_γ values of the GRBs of known z span the surprisingly narrow[9] interval $10^{44\pm0.3}$ ergs, the spread in $E^{\rm iso}$ being mainly due to the spread in their

[8] It is possible to construct models that disagree with observation or are unphysical but have even more parameters. For the case of GRB 991208, see § 2 of Dado et al. (2002d).

[9] GRBs in the CB model are much better standard candles than those in the standard model (Frail et al. 2001).

values of δ_0 (deduced from the fits to their AGs). For GRB 021211, the CB model expectation is $E^{\rm iso} \approx \delta_0^3$, $E_\gamma \approx 0.8 \times 10^{52\pm0.3}$ ergs, in agreement with the observed $E^{\rm iso} \approx 1 \times 10^{52}$ ergs, deduced from its measured redshift ($z = 1.006$; Vreeswijk et al. 2002) and fluence in the 8–40 keV band ($\sim 10^{-6}$ ergs cm^{-2}; Crew et al. 2002).

10. GRB 990123 AND GRB 021004

The AG of these two GRBs was also observed particularly early, by Akerlof et al. (1999) in the case of GRB 990123. We have recalibrated their data, assuming $V-R = 0.28$ mag (our predicted $\alpha_l = 0.5$) rather than a constant color. We have also recalibrated the later time data compiled in Castro-Tirado et al. (1999), Kulkarni et al. (1999), Galama et al. (1999), and Fruchter et al. (1999), assuming $R-r = 0.015$ mag ($\alpha_l = 0.5$). The R-band results of our broadband fit are shown in Figure 4, in which $t = 0$ corresponds to the start of the last (second) prominent pulse in the GRB, 37 s after the trigger (Briggs et al. 1999). There is an excellent agreement between the early data tracing the circumburst windy density and the prediction of equation (6). A fit with an arbitrary power a in the windy term, $n_w(x_w/x)^a$, results in a best-fitted $a = 1.98 \pm 0.06$, again in agreement with the canonical expectation: $a = 2$.

Although the data have been recalibrated, the parameters we fit to the AG of GRB 990123 are close to those in Dado et al. (2002a, 2003a). In particular, $\gamma_0 = 1204$ and $\delta_0 = 1630$—determined from the *shape* of the AG—are the highest for any GRB of known z, implying that the *magnitude* of the GRB and AG fluences should also be record-breaking, as they are (even for this GRB, the value of E_γ in eq. [8] is not exceptional). Since γ and δ are so large, the bend frequency ν_b of equation (4) "crosses" the optical band very late in time, where the data are quite imprecise. As a consequence, the R-band and broadband fits are very insensitive to ν_b, and we cannot reliably use its value to determine the absolute magnitude of the ambient and wind densities. If we assume that the density profile $n_w \propto x_w^{-2}$ prevails until n_w declines to the typical superbubble or halo value, $n_p \sim 10^{-3}$, we find that $\rho_w x_w^2 = m_p n_p x_w^2 \approx 4.2 \times 10^{13}$ g cm^{-1}, again in agreement with the expectation, quoted in § 4, for a canonical wind: 5.1×10^{13} g cm^{-1}. The windy profile would in this case extend all the way to $x_w \sim 50$ pc, yielding a total mass loss of $\sim 40\ M_\odot$ during the life of the very massive progenitor star. Such a large total mass loss is not unusual for the progenitors of SNe of Type Ib and Ic.

The CB model fit to the R-band AG of GRB 021004 is shown in Figure 5. The data are those measured and compiled by Fox et al. (2002), Holland et al. (2003), Pandey et al. (2002), and Bersier et al. (2003). Once more, the agreement between the prediction of equation (6) and the early data is good, although these data are neither as abundant nor as close to the GRB trigger as those for the other two cases we discussed, implying that we cannot claim to have clearly spotted, for this GRB, a typical windy profile. The fitted result for the asymptotic density is $n_0 = (1.26 \pm 0.10) \times 10^{-2}$ cm^{-3}. Combined with the fitted value $\bar{x} \sim 2.6$ pc in equation (6), this yields $\rho_w x_w^2 = m_p n_w x_w^2 \sim 1.4 \times 10^{12}$ g cm^{-1}, a bit over an order of magnitude below the central canonical expectation.

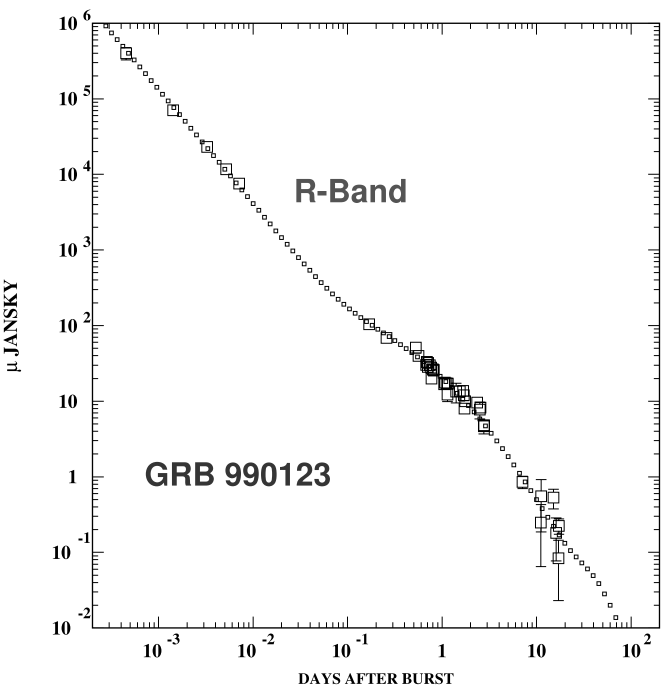

FIG. 4.—Optical observations of the R-band AG of GRB 990123 and their CB model fit. The ISM density is a constant plus a wind contribution decreasing as the inverse square of the distance. The contribution of the host galaxy has been subtracted. The small extinction in the galaxy (Schlegel, Finkbeiner, & Davis 1998) was neglected. [*See the electronic edition of the Journal for a color version of this figure.*]

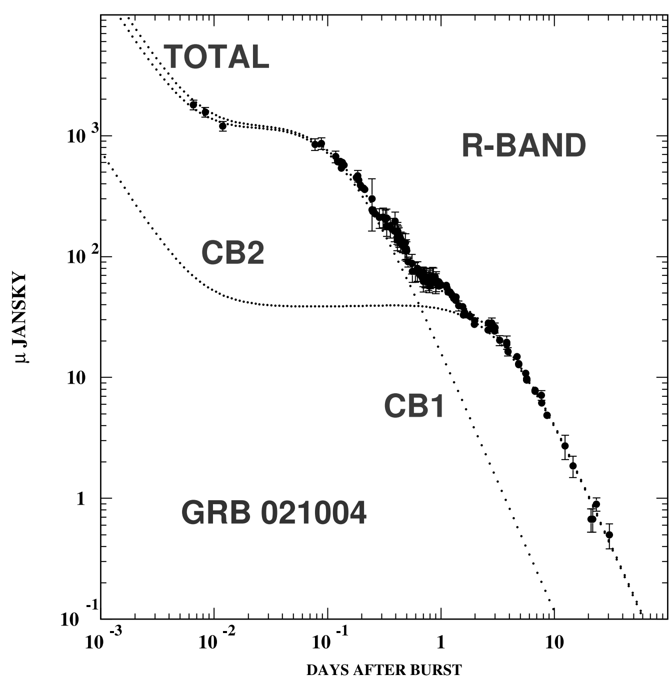

FIG. 5.—Optical observations of the R-band AG of GRB 021004, and their CB model fit with two CBs, whose individual contributions are depicted along with the total (Dado et al. 2002d). The ISM density is a constant plus a wind contribution decreasing as the inverse square of the distance. These two contributions are equal at $\bar{x} \simeq 3$ pc, a distance reached by the CBs in an observer's time $\bar{t} \simeq 0.01$ day after the burst. The data are the same as the ones quoted in Dado et al. (2002d). The contribution of an SN 1998bw–like SN at the GRB position and the host galaxy's contribution were subtracted in this plot. [*See the electronic edition of the Journal for a color version of this figure.*]

11. DISCUSSION AND CONCLUSIONS

It is, as usual, interesting to compare the CB model with the "standard" fireball or blast-wave models of GRBs. For GRB 021211 a detailed standard model (SM) analysis is given in Fox et al. (2003). The relevant issues at hand concern the signatures for windy neighborhoods and the predictive power for early AGs.[10]

In the SM the scarcity of AGs indicating a windy circumburst density distribution is a problem, admitted even by its staunchest defenders (Piran 2001; Price et al. 2002). In the CB model all the observed AGs that should show a windy signature do. Indeed, the relation equation (1) between observer's time and CBs traveled distance implies that, for the typical $\gamma_0 \sim \delta_0 \sim 10^3$, the AG of a GRB at a cosmological distance must be "caught" within the first few minutes for the CBs to be still traveling close enough to the parent star, so that the contribution of its wind to the ambient density is still significant and observable. Only the three GRBs that we have discussed pertain to this category.

In the SM the fast-decreasing early optical AG, as first observed in GRB 990123, is generally attributed to a *reverse* shock (Mészáros & Rees 1999). For GRB 021211, this is the interpretation espoused by the observers (Fox et al. 2003; Li et al. 2003). In this view the index of the approximate power law of the decay of the early AG is not fixed, and its normalization is unrelated to that of the late AG. In the CB model, contrariwise, the early optical AG does not have its own separate origin: it is made by the very same mechanism as the late AG. The temporal shape of the AG is not a succession of power laws with breaks between different mechanisms or regimes. This temporal shape is not arbitrary: at early times it is directly related to the shape of the circumburst density profile, as in equation (7), and this relation is fully vindicated by the data for the expected windy profile. The AGs shown in our figures depend, in the early domain, on only one parameter: the absolute normalization. The ambient density that defines the early temporal shape can also be extracted from the CB model fit, via the bend frequency of equation (4), and its magnitude turns out to coincide with the expected density for the canonical wind of a heavy star.

Fast-declining optical light curves—masquerading as dark AGs—are expected in the CB model (Dado et al. 2002a), and GRB 021211 is an example. The CB model fit to its AG has allowed us to infer the presence of an associated SN akin to SN 1998bw, as for all other GRBs where the SN could in practice be detected. The fit also yields the "color" of the host galaxy, which is the expected one.

We have seen how, concerning the early optical AGs, the CB model is very predictive and successful. In previous works we have shown this to be the case also for all properties of the AGs of all GRBs of known redshift: they can *all* be described in a simple, analytical, and parameter-thrifty manner, which does not involve multiple choices, multiple mechanisms, and multiple exceptions. To put it in a way with which even the most allegiant apologists for the SM might agree: the contrast between the CB model and the standard model is striking.

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[10] For Fox et al. (2003) the nonobservation of a radio AG is also significant, suggesting that "the burst may have suffered substantial radiative corrections." No such specific cure is necessary in the CB model.

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