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Is there a 1998bw-like supernova in the afterglow of gamma ray burst 011121?

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Abstract. We use the very simple and successful Cannonball Model (CB) of gamma ray bursts (GRBs) and their afterglows (AGs) to analyze the observations of the strongly extinct optical AG of the relatively nearby GRB 011121, which were made with ground-based telescopes at early times, and with the HST at later time. We show that GRB 011121 was indeed associated with a 1998bw-like supernova at the GRB's redshift, as we had specifically predicted for this GRB before the supernova could be observed.

The identity of the progenitors of gamma ray bursts is still unknown, but it is becoming clearer and clearer. It has been suggested that GRBs are produced by highly relativistic jets (e.g., Shaviv and Dar 1995; Dar 1998), mostly in core collapse supernovae like SN1998bw (Dar and Plaga 1999; Dar 1999a; Dar and De Rújula 2000 and references therein). Possible evidence for a SN1998bw-like contribution to a GRB afterglow (Dar 1999a; Castro-Tirado & Gorosabel 1999) was first found by Bloom et al. (1999a) for GRB 980326, but its unknown redshift prevented a definite conclusion. The AG of GRB 970228 (located at redshift $z = 0.695$) appears to be overtaken by a light curve akin to that of SN1998bw (located at $z_{bw} = 0.0085$), when properly scaled by their differing redshifts (Dar 1999b; Reichart 1999; Galama et al. 2000). Evidence of similar associations was found for GRB 990712 (Hjorth et al. 2000; Sahu et al. 2000; Bjornsson et al. 2001), GRB 980703 (Holland et al. 2000), GRB 000418 (Dar and De Rújula 2000), GRB 991208 (Castro-Tirado et al. 2001), GRB 970508 (Sokolov et al. 2001), GRB 000911 (Lazzati et al. 2001; Dado et al. 2002a) and GRB 010921 (Dado et al. 2002b).

Unlike supernovae of type Ia (SNe Ia), core-collapse supernovae (SNe II/Ib/Ic) are far from being standard candles. But if their explosions are fairly asymmetric —as they would be if a fair fraction of them emit two opposite jets of cannonballs— much of the variability could be a reflection of 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), Dado et al. (2001a) and De Rújula (2002) have shown that the optical AG of *all* relatively nearby GRBs with known redshift (all the ones with $z < 1.12$) contain evidence or clear hints for a 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). However, in several of the above cases, 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 will take a few more clear cases to reach a generally accepted conclusion.

On Nov. 21, 18:47:21 UT a very bright GRB (011121) was simultaneously detected and localized by BeppoSAX (Piro 2001a,b) and IPN (Hurley et al. 2001). Its optical afterglow was first detected 10.3 hours after the burst in the R-band (Krzysztof et al. 2001). In further observations four additional R-band spectral energy densities were reported for the fading source during the first two days after burst (Stanek et al. 2001a,b,c), as well as a possible redshift (Infante et al. 2001b) for the host galaxy: $z = 0.36$. A candidate for this host galaxy was detected 0.5" (approximately 2.5 kpc) from the GRB's location (Stanek et al. 2001a). As was pointed out by Stanek et al. (2001b), the relatively low redshift and the afterglow's fast decay made GRB 011121 an attractive search-target for a possible GRB/SN association.

In order to urge and assist the search for a SN in the AG of GRB 011121, we used the Cannonball Model of GRBs (Dado et al. 2001a and references therein) and the early time R-band observations, recalibrated by the photometry of Olsen et al. (2001), to predict the late time behaviour of the AG in the BVRI bands and to demonstrate that *"The inescapable conclusion is that the supernova associated with GRB 011121 will, at about day 20 after burst, tower in the BVRI bands above the proper GRB afterglow"* (Dado et al. 2001b) in spite of the strong extinction in the host galaxy and in ours.

Late-time ground-based optical observations were made with the the 6.5m Magellan telescope, and an extensive space-based monitoring campaign was made with the Hubble Telescope (HST). Indeed, from the first observations on December 4, 2001, Garnavitch et al. (2002) concluded that the AG of GRB 011121 shows the anticipated SN1998bw-like contribution. Price and coauthors concluded from observations with HST that *"This curious bump is inconsistent with an underlying SN similar to SN 1998bw"* one day (Bloom et al. 2002a), and *"It appears that the case for an underlying SN in GRB 011121 is well established"* the day after (Kulkarni et al. 2002). As these authors caution, the conclusions (in the standard fireball paradigm) are affected by possible jet breaks (whose position and sharpness cannot be easily predicted).

In this letter we use the Cannonball Model to estimate the extinction in the host galaxy of GRB 011121, and to predict its late time optical AG[1]. We show that the evidence is clear: this GRB was indeed associated with a standard-candle 1998bw-like supernova at z = 0.36, the GRB's redshift.

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 –the persistent radiation in the direction of an observed GRB– 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:

$$\mathrm{F_{AG} = F_{CBs} + F_{SN} + F_{HG}}\,. \tag{1}$$

The contribution of the candidate host galaxy depends on the angular aperture of the observations and it is usually determined by late time observations when the CB and SN contributions become negligible.

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

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

where $\mathrm{D_L(z)}$ is the luminosity distance[2] and $\mathrm{A}(\nu,\mathrm{z})$ is the extinction along the line of sight.

The contribution of a jet of CBs to the GRB afterglow at "late" times (t > 1 day) is given by (Dado et al. 2001a):

$$\mathrm{F_{CB}} = \mathrm{f}\ [\gamma(\mathrm{t})]^{3\alpha-1}\ [\delta(\mathrm{t})]^{3+\alpha}\ \nu^{-\alpha}, \tag{3}$$

where f is a normalization constant (see Dado et al. 2001a for its theoretical estimate), α is the spectral index of the electron synchrotron radiation, $\gamma(\mathrm{t})$ is the Lorentz factor of the CB and $\delta(\mathrm{t})$ is its Doppler factor:

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

[1] In the CB model, like in the data, there are no sharp temporal breaks; and there is nothing sufficiently specific and conspicuous to be called a break time nor, therefore, any uncertainty associated with it.

[2] The cosmological parameters we use are: $\mathrm{H_0} = 65$ km/(s Mpc), $\Omega_\mathrm{M} = 0.3$ and $\Omega_\Lambda = 0.7$.

whose approximate expression is valid for small observing angles $\theta \ll 1$, and $\gamma \gg 1$: the domain of interest for GRBs. For an interstellar medium of constant baryon density n_p, the Lorentz factor, $\gamma(t)$ is given by (Dado et al. 2001a):

$$\gamma \;=\; \gamma(\gamma_0, \theta, x_\infty; t) = \frac{1}{B}\left[\theta^2 + C\,\theta^4 + \frac{1}{C}\right]$$
$$C \;\equiv\; \left[\frac{2}{B^2 + 2\,\theta^6 + B\,\sqrt{B^2 + 4\,\theta^6}}\right]^{1/3}$$
$$B \;\equiv\; \frac{1}{\gamma_0^3} + \frac{3\,\theta^2}{\gamma_0} + \frac{6\,c\,t}{(1+z)\,x_\infty} \tag{5}$$

where $\gamma_0 = \gamma(0)$, and

$$x_\infty \equiv \frac{N_{CB}}{\pi\, R_{max}^2\, n_p} \tag{6}$$

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, $A(\nu, t)$ in Eq. (2), can be estimated from the difference between the observed spectral index and the one expected[3] in the CB model ($\alpha \approx 0.5$ at $t < 1$ day, and $\alpha \approx 1.1$ after a couple of days). From the early-time relative intensities in the B and V bands of the AG of GRB 011121 we obtain a total selective extinction of $E(B-V) = 0.615 \pm 0.07$ magnitudes along the line of sight to GRB011121. Most of this extinction is due to dust in the Galaxy, $E(B-V) = 0.50$ (Schlegel et al. 1998) in the direction of GRB 011121. The total selective extinction yields an estimated attenuation factor $A(\nu, z) = 0.18$ in the V band ($A_V \approx 3.05\, E(B-V) = 1.87$ magnitude, Whittet 1991). From the early-time relative intensities in the I, R, V and B bands we deduce the attenuation factors $A(\nu, z) \sim 0.26\,, 0.22\,, 0.18$ and 0.11, to be used in Eq. (2) to estimate the expected spectral energy densities of SN1998bw at the position of GRB 011121.

We assume, for the late-time AG of GRB 011121, a spectral slope $\alpha = 1.1$, compatible with that of all other GRB AGs (Dado et al. 2001a). The rest of the fitted parameters are: $\gamma_0 = 1222$, $\theta = 0.104\,$mrad, and $x_\infty = 0.83\,$Mpc. The resulting lat-time R-band light curve is presented in Fig. (1). The contribution of the host galaxy has been subtracted. This contribution —$F_{HG} \approx 2\,\mu$J ($R_{host} \approx 23$) to the early-time measurement, and $0.127 \pm 0.026\,\mu$Jy to the late-time HST measurements— is a rough estimate: its true value depends, respectively, on the angular aperture of the observations and on the unknown extinction of the host galaxy's light within this aperture. In Figs. (2), (3) and (4) we present the CB-model's predictions for the light curves of the AG in the IVB bands, with the host galaxy's contribution subtracted with use of its magnitudes in these bands, as estimated by Bloom et al. (2002b), which correspond to $0.0209 \pm 0.059\,\mu$Jy,

[3] The time dependence of α is analized in detail in Dado et al. (2002c). The CB model predicts, and the data confirm with precision, the predicted gradual evolution of $\alpha(t)$ in the first day or two to the constant value ≈ 1.1 observed in all "late" AGs (Dado et al. 2001a).

$0.087 \pm 0.027\,\mu$Jy, and $0.098 \pm 0.039\,\mu$Jy, respectively. The theoretical contribution of an unextinct SN1998bw at redshift 0.36 to the BVRI bands was reduced by the attenuation factors $\mathrm{A}(\nu, \mathrm{z}) = 0.11$, 0.18, 0.22, and 0.26, due extinction by dust in the host galaxy and in ours, as estimated above.

The agreement between theory and observations in Figs (1) to (4) is almost surprisingly good, in view of the large observational uncertainties and the theoretical approximations. A similarly strong correspondence between predictions and observations is shown in Figs. (5) to (8), where we compare the predicted late-time spectral energy distribution, which is to a large extent dominated by the SN1998bw-like contribution, with the HST observations (Bloom et al. 2002b) on days 13-14, 23-24, 27-28 and 76-77.

Conclusion

In Dado et al. (2001b) we used the early afterglow data for GRB 011121 to predict the later AG, in particular the presence of a SN1998bw-like supernova transported to the GRB's redshift, which at the earlier time was still unobservable. All we have done in this letter is to update and refine these expectations with use of the improved observational constraints on absorption in the host galaxy, and to compare the prognosis with the early and late AG data. The 1998bw-like contribution is clearly there, in all of the light-curves at different frequencies, in all of the spectra at different times.

In Dar and De Rújula (2000) we argued that long-duration GRBs may all be associated with 1998bw-like supernovae, and that the diversity 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. (2001a) 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 afterglows of nearby GRBs discovered after these quoted works — that of GRB 000911, discussed in Dado et al. (2002a), that of GRB 010921, discussed in Dado et al. (2002b) and that of GRB 011121, discussed here— strengthen the conclusion: so far, in all AGs in which a SN like 1998bw was visible (in practice, in all 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 variations in this particular one. But the important fact is that the supernovae allegedly associated with all long-duration GRBs (Dado et al. 2001a, and references therein) **are indeed there**.

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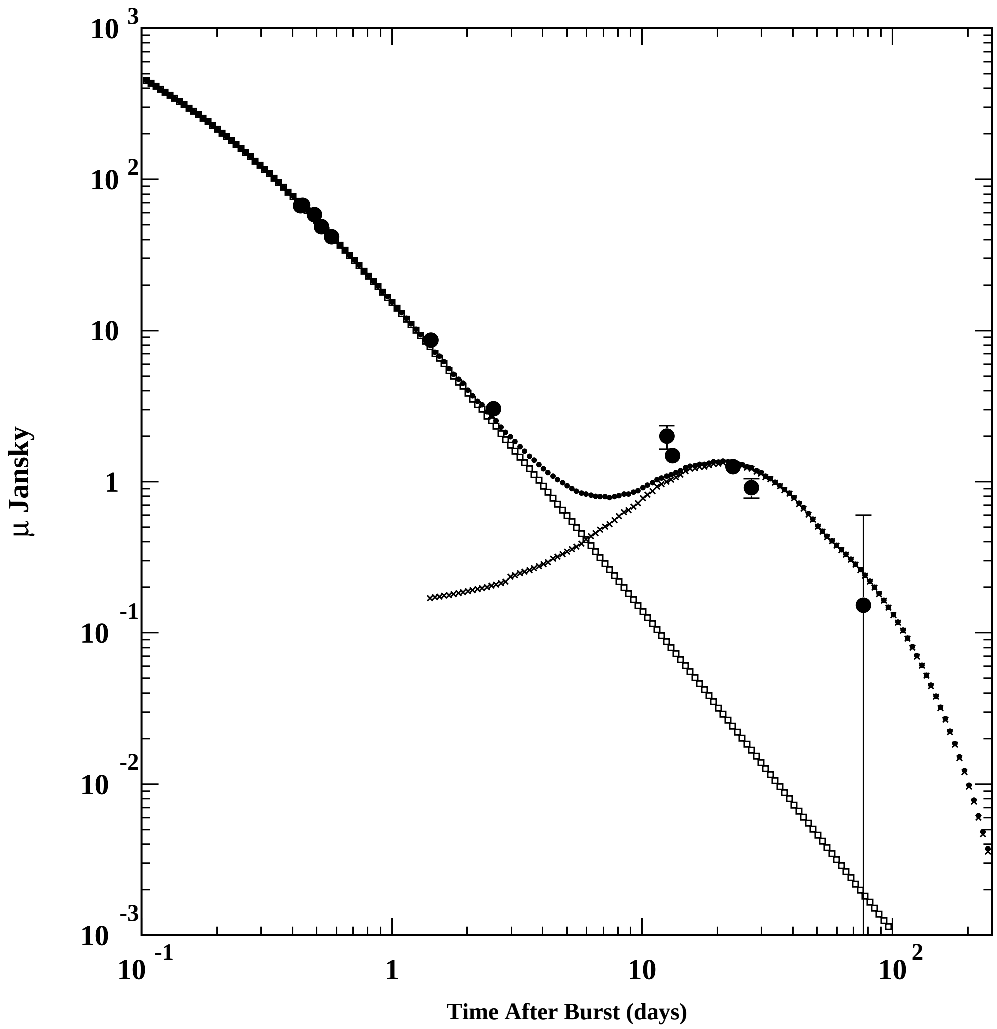

Fig. 1. Comparisons between our fitted R-band afterglow and the observations for GRB 011121 at z = 0.36. The CB's AG (the line of squares) is given by Eqs. (3) to (6). The observations are not corrected to eliminate the effect of extinction, so that the theoretical contribution from a 1998bw-like supernova placed at the GRB's redshift, Eq. (2), indicated by a line of crosses, is corrected by the corresponding estimated extinction factor. The contribution of the host galaxy has been subtracted.

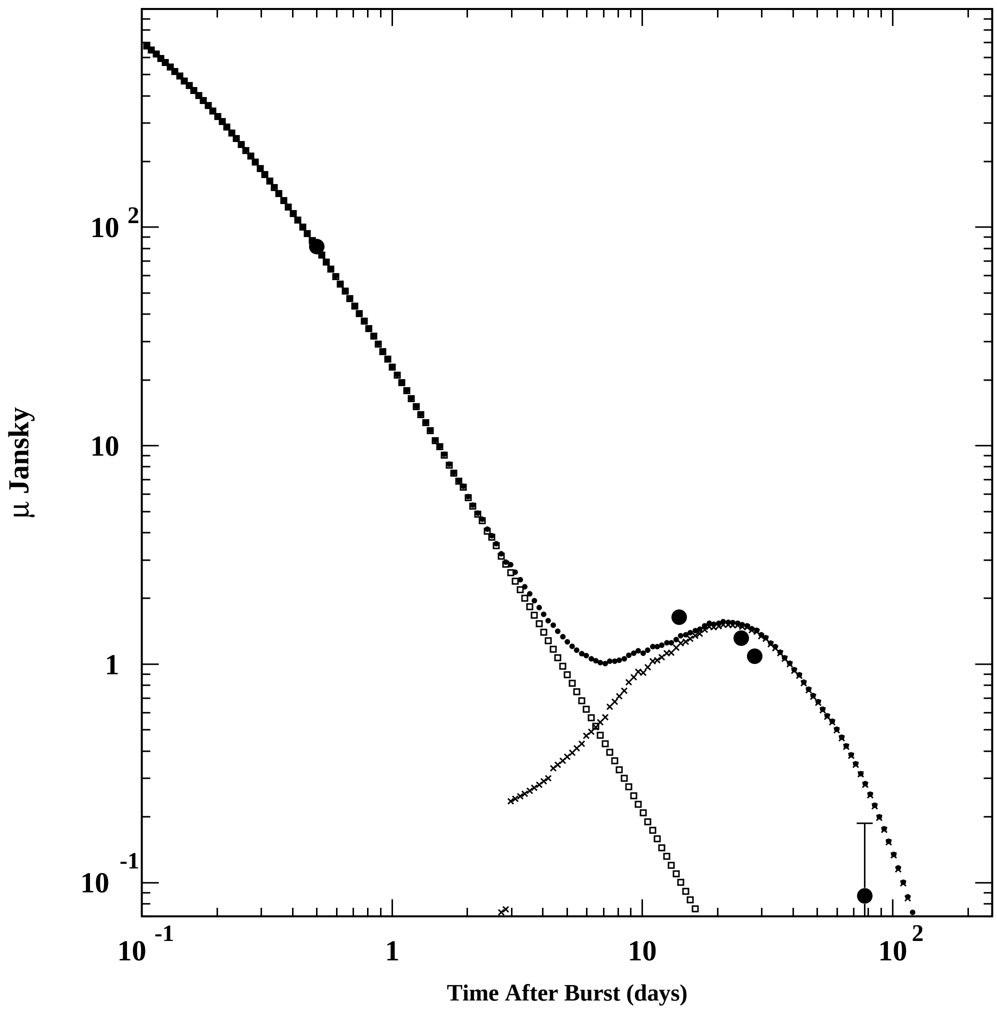

Fig. 2. Comparisons between our fitted I-band afterglow and the observations for GRB 011121 at z = 0.36. The CB's AG (the line of squares) is given by Eqs. (3) to (6). The observations are not corrected to eliminate the effect of extinction, so that the theoretical contribution from a 1998bw-like supernova placed at the GRB's redshift, Eq. (2), indicated by a line of crosses, is corrected by the corresponding estimated extinction factor. The contribution of the host galaxy has been subtracted.

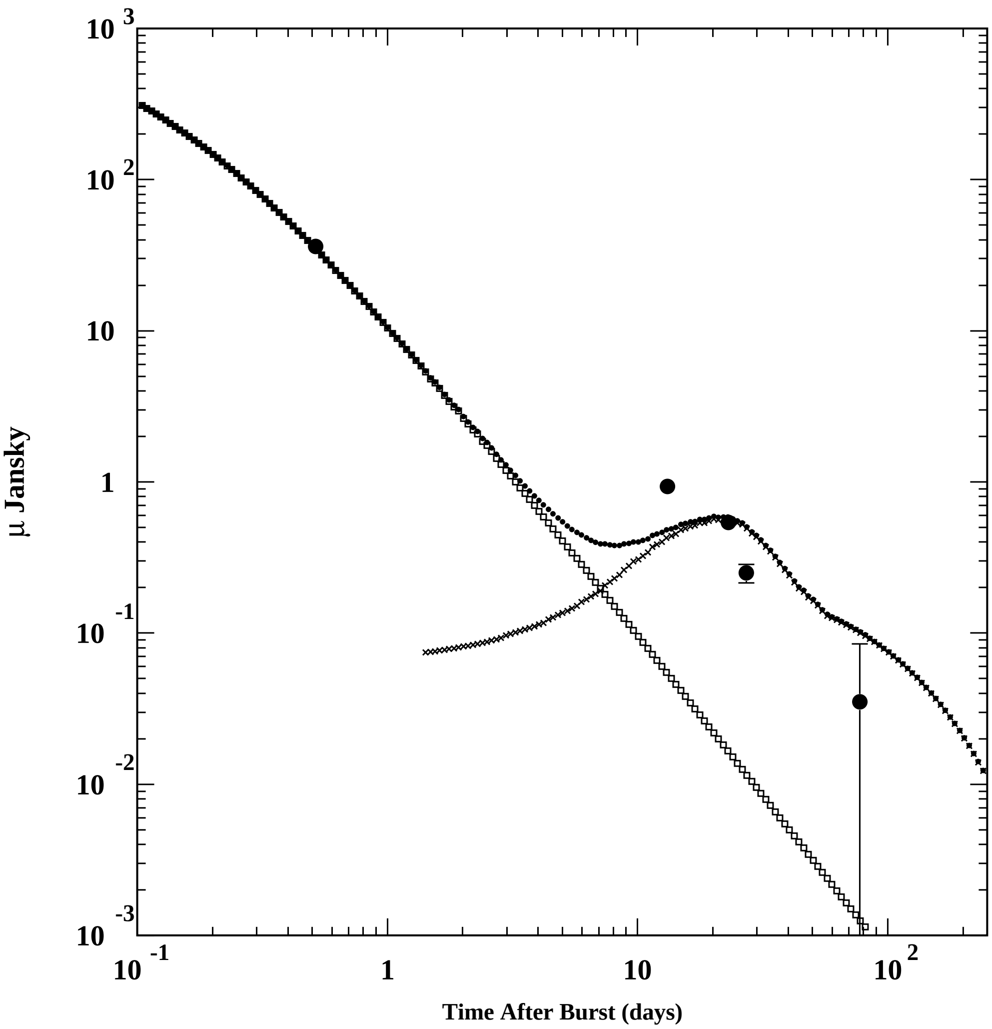

Fig. 3. Comparisons between our fitted V-band afterglow and the observations for GRB 011121 at z = 0.36. The CB's AG (the line of squares) is given by Eqs. (3) to (6). The observations are not corrected to eliminate the effect of extinction, so that the theoretical contribution from a 1998bw-like supernova placed at the GRB's redshift, Eq. (2), indicated by a line of crosses, is corrected by the corresponding estimated extinction factor. The contribution of the host galaxy has been subtracted.

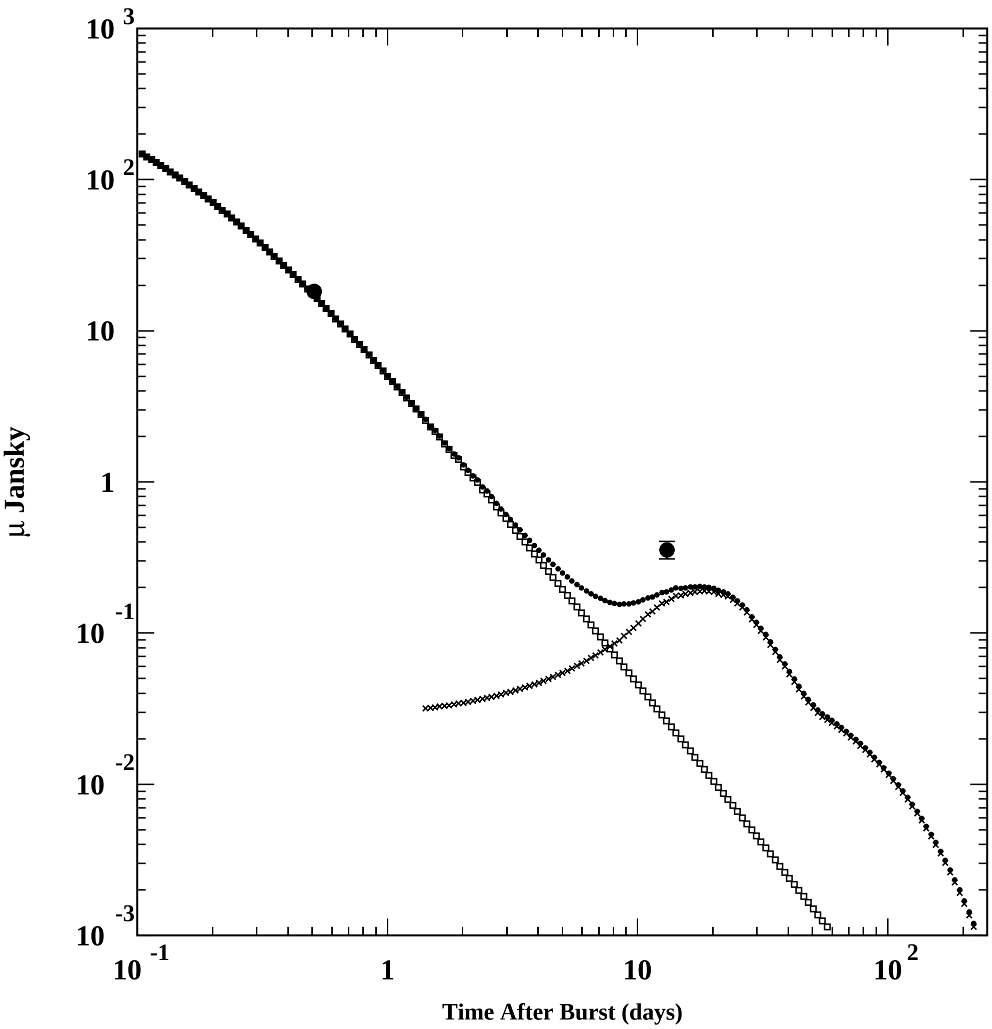

Fig. 4. Comparisons between our fitted B-band afterglow and the observations for GRB 011121 at z = 0.36. The CB's AG (the line of squares) is given by Eqs. (3) to (6). The observations are not corrected to eliminate the effect of extinction, so that the theoretical contribution from a 1998bw-like supernova placed at the GRB's redshift, Eq. (2), indicated by a line of crosses, is corrected by the corresponding estimated extinction factor. The contribution of the host galaxy has been subtracted.

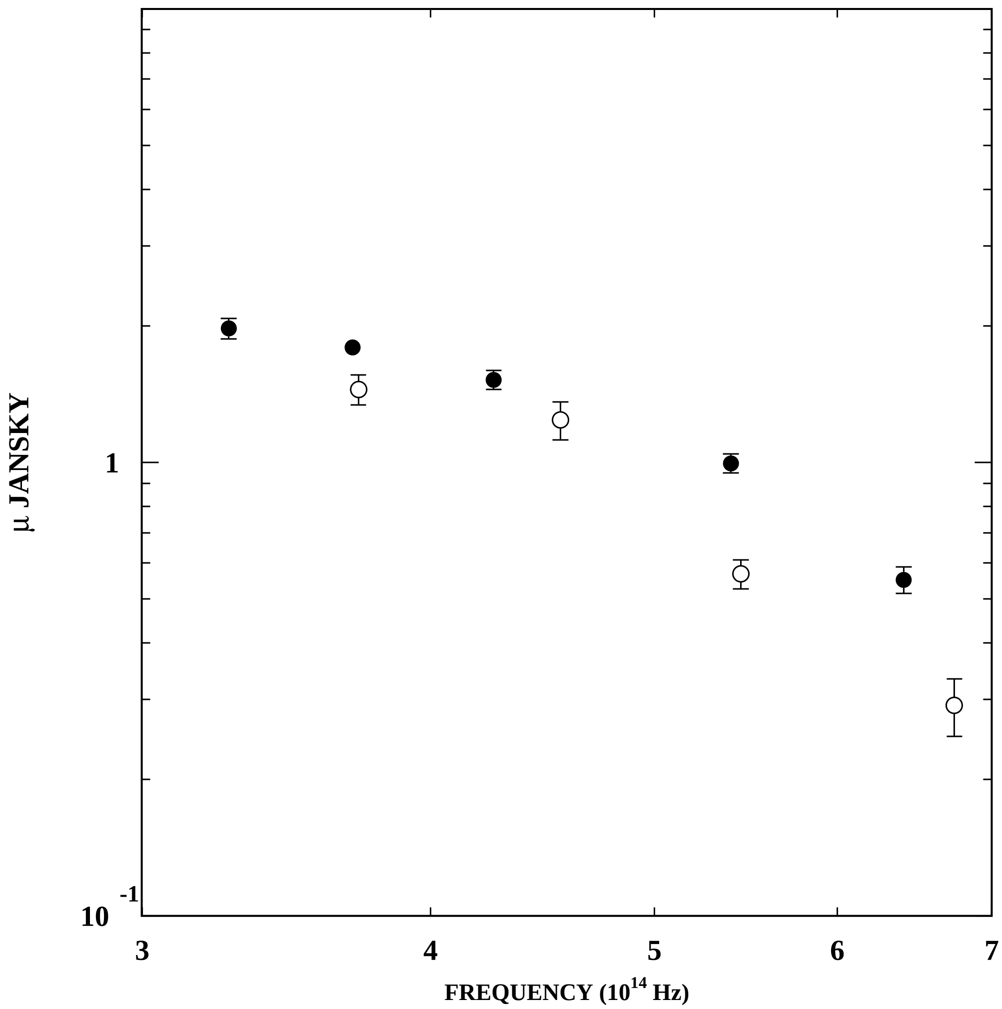

Fig. 5. The spectral energy density of the afterglow of GRB 011121 at days 13-14, at which the SN contribution is fairly dominant. The filled circles are the HST data of Bloom et al. (2002b), they are not corrected to eliminate the effect of extinction. The open circles are the CB-model's predictions: the CB AG plus a contribution from the host galaxy as estimated by Bloom et al. (2000b) and a SN1998bw-like contribution, properly redshifted in its time- and frequency-dependence, and corrected for extinction, all as in Eq. (2).

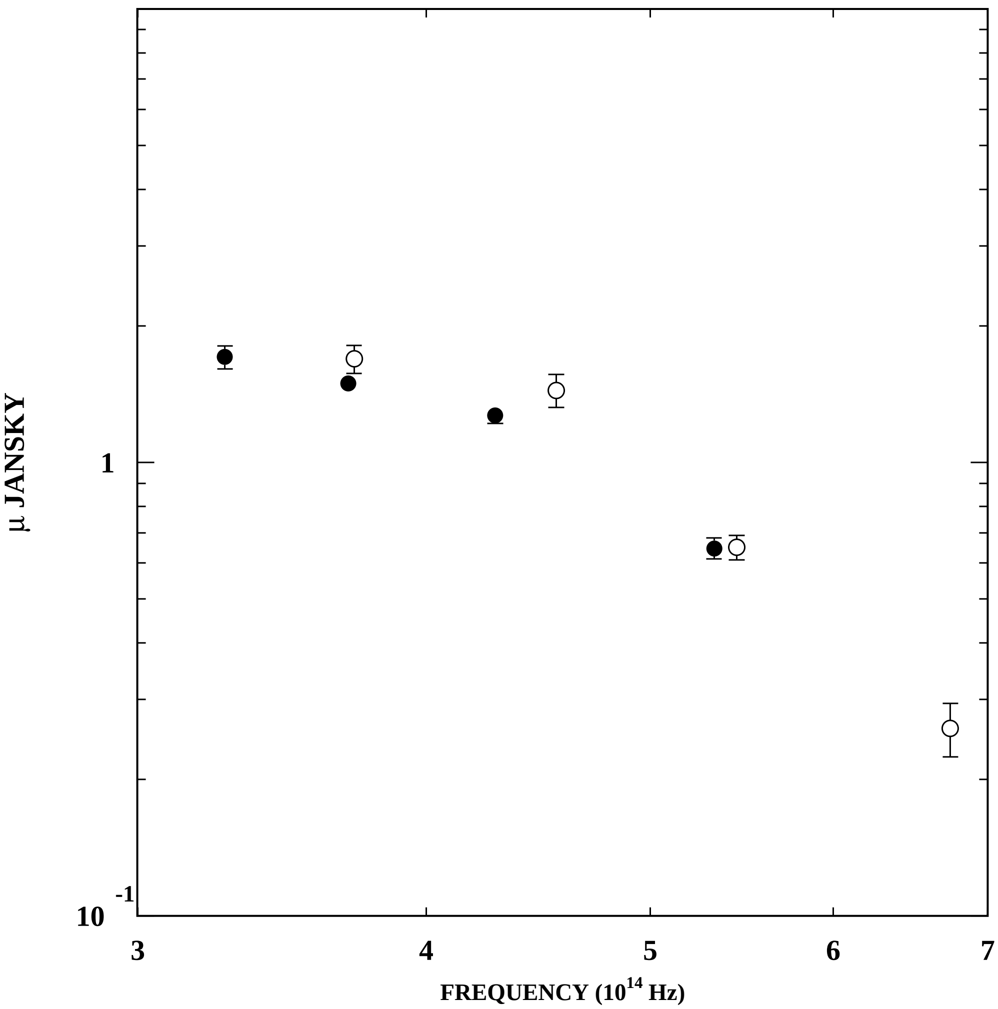

Fig. 6. The spectral energy density of the afterglow of GRB 011121 at days 23-24, at which the SN contribution is fairly dominant. The filled circles are the HST data of Bloom et al. (2002b), they are not corrected to eliminate the effect of extinction. The open circles are the CB-model's predictions: the CB AG plus a contribution from the host galaxy as estimated by Bloom et al. (2000b) and a SN1998bw-like contribution, properly redshifted in its time- and frequency-dependence, and corrected for extinction, all as in Eq. (2).

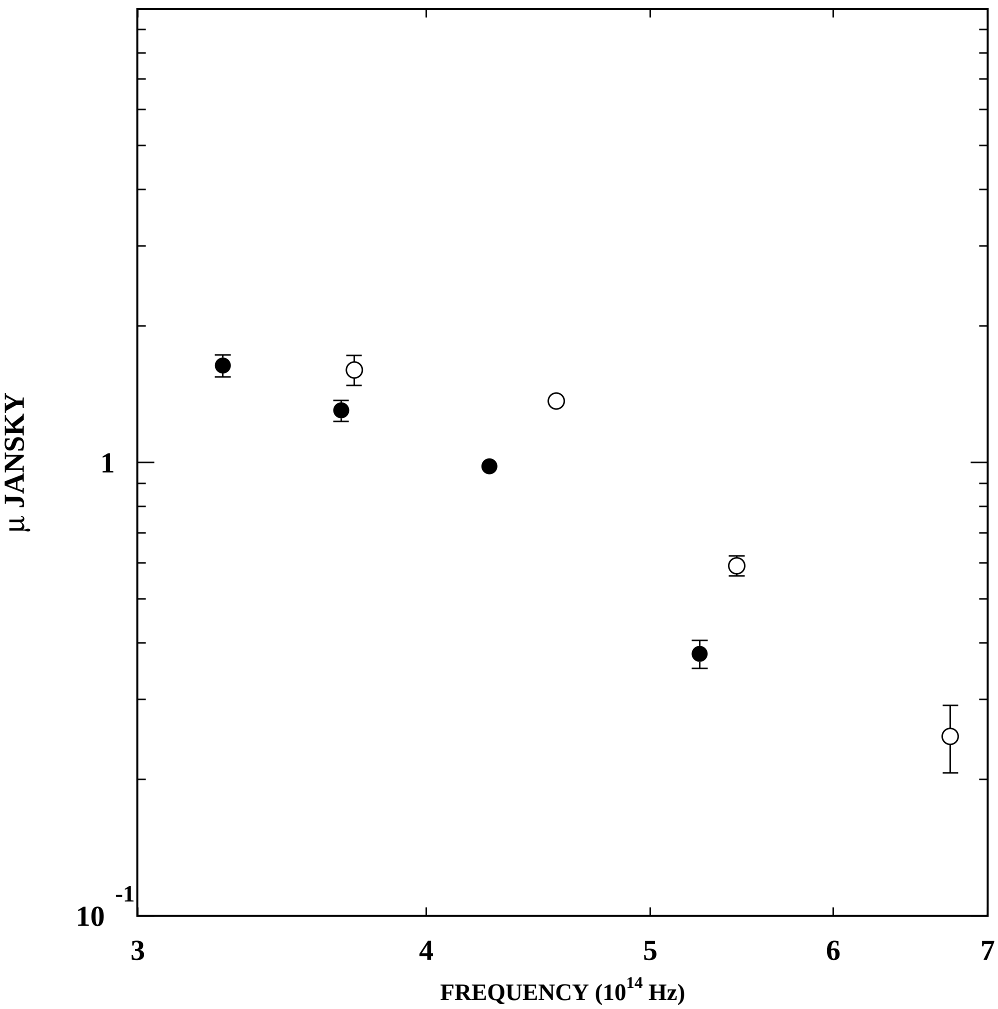

Fig. 7. The spectral energy density of the afterglow of GRB 011121 at days 27-28, at which the SN contribution is fairly dominant. The filled circles are the HST data of Bloom et al. (2002b), they are not corrected to eliminate the effect of extinction. The open circles are the CB-model's predictions: the CB AG plus a contribution from the host galaxy as estimated by Bloom et al. (2000b) and a SN1998bw-like contribution, properly redshifted in its time- and frequency-dependence, and corrected for extinction, all as in Eq. (2).

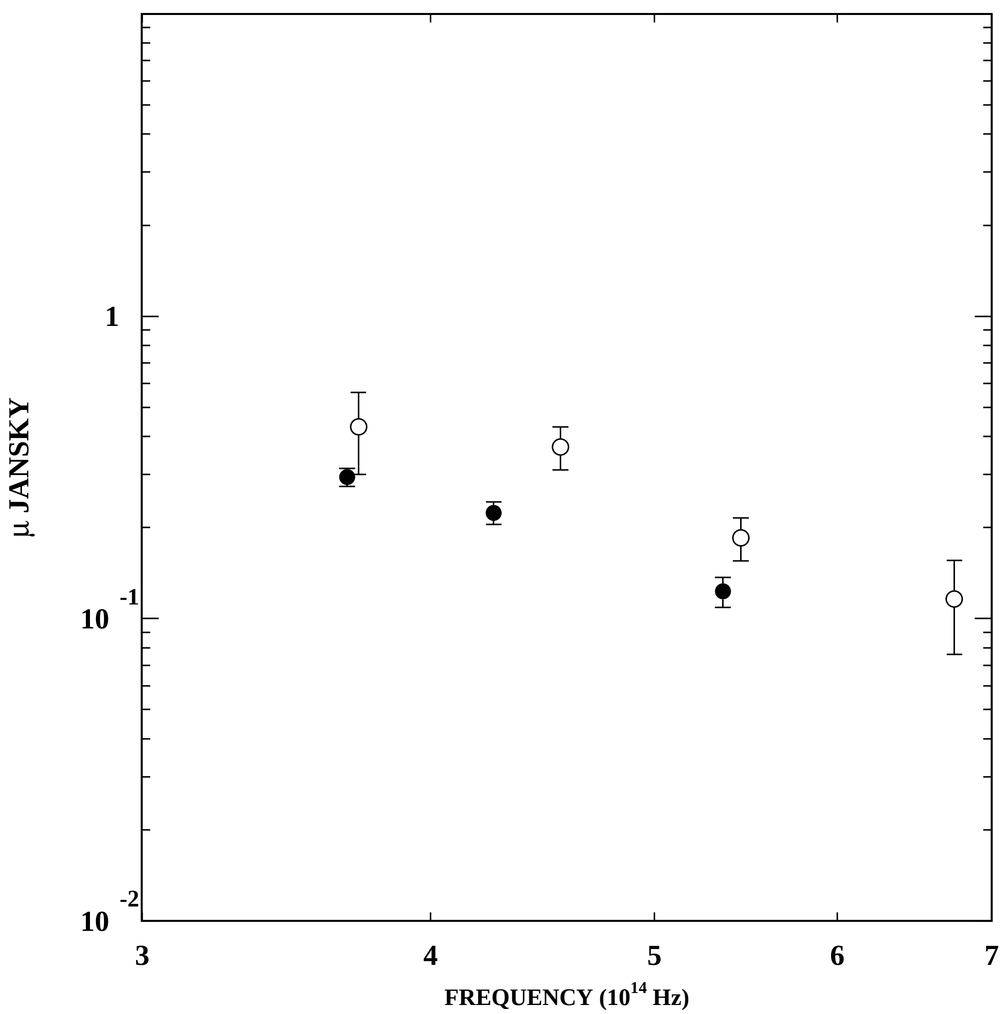

Fig. 8. The spectral energy density of the afterglow of GRB 011121 at days 76-77, at which the SN contribution is fairly dominant. The filled circles are the HST data of Bloom et al. (2002b), they are not corrected to eliminate the effect of extinction. The open circles are the CB-model's predictions: the CB AG plus a contribution from the host galaxy as estimated by Bloom et al. (2000b) and a SN1998bw-like contribution, properly redshifted in its time- and frequency-dependence, and corrected for extinction, all as in Eq. (2).