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Is there a 1998bw-like supernova in the afterglow of gamma ray burst 010921?

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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 GRB 010921 with ground-based telescopes at early times, and with the HST at later time. We show that GRB 010921 was indeed associated with a 1998bw-like supernova at the GRB's redshift.

The identity of the progenitors of gamma ray bursts is still debated. It has been suggested that GRBs are produced by highly relativistic jets (e.g., Shaviv and Dar 1995, Dar 1998) mostly from supernovae like SN1998bw (Dar and Plaga 1999, Dar 1999a, Dar and De Rújula 2000 and references therein). 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 the unknown redshift prevented a quantitative analysis. 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 990510 (Sokolov et al. 2001) and GRB 000911 (Lazzati et al. 2001).

Dar and De Rújula (2000) and Dado et al. (2001a) have shown that the optical AG of all relatively nearby GRBs with known redshift (all the ones with $z < 1.12$) contain evidence or 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, but more cases are needed before a firm conclusion can be reached.

On 2001 September 21.21934 UT a bright gamma ray burst (GRB 010921) was detected and localized (Ricker et al. 2002) by the High Energy Transient Explorer (HETE2) and the Interplanetary Network IPN (Hurley et al. 2001). Early observations of the error box of GRB 010921 with large aperture telescopes found no evidence of an optical afterglow to the limit R $\sim$ 20.5 (Fox et al. 2001, Henden et al. 2001). However, follow-up observations by Price et al. (2001) resulted in the discovery of its optical and radio AGs. This event was the first GRB localized by HETE2 which has resulted in the detection of an AG. Further observations by various telescopes (Park et al. 2002, Price 2002a and references therein) have shown that the GRB is located in a relatively nearby host galaxy with redshift z = 0.451 (Djorgovski et al. 2001) and that its optical afterglow exhibits a fast temporal decline and has a large spectral slope, -2.22 ± 0.23, after correcting for extinction in our galaxy, (E(B-V)=0.148; Schlegel et al. 1998), in the direction of the GRB. Due to its relative proximity and fast temporal decline, the AG of GRB 010921 should have shown an SN1998bw-like contribution, after subtraction of its host galaxy contribution, if it was associated with a supernova akin to 1998bw, located at z = 0.451.

In order to detect or constrain an underlying supernova in GRB 010921, observations with HST were obtained on 2001 October 26, November 6 and 25, and 2002 Jan 4 by Price et al. (2002b). From a fireball-model analysis of these observations, these authors identified a break in the optical light-curve around day 35 which they argued is due to the collimated ejecta, and concluded that the existence of a SN with a luminosity greater than 20% of SN 1998bw at z = 0.451 is ruled out. However, in this note, using the very successful Cannonball Model of GRBs (Dar and De Rújula 2000) and their afterglows (Dado et al. 2001a) to analyze the light-curve and spectral evolution of the AG of GRB 010921, we show that there is strong and clear evidence that GRB 010921 was associated with a supernova akin to 1998bw, at the GRB's redshift[1].

The CB model of GRBs

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

[1] Another nearby GRB that was predicted (e.g., Dado et al. 2001b) to show a clear SN1998bw like bump in its optical AG is GRB 011121 at z=0.36. Indeed, from their analysis of ground based and HST 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" (Bloom et al. 2002) one day, and "it appears that the case for an underlying SN in GRB 011121 is well established" the day after (Kulkarni et al. 2002).

are usually unresolved in the measured "GRB afterglows", so that the corresponding light curves and spectra refer to the cumulative energy flux density:

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

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

Core-collapse supernovae (SN of Types 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 CBs— 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, we use SN1998bw as an ansatz standard candle (Dado et al. 2001a and references therein). 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:

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

where $D_L(z)$ is the luminosity distance[2] and $A(\nu, z)$ is the extinction along the line of sight. The selective extinction in the Galaxy in the direction of GRB 010921 is $E(B-V) = 0.148$ (Schlegel et al. 1998). One can use standard conversion of E(B-V) to the attenuation in our galaxy, due to dust along the line of sight to the GRB at different wave lengths. The selective extinction in our Galaxy in the direction of GRB 010921 is expected to increase the spectral slope of the observed optical light by -0.64 ± 0.04.

The unextinct late time contribution of a CB to the GRB afterglow is given by:

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

where f is a normalization constant (see Dado et al. 2001a for its theoretical estimate), $\alpha \approx -1.1$ is the spectral index of the synchrotron radiation from Fermi-accelerated electrons in the CB whose acceleration rate is in equilibrium with their synchrotron cooling rate, $\gamma(t)$ is the Lorentz factor of the CB, and $\delta(t)$ is its Doppler factor:

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

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,

[2] The cosmological parameters we use in our calculations are: $H_0 = 65$ km/(s Mpc), $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

the Lorentz factor, $\gamma(t)$, as a function of observer's time, is given by (Dado et al. 2001a):

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

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).

After a correction for selective extinction in our galaxy (E(B−V) = 0.148 magnitudes in the direction of GRB 010921) the photometric measurements of its optical AG yield a spectral slope $\alpha = -2.22 \pm 0.23$ (Park et al. 2001; Price et al. 2002a). This slope is much steeper than the normally observed spectral slopes of GRB afterglows: ~ -0.5 at early time (the first couple of days) and ~ -1.1 later. We interpret this steepening as the effect of selective extinction in the host galaxy; a similarlly strong steepening of the spectral index, also consistent with strong extinction in the host galaxy, has been observed in the AG of a few GRBs, e.g., GRB 990712 (Bjornsson et al. 2001) and GRB 000926 (Harrison et al. 2001). Supportive evidence for strong extinction in the host galaxy of GRB 010921 is provided by the spectral index of its continuum light and by the relative intensity of its measured H_α to H_β emission lines (Price et al. 2002a), which is different from the expected intrinsic ratio of 2.87 (Mathis 1983) and yields an optical depth at H_β due to dust of 1.51.

Light-curve evidence

Assuming an intrinsic $\alpha = -1.1$ for the late-time AG (in agreement with all observed AGs of GRBs of known redshift, see Dado et al. 2001a), the best-fitted parameters to the AG of GRB 011121 are: $\gamma_0 = 1013$, $\theta = 0.15$ mrad, and $x_\infty = 0.48$ Mpc. In Figs. 1 to 3, we show the fitted light curves and the observations in the V, R and I bands, assuming a SN1998bw-like contribution at z = 0.451. The relative intensities were adjusted to fit the early time data. The difference between the expected intensity ratios for a spectral slope -1.1 and the observed relative intensities were used to correct the SN1998bw contribution for selective extinction in the host galaxy and in the Milky Way. The selective extinction in our Galaxy and in the host was also used to estimate roughly the overall attenuation normalization: $A_R \approx 2.8$ magnitudes in the R band. The fits are clearly very satisfactory.

Spectral evidence

The spectral index of the optical AG for most GRBs after a couple of days is approximately -1.1 (e.g., Simon et al., 2001). When dominated by a supernova contribution, the optical afterglows of GRBs become much more red (see, e.g., Reichart 1999; Bloom et al. 1999). The spectral index of the optical AG of GRB 010921 steepened to -3.5 ± 0.3 on day 35 and to -4.5 on day 46 (Price et al. 2002b) as expected when the AG is dominated by a supernova like SN1998bw. This is demonstrated in Figs. 4 and 5 where we compare the colours of SN1998bw at z = 0.451 —after extinction in the host galaxy and in ours— and the colours of the AG of GRB 010921, as measured with HST on days 35 and 46 after burst. The colours observed by HST are in good agreement with the expectation.

Conclusions

Contrary to the questionable[3] and inconclusive fireball-model analysis of the optical afterglow of GRB 010921, our analysis, based on the Cannonball Model, shows strong evidence for the contribution of a supernova akin to SN1998bw, seen at the GRB's redshift. The evidence is clearly there in all of the relevant observations: the I, R and V light curves, and the spectra at the times when the supernova's contribution is dominant.

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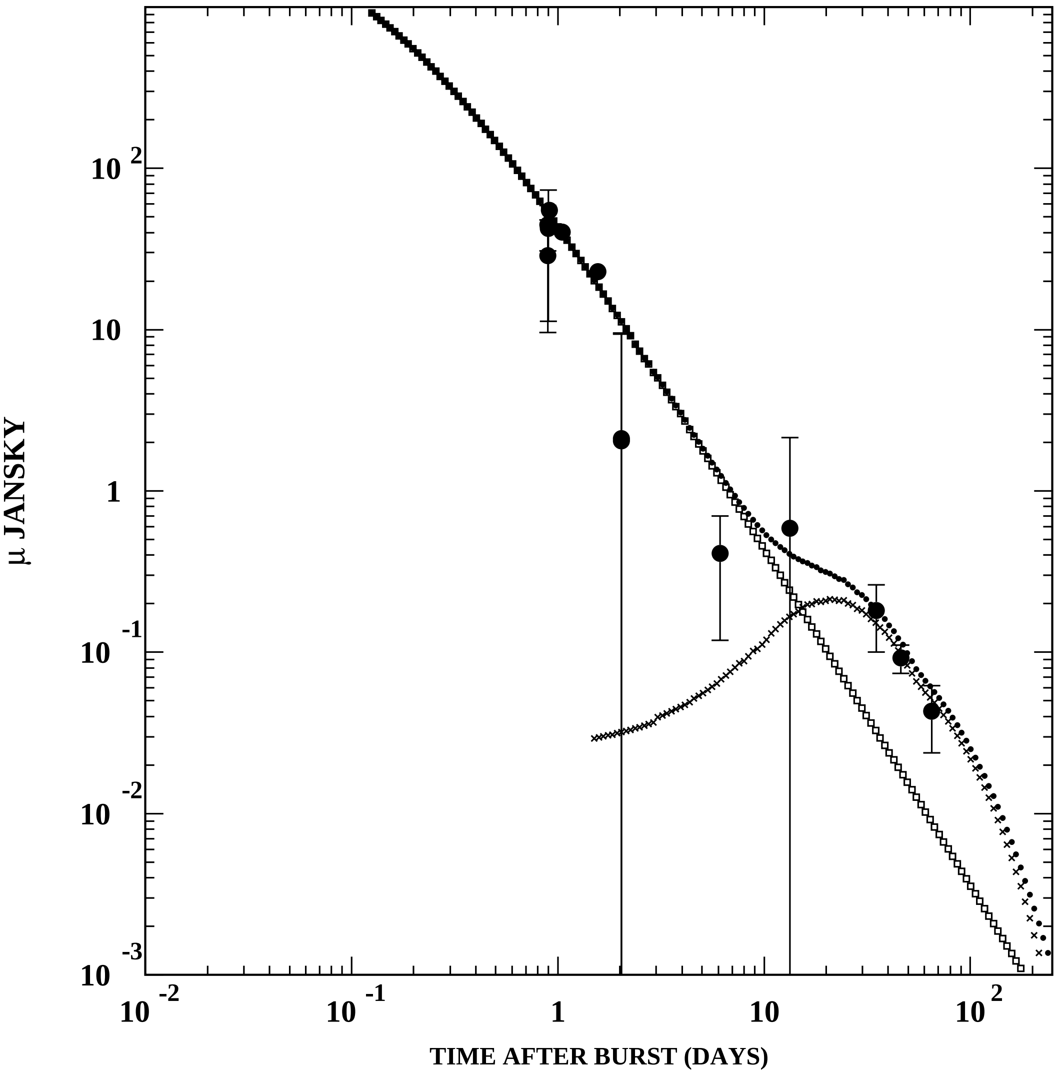

Fig. 1. The CB model fit and and the observations (Park et al 2001; Price et al. 2002a, 2002b) of the R band afterglow of GRB 010921 at z = 0.45. The CB's AG (the line of squares) is given by Eqs. (3) to (5). The contribution from a 1998bw-like supernova placed at the GRB's redshift and modified by galactic extinction, Eq. (2), is indicated by a line of crosses. The SN 1998bw-like contribution, is clearly observed.

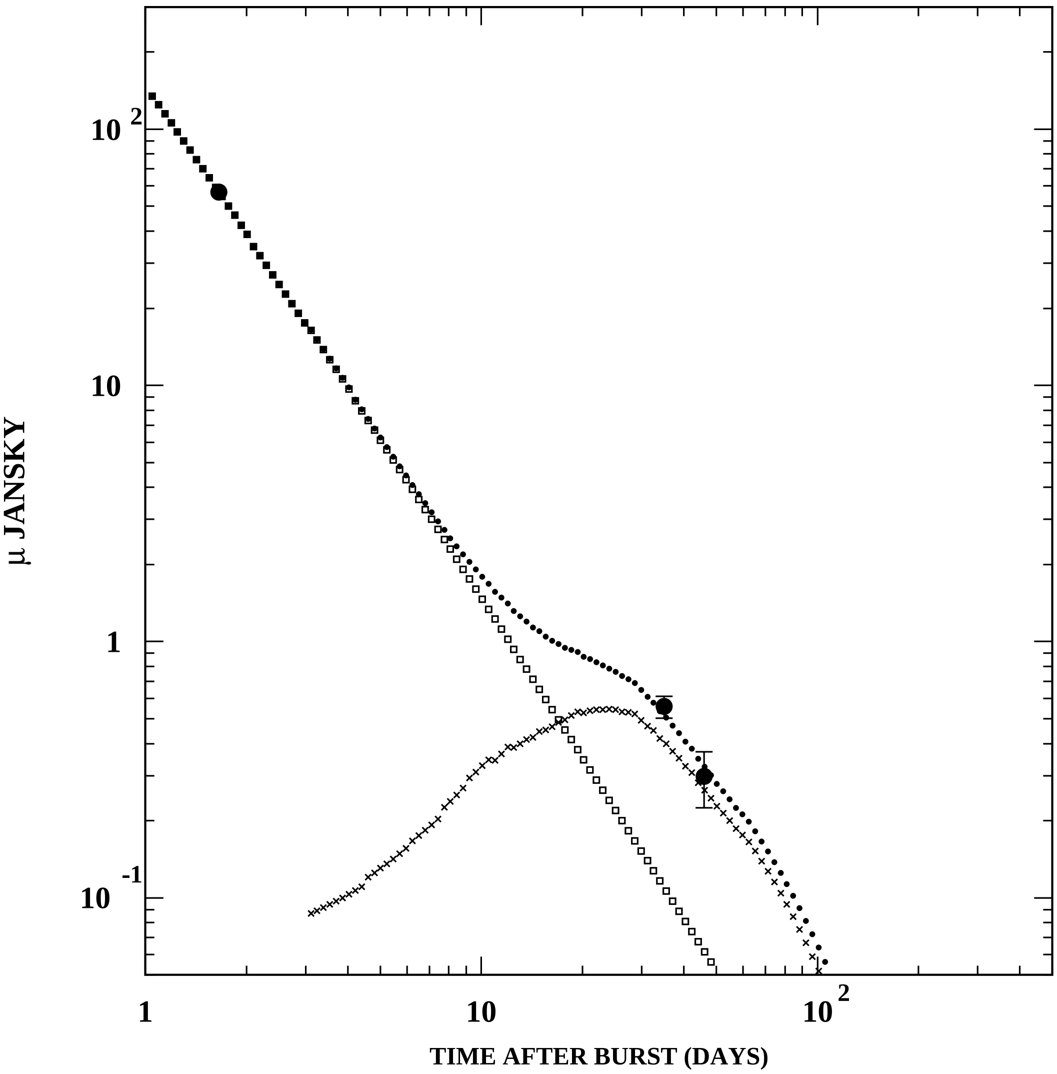

Fig. 2. The CB model fit and and the observations (Park et al 2001; Price et al. 2002a, 2002b) of the I band afterglow of GRB 010921 at z = 0.451. The CB's AG (the line of squares) is given by Eqs. (3) to (5). The contribution from a 1998bw-like supernova placed at the GRB's redshift and modified by galactic extinction, Eq. (2), is indicated by a line of crosses. The SN 1998bw-like contribution, is clearly observed.

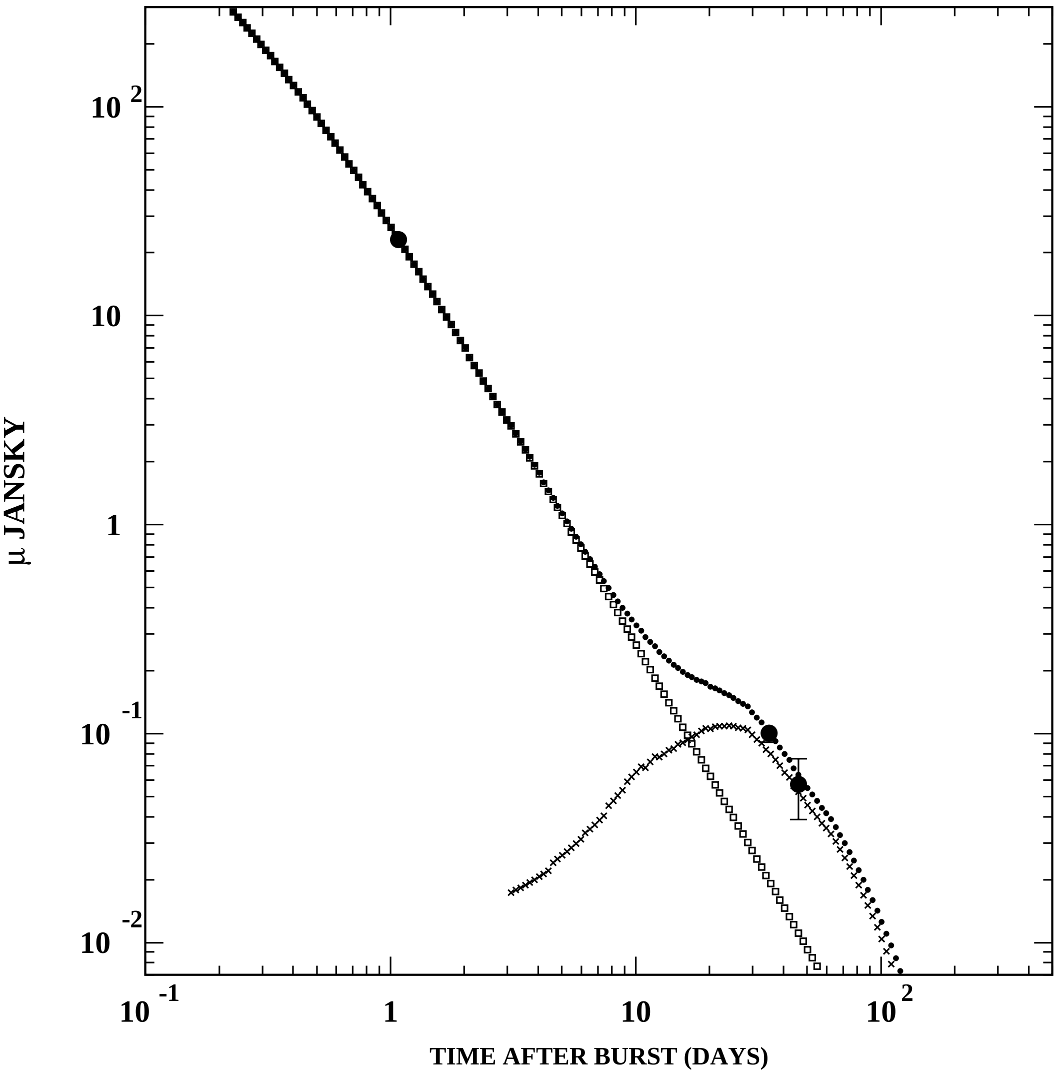

Fig. 3. The CB model fit and and the observations (Park et al. 2001; Price et al. 2002a, 2002b) of the V band afterglow of GRB 010921 at z = 0.451. The CB's AG (the line of squares) is given by Eqs. (3) to (5). The contribution from a 1998bw-like supernova placed at the GRB's redshift and modified by galactic extinction, Eq. (2), is indicated by a line of crosses. The SN 1998bw-like contribution, is clearly observed.

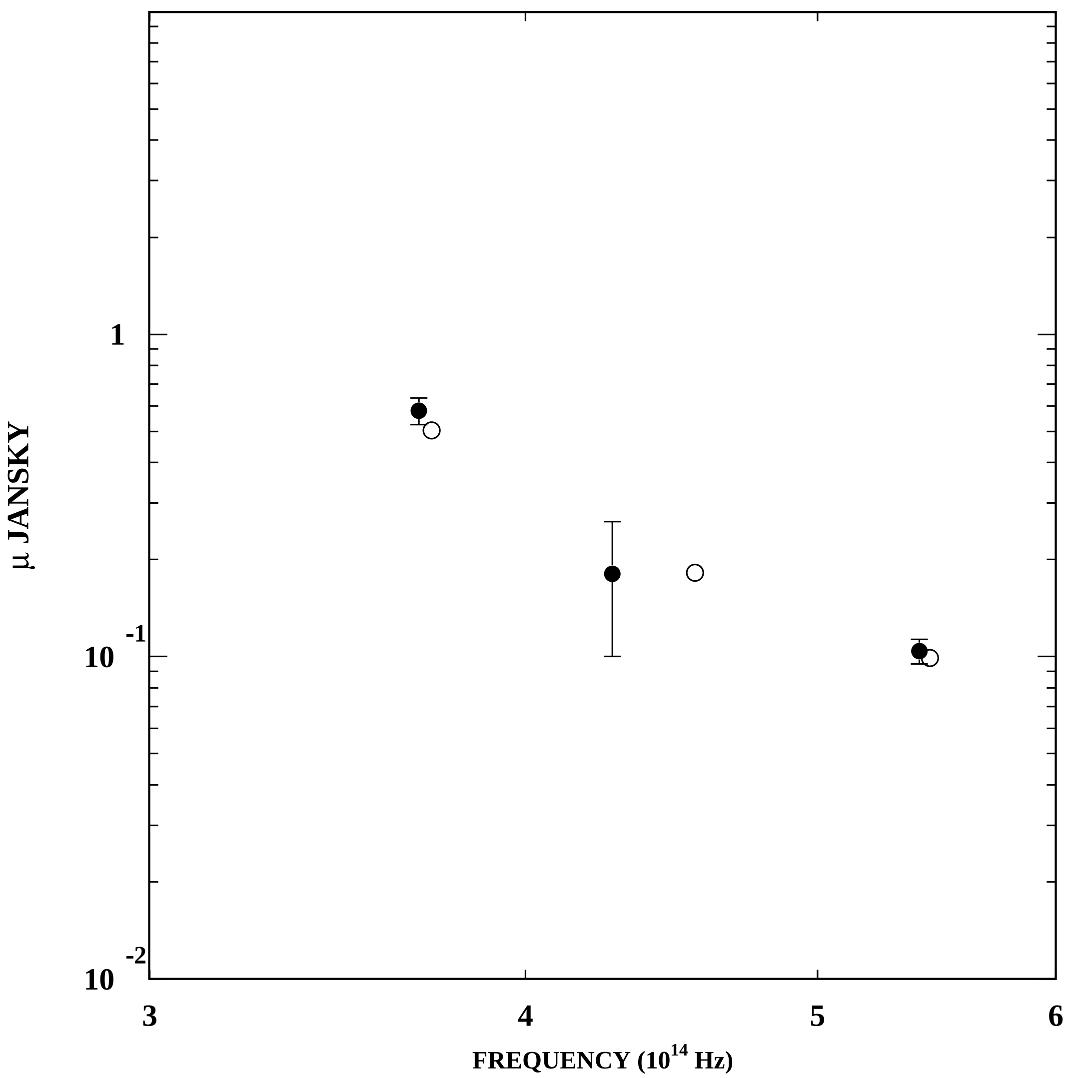

Fig. 4. Comparison between the CB model predictions (circles) for the spectral energy density in the I, R, V bands of the afterglow of GRB 010921 on day 35 after burst and the colours measured with HST (Price et al. 2002b) on that day (full circles). The predicted values are the sum of the light from the cannonballs and from a SN1998bw placed at z = 0.451, corrected for extinction in the host galaxy and in ours.

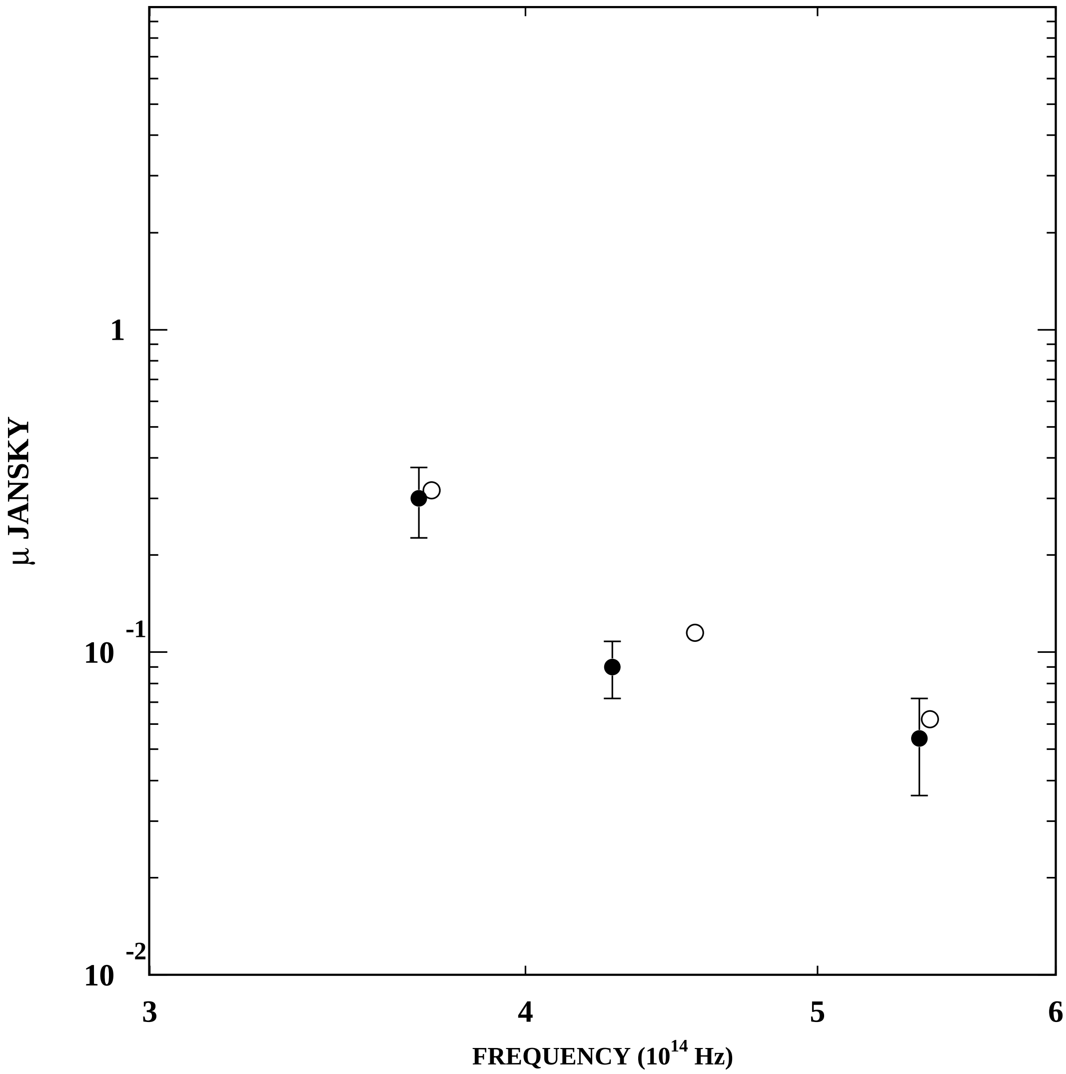

Fig. 5. Comparison between the CB model predictions (circles) for the spectral energy density in the I, R, V bands of the afterglow of GRB 010921 on day 46 after burst and the colours measured with HST (Price et al. 2002b) on that day (full circles). The predicted values are the sum of the light from the CB and from a SN1998bw placed at $z = 0.451$, corrected for extinction in the host galaxy and in ours.