Fireballs and cannonballs confront the afterglow of GRB 991208

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ABSTRACT

Galama et al. have recently reported their follow-up measurements of the radio afterglow (AG) of the Gamma Ray Burst (GRB) 991208, up to 293 days after burst, and their reanalysis of the broad-band AG, in the framework of standard fireball models. They advocate a serious revision of their prior analysis and conclusions, based on optical data and on their earlier observations during the first two weeks of the AG. We comment on their work and fill a lacuna: these authors have overlooked the possibility of comparing their new data to the available predictions of the cannonball (CB) model, based —like their incorrect predictions— on the first round of data. The new data are in good agreement with these CB-model predictions. This is in spite of the fact that, in comparison to the fireball models, the CB model is much simpler, much more predictive, has many fewer parameters, practically no free choices... and it describes well —on a universal basis— all the measured AGs of GRBs of known redshift.

Subject headings: gamma rays: bursts

Introduction

We discuss the afterglow of GRB 991208 as a good and simple example of a three-sided confrontation: the data, the generally accepted theory (the fireball model in its various incarnations, thereafter the "standard model": SM), and the cannonball (CB) model.

Gamma Ray Burst (GRB) 991208 was detected with the Interplanetary Network (IPN) on December 8.192 UT, 1999 and its afterglow (AG) was first detected on December 10.92 UT in the radio band (Hurley et al. 2000). The optical AG of GRB 991208 was first detected 2.1 days after burst and has been measured by Castro-Tirado et al. (2001) and Sagar et al. (2000). "Early" radio measurements, from 11.77 UT to 21.96 UT, December 1999 between 1.4 and 250 GHz were reported by Galama et al. (2000) (thereafter G1) and were analyzed in

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the framework of the SM along with the optical data. Follow up observations, up to day 293 after burst have been recently reported and reanalyzed by Galama et al. (2002), (thereafter G2), requiring a severe revision of their prior analysis and conclusions.

We have analized the AG of GRB 991208 in the realm of the CB model twice before: in Dado et al. (2002a), thereafter DDD1, we fitted the available R-band data on all GRBs of known redshift, z, including this one. In Dado et al. (2002b), hereinafter DDD2, we extended the analysis to wide-band fits of all the available optical and radio data. We present here a comparison between these CB-model predictions and the new data of G2. We also refit all the data including the new observations in G2. Consistently, the fit parameters change little as the new data are added. More importantly, the CB model, in spite of its simplicity and its scarcity of parameters and choices, is found to be successful: the predictions of DDD2 agree with the new data of G2, which is not the case for the SM predictions in G1.

GRB 991208 secundum Galama et al. (2000) [G1]

In G1 the authors first make a fit to the radio-to-optical spectral behaviour of data modified to pertain to a fixed "unified" date: December 1999, 15.5 UT. The "spectral parameters" are the self-absorption and peak frequencies, $\nu_{\rm a}$ and $\nu_{\rm m}$, the peak flux density, $\rm F_m$, and the power-law index of the electron distribution, p. With the resulting $\rm p = 2.52$ fixed, they fit the radio-only spectrum at 3 other unified dates within the first 2 weeks, by extracting values of $\nu_{\rm a}$, $\nu_{\rm m}$ and $\rm F_m$ separately for each of these dates. This procedure is useful as a test of the time evolution of these quantities but, *in totto*, theirs is a 13-parameter fit.

On the basis of their measured parameter-evolution, the authors of G1 discard spherical-explosion models, either with a constant-density interstellar medium (ISM), or a $1/\rm r^2$ "wind" circumburst profile (the "ISM" and "WIND" models). They also note that a "JET" model disagrees by $>4\sigma$ with the predicted power decline of $\rm F_m$. They advocate a model with a transition from a quasi-spherical to a jet evolution (Kumar and Panaitescu, 2000), but they stop short of an explicit analysis on these grounds. Yet, they conclude, with no proof, that "the jet model can account for the [observations...] provided that the jet transition has not been fully completed in the first two weeks after the event".

The closing predictions in G1 are that $\nu_{\rm a} \propto \rm t^{-14/13}$ at $\rm t > 10$ days, and the flux density $\rm F_\nu \propto t^{-(2.2\ to\ 2.5)}$ for $\nu = 8.46$ GHz at $\rm t > 12$ days, as well as for $\nu = 4.86$ GHz at $\rm t > 17$ days.

GRB 991208 secundum Galama et al. (2002) [G2]

Two of the results of the analysis in G2 are that $\nu_{\rm a} \propto {\rm t}^{-0.29^{-0.21}_{+0.17}}$ for a "FREE fit" to the ensemble of data, and $F_\nu \propto {\rm t}^{-1.07\pm0.09}$ at $\nu = 8.46$ GHz, for t = 53 to 293 days after burst. These results are in stark contrast with the quoted predictions of G1.

In the FREE model of G2 one extra cooling frequency, $\nu_{\rm c}$, is introduced, and $F_{\rm m}$ as well as $\nu_{\rm a}$, $\nu_{\rm m}$ and $\nu_{\rm c}$ are assumed to behave as ${\rm C_i\, t}^{-\alpha_{\rm i}}$, for a total of nine parameters (including p). Three SM variations are also discussed: ISM, WIND and JET, each of which predicts the values of $\alpha_{\rm F}$, $\nu_{\rm a}$, $\nu_{\rm m}$ and $\nu_{\rm c}$. The ISM and WIND models turn out to be inadequate, as in G1. The JET model (with its two new parameters) is an improvement over that of G1, but fails to reconcile the late-time decay $F_\nu \sim {\rm t}^{-1.1}$ at 8.46 GHz with the much steeper optical decay $F_{\rm R} \propto {\rm t}^{-2.2\pm0.1}$ —observed by Sagar et al. (2000) at t = 2 to 10 days after burst— which should similarly decline. The FREE model provides a satisfactory fit to the data, but implies that the combination $\gamma\,B^3$ of the bulk Lorentz factor of the flow and the post-shock magnetic field ought to be roughly constant, while both are expected to decline with time. In G2, the predictions by Li and Chevalier (2001) on the late-time behaviour of this AG (in a model with two electron energy distributions) are also found to fail.

Faced with so much unsuccess, the authors of G2 conclude that, in analogy to work by Frail et al. (2000) on GRB 970508, "the simplest explanation which is consistent with the data and requires no significant modifications is that the blast wave of GRB 991208 entered a non-relativistic expansion phase several months after the burst". As in G1, no explicit support is given to the conclusion.

The authors of G2 do not explain why they eliminate from their analysis the optical measurements at $t > 7$ days, a total of 10 points in the R, V, B and I bands (Fig. 2 of Castro-Tirado et al. 2001). Just the two R-band points at days $\sim$24 and 30 in our Fig. 1 are each 7σ above the extrapolation of the R-band fit in G2, after subtraction of the host galaxy contribution ($R = 24.27 \pm 0.13$, Castro-Tirado et al. 2001). It is not obvious that the advocated late non-relativistic blast-wave would remedy this discrepancy.

The parameters of the CB model

In the CB model four parameters suffice to describe the *optical* AGs in their various frequency bands. Three of them are "intrinsic" to the model: γ_0, the initial Lorentz factor of the CBs; x_∞, the single parameter governing the deceleration of a CB in the approximation of a constant-density interstellar medium (x_∞/γ_0 is the distance required to half the original Lorentz factor); and an overall normalization. A fourth parameter θ, the angle between the line of sight to the observer and the direction of the CBs, must be extracted from the AG fits, but it is, in the same sense as the redshift, not a parameter describing the model per se.

In extending the description of AGs from the optical to the radio domain only one extra time-independent parameter is necessary: a characteristic frequency for self-absorption within the CBs, $\nu_{\rm a}$, for a total of 4 intrinsic parameters (DDD2). In DDD1 we fit yet another parameter to the observations: the index p of the electron spectrum, prior to radiation losses. Having found that, in the CB model, it was always compatible with the theoretical expectation $\rm p \sim 2.2$, we no longer use it here, or elsewhere, as a free parameter.

GRB 991208 in the CB model

In Fig. 1 we show the fit of DDD1 to the R-band AG. The upper panel contains three contributions: the AG proper, the host galaxy and a “standard candle” supernova akin to SN1998bw, transported to the GRB’s redshift[3]. In the lower panel the galaxy is subtracted, demonstrating the presence of the SN: in a CB-model analysis, in all instances wherein such a SN could be seen, it was seen. This is so for all AGs with $\rm z < 1.2$ (DDD1), including the cases where the presence of a 1998bw-like SN was a prediction, based on the optical data *preceding* the observable SN contribution (GRBs 011121 and 020405; Dado et al. 2002c,d).

In Figs. 2 and 3 we show two fits to the radio data of GRB 991208, for $\nu = 1.43$, 4.86, 8.46 GHz (for which there is abundant new data in G2) and for 15 GHz, at which an earlier measurement had escaped our attention in DDD2. One of these wide-band fits (WB1) is the one published in DDD2, the other is a new fit (WB2), along identical lines, including the new radio data of G2. The figures show that the predictions of DDD2 were very satisfactory: the WB1 and WB2 curves are very similar and they both provide a good description of the data, their difference not being larger than the scintillating ups and downs of the data.

In the Table we give the parameters for the R-band fit of DDD1, the WB1 fit of DDD2 and the current WB2 fit. They appear to be quite stable. Even the fit to only the R-band data determines γ_0, θ and $\rm x_\infty$ to within a few percent of the results of the WB2 fit (117 data points in total), even though it is based on the mere dozen of early data points that are not dominated by the SN. The value of $\rm x_\infty$ in the WB1 fit is a bit smaller than in the others, the reason being that —as can be seen by inspection of Figs. 2, 3— this parameter is sensitive to the late observations, and the early radio data of G1 dominated the WB1 fit.

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[3] In the CB model, GRB 980425 —associated to SN1998bw— is in no way exceptional (Dar and De Rújula 2000, DDD1, DDD2). Unlike in the SM, it makes sense to use this SN as a putative standard candle.

For fits that are so similar, their single parameters describing the overall normalization are also necessarily similar: we have not reported them in the Table.

The CB model could be tested further by comparing the sky-projected superluminal velocity of the CBs (that may be extracted from the AG's radio scintillations, as for Galactic pulsars) with the predicted $\mathrm{v_{_T}(t)} \simeq \mathrm{c}\,\gamma(\mathrm{t})\,\delta(\mathrm{t})\,\theta/(1+\mathrm{z})$ (DDD2).

Asymptotic behaviours in the CB model

According to G2 *"one of the main challenges in modelling the AG of GRB 991028"* is to reconcile the late radio decline at 8.46 GHz with the optical decay, which is "twice" as fast. In the CB model this is not a challenge, both behaviours are correctly predicted:

Let SEF refer to the "proper" CB wide-band spectral energy flux (after subtraction of the host galaxy and the associated SN). Let $\gamma = \gamma(\mathrm{t})$ be the explicit function describing the decreasing Lorentz factor of the CBs (DDD1) and $\delta \simeq 2\,\gamma/(1+\theta^2\gamma^2)$ the varying Doppler factor of the radiation. The CB-model SEF has only two "bends". Self-absorption within the CBs results, in their rest system, in an opacity $\tau = (\nu_\mathrm{a}/\nu)^2\,(\gamma/\gamma_0)^2$, parametrized by the single parameter ν_a, and responsible for the turn down of the SEF towards low ν. At higher ν the spectral index steepens from $\sim\!-1/2$ to $-\mathrm{p}/2$ at an "injection bend" frequency:

$$\nu_\mathrm{b}(\mathrm{t}) \simeq \frac{1.87\times 10^{15}}{1+\mathrm{z}}\left[\frac{\gamma^3\,\delta}{10^{12}}\right]\left[\frac{\mathrm{n_p}}{10^{-3}\mathrm{cm}^{-3}}\right]^{1/2}\ \mathrm{Hz}, \tag{1}$$

in the observer's frame, with $\mathrm{n_p}$ the ISM number density (DDD2).

After a couple of (observer) days, $\gamma(\mathrm{t}) \sim \delta(\mathrm{t}) \sim \mathrm{t}^{-1/3}$ and for frequencies above the opacity bend, or "peak", the SEF behaves as:

$$\mathrm{F}_{\nu(\mathrm{t})\ll\nu_\mathrm{b}(\mathrm{t})} \ \sim\ \gamma^4\,\nu^{-0.5} \sim \mathrm{t}^{-1.33}\,\nu^{-0.5}\,, \tag{2}$$

$$\mathrm{F}_{\nu(\mathrm{t})\gg\nu_\mathrm{b}(\mathrm{t})} \ \sim\ \gamma^{2\mathrm{p}+2}\,\nu^{-\mathrm{p}/2} \sim \mathrm{t}^{-2.13}\,\nu^{-1.1}\,, \tag{3}$$

where there may be a $\sim\pm 0.1$ indetermination in the the exponents of t and ν, due to the uncertainty around our adopted value, $\mathrm{p} = 2.2$. These predictions (or, rather, the explicit formula in DDD2 interpolating them) are in agreement with the observations of all GRBs of known z. For the parameters that we fit to GRB 991208, $\nu(\mathrm{t})<\nu_\mathrm{b}(\mathrm{t})$ in the radio at the late observed times, and $\nu(\mathrm{t}) > \nu_\mathrm{b}(\mathrm{t})$ in the optical, even during the early optical observations. In spite of their dependence on the arbitrarily chosen time intervals, the observed late radio-behaviour at 8.46 GHz ($\sim \mathrm{t}^{-1.07\pm0.09}$, G2) and the optical result ($\sim \mathrm{t}^{-2.3\pm0.07}\,\nu^{-1.05\pm0.09}$, Castro-Tirado et al. 2001; $\sim \mathrm{t}^{-2.2\pm0.1}$, Sagar et al. 2000) are compatible with the above CB-model expectations, q.e.d.

Conclusions

We have reviewed a particular example of the failure of the standard model of GRBs in describing an afterglow (G1, G2), and the existence of a much simpler, predictive and successful alternative. This is not an exception, to date there is no satisfactory and comprehensive SM explanation of the AGs of all GRBs of known redshift. In DDD1 we have commented on some of the most complete studies (Frail et al. 2001; Kumar and Panaitescu 2001), which have, among others, the limitation of being "anthropoaxial" (all jets point to the observer, an unlikely circumstance).

Most researches in most areas of science are motivated by challenging their respective "standard models". This is the case even for models that are currently flawless, such as the SM of particle physics, or even for "sacred" pillars of science, such as quantum mechanics and general relativity. In studying G1 and G2, as well as most of the current GRB literature, it is difficult to suppress the impression that, for observers and theorists alike, the opposite motivation prevails. True enough, some of the profound inadequacies of the "fireball" or "firecone" SMs models are occasionally aired (e.g. Ghisellini 2001, Lazzati 2002), but the final verdict is always benevolent. The fact that new epicycles must be added with every "novel" observation is not unwelcome, even if the additions are ponderous and totally adhoc, as is the case in the interpretation of the Fe or other "metal" X-ray lines in GRB AGs (reviewed in Lazzati 2002) or of the wiggly AG of GRB 021004 (Lazzati et al. 2002; Nakar et al. 2002; Heyl and Perna 2002). In everyone of these cases the CB model offers an incredibly simpler alternative (Dado et al. 2002e,f).

We are not saying that the CB model is entirely correct, it is a simplification of what is no doubt a very complicated phenomenon; it will either require modifications or turn out to be completely wrong. But its assumptions and predictions should be tested against observations, or challenged for consistency. In other realms of science the existence of a sensible model challenging the standard lore would be very welcome, as opposed to ignored.

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AAS LaTeX macros v5.0.

Table: Successive CB-model fits to the AG of GRB 991208. R-band is a fit to only that optical frequency (DDD1). WB1 is the wide-band fit in DDD2, with only the early radio-data. WB2 is the current fit to all data.

Parameter	R-band	WB1	WB2
θ [mrad]	0.100	0.111	0.103
γ_0	1034	1034	1089
x_∞ [Mpc]	1.357	1.014	1.382
ν_a [MHz]	****	103	89

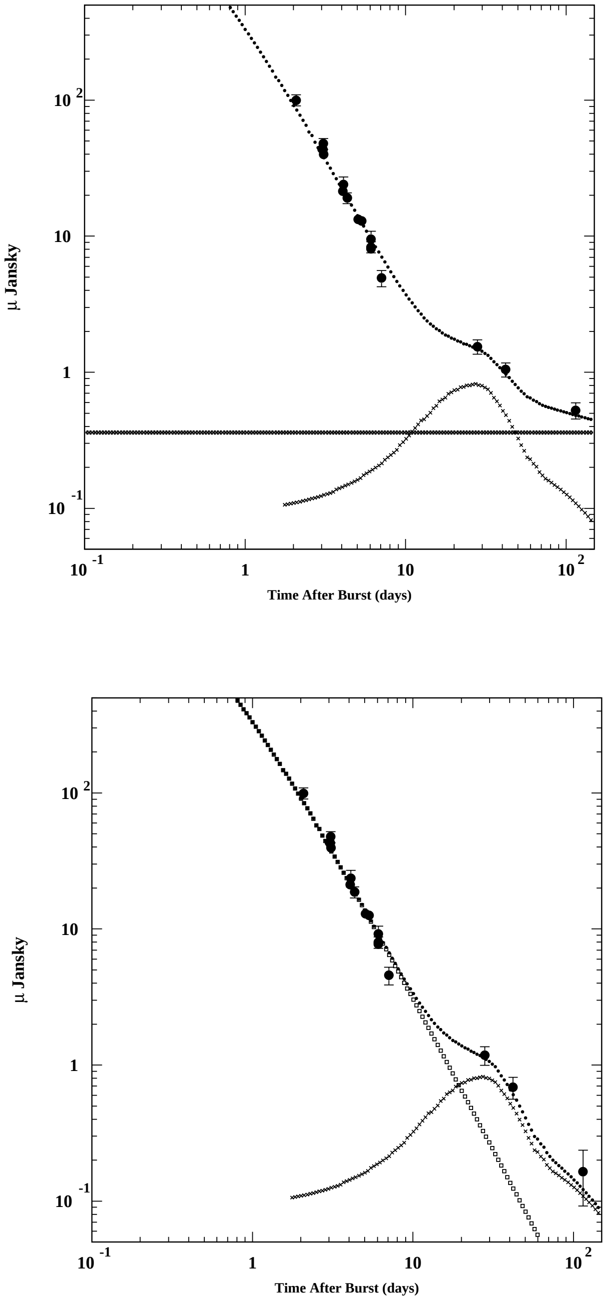

Fig. 1.— Comparisons between the R-band AG (upper curves) and the observations, not corrected for extinction, for GRB 991208, at z = 0.706 (DDD1). Upper panel: without subtraction of the host galaxy's contribution (the straight line). Lower panel: with the host galaxy subtracted. The contribution from a 1998bw-like supernova placed at the GRB's redshift, corrected for extinction, is indicated in both panels by a line of crosses. The SN contribution is clearly discernible.

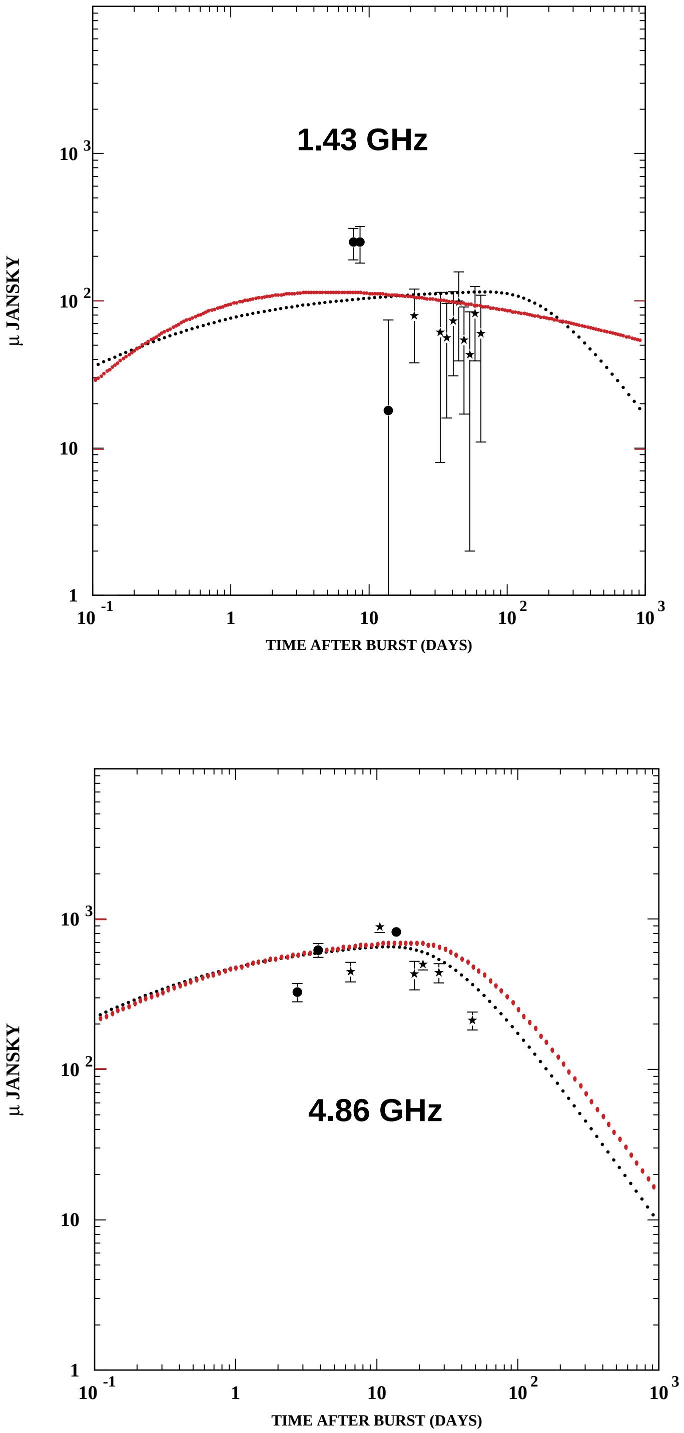

Fig. 2.— Comparisons between the CB-model radio light-curves and the observations at 1.43 and 4.86 GHz. The (red) continuous curve in the upper panel and the (red) higher-up dotted line in the lower panel are the results of DDD1, obtained without the new data, represented by stars. The other dotted lines in both panels depict the current fit to all data.

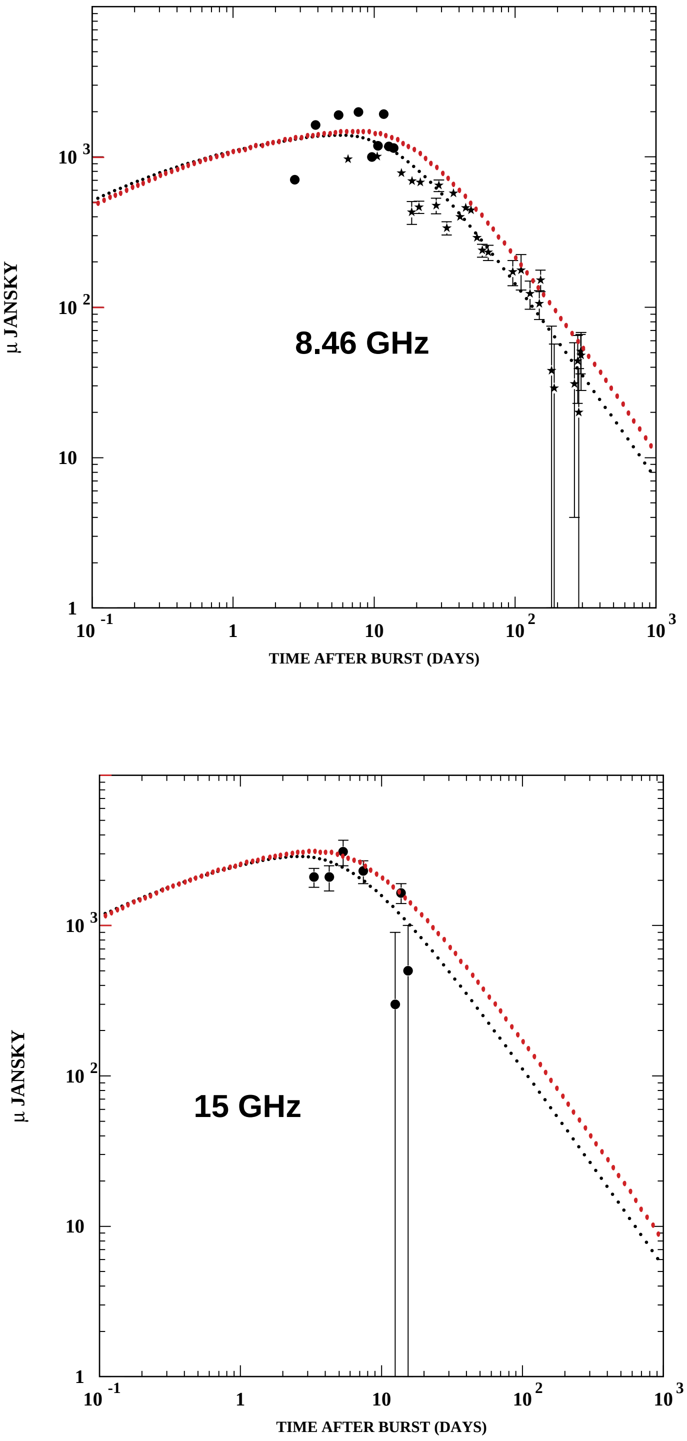

Fig. 3.— Comparisons between the CB-model radio light-curves and the observations at 8.46 and 15 GHz. The (red) higher-up dotted lines are the results of DDD1, obtained without the new data, represented by stars. The other dotted lines in both panels depict the current fit to all data.