

# The afterglow of GRB 021004: Surfing on density waves

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**Abstract.** We present a model for the early optical afterglow of GRB 021004. This burst had one of the earliest detected optical afterglows, allowing for a dense optical sampling. The lightcurve was peculiar, since bright bumps were superimposed to the regular power-law decay observed in many other events. We show that, given their time scale and shape, the bumps are likely due to the interaction of the fireball with moderate density enhancements in the ambient medium. The enhancements have a density contrast of order 10, modifying only slightly the dynamics of the fireball, which therefore surfs on them rather than colliding into them. A relativistic reverse shock does not develop. Since the interaction takes place when the fireball is still hyper-relativistic it is not possible to understand if the overdensities are localized in clumps or are spherically symmetric around the GRB progenitor. The monotonic decrease of the contrast of successive rebrightenings suggests however the presence of clumps embedded in a uniform environment. Such an interpretation, complemented by the detection of several high velocity absorption systems in the optical spectrum, strongly suggests that GRB 021004 exploded within the remnant of a previous explosion.

**Key words.** gamma rays: bursts – radiation mechanisms: non-thermal – ISM: structure

## 1. Introduction

On the 4th of October 2002 at 12:06:13 UT, HETE II detected a burst of  $\sim 100$  s duration (Shirasaki et al. 2002) with a 7–400 keV fluence of  $3.2 \times 10^{-5}$  erg cm<sup>-2</sup> (Lamb et al. 2002). The fast accurate localization allowed the robotic telescope Oschin/NEAT to detect the optical afterglow (OA)  $\sim 9$  min after the trigger (Fox 2002), at the level of  $R = 15.52$ . Observations performed earlier by Torii et al. (2002) yielded upper limits around  $R \sim 13.6$ ,  $\sim 3.5$  min after the trigger. The prompt OA identification allowed a very dense sampling of its light curve at early times (see the references listed in the caption of Fig. 1), and spectroscopic observations at medium to high resolution (Matheson et al. 2002; Møller et al. 2002; Fox et al. 2002; Anupama et al. 2002; Eracleous et al. 2002; Chornock & Filippenko 2002; Mirabal et al. 2002b; Sahu et al. 2002c; Salamanca et al. 2002; Djorgovski et al. 2002; Savaglio et al. 2002). The spectra revealed an emission line interpreted as Ly- $\alpha$  at  $z = 2.328$  and several absorption lines at slightly different redshifts, corresponding to velocity differences up to 3000–4000 km s<sup>-1</sup>, suggesting that the absorbing material could be either a clumpy wind ejected by a massive star progenitor or a clumpy remnant of a precursor supernova explosion (Salamanca et al. 2002; Mirabal et al. 2002b). The X-ray afterglow (XA), observed by *Chandra* (Sako & Harrison 2002) decays in time as  $t^{-1 \pm 0.2}$  with an average flux

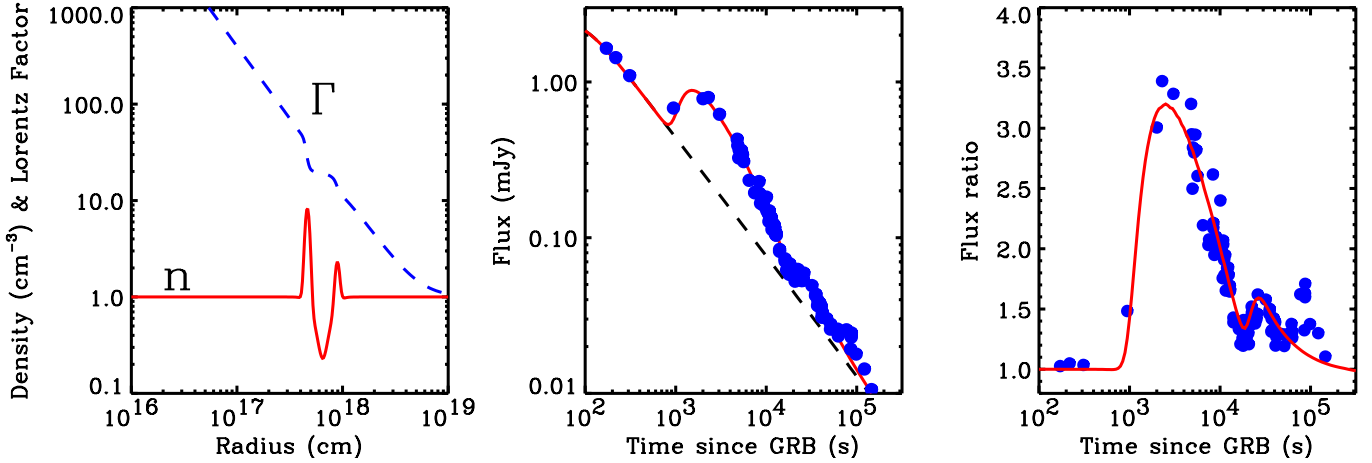
of  $4.3 \times 10^{-13}$  erg cm<sup>-2</sup> s<sup>-1</sup>. A preliminary spectral analysis shows no distinct features.

The peculiarity of this OA is the presence of a major rebrightening, with a rise time  $t_{\text{rise}} \sim t_{\text{start}}$  where  $t_{\text{start}}$  is the moment in which the rebrightening starts (see the central panel of Fig. 1). The flux then reconnects to the extrapolation of the early time observations for  $15 \lesssim t \lesssim 100$  hours after the GRB. In this time span, the lightcurve shows at least one (maybe two) additional bumps, but with smaller contrast. Such a behavior is unprecedented and is not due to a calibration problem (Henden 2002b).

In the lightcurve of GRB 970508, a major rebrightening was observed from the optical to the X-rays (Galama et al. 1998; Piro et al. 1998); in this case, however, after the rebrightening the flux remained larger than the extrapolation of the early time data and no additional feature was detected for a long time. Such a behavior was interpreted as due to the impact of a late shell of the fireball that gave additional energy to the forward shock (Panaitescu et al. 1998). In the case of GRB 000301C an achromatic rebrightening was observed. It had a very small time scale compared to the time at which it took place and was consequently interpreted as due to a micro-lensing effect (Loeb & Perna 1998; Garnavich et al. 2000).

In this Letter we propose that the rebrightenings observed in the lightcurve of GRB 021004 are the result of the interaction of the fireball with density enhancements (and possibly gaps) in the surrounding medium (Wang & Loeb 2000; Dai & Lu 2002). These inhomogeneities may either be in the form

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**Fig. 1.** ISM model and fits to the  $R$ -band light curve of GRB 021004. The left panel shows the density model, with an enhancement at  $R \sim 5 \times 10^{17}$  cm. The dashed line shows the evolution of the Lorentz factor of the fireball. The central panel shows a compilation of  $R$ -band photometry from GCNs. The solid line shows the lightcurve predicted for the density structure shown in the left panel, while the dashed line shows how the lightcurve would be in a uniform ISM. The right panel shows an emphasized version of the central one, in which the lightcurve variability is enhanced by dividing the data and the model by the uniform ISM case (the dashed line in the central panel). A third bump may be present at  $t \sim 10^5$  s, but we did not attempt to model it given the paucity of the data. In addition, further complications should be considered, since our model predicts the transit of the cooling break at  $t \sim 2$  d (possibly observed by Matheson et al. 2002), and a jet break is expected to appear at  $1.5 \lesssim t \lesssim 10$  d (Malesani et al. 2002). All the times are in the rest frame of the GRB host, and no correction for reddening was applied. Magnitudes are calculated using the calibration of Henden (2002a). Data from: Anupama et al. (2002), Balman et al. (2002), Barsukova et al. (2002), Bersier et al. (2002), Cool & Schaefer (2002), Di Paola et al. (2002), Fox (2002), Halpern et al. (2002a, 2002b); Holland et al. (2002b, 2002c), Klotz & Boer (2002), Klotz et al. (2002), Malesani et al. (2002), Masetti et al. (2002), Matsumoto et al. (2002a, 2002b), Mirabal et al. (2002a, 2002b), Oksanen & Aho (2002), Oksanen et al. (2002), Sahu et al. (2002a, 2002b), Stanek et al. (2002), Stefanon et al. (2002), Uemura et al. (2002), Weidinger et al. (2002), Winn et al. (2002), Zharikov et al. (2002).

of spherical shells – possibly due to instabilities in the wind ejection history of the progenitor star – or of clumps and filaments – possibly associated to a cooling supernova remnant (SNR). This latter interpretation seems to be corroborated by multiwavelength photometry and spectroscopy.

## 2. The model

We applied a numerical code to compute the lightcurve. The code takes fully into account the light travel-time effects, and assumes standard synchrotron emission equations to compute the comoving frame intensity (Panaitescu & Kumar 2000; Granot & Sari 2002). The fireball dynamics in a non uniform medium is treated by a numerical integration of the energy and momentum conservation equations (Rhoads 1999; Kumar & Panaitescu 2000), with the possibility of adding a reverse shock if a large density contrast is present.

The code assumes spherical symmetry for the environment properties and therefore we can model only radial inhomogeneities in the external medium. The results can be extended to a clumpy geometry with simple considerations (see Sect. 3). We did not include the detailed treatment of the fireball impact (Dai & Lu 2002) since the transient features that are predicted have a time scale much smaller than that due to the curvature of the fireball and are therefore smeared out by the integration on the equal arrival time surface.

When the fireball impacts on an overdensity, it goes through a transient phase, in which the flux increases sharply, relaxing asymptotically to the solution for an unperturbed medium with

the higher density (Sari & Piran 1995). The effect of the interaction depends on the spectral range, on the radial dependence of the average density (wind or interstellar medium, hereafter ISM) and on the cooling regime of the electrons. Since the transitory increase is smeared out, the increase in the flux can be estimated with the asymptotic solution. In a uniform density ISM for the slow cooling electron regime, an observation at a frequency above the cooling break will be insensitive to the density variation, while an observation between the peak (in  $F_\nu$  vs.  $\nu$ ) and the cooling frequency will yield a flux increase  $F_1/F_0 \propto (n_1/n_0)^{1/2}$ , where the subscripts 0 and 1 refer to the smaller and larger densities, respectively. In a wind environment, the same observation would depend linearly on the density contrast. In the case of fast cooling electrons any observation above the peak frequency will be insensitive on the density, both for the ISM and wind environments. In the radio band, the behavior can be even more complicated, since below the self-absorption break the flux will decrease in response to a density increase, while above the self-absorption the flux will increase. Finally, the situation can be made even more complicated by the fact that the break frequencies are shifted by the overdensity and may cross the observational band during the rebrightening.

As mentioned above, if the fireball bumps up against a density jump, a reflected (as well as a forward) shock can be generated, which propagates back into the hot relativistic shell. Its capability of modifying the fireball dynamics depends on the density contrast  $n_1/n_0$ . If  $n_1/n_0 > 250$  the bulk Lorentz factor of the reverse shocked hot shell is significantly ( $\sim 0.3$ ) lower

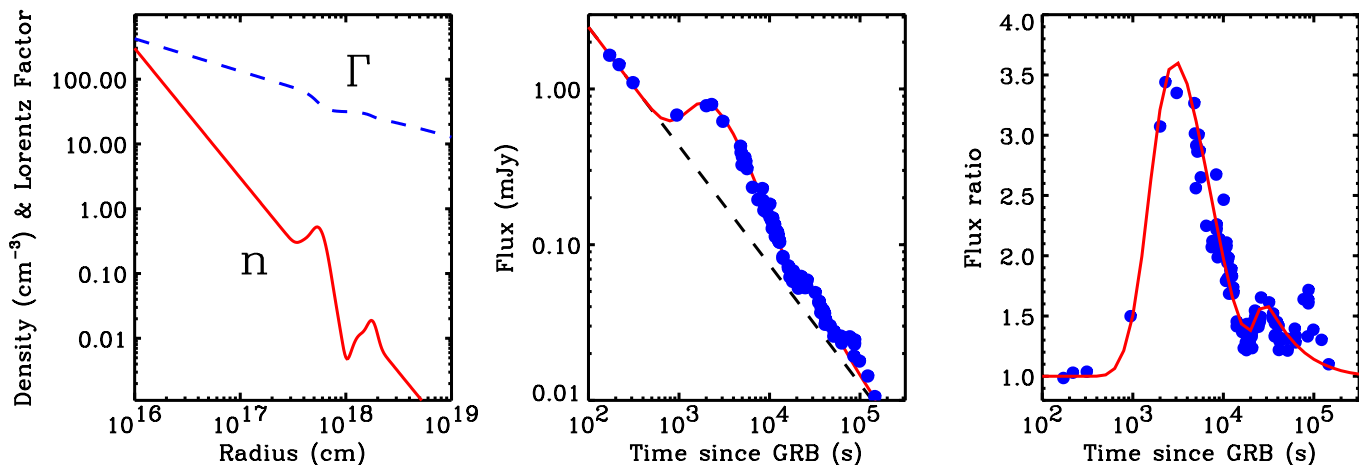


Fig. 2. Same as Fig. 1 but for a wind environment.

than that of the unshocked hot shell (at a fixed radius), since the relative Lorentz factor of the two shells is  $\Gamma_{\text{rel}} > 2$ . Therefore such a relativistic reverse shock substantially slows down the incoming fireball, converting most of the initial kinetic energy into internal energy. Its contribution to the emission must be taken into account. This is not the case with GRB 021004: the fireball encounters smaller density contrasts (see below and the left panels of Figs. 1 and 2) and the hot shell continues its run with an asymptotically almost unchanged Lorentz factor. Therefore in the following we will neglect any contribution from the reverse shock emission.

### 3. Results

Figures 1 and 2 show our model in the cases of an ISM and wind environment, respectively. Let us first discuss the wind case in Fig. 2, which we consider less likely.

As discussed above, a requirement in order to observe a rebrightening in a given band ( $R$  in our case) is that the electrons must be in the slow cooling regime and the band must lie between the peak and cooling frequencies. Such a constraint is easily fulfilled in a wind environment, since the cooling frequency increases with time. Under these conditions, the lightcurve should decay as a power law with an index<sup>1</sup>  $\delta_w = (p + 8)/8$  where  $p$  is the power-law index of the electron distribution [ $n(\gamma) \propto \gamma^{-p}$ ] and  $\delta_w$  is defined through  $F(t) \propto t^{-\delta}$ . The fitted lightcurve decay is  $\delta \sim 0.75$ , which would imply an unphysical distribution with  $p < 0$ . In addition (see Fig. 2) the density enhancements take place at a fairly large distance from the progenitor star, when the wind density is very small ( $n \sim 0.3 \text{ cm}^{-3}$ ). In these conditions, a more complicated density structure, due to the interaction of the wind with the ISM, would be expected (Ramirez-Ruiz et al. 2001).

We consider the case of a uniform environment more likely. In this case, the relation between the temporal decay of the OA and the electron distribution is  $\delta_{\text{ISM}} = 3(p - 1)/4$ , yielding  $p \approx 2$ . This value is theoretically acceptable, and is comparable to the values derived in other afterglows

<sup>1</sup> This relation holds if  $p < 2$  (Dai & Cheng 2001). We use it since the  $p > 2$  relation  $\delta_w = (3p - 1)/4$  yields inconsistently  $p = 1.35$ .

(Panaitescu & Kumar 2002). Moreover, it is consistent with the X-ray spectrum and temporal decay detected by *Chandra* at later times (Sako & Harrison 2002), if the X-ray band lies above the cooling frequency. Again, this is usual in observed XAs (see e.g. GRB 010222, in 't Zand et al. 2002). The required density contrast to explain the bump is  $n_1/n_0 \approx 8.5$  (Fig. 1).

The density of the ISM and the other afterglow parameters can be constrained by requiring that the optical  $R$  band lies between the peak and cooling frequencies and that the OA flux is consistent with observations. Such a procedure yields a moderately low density,  $n \sim 1 \text{ cm}^{-3}$ , of the uniform part of the environment. For the fit shown in Fig. 1 we also assumed an electron energy fraction  $\epsilon_e = 0.01$ , a magnetic field energy fraction  $\epsilon_B = 0.001$ , and an efficiency of converting the kinetic energy of the fireball into photons during the prompt phase of  $\eta = 5\%$ . It should be emphasized, however, that modeling with the standard afterglow theory is sensitive to some simplistic assumptions about the shock physics and about the magnetic field generation mechanisms (see, e.g., Rossi & Rees 2002). Due to the lack of a complete broad-band coverage of the lightcurve, a larger density could be envisaged. A robust upper limit to the average density can however be set by considering that a non-relativistic transition was not observed several days after the explosion. This yields  $n \leq 10^6 \text{ cm}^{-3}$ . It should also be mentioned that, even though all the magnitudes are corrected for the comparison star discussed by Henden (2002b), the data we are attempting to model have been taken with different telescopes and therefore absolute values and errors should be taken with caution. In addition, significant fast variability was detected (Halpern et al. 2002a). For these reasons we did not attempt to perform a formal fit to the data set, but rather to reproduce its general behavior. We also did not try to model the very small time scale variability of the lightcurve, which may be produced by small scale ISM turbulence as in GRB 011211 (Holland et al. 2002a).

What can be safely concluded from the observed rise time is that the overdensity lays at a distance  $R \sim 5 \times 10^{17} (E_{54}/n)^{1/4} \text{ cm}$  from the explosion centre, a value that is fairly independent of the assumed density. Interestingly, the value of the Lorentz factor at the beginning of the interaction

is even more robustly constrained, being  $\Gamma_1 \sim 50 (E_{54}/n)^{1/8}$ . This, together with the fact that we can reproduce the bump shape with a spherical overdensity (we do not see the edges of the clump), allows us to put a lower limit to the angular size of the clump  $\theta_1 \gtrsim 1^\circ$ . Interestingly, the Gaussian density enhancement we used has a radial width  $\delta R/R = 0.04$ , comparable to the inferred lower limit on the angular size. Two more considerations support the idea that the density structure is indeed clumpy rather than made by under and over-dense shells. First, we had to include in the radial density structure an under-dense part, due to the need of reproducing at best the decaying part of the first enhancement. The same behavior can be due to a clump that has an angular size similar to the relativistic beaming of the fireball ( $\theta \sim 1/\Gamma$ ). As soon as the fireball is slowed down by the interaction with the clump, the edges of the clump can be detected, with a corresponding decrease of flux. Secondly, the luminosity ratio of the second (and possibly the third) bump with respect to the underlying power-law is smaller than the contrast of the first bump (see right panel of Fig. 1). Our radial overdensity had therefore to be smaller (see Fig. 1). However, should a clump with the same overdensity and size of the first one be present at a larger distance, it would produce a bump in the lightcurve with a flux increase of a factor  $\mathcal{R}_2 \approx 1 + \mathcal{R}_1 (\Gamma_2/\Gamma_1)^2$ , where  $\mathcal{R}_1$  is the flux ratio for the main bump and  $\Gamma_2 < \Gamma_1$  is the Lorentz factor of the fireball at the moment of the interaction with the second clump. This is due to the fact that the second bump would interact with a smaller portion of the visible area of the fireball. The predicted ratio is  $(\Gamma_1/\Gamma_2)^2 \approx 7$  (left panel of Fig. 1), in excellent agreement with the data (right panel of Fig. 1). As a consequence, the lightcurve should evolve to a smooth decay due to (i) the smaller area of the visible fireball that would be affected by the interaction with a clump and (ii) the possibility of interaction with more and more clumps simultaneously.

We therefore conclude that the most likely environment for GRB 021004 is a uniform medium with clumps of density contrast of order 10 and size  $\Delta R \sim 10^{16}$  cm. Such an environment may be quite typical for relatively young SNRs (Böttcher et al. 2002). This evidence adds to the multiple high velocity absorption systems detected in the optical spectra (Salamanca et al. 2002), suggesting that the explosion of the burst took place within the remnant of a former explosion, likely a SN.

#### 4. Discussion and conclusions

We have presented a model to fit the OA of GRB 021004, which is characterized by the presence of bright bumps on top of the usual power-law decay. We suggest that the most likely origin for the bumps is the interaction of the fireball with density clumps, with a density contrast  $n_1/n_2 \sim 10$  and size  $\Delta R \sim 10^{16}$  cm. These clumps should lie at a distance of the order of  $\sim 5 \times 10^{17}$  cm from the explosion site, even though this number is uncertain due to the lack of a precise measure of the average density of the environment.

One possible alternative to this explanation is the presence of a very narrow and energetic component of the fireball, lying slightly off-axis from the line of sight (Panaietscu et al. 1998). In this case such a bump should be a common feature of all OAs

that an unprecedented early monitoring has now disclosed. Such a component, was however not seen in GRB 990123. In addition, the equality of  $t_{\text{start}}$  with the rise time  $t_{\text{rise}}$  would be a mere coincidence. It would also be difficult to explain the second (and possible third) rebrightening. Alternatively, the bump may be produced by a neutron decay trail ahead of the external shock (Beloborodov 2002). Again, a single bump would be expected in the simplest case.

Evidence for a clumpy geometry of the medium surrounding the GRB explosion site comes also from the detection, in the optical spectra, of multiple absorption features from intermediate ionization ions (e.g. CIV). The large velocity spacing of  $\sim 3000 \text{ km s}^{-1}$ , suggests a clumpy medium outflowing from the explosion site (Mirabal et al. 2002; Salamanca et al. 2002). The possible physical association of the absorbing clouds with those producing the afterglow rebrightenings is tantalizing, even though the former should lie at a larger distance, since all the carbon atoms are completely ionized within a distance  $R \gtrsim 10^{19}$  cm from the explosion site (a density of  $\sim 10^7 \text{ cm}^{-3}$  would be required to have recombination of free electrons onto the carbon nuclei in  $\sim 1$  day).

We speculate that the burst exploded within a Crab-like SNR, produced by a supernova that exploded 10–100 years before the GRB. Such a time interval is in the upper extreme, yet consistent, with what predicted by the Supranova scenario (Vietri & Stella 1998). This possibility was also suggested to account for the possible detections of X-ray lines (Piro et al. 1999, 2000; Antonelli et al. 2000; Reeves et al. 2002) in the early XA of several GRBs. In those cases, the SN-GRB delay should have been smaller (Lazzati et al. 1999, 2002). Consistently, no X-ray feature is detected in the X-ray spectrum of GRB 021004 (Sako & Harrison 2002) since the remnant is too far from the explosion site and its density too small. Also, the outflow velocity of the SNR inferred for this burst is much smaller than that required in bursts with X-ray features, consistent with the slow-down of the SN ejecta with time. Finally, if this interpretation is correct, the OA of GRB 021004 should not have a SN component in its lightcurve (see, e.g., Bloom et al. 2002), even though such a component would be in any case difficult to detect given the large redshift of the event.

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