Mem. S.A.It. Vol. 76, 655

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Modelling the afterglow of GRB 021004 with multiple energy injections

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Abstract. GRB 021004 is one of the best sampled gamma-ray bursts (GRB) to date. However, the nature of its light curve is still uncertain. We present a model in which 7 refreshed shocks take place during the evolution of the afterglow. The model has ben fitted using a compilation of multiwavelength (from radio to X-rays) observations from the literature together with more than 100 new optical near-infrared (NIR) and millimetre observations. The result implies a total energy release (collimated within an angle of $1^{\circ}.8$) of $\sim 8 \times 10^{51}$ erg. Analysis of the late photometry reveals that the GRB 021004 host is a low extinction ($A_V \sim 0.1$) starburst galaxy with $M_B \simeq -22.0$.

Key words. gamma rays: bursts – galaxies: fundamental parameters – techniques: photometric

1. Introduction

At 12:06:13.57 UT 4th October 2002 a long-duration GRB triggered the instruments aboard the HETE-2 satellite. The coordinates of the burst were rapidly transmitted to observatories all around the globe that pointed their telescopes a few minutes after the burst. A fast identification of the optical afterglow Fox (2002) allowed to produce one of the best multiwavelength coverages of a GRB obtained to date.

We analyse the light curve of GRB 021004 using new data together with observations from the literature. Our study covers the almost complete history of the event, from a few minutes after the trigger to more than a year after, when the afterglow light disappeared into the underlying galaxy. We pay special atten-

Send offprint requests to: A. de Ugarte Postigo tion to the bumpy nature of the light curve and, using the best multiwavelength sampling to date, apply a multiple energy injection model Björnsson et al. (2004).

Throughout, we assume a cosmology where $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and $H_0 = 72$ km s^{-1} Mpc^{-1}. Under these assumptions, the luminosity distance of GRB 021004, at the meassured redshift of z=2.3293 Castro-Tirado et al. (2005), is $d_l = 18.2$ Gpc and the look-back time is 10.4 Gyr.

2. Observations

For the study of GRB 021004 we obtained a large amount of observations from 11 telescopes world-wide de Ugarte Postigo et al. (2005), 9 in the optical and 2 in the near-infrared. We also made use of the radio telescope at Plateau de Bure for the millimetre ranges. These photometric information were combined with previously published multi-wavelenght observations, covering from radio to X-rays (Fox et al. 2003, Uemura et al. 2003, Pandey et al. 2003, Bersier et al. 2003, Holland et al. 2003, Mirabal et al. 2003, Pak et al. 2005, Sako et al. 2002a, Sako et al. 2002b, Berger et al. 2002, Frail et al. 2002) to obtain the completest possible data set.

3. Results and discussion

3.1. Host Galaxy

In order to constrain the model of the afterglow we need to isolate the flux produced by the afterglow from that of the underlying host galaxy. For the study of the host galaxy we use the $BVIJ$-band magnitudes measured when the contribution of the afterglow was negligible.

The fit of the host galaxy spectral flux distribution (SFD) is based on HyperZ Bolzonella et al. (2000), which compares our photometry whith available galaxy templates. The fitting assumes Solar metallicity, a Miller & Scalo (1979) initial mass function (IMF), a Small Magellanic Cloud (SMC) extinction law Prévot et al. (1984) and a redshift of z=2.3293 Castro-Tirado et al. (2005). The best fit is obtained with a ~ 15 Myr starburst galaxy with

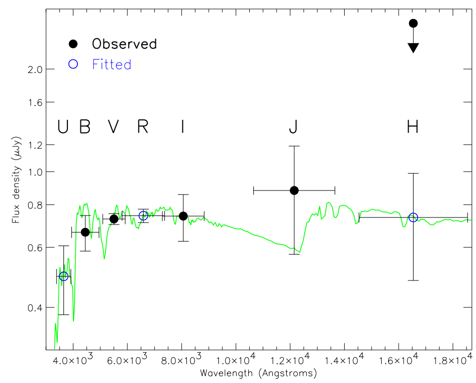

Fig. 1. A fit to the photometric points of the GRB 021004 host galaxy yielding a starburst galaxy template. The filled points are our observations while the void ones are obtained from the fit of the galaxy. The flux density is represented in logarithmic scale.

Table 1. Magnitudes for the GRB 021004 host galaxy. The values marked with * are measured values, while the rest are predictions obtained from the fitted template. The magnitudes are given in the Vega system.

Band	Magnitude
U	24.49 ± 0.28
B	$24.65 \pm 0.13^\star$
V	$24.45 \pm 0.04^\star$
R	24.21 ± 0.05
I	$23.82 \pm 0.17^\star$
J	$23.15 \pm 0.38^\star$
H	22.92 ± 0.31
K	22.42 ± 0.37

an absolute magnitude of $M_B = -22.0 \pm 0.3$ and an intrinsic extinction of $A_V = 0.06 \pm 0.08$ (see Fig. 1).

A prediction of the $URHK$-bands for the host galaxy can be made convolving the spectra of the fitted galaxy with standard optical and infrared filters (see Table 1). Errors are calculated using a Monte Carlo method in which the fitting of the galaxy is repeated with 20 randomly modified input $BVIJ$ magnitudes (Gaussianly weighted) in the measured error range.

The inferred host galaxy extinction, dominant stellar age and galaxy type are consistent with the findings reported by Fynbo et al. (2005) for GRB 021004. The age and the extinction are also consistent with the ones derived for GRB hosts in general, being similar to young starburst galaxies present in the Hubble Deep Field sample (Christensen et al. Christensen et al. (2004)). However, the *B*-band absolute magnitude of the host galaxy of GRB 021004 ($M_B \simeq -22.0$) is brighter than the 10 hosts present in the above mentioned sample.

3.2. Modelling

We adopt the standard fireball model Sari et al. (1998) to interpret the data. To account for the observed light curve brightenings, we modify the model by adding multiple energy injection episodes Björnsson et al. (2004); Jóhannesson et al. (2005).

Due to the high redshift of this object, the Lyman-α break is shifted to the range of the *U*-band. Thus, we must consider a correction for the Lyman-α blanketing that attenuates the flux in this band. We use the model described by Madau et al. (1995) at this redshift and convolve it with the Johnson *U*-band. This yields a reduction of the measured flux to 82% of the original one. Due to the uncertainty of this approximation, we do not use the corrected *U*-band for fitting the model, but only for the verification of it.

The best fit of the afterglow light curves (see Fig. 2 and Fig. 3) is obtained when we correct the photometry with a Small Magellanic Cloud (SMC) extinction law and $A_V \sim 0.1$. The parameters that result from the modelling are displayed in Table 2.

The bumpy light curve behaviour may also be explained by the patchy shell model Nakar et al. (2003), or by density variations in the surrounding medium Lazzati et al. (2002), although in the latter case, simultaneously accounting for the polarization measurements appears to be problematic. As in the refreshed shock model, the number of required parameters in these models also increases with the amount of structure in the light curve.

Table 2. Model parameters. E_i are the injection ernergies, being E_0, the initial energy. Other parameters: initial Lorentz factor Γ_0, ambient density n_0, half opening angle θ_0, line of sight angle θ_v, electron energy index p, fraction of internal energy stored in electrons after acceleration ϵ_e and fraction of internal energy stored in the form of magnetic field ϵ_B.

Parameter	Value
E_0	$1.5\ 10^{50}$erg
E_1 (0.046 days)	2.2 E_0
E_2 (0.347 days)	0.7 E_0
E_3 (0.694 days)	4.6 E_0
E_4 (1.736 days)	10.0 E_0
E_5 (3.877 days)	8.6 E_0
E_6 (13.89 days)	10.0 E_0
E_7 (48.61 days)	15.0 E_0
Γ_0	770
$n_0(cm^{-3})$	60.0
θ_0	1°.8
θ_v	$0.8\theta_0$
p	2.2
ϵ_e	0.35
ϵ_B	1.7×10^{-4}

The afterglow model assumes an adiabatic expansion, so the proposed scenario might not be valid at very early times, when this assumption does not apply. Additionally, at early time, there can also be a strong contribution from the early reverse shock to the light curve. This might explain the excess of *R*-band flux observed during the first minutes that followed the burst. The very last points of our dataset for GRB 021004 may indicate a transition to a non-relativistic expansion regime. We have not included all of the relevant modifications required to capture such a transition in detail and our model results may therefore be inaccurate at very late times.

4. Conclusions

Due to the early detection and rapid follow-up of GRB 021004, we had the opportunity to obtain a very complete dataset concerning temporal range, wavelength coverage and sample density. This allowed us to introduce important

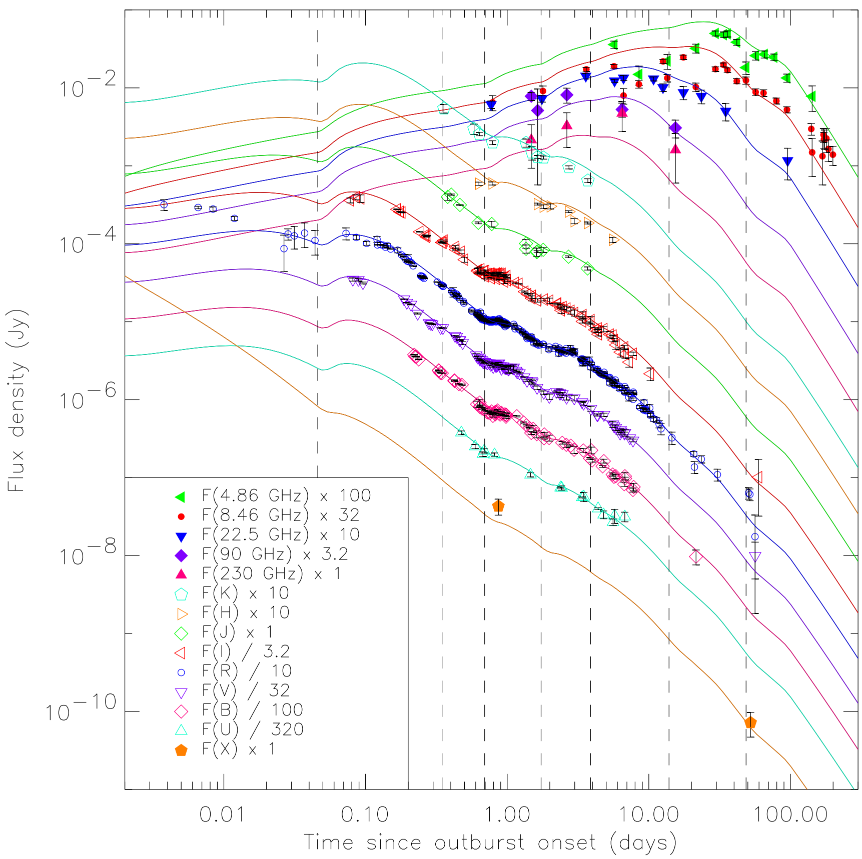

Fig. 2. Multiband light curves from X-rays to radio. The dashed lines mark the time of the energy injections.

constrains on the models capable of explaining the bumps present in the afterglow light curve.

In our analysis, we assume several energy injection episodes to explain the light curve. A reasonable scenario includes an initial burst followed by 7 refreshed shocks. These add up to a total burst energy of 7.8×10^{51} ergs, that were emitted through a collimated jet with an initial half-opening angle of $1.^\circ8$, pointing almost directly towards us.

A study of the photometric data of the host galaxy of GRB 021004 reveals a bright ($M_B = -22.0 \pm 0.3$) starburst galaxy with low extinction ($A_V = 0.06 \pm 0.08$).

Further tests of afterglow models with this multiwavelength dataset are encouraged. Future efforts should be aimed towards obtaining multiwavelength photometry and polarimetric observations in order to be able to discriminate between the different models.

Acknowledgements. This research has been partially supported by the Spain's Ministerio de Ciencia y Tecnología (programme AYA2004-01515, including FEDER funds). AdUP acknowledges support from a FPU grant from Spain's Ministerio de Educación y Ciencia. GJ, GB and EHG acknowledge support from a special grant from the Icelandic Research Council.

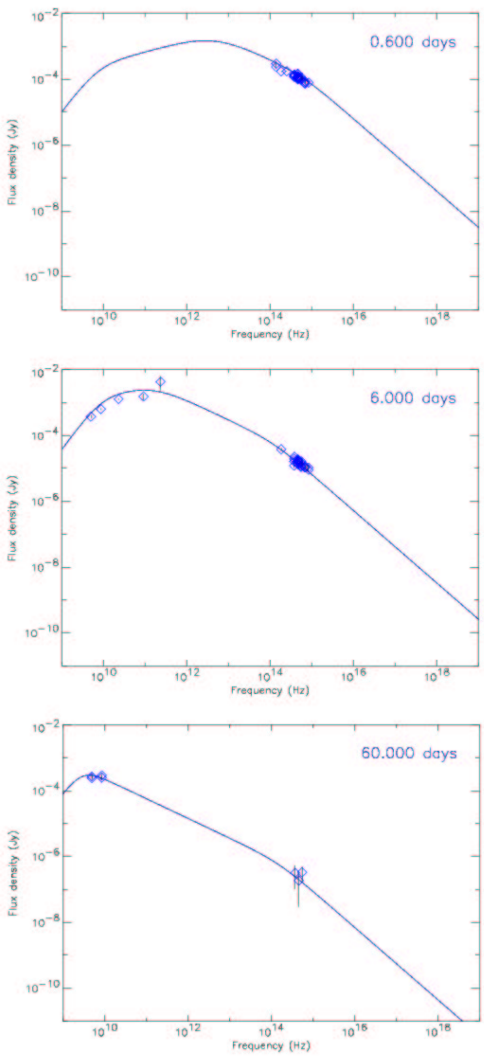

Fig. 3. Evolution of the GRB 021004 afterglow SFDs at 0.6 (top), 6 (middle) and 60 days (bottom) after the burst.

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