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Optical Photometry of GRB 021004: The First Month[1]

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ABSTRACT

We present $UBVR_CI_C$ photometry of the optical afterglow of the gamma-ray burst GRB 021004 taken at the Nordic Optical Telescope between approximately eight hours and 30 days after the burst. This data is combined with an analysis of the *Chandra* X-ray observations of GRB 021004 taken approximately 33 hours after the burst to investigate the nature of the burst. We find an intrinsic optical spectral slope of $\beta_O = 0.39 \pm 0.12$ and an X-ray slope of $\beta_X = 0.93 \pm 0.03$. There is no evidence for color evolution between 8.5 hours and 5.5 days after the burst. Our data suggest that the extinction within the host along the line of sight to the burst is $A_V = 0.26$ and that the host galaxy has an SMC extinction law. The optical and X-ray data are consistent with a relativistic fireball with the shocked electrons being in the slow cooling regime and an electron index of $p = 1.9 \pm 0.1$. The burst occurred in an ambient medium that is homogeneous on scales larger than $\approx 10^{18}$ cm with a mean particle density no greater than ≈ 60 cm^{-3}. Our results support the idea that the brightening seen at ≈ 0.1 days was due to interaction with a clumpy ambient medium within 10^{17}–10^{18} cm of the progenitor. There is evidence that a jet break occurred gradually at ≈ 6 days after the burst and that the jet is undergoing sideways expansion.

Subject headings: gamma rays: bursts

1. Introduction

The gamma-ray burst (GRB) GRB 021004 was detected in the constellation Pisces by the FREGATE, WXM, and SXC instruments on board the *High Energy Transient Explorer*

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[1]Based on observations taken with the Nordic Optical Telescope (NOT), operated on the island of Santa Cruz de La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, and on observations taken with the *Chandra* X-ray Observatory.

II (*HETE-II*) satellite at 12:06:13.57 UT on 2002 Oct. 4 (Shirasaki et al. 2002). The burst had a duration of ≈ 100 s and consisted of two peaks separated by ≈ 25 s. Each peak had a fast rise and exponential decay profile and a power law spectrum with $\alpha = 1.64$ (Lamb et al. 2002). The FREGATE instrument on *HETE-II* measured a fluence of 1.3×10^{-6} erg cm^{-2} between 50 and 300 keV and 3.2×10^{-6} erg cm^{-2} between 7 and 400 keV. The WXM fluence (2–25 keV) is 7.5×10^{-7} erg cm^{-2} (Lamb et al. 2002). Therefore, GRB 021004 was an X-ray rich burst and fits into the long–soft class of bursts.

The redshift of the burst was initially constrained to be $z \geq 1.60$ based on the detection of a Mg II absorption system in the spectrum of the afterglow (Fox et al. 2002). Chernock & Filippenko (2002) found absorption and emission due to Lyα at $z = 2.33$. Møller et al. (2002) report on five absorption systems and confirm the presence of the Lyα emission line, from which they derive a host galaxy redshift of $z = 2.3351$. The GRB absorption system shows strong similarities with associated QSO absorbers, i.e., an outflow velocity of several 1000 km s^{-1}, high ionization and line-locking (Møller et al. 2002).

Torii et al. (2002) observed the location of the GRB 3.5 minutes after the burst with the RIKEN automated telescope and found an upper limit for the unfiltered magnitude of ≈ 13.6. The optical afterglow (OA) was identified 9.45 minutes after the *HETE-II* trigger by the 48-inch Oschin/NEAT robotic telescope (Fox 2002). The rapid identification allowed for near-continuous monitoring of this burst's OA. It quickly became apparent that the OA was not following a simple power law decay but had rebrightened at ≈ 0.1 days after the burst. Further observations suggested that there were rapid variation in the optical decay (Winn et al. 2002) similar to those seen in GRB 011211 (Holland et al. 2002; Jakobsson et al. 2002), and larger deviations from a power law decay on scales of hours to days (Winn et al. 2002; Sahu et al. 2002).

The large variations in GRB 021004's optical decay are unusual, but not unheard of in GRB afterglows. GRB 970508 was the second GRB for which an OA was identified. This OA had a constant luminosity for approximately one day after the burst then brightened by a factor of approximately six before taking on the familiar power-law decay (Castro-Tirado et al. 1998; Pedersen et al. 1998). Panaitescu et al. (1998) showed that this behaviour could be explained if there is an additional injection of energy into the external shock at later times. This additional energy could come from the a shell of ejecta moving more slowly than the main body of ejecta impacting on the external medium. GRB 000301C also exhibited significant deviations from a broken power-law decay for several days after the burst. Garnavich et al. (2000) found that these deviations were consistent with the OA being microlensed. Holland et al. (2002) and Jakobsson et al. (2002) observed rapid variations in the optical decay of GRB 011211 which they interpert as being due to small-scale density

fluctuations in the ambient medium within 0.1 pc of the progenitor. As rapid responses to GRBs become more common optical observations will be able to probe the first few hours of more GRBs. This will provide a window into the physics of the early OA. In this paper we present a self-consistent set of optical observations of GRB 021004 starting approximately 8.5 hours after the burst. We use this data to constrain the physics of the relativistic fireball and probe the ambient medium around the progenitor.

In this paper we adopt a cosmology with a Hubble parameter of $H_0 = 65$ km s^{-1} Mpc^{-1}, a matter density of $\Omega_m = 0.3$, and a cosmological constant of $\Omega_\Lambda = 0.7$. For this cosmology a redshift of $z = 2.3351$ corresponds to a luminosity distance of 20.22 Gpc and a distance modulus of 46.53. One arcsecond corresponds to 29.39 comoving kpc, or 8.81 proper kpc. The lookback time is 11.56 Gyr.

2. The Data

2.1. Optical Photometry

The OA for GRB 021004 is located at R.A. = 00:26:54.69, Dec. = +18:55:41.3 (J2000) (Fox 2002), which corresponds to Galactic coordinates of $(b^{\rm II}, l^{\rm II}) = (-43\overset{\circ}{.}5616, 114\overset{\circ}{.}9172)$. The reddening maps of Schlegel et al. (1998) give a Galactic reddening of $E_{B-V} = 0.060 \pm 0.020$ mag in this direction. The corresponding Galactic extinctions are $A_U = 0.325$, $A_B = 0.258$, $A_V = 0.195$, $A_{R_C} = 0.160$, and $A_{I_C} = 0.116$.

We obtained $UBVR_CI_C$ images of the field containing GRB 021004 using the Andalucía Faint Object Spectrograph and Camera (ALFOSC) and the Mosaic Camera (MOSCA) on the 2.56-m Nordic Optical Telescope (NOT) at La Palma between 2002 Oct. 4 and 2002 Nov. 4. The ALFOSC detector is a 2048×2048 pixel thinned Loral CCD with a pixel scale of $0\overset{''}{.}189$. The instrumental gain was 1.0 e$^-$/ADU and the read-out noise was 6 e$^-$/pixel. The MOSCA detector is a 2×2 mosaic CCD camera containing four flash-gated Loral-Lesser thinned 2048×2048 CCDs. The pixel size is 15 μm and the pixel scale is $0\overset{''}{.}11$. The instrumental gain is 1.24 e$^-$/ADU and the read-out noise is 8.5 e$^-$/pixel. The data from Oct. 19 and Nov. 4 were obtained using MOSCA. All other data were obtained using ALFOSC. Fig. 1 shows the field of GRB 021004.

The data were preprecessed using standard techniques for bias and flat field corrections. Photometry was performed using DAOPHOT II (Stetson 1987; Stetson & Harris 1988) and calibrated using seven secondary standard stars from the catalogue of Henden (2002) (see Table 2). The magnitude was determined as the weighted average over the OA magnitude computed relative to each of the secondary standard stars. The weights were the quadratic

sum of the DAOPHOT II error and the photometric error of the standard star. The corresponding error was computed as dispersion of the OA magnitude calculated relative to each of the secondary standards. The log of the observations and the photometry of the OA is presented in Table 1. In some images the stars B and F were saturated and were not used for calibration. Henden (2002) did not detect stars C and D in the U-band, so we could not use them to calibrate our U-band photometry. No color corrections were applied to the photometry.

2.2. X-Ray Data

Chandra High-Energy Transmission Grating data were obtained between 2002 Oct. 5.37 and 2002 Oct. 6.38 (Sako & Harrison 2002). We analyzed the zero'th and first order spectra adopting standard screening criteria for *Chandra* data. In order to constrain the spectral index in the X-ray band, and to look into any dependence on absorption, we made two joint zero'th and first order fits to the data. First, a power law model was fit to the data in the 2–10 keV. Second, the data in the full well calibrated spectral range 0.5–10 keV was fit with a power law model that included absorbtion by Galactic hydrogen. The column density was fixed at 1.23×10^{20} cm^{-2} (Dickey & Lockman 1990) plus absorption at the redshift of the GRB ($z = 2.3351$). The absorbing column density was left as a free parameter. The *Chandra* data and our fits are shown in Fig. 2.

A pure power law is an excellent fit ($\chi^2 = 47.8$ for 74 degrees of freedom (DOF)) to the data in the 2–10 keV band with a best fit spectral index of $\beta_X = 1.03 \pm 0.06$. A lower, but consistent, spectral index ($\beta_X = 0.94 \pm 0.03$ with $\chi^2 = 127$ for 98 DOF) is obtained when including the absorption and fitting data in the full 0.5–10 keV band (this data has superior photon statistics compared to the 2–10 keV band). We adopt $\beta_X = 0.94 \pm 0.03$ since this value was derived from the spectrum with the better noise properties.

No absorption is required in the vicinity of GRB 021004 and the upper limit on the absorbing column density is 3.4×10^{21} cm^{-2}. This result is consistent with the upper limit of 1.1×10^{20} cm^{-2} on the H I column density found by Møller et al. (2002). We find no evidence for additional spectral features such as lines or absorption edges.

Table 1. Log of the GRB 021004 observations and the results of the photometry.

UT Date	Magnitude	Seeing ($''$)	Exposure (s)	UT Date	Magnitude	Seeing ($''$)	Exposure (s)
U-band:				**R_C-band cont.:**			
Oct. 6.8880	20.88 ± 0.02	1.3	1000	6.0092	19.76 ± 0.03	1.2	300
7.8880	21.18 ± 0.02	1.9	1000	6.1221	19.91 ± 0.03	1.6	600
8.8880	21.52 ± 0.03	1.7	1000	6.1733	19.94 ± 0.03	1.4	600
10.0925	21.92 ± 0.12	1.8	900	6.2085	19.92 ± 0.03	1.6	600
				6.8348	20.03 ± 0.03	1.4	600
B-band:				6.8633	20.10 ± 0.03	1.3	600
Oct. 5.9441	20.71 ± 0.02	1.0	600	6.9175	20.13 ± 0.03	1.2	600
10.0639	22.15 ± 0.05	1.8	600	6.9255	20.12 ± 0.03	1.2	600
				7.0391	20.16 ± 0.03	1.0	600
V-band:				7.8451	20.40 ± 0.03	1.5	600
Oct. 10.0710	21.49 ± 0.09	1.8	300	7.8531	20.40 ± 0.03	1.5	600
				7.8925	20.43 ± 0.03	1.5	600
R_C-band:				7.9479	20.42 ± 0.03	1.5	600
Oct. 4.8472	18.02 ± 0.03	1.5	300	8.0151	20.43 ± 0.03	1.2	600
4.8517	18.04 ± 0.03	1.5	300	8.1412	20.49 ± 0.03	1.2	600
4.9103	18.23 ± 0.03	1.6	300	8.8514	20.70 ± 0.03	1.5	600
4.9445	18.32 ± 0.03	1.8	300	8.9249	20.77 ± 0.03	1.4	600
4.9987	18.60 ± 0.03	1.8	300	9.0047	20.81 ± 0.03	1.1	600
5.0638[a]	18.84 ± 0.02	3.6	300	9.0726	20.83 ± 0.02	1.5	600
5.0687[a]	18.86 ± 0.03	3.3	300	9.1434	20.85 ± 0.03	1.3	600
5.1193[a]	18.98 ± 0.02	3.7	500	10.0759	21.05 ± 0.02	1.5	300
5.1264[a]	18.98 ± 0.02	3.3	500	10.1022	21.08 ± 0.02	1.5	6480
5.1332[a]	19.01 ± 0.02	4.1	500	14.0431	21.90 ± 0.02	0.8	600
5.1402[a]	19.02 ± 0.03	3.7	500	14.0518	21.95 ± 0.03	0.9	600
5.1470[a]	19.06 ± 0.02	3.6	500	14.0600	21.93 ± 0.03	0.9	600
5.1541[a]	19.08 ± 0.03	4.0	500	19.0622[b]	22.70 ± 0.16		1800
5.1609[a]	19.09 ± 0.02	4.0	500	27.9970	23.22 ± 0.08	1.0	3600
5.1678[a]	19.13 ± 0.02	4.7	500	Nov. 4.0158[b]	23.54 ± 0.11	1.0	7200
5.1746[a]	19.11 ± 0.02	5.1	500				
5.1802[a]	19.11 ± 0.02	4.7	300	**I_C-band:**			
5.1860[a]	19.13 ± 0.02	3.7	500	Oct. 4.8563	17.55 ± 0.02	1.3	300
5.1929[a]	19.14 ± 0.03	3.8	500	7.8851	19.92 ± 0.02	1.2	500
5.8541	19.61 ± 0.03	2.0	600	8.8851	20.27 ± 0.02	1.5	500
5.8621	19.62 ± 0.03	1.7	600	10.0828	20.49 ± 0.01	1.3	600
5.9358	19.69 ± 0.03	1.8	600				

[a]The image was rebinned 2×2 to improve the signal-to-noise ratio.

[b]The image was obtained with MOSCA.

3. Results

3.1. Extinction in the Host Galaxy

We used our $UBVR_CI_C$ photometry from Oct. 10 and the near-simultaneous H-band photometry of Stefanon et al. (2002) to construct the spectral energy distribution (SED) of the OA. The optical magnitudes were rescaled to the epoch of the H-band measurement (Oct. 10.072 UT) and converted to flux densities based on Fukugita et al. (1995). H-band magnitude–flux density conversion factor was taken from Allen (2000). Finally, the photometric points were corrected for Galactic reddening.

The SED was fit by $f_\nu(\nu) \propto \nu^{-\beta_O} \times 10^{-0.4*A(\nu)}$, where $f_\nu(\nu)$ is the flux density at frequency ν, β_O is the intrinsic optical spectral index, and $A(\nu)$ is the extinction in the host. The dependence of $A(\nu)$ on ν has been parameterized in terms of the rest frame A_V following the three extinction laws given by Pei (1992) for the Milky Way (MW), Large Magellanic Cloud (LMC), and the Small Magellanic Cloud (SMC). The fit provides β_O and A_V simultaneously for the assumed extinction laws. For comparison purposes the unextincted case ($A_V = 0$) was also considered.

Fig. 3 shows that $A_V = 0$ is not consistent with our data ($\chi^2/\mathrm{DOF} = 12.3$). We find the best fit ($\chi^2/\mathrm{DOF} = 0.48$) with an SMC extinction law having $A_V = 0.26 \pm 0.04$ and $\beta = 0.39 \pm 0.12$. The MW and LMC extinction laws give unacceptable fits ($\chi^2/\mathrm{DOF} = 16.0$ and $\chi^2/\mathrm{DOF} = 3.2$ respectively). If we fix $\beta_O = 1$, so that it is the same as the spectral slope at X-ray frequencies, then none of the extinction laws give acceptable fits ($\chi^2/\mathrm{DOF} > 8$). This strongly suggests that there is a spectral break between the optical and X-ray bands.

Møller et al. (2002) find absorption systems at $z = 1.38$ and 1.60 in addition to those at $z \approx 2.3$. We repeated our fits using these lower redshifts and found that the fits were

Table 2. Positions and photometry of the secondary standard stars A–G taken from Henden (2002).

Star	R.A.	Dec.	I_C	R_C	B	U
A	00:27:00.84	+18:56:38.4	16.084 ± 0.051	17.058 ± 0.023	19.480 ± 0.018	20.699 ± 0.038
B	00:26:57.89	+18:56:06.7	15.948 ± 0.025	16.333 ± 0.013	17.341 ± 0.026	17.372 ± 0.027
C	00:26:53.61	+18:56:22.6	17.828 ± 0.065	18.785 ± 0.057	21.116 ± 0.11	···
D	00:26:52.36	+18:56:39.5	16.455 ± 0.033	17.364 ± 0.028	19.765 ± 0.032	···
E	00:26:51.42	+18:54:36.0	16.787 ± 0.027	17.142 ± 0.013	18.091 ± 0.013	18.099 ± 0.021
F	00:26:58.77	+18:56:56.0	14.896 ± 0.028	15.538 ± 0.016	17.430 ± 0.029	18.545 ± 0.044
G	00:27:00.56	+18:54:14.8	16.643 ± 0.015	17.002 ± 0.008	17.836 ± 0.033	17.616 ± 0.060

worse than those for $z = 2.3351$. Therefore, we believe that the dust is in the host galaxy and not in one of the intervening absorption systems. For a chemically-rich environment like the MW we expect a prominent extinction bump at $2175(1+z)$ Å which should have been detected as a decrement of the $R_C I_C$-band fluxes. This absorption bump is very prominent for the MW, moderate for the LMC and almost nonexistent for the SMC extinction curve. Therefore, our fits suggest that the host galaxy is in an early stage of chemical enrichment similar to the SMC.

3.2. The Location of the Cooling Break

We find $U{-}R_C = 0.76{\pm}0.02$ between Oct. 6.9 and Oct. 10.1. When Galactic reddening is taken into consideration this color is consistent with the Oct. 7.29 spectrum of Matheson et al. (2002). This suggests that there was no significant spectral evolution in the optical between 2.4 and 5.5 days after the burst. Our photometry shows no evidence for color evolution redward of ≈ 6588 Å between 0.35 and 5.5 days, therefore we believe that $\beta_O = 0.4 \pm 0.1$ at optical wavelengths between 0.35 and 5.5 days. The lack of color evolution redward of ≈ 6588 Å, and the change in the intrinsic spectral slope between the optical and X-ray bands, suggest that the increase in $B{-}V$ seen by Matheson et al. (2002) between 0.76 and 2.75 days after the burst was not due to a spectral break passing through the optical frequencies.

The change in the slope between the optical and X-ray bands suggests that there is a spectral break between them at this time. We find $R_C{-}I_C = 0.53 \pm 0.02$ for $0.35 < t < 5.5$ days, which suggests that this break did *not* pass through the optical during our observations.

The relationships between β_O, the slope of the optical decay, α, and the electron index, p, given by Sari et al. (1999) (for a homogeneous interstellar medium (ISM)) and Chevalier & Li (1999) (for a pre-existing stellar wind) allow us to use β_O and β_X to predict p and α during this period. These predictions are listed in Table 3 where p_O and p_X are the electron indices predicted from the optical and X-ray spectral slopes respectively. In cases where $1 < p < 2$ the relationships of Dai & Cheng (2001) were used. Situations with $p < 1$ are unphysical and can be ruled out. We can also rule out cases where both the cooling frequency, ν_c, and the synchrotron frequency, ν_m, are above the optical since they predict a rising spectrum ($\beta_O < 0$) in the optical. Therefore, $\beta_O = 0.39 \pm 0.12$ and $\beta_X = 0.94 \pm 0.03$ require that either $\nu_m < \nu < \nu_c$ or $\nu_c < \nu < \nu_m$.

Fig. 4 shows the NOT data for GRB 021004 and Fig. 5 shows the NOT R_C-band data and the R_C-band data from the GCN Circulars up to GCN 1661 for GRB 021004. These data constrain the decay slope to be $0.75 \lesssim \alpha \lesssim 1.00$, so we can rule out $\nu_c < \nu < \nu_m$, which

predicts $\alpha = 0.25$. Therefore, we suggest that $\nu_m < \nu < \nu_c$ during this period and that the electrons were in the slow cooling regime. This implies that the cooling frequency is between the optical and X-ray bands between 1.0 and 5.5 days after the burst. Averaging p_O and p_X gives $p = 1.9 \pm 0.1$ (standard error). If the burst occurred in a pre-existing stellar wind then the predicted optical decay slope is $\alpha = 1.24$, which is ruled out by the data. Therefore, we believe that the burst occurred in an ambient medium that was homogeneous over large scales and that the cooling frequency is falling. In this scenario the predicted optical decay slope is 0.73 below the cooling break and 0.98 above the cooling break.

3.3. The Optical Light Curve

To search for a break in the optical decay we fit the NOT R_C-band data with a broken power law of the form

$$R_{\rm fit}(t) = \begin{cases} -48.80 - \log_{10}\left(f_\nu(t_b)(t/t_b)^{-\alpha_1} + f_{\rm host}\right), & \text{if} \quad t \le t_b \\ -48.80 - \log_{10}\left(f_\nu(t_b)(t/t_b)^{-\alpha_2} + f_{\rm host}\right), & \text{if} \quad t > t_b \end{cases} . \tag{1}$$

where t_b is the time of the break in the power law, $f_\nu(t_b)$ is the flux in the R_C band at the time of the break, $f_{\rm host}$ is the R_C-band flux from the host galaxy, and α_1, α_2 are the decay slopes before and after the break respectively. The best fit occurs with $\alpha_1 = 0.90^{+0.01}_{-0.10}$, $\alpha_2 = 2.01^{+0.64}_{-0.54}$, $t_b = 6.25^{+0.89}_{-2.75}$ days, $f_\nu(t_b) = 10.183^{+9.586}_{-1.362}$ μJy which corresponds to $R_C(t_b) = 21.18 \pm 0.19$, and $f_{\rm host} = 0.791^{+0.301}_{-1.618}$ which corresponds to $R_{C,{\rm host}} = 24.0 \pm 0.5$. This fit is shown in Fig. 4. The large formal errors in the break time indicate that the break was probably gradual and occurred over a period of ≈ 3.5 and 7 days after the burst.

The lack of color evolution between 0.35 and 5.5 days means that the break can not be due to the cooling frequency passing through the optical. In addition, the predicted slope after the cooling break is $\alpha_2 = 0.98$ whereas we find $\alpha_2 = 2.01^{+0.64}_{-0.54}$, which is $\approx 2\sigma$ steeper than the expected slope after the cooling break. Therefore, the break at $t \approx 6$ days is most likely due to the Lorentz factor of the fireball falling below $1/\theta_j$ where θ_j is the half-opening angle of the jet. For a jet that is undergoing sideways expansion $\alpha_j = (p+6)/4$ (Dai & Cheng 2001), so we expect $\alpha_j = 1.98 \pm 0.03$. An examination of Figs. 4 and 5 suggests that the break seen approximately six days is gradual and that we may be overestimating the break time.

The flattening of the optical decay seen at approximately twenty days after the burst is consistent with a host galaxy with $R_C = 24.0 \pm 0.5$. GRB 021004 is far enough away ($z = 2.3351$) that a type Ib/c supernova like SN1998bw would be significantly fainter than

this and not detectable with our photometry.

3.4. The Properties of the Jet

We applied cosmological k corrections (Bloom et al. 2001) and averaged the FREGATE fluences in the 50–300 keV and 7–400 keV bands to correct then to the 20–2000 keV band. The corrected fluences were then averaged to get an isotropic equivalent energy of $E_{\rm iso} = (2.2 \pm 0.3) \times 10^{52}$ erg. We estimate the opening angle of the GRB jet using Rhoads (1999) and Sari et al. (1999) and the formalism of Frail et al. (2001). This yields $\theta_j \approx (5\overset{\circ}{.}2 \pm 0\overset{\circ}{.}3)(n/0.1)^{1/8}$ rad if we assume, as did Frail et al. (2001), that the efficiency of converting energy in the ejecta into gamma rays is 0.2. We note that our result is not very sensitive to this efficiency. Reducing the efficiency to 0.01 only changes θ_j by $\approx 30\%$. We estimate that GRB 021004's intrinsic energy in gamma rays, after correcting for the jet geometry, was $E_\gamma \approx (1.0 \pm 0.2) \times 10^{50}(n/0.1)^{1/4}$ erg. This is $\approx 2\sigma$ smaller than the canonical value of $(5 \pm 2) \times 10^{50}$ erg (Frail et al. 2001; Piran et al. 2001; Panaitescu & Kumar 2002).

In order for this burst to have had the "standard" energy the ambient density must be $n \approx 60$ cm^{-3}. This is in agreement with the particle densities ($0.1 < n < 100$ cm^{-3}) found by Panaitescu & Kumar (2001) for ten GRBs. It is also similar to the densities found in some supernova remnants. Cox et al. (1999) and Shelton et al. (1999) find a mean density of 6 cm^{-3} with large density gradients for the supernova remnent W44 while Achterberg & Ball (1994) find $n \approx 125$ cm^{-3} at ≈ 1 pc from the progenitor of SN1978K. Lazzati et al. (2002) and Nakar et al. (2002) find that the observed variations in the optical decay of GRB 021004 are consistent with density variations of a of $\Delta n/n \approx 10$ within $\approx 10^{17}$–10^{18} cm of the progenitor.

4. Discussion

The NOT photometry, when combined with the *Chandra* X-ray spectrum suggests that the electron index is $p = 1.9 \pm 0.1$. Most GRBs are well fit by models with $p \approx 2.3$–2.5 (van Paradijs et al. 2000). Panaitescu & Kumar (2002) present models for ten GRBs and find that five are best fit with $p < 2$. The mean electron index for the ten bursts in their study is $\overline{p} = 1.9$. Electron indices of less than two represent infinite energy in the standard relativistic fireball model (Mészáros 2002). This can be avoided by introducing an upper limit for the electron energy distribution (Dai & Cheng 2001) but detailed modelling of the acceleration of particles in highly relativistic shocks predict that the electron index should

be ≈ 2.3 (Achterberg et al. 2001), which is inconsistent with our results. The fact that many GRBs appear to have electron indices of less than two may indicate the need for detailed hydrodynamic modelling of GRB afterglows in order to accurately determine the fireball parameters.

Our results are consistent with a clumpy ISM near the progenitor as proposed by Lazzati et al. (2002). Their scenario assumes that the GRB occurred in an ISM that is inhomogeneous on sub-parsec scales and predicts $p \approx 2$. Variations in the density of the ambient medium of $\Delta n/n \approx 10$ can explain the observed fluctuations on the optical decay of GRB 021004. Nakar et al. (2002) have shown that the deviations from a power law in the optical flux can be used to reconstruct the density profile in the vicinity of the progenitor. Both groups find that the observed variations are consistent with an ambient medium that is homogeneous on scales of $\approx 10^{18}$ cm with a density enhancement of $\Delta n/n \approx 10$ at $\approx 10^{17}$ cm from the progenitor.

Extrapolating the predicted pre-cooling break slope to ≈ 10 minutes after the burst (see Fig. 5) shows that the early data of Fox (2002) are consistent with our predicted optical decay of $\alpha = 0.73$ before the cooling break. Kobayashi & Zhang (2002) present a model where the optical flux before ≈ 1 hour after the burst is dominated by optical emission from reverse shocks. Their model requires $p \approx 2.4$, which is significantly higher than the electron index which we deduce from the X-ray and optical spectra. The agreement between the optical decay which is predicted by the spectral slopes and that seen at ≈ 10 minutes after the burst suggests that the physical mechanism controlling the observed flux at $t \approx 10$ minutes is the same as the one operating at $t > 0.5$ days.

5. Conclusions

We present $UBVR_CI_C$ photometry of the OA of GRB 021004 taken at the NOT. These data were taken between approximately eight hours and 30 days after the burst. The broad-band optical SED yields an intrinsic spectral slope of $\beta_O = 0.39 \pm 0.12$ while the X-ray data gives $\beta_X = 0.94 \pm 0.03$. There is no evidence for color evolution between 8.5 hours and 5.5 days after the burst. We find $A_V = 0.26 \pm 0.04$ in the host galaxy along the line of sight to the burst. Our data suggest that the host has an SMC extinction law, which implies that the host has a level of chemical enrichment that is lower than that of the MW and probably no greater than that of the SMC.

The spectral slopes have been combined with the observed R_C-band optical decay to determine that the shocked electrons are in the slow cooling regime with an electron index

of 1.9 ± 0.1, and that the burst occurred in an ISM that is homogeneous on large scales. Our data are consistent with an optical decay of $\alpha = 0.73$ at $t \lesssim 6$ days after the burst, and $\alpha = 1.98$ after that. There is evidence that the transition between the early and late decay slopes occurred over a period of approximately three days. This is consistent with a sideways expanding jet that slows to a Lorentz factor of $\Gamma \approx 11$ approximately six days after the burst. The total gamma-ray energy in the burst was $E_\gamma = (1.0 \pm 0.2) \times 10^{50} (n/0.1)^{1/4}$ erg. If the burst had the "standard" energy (Frail et al. 2001; Piran et al. 2001; Panaitescu & Kumar 2002) for a GRB then the ambient density is $n \approx 60$ cm^{-3}. This is consistent with what is seen around other GRBs and is consistent with densities seen in supernova remnants (Achterberg & Ball 1994; Cox et al. 1999; Shelton et al. 1999).

The rapid localization of GRB 021004 and the near-continuous monitoring of its OA from ≈ 10 minutes after the burst occurred has allowed this burst to be studied in unprecedented detail. The afterglow shows a large increase in luminosity ≈ 2.5 hours after the burst and a possible second, smaller increase at $t \approx 1$ day. Both of these features would have been missed if optical follow-up had not been immediate and continuous. Further, if the OA had not been identified until more than ≈ 3 hours after the burst the true nature of the early-time slope would not have been known. GRB 021004 demonstrates the need for continuous early-time monitoring of GRB OAs.

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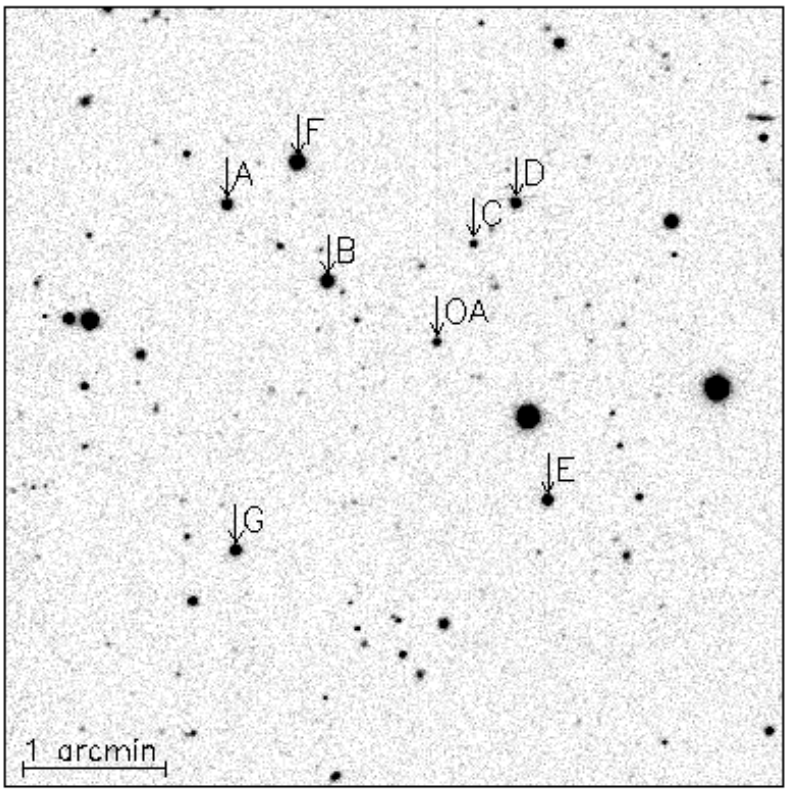

Fig. 1.— The field of GRB 021004 in the R_C band. The stars marked A–G are used as secondary standards for the relative photometry. The positions and photometry of these secondary standard stars is given in Table 2. North us up and east is to the left.

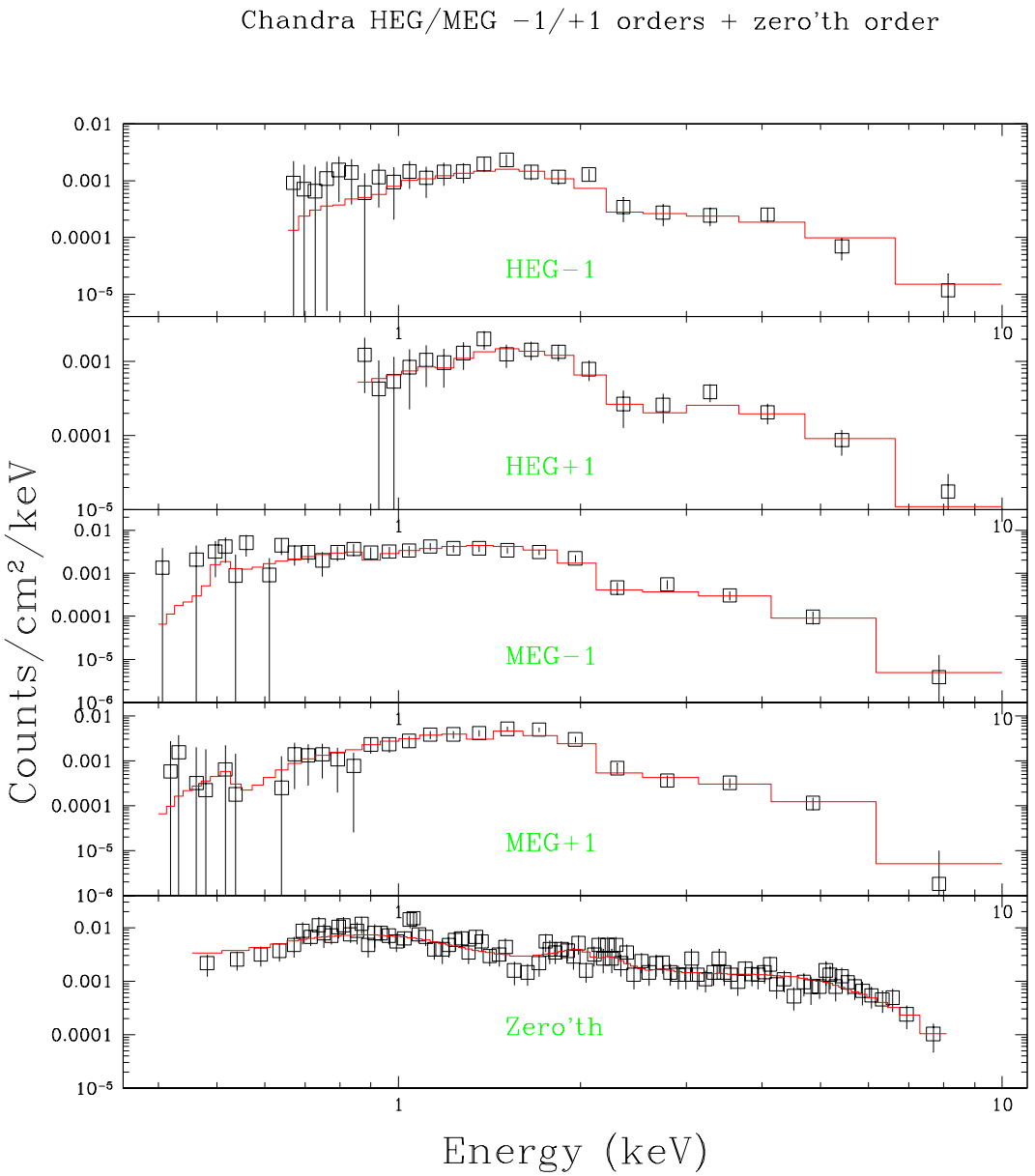

Fig. 2.— First orders *Chandra* High Energy Grating/Medium Energy Grating spectra and zero'th order spectrum of GRB 021004 with the best fit model jointly fit to all spectra. The lines show an intrinsic power law with absorption in the vicinity of GRB 021004 (at $z = 2.34$) and a fixed Galactic absorption of $N(\mathrm{H}) = 1.23 \times 10^{20}$ cm^2.

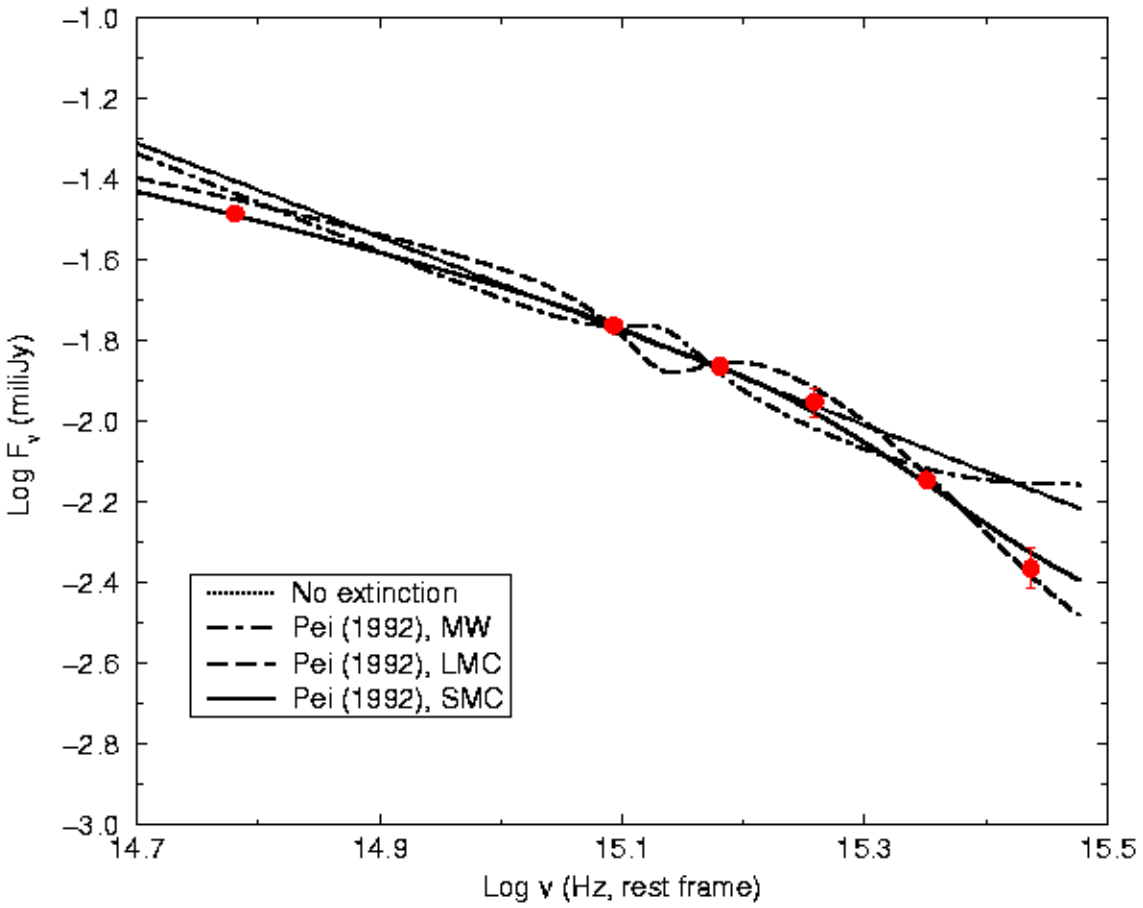

Fig. 3.— The SED of the OA of GRB 021004 on 2002 Oct. 10.072 UT. The filled circles represent our NOT $UBVR_CI_C$ data and the H-band data point from Stefanon et al. (2002). In most bands the error bars are smaller than the circles. The lines represent the SED fits when the SMC (solid), LMC (dashed) and MW (dot-dashed) extinction laws given by Pei (1992) are applied. A fit (dotted line) assuming no extinction of the host is shown for comparison. If we assume that the unextincted spectrum follows $f_\nu(\nu) \propto \nu^{-\beta}$ then only the SMC extinction provides an acceptable fit to the data points.

Table 3. Predicted electron indices and decay slopes assuming $\beta_O = 0.39 \pm 0.12$ and $\beta_X = 0.94 \pm 0.03$. The predicted early-time slope of the optical decay is denoted α.

		p_O	p_X	α	Comments
$\nu_m < \nu_c < \nu$	ISM	0.8 ± 0.2	1.9 ± 0.1	$\cdots$	p_O and p_X are inconsistent
	Wind			$\cdots$	p_O and p_X are inconsistent
$\nu_m < \nu < \nu_c$	ISM	1.8 ± 0.2	1.9 ± 0.1	0.73 ± 0.02	
	Wind			1.24 ± 0.01	α does not fit data
$\nu < \nu_m < \nu_c$	ISM	$\cdots$	1.9 or 2.9	$\cdots$	Rising spectrum
	Wind	$\cdots$		$\cdots$	Rising spectrum
$\nu_c < \nu_m < \nu$	ISM	0.8 ± 0.2	1.9 ± 0.1	$\cdots$	p_O and p_X are inconsistent
	Wind			$\cdots$	p_O and p_X are inconsistent
$\nu_c < \nu < \nu_m$	ISM	$\cdots$	1.9 ± 0.1	1/4	α does not fit data
	Wind	$\cdots$		1/4	α does not fit data
$\nu < \nu_c < \nu_m$	ISM	$\cdots$	1.9 ± 0.1	$\cdots$	Rising spectrum
	Wind	$\cdots$		$\cdots$	Rising spectrum

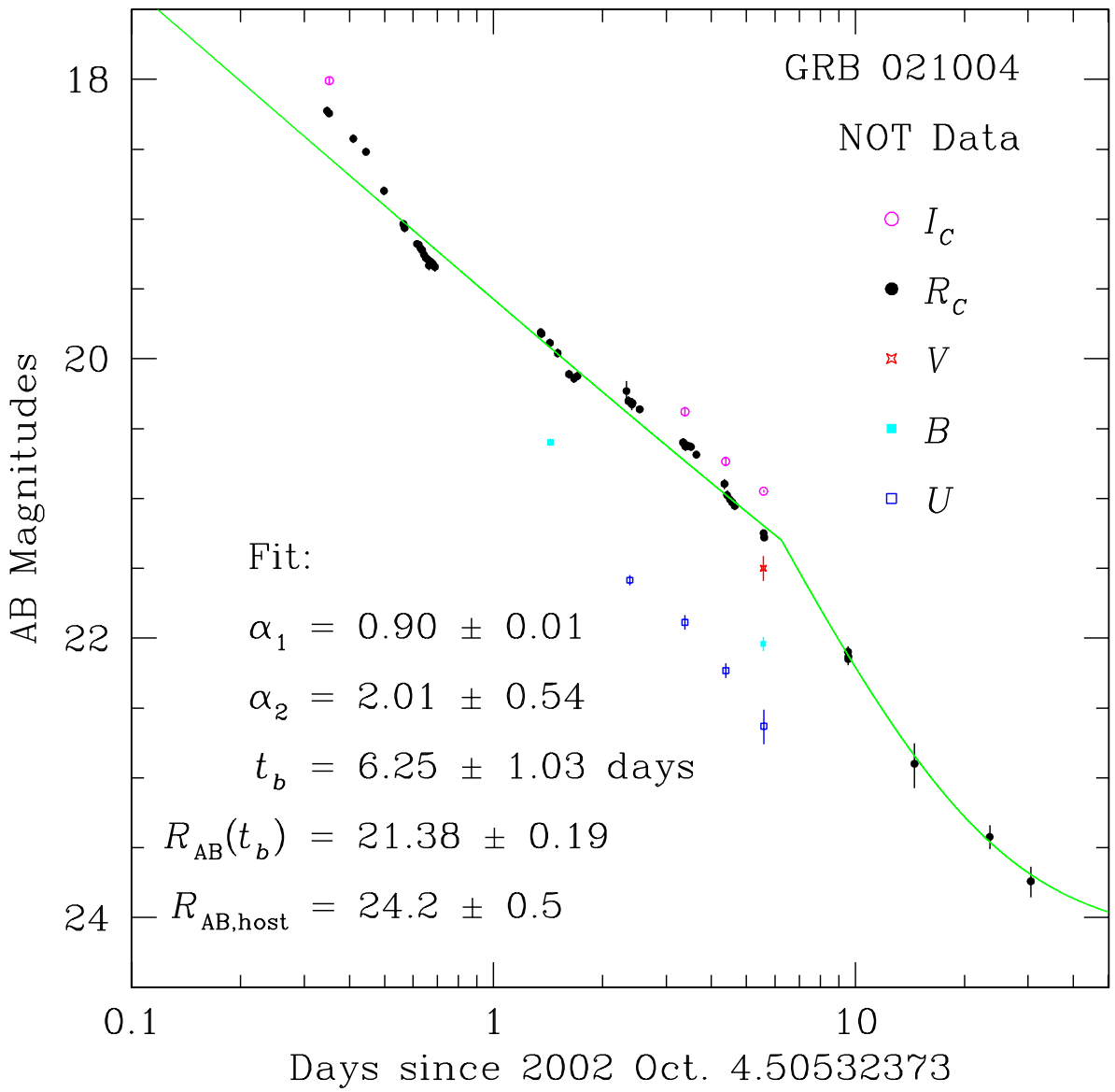

Fig. 4.— This is the NOT data for GRB 021004. The open squares represent the U band, the closed squares represent the B band, the star represents the V band, the closed circles represent the R_C band, and the open circles represent the I_C band. The line is the best-fitting broken power law plus a host galaxy to the R_C-band data as described in § 3.3. All of the data in this panel have been scaled to AB magnitudes. The fitted AB magnitude of the host galaxy is $R_{\rm AB,host} = 23.9 \pm 0.3$.

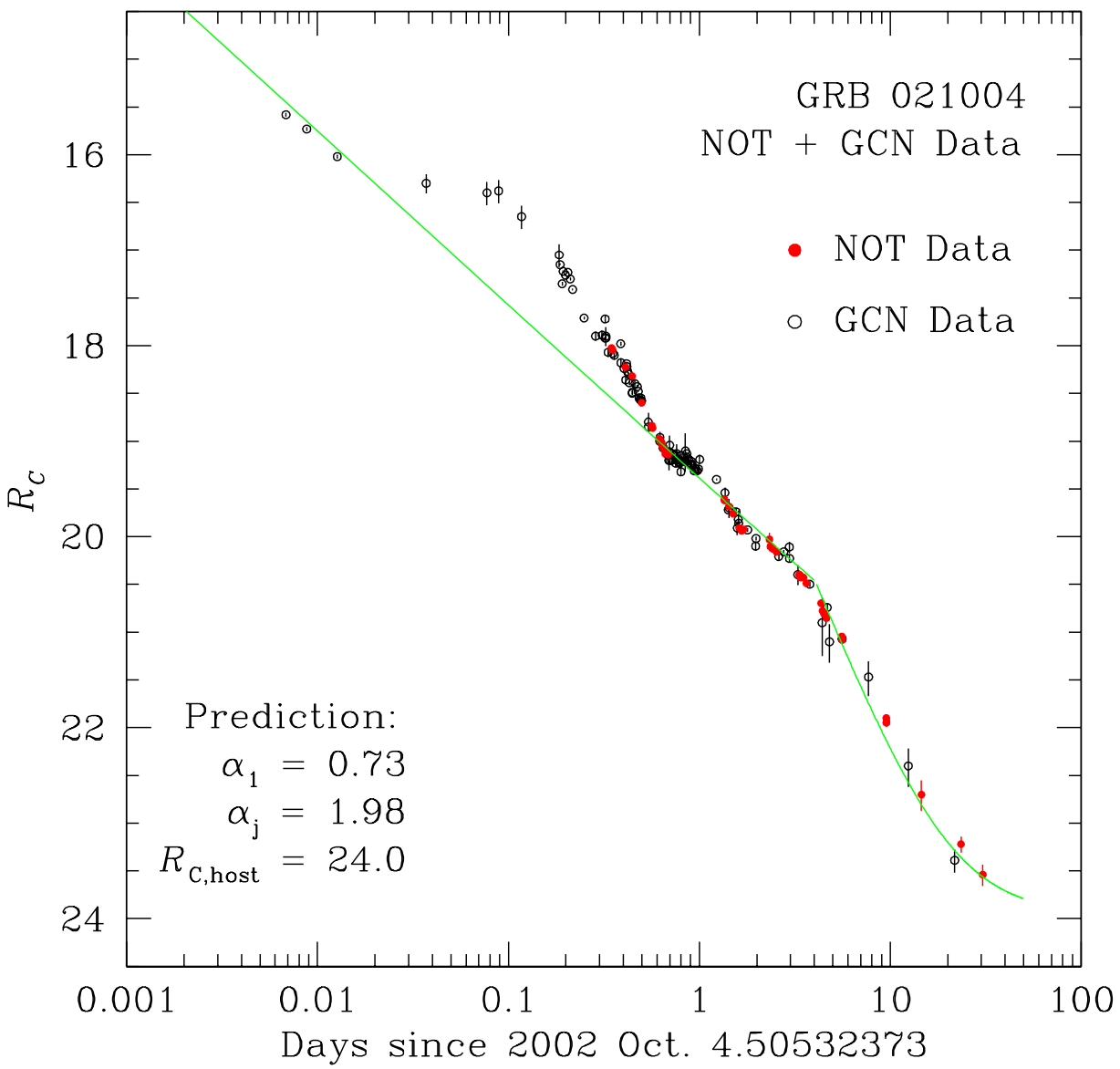

Fig. 5.— This is the NOT R_C-band data (closed circles) and the R_C-band data taken from the GCN Circulars (open circles) for GRB 021004. The later data have been corrected so that the Fox (2002) comparison star has $R_C = 15.54 \pm 0.02$ (Henden 2002). The line is the predicted (not fitted) R_C-band decay with $p = 2$ in a homogeneous ISM. The predicted decay flux has been scaled to the NOT data.