A&A 396, L21–L24 (2002)
DOI: 10.1051/0004-6361:20021612

Astronomy & Astrophysics

Absorption systems in the spectrum of GRB 021004[⋆]

P. Møller[1], J. P. U. Fynbo[2,3], J. Hjorth[3], B. Thomsen[2], M. P. Egholm[4,2], M. I. Andersen[5], J. Gorosabel[6,7], S. T. Holland[8], P. Jakobsson[3], B. L. Jensen[3], H. Pedersen[3], K. Pedersen[3], and M. Weidinger[2]

[1] European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748, Garching bei München, Germany
[2] Department of Physics and Astronomy, Århus University, Ny Munkegade, 8000 Århus C, Denmark
[3] Astronomical Observatory, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark
[4] Nordic Optical Telescope, Apartado Postal 474, 38700 Santa Cruz de La Palma, Canary Islands, Spain
[5] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[6] Instituto de Astrofísica de Andalucía (IAA-CSIC), PO Box 03004, 18080 Granada, Spain
[7] Laboratorio de Astrofísica Espacial y Física Fundamental, PO Box 50727, 28080 Madrid, Spain
[8] Department of Physics, University of Notre Dame, Notre Dame, IN 46556-5670, USA

Received 18 October 2002 / Accepted 31 October 2002

Abstract. We report on a 3600 s spectrum of GRB 021004 obtained with the Nordic Optical Telecope on La Palma 10.71 hours after the burst. We identify absorption lines from five systems at redshifts 1.3806, 1.6039, 2.2983, 2.3230, and 2.3292. In addition we find an emission line which, if due to Lyα from the host galaxy, gives a redshift of 2.3351. The nearest absorber is blueshifted by 530 km s^{-1} with respect to this line, consistent with shifts seen in Damped Lyα and Lyman-Break galaxies at similar redshifts. The emission line flux is $2.46 \pm 0.50 \times 10^{-16}$ erg s^{-1} cm^{-2}. Some of the absorption systems are "line-locked", an effect often seen in QSO absorption systems believed to originate close to the QSO central engine.

Key words. cosmology: observations – gamma rays: bursts – quasars: absorption lines

1. Introduction

More than 30 Optical Afterglows (OAs) to Gamma-Ray Bursts (GRBs) have been detected to date. Absorption lines due to metal enriched gas in the host galaxy of the GRB have been detected in all cases where a spectrum with a good signal-to-noise ratio of the OA has been obtained. Prior to GRB 021004 the redshift has been determined from such detected metal absorption for about a dozen OAs. Absorption line spectra of GRBs have primarily been used to constrain the redshift of the burst but also to gain insight into the nature of the burst, the gas phase of its host galaxy, and of its large scale environment (e.g. Vreeswijk et al. 2001; Mirabal et al. 2002).

Furthermore, it is interesting to consider how the GRB absorption line systems compare to the well-studied QSO absorption line systems, and to examine whether the physical conditions (e.g. column densities, metallicities, ionizations states, and kinematics) in the absorbers detected in GRB afterglow spectra are similar to any of the various classes of QSO absorbers (e.g. Jensen et al. 2001; Savaglio et al. 2002a; Salamanca et al. 2002).

In this *Letter* we present optical spectroscopy of the afterglow of GRB 021004. GRB 021004 was detected by the HETE-II satellite on October 4.5043 2002 UT (Shirasaki et al. 2002). An optical afterglow was reported already 10 min after the burst (Fox 2002). The first optical spectroscopy reported two absorption systems at $z = 1.38$ and 1.60 (Fox et al. 2002), which were later confirmed by Eracleous et al. (2002), Anupama et al. (2002) and Castander et al. (2002). Lyα absorption at $z = 2.323$ was first reported by Chornock & Filippenko (2002). The presence of this system was confirmed by Salamanca et al. (2002b), Savaglio et al. (2002b), Sahu et al. (2002) and Castro-Tirado et al. (2002). Its lightcurve showed strong deviations from the usual power-law decay indicating structure in the surrounding medium (Lazzati et al. 2002; Holland et al. in prep).

2. Observations and data reduction

2.1. Observations

The spectrum of GRB 021004 presented in Fig. 1 was obtained with the 2.56-m Nordic Optical Telescope (NOT) using the Andalucía Faint Object Spectrograph (ALFOSC). The detector was a 2048^2 pixels thinned Loral CCD with a pixel scale of 0.″189. We used a grism covering 3850 Å–6850 Å and a slit

---

Send offprint requests to: P. Møller, e-mail: `pmoller@eso.org`

[⋆] Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden.

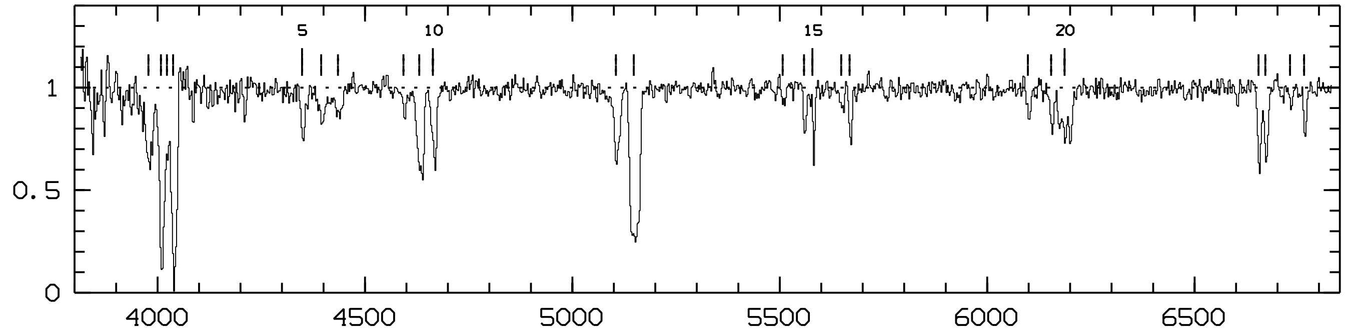

Fig. 1. Normalised spectrum of GRB 021004. Absorption lines are marked and numbered as in Table 1.

of 1.3 arcsec providing a resolution of 6.5 Å and a sampling of 1.5 Å per pixel.

The spectroscopic observations consisted of a single 3600 s exposure started at Oct. 4.9505 (10.71 hrs after the burst). Photometric observations obtained on the same and the following nights at the NOT and elsewhere made it possible to closely follow the GRB light-curve. The brightness of the OA at the start of the exposure was $R = 18.48 \pm 0.03$ and $B = 19.15 \pm 0.10$. During the one-hour exposure the OA faded by 0.08 mag. These broad band magnitudes were used for the flux calibration.

2.2. Data reduction and absorption line-list

Standard techniques were used for bias, dark and flat field corrections. For the optimal 1D extraction, and for the line-search, measurement, identification, and fitting we used a code originally developed for 2D spectral PSF fitting (Møller 2000) and for QSO spectral analysis (for details see Møller & Kjærgaard 1992).

In Table 1 we list centroid (vacuum corrected) and observed equivalent width of all absorption lines found above our 5σ detection limit. Several of the listed lines are complex blends, and for those we provide the total observed quantities with no attempt at this point to deblend them. Inferred redshifts are listed only for the single unblended lines. The absorption lines are marked above the normalised spectrum shown in Fig. 1.

We have identified five absorption systems at redshifts 1.3806, 1.6039, 2.2983, 2.3230, and 2.3292 and we shall in what follows refer to them as systems A, B, C, D, and E. The identification of those systems was carried out independently of the early GCNCs, but is seen to agree well with the circulars summarised in Sect. 1.

For systems C, D, and E our spectrum covers Lyα. No line redwards of the Lyα line of system E is unidentified, and we conclude that line No 4 in Table 1 marks the onset of the Lyman forest. System E is therefore most likely associated with the GRB itself, and could mark the redshift of the GRB host galaxy. There are however a few caveats and we shall return to this question in Sect. 4.

Most of the absorption lines are blended, making it impossible to obtain a good redshift directly from line centroiding. The redshifts given above were therefore derived through line profile fitting. Detailed fits to the blends are shown in Fig. 2, and the redshifts required to fit each species are listed in Table 2.

Table 1. Absorption lines in GRB 021004.

No.	λ_{vac} (Å)	W_{obs} (Å)	σ_{W} (Å)	line ID (system)	z_{abs}
1	3981.75	7.10	0.63	complex (Fig. 2)	
2	4011.90	13.11	0.54	complex (Fig. 2)	
3	4026.32	2.46	0.31		
4	4041.43	14.18	0.47	complex (Fig. 2)	
5	4352.06	2.79	0.30	Al II (B)	1.6048
6	4398.21	2.95	0.35	C II (C)	2.2957
7	4438.65	2.57	0.34	C II (D+E)	
8	4596.82	1.26	0.21	Si IV (C)	2.2982
9	4634.89	7.97	0.29	Si IV (C+D+E)	
10	4667.64	4.95	0.28	Si IV (D+E)	
11	5108.88	5.96	0.26	C IV (C)	
12	5152.16	19.56	0.26	C IV (D+E)	
13	5511.21	0.84	0.20	Al II (C)	2.2986
14	5562.56	1.99	0.19	Al II (E)	2.3293
[a]15	5582.76	2.41	?	Fe II (A)	
16	5652.16	1.32	0.19	Fe II (A)	1.3804
17	5672.26	2.38	0.17	Fe II (A)	1.3805
18	6102.42	1.64	0.23	Fe II (B)	1.6032
19	6158.50	2.41	0.23	Fe II (A)	1.3809
20	6190.76	7.58	0.33	complex (Fig. 2)	
21	6658.57	4.19	0.22	Mg II (A)	1.3812
22	6675.02	3.83	0.21	Mg II (A)	1.3809
[b]23	6734.36	0.84	?	Fe II (B)	
24	6768.53	2.00	0.18	Fe II (B)	1.6031

[a] Line 15 is influenced by strong sky subtraction residuals.

[b] Line 23 is strongly influenced by a cosmic.

The lines are heavily saturated and the resolution low enough that the line profiles are dominated by the resolution. Therefore the column densities used in the fits are mostly too poorly constrained to be useful. Nevertheless, from the Lyα line profiles we can set a strict upper limit of 1.1×10^{20} cm^{-2} on the H I column density. The total H I column actually used in the fit of systems C, D, and E was 5.7×10^{19} cm^{-2}.

3. Lyα in emission

Inspection of the top panel of Fig. 2 shows that what is mostly a very good fit of the Lyα absorption lines of systems C, D,

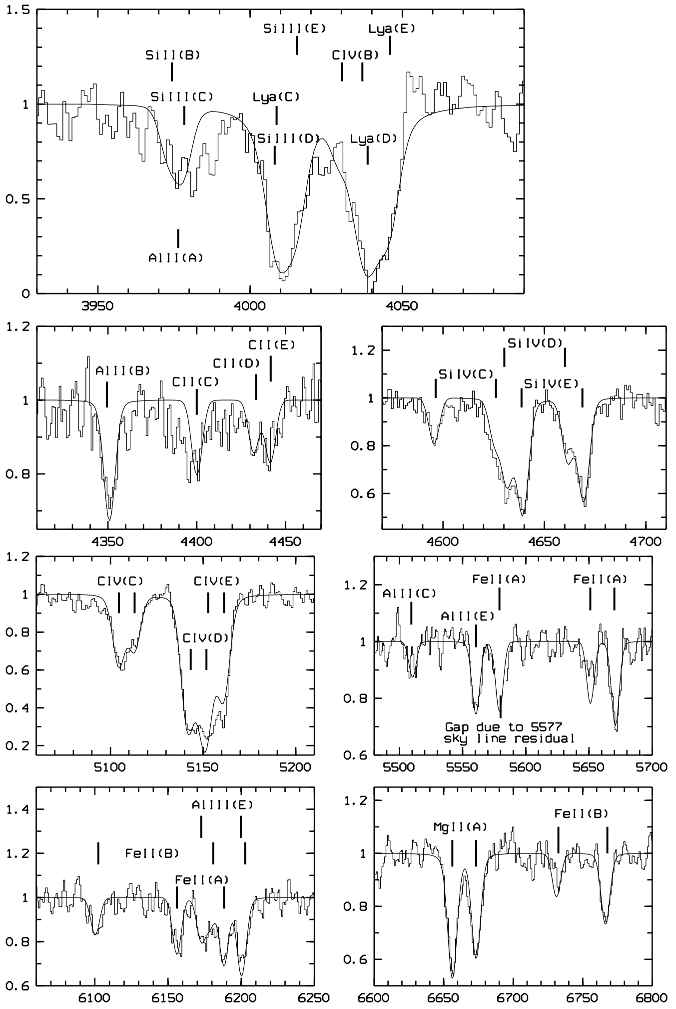

Fig. 2. Profile fits and line identifications.

Table 2. Absorption redshift constraints from line fitting.

	Fe II	C IV	Al II	Si IV	Total
A	1.3806	-	-	-	1.3806 ± 0.0005
B	1.6030	-	1.6048	-	1.6039 ± 0.0009
C	-	2.2980	2.2990	2.2982	2.2983 ± 0.0004
D	-	2.3220	-	2.3240	2.3230 ± 0.0010
E	-	2.3290	2.3290	2.3296	2.3292 ± 0.0004

and E, becomes very poor on the red shoulder of the last line. Subtraction of the fit (Fig. 3) reveals that the poor fit is caused by the presence of an emission line shortly redwards of the Lyα-E line. As suggested in several GCN Circulars (Chornock & Filippenko 2002; Salamanca et al. 2002b; Djorgovski et al. 2002; Castro-Tirado et al. 2002), this line is likely Lyα emission from the host galaxy. The line (Fig. 3, right panel) is unresolved, has its centroid at 4054.4 Å, and a flux of 2.46 ± 0.50×10^{-16} erg s^{-1} cm^{-2} identical to other reported measurements to within 1σ. The flux is comparable to the Lyα flux of the GRB 000926 host galaxy (Fynbo et al. 2002). The inferred redshift (2.3351) is 530 km s^{-1} higher than that of the E system. At the time of writing the limit on the host galaxy magnitude

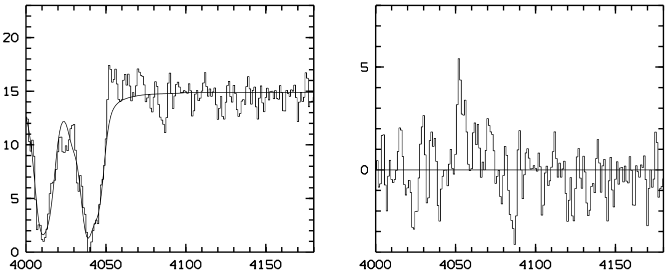

Fig. 3. Left: section of the spectrum with Lyα absorption lines. Note the poor fit to the extreme right wing of the second line. Right: residual after subtraction of the fit shown to the left. A narrow Lyα emission line is now clearly visible. The vertical scale in both plots is in units of 10^{-17} erg s^{-1} cm^{-2} Å^{-1}.

is $B > 24$, providing a lower limit on the observed emission line equivalent width of 170 Å.

4. Discussion

4.1. Properties of Lyα absorption and emission lines

A shift of a few hundred km s^{-1} between redshifts determined from Lyα absorption and emission is commonly seen for DLA galaxies (Møller et al. 2002) and for Lyman-Break galaxies (e.g. Adelberger et al. 2002, their Figs. 2 and 3). Two effects are thought to contribute to this observed velocity shift: if the absorbing gas is in a galactic wind moving towards us, that will blueshift the absorber and at the same time cause the resonantly scattered Lyα photons to become redshifted in order to escape the cloud. A spread in absorption/emission redshifts as large as that seen in systems C–E and host Lyα emission (3300 km s^{-1}) has never been seen in Lyman-Break Galaxy spectra, and in fact Eq. (2) from Adelberger et al. (2002) shows that the velocity shift of the Lyα emission line should be less than 200 km s^{-1} for an emission line rest equivalent width larger than 50 Å. Therefore the large velocity range spanned here cannot be explained in terms of normal host galaxy properties, and we conclude that the absorbers must be in the local environment of the GRB.

4.2. The nature of the GRB absorption systems

Any absorption seen in the spectra of high-redshift QSOs may be classified as belonging to one of three basic categories (Weymann et al. 1979). The "intervening systems" are cosmologically distributed and can have any redshift lower than that of the source, "local cluster systems" will have the same redshift as the source to within ± the velocity dispersion of the local cluster or filament, and "ejected systems" (physically closest) can be radiatively accelerated to large velocities.

In QSOs the ejected systems are often seen as BALs (P-Cygni type broad absorption line systems) and/or as line-locked systems (Foltz et al. 1987; Srianand et al. 2002). Ejection velocities as high as 0.1c have been reported (Vilkoviskij & Irwin 2001), and the systems are found to be highly ionized and to have extremely high metallicities

(Savaglio et al. 1994; Møller et al. 1994). The high ionization is easily understood because of the intense UV flux of the QSO. The line-locking is explained as an effect of cloudlets being accelerated via absorption at a given transition until its wavelength falls into the shadow of another line in a cloud in front of it (Vilkoviskij et al. 1999).

In this scheme we would classify systems A and B as intervening systems, while systems C, D and E display a surprising similarity to the ejected systems of QSOs. They all have strong absorption of highly ionized C IV and Si IV but no detectable Si II absorption, they have high column densities compared to stellar winds, and at intermediate resolution they show evidence for line-locking in C IV, Si III/Lyα and possibly Si IV (see also Savaglio et al. 2002b; Salamanca et al. 2002b). For confirmation of the line-locking higher resolution spectra (already obtained) are needed.

It is difficult to understand why there is this resemblance between systems C–E and ejected systems of QSOs. We concluded above that the systems arise in the local environment of the GRB. They may therefore be related either directly or indirectly to the GRB or the GRB progenitor itself, or they may be caused by an unrelated phenomenon which just happens to be sharing the same volume of space. Firstly we would consider it unlikely that the systems are directly related to the burst itself. So soon after the burst any material ejected simultaneous with the GRB itself should undergo significant changes on relatively short timescales, yet there is no evidence for such changes between our spectrum and that of Matheson et al. 2002. Secondly one may ask if stellar winds could create such signatures. Radiatively driven winds with terminal velocities of up to several 1000 $\mathrm{km\,s^{-1}}$ are ubiquitous for very hot stars such as O stars and WR stars (Lucy & Abbott 1993; Kudritzki 2002) but these winds cannot reach the required column densities. Also, presumably for the same reason, actual line-locking has never been observed in stellar winds.

We cannot exclude that the GRB is located close to the inner region of a recently deceased QSO, especially at $z \sim 2$, where the QSO density is high. However, given the existing evidence that GRBs seem to be related to the deaths of massive stars it is more likely that the GRB progenitor was a massive, hot star and that this star radiatively drove the fast outflow now observed in absorption against the light of the afterglow. Other massive stars and supernova explosions could be contributing to the wind if the progenitor was located in a compact star-forming region similar to that of GRB 980425 (Fynbo et al. 2001). A similar scenario was suggested for GRB 971214 by Ahn (2000).

Alternatively, as suggested by Lazzati et al. (2002), in the supra-nova scenario (Vietri & Stella 1998) the wind and the clumpy surrounding medium could be the result of a supernova predating the GRB by several years.

Acknowledgements. We thank E. Y. Vilkoviskij for helpful discussions and our referee Davide Lazzati for fast, thorough and constructive criticism. We are grateful to the staff at the Nordic Optical Telescope for keeping the Telescope working so well and for excellent support. JPUF gratefully acknowledge support from the Carlsberg foundation. This work is supported by the Danish Natural Science Research Council (SNF).

References

Adelberger, K. L., Steidel C. C., Shapley, A. E., & Pettini, M. 2002, ApJ, in press
Ahn, S. H. 2000, ApJL, 520, 9
Anupama, G. C., Sahu, D. K., Bhatt, B. C., & Prabhu, T. P. 2002, GCNC #1582
Castro-Tirado, A. J., Perez, E., Gorosabel, J., et al. 2002, GCNC #1635
Chornock, R., & Filippenko, A. V. 2002, GCNC #1605
Djorgovski, S. G., Barth, A., Price, P., et al. 2002, GCNC #1620
Eracleous, M., Schaefer, B. E., Mader, J., & Wheeler, C. 2002, GCNC #1579
Foltz, C. B., Weymann, R. J., Morris, S. L., & Turnshek, D. A. 1987, ApJ, 317, 450
Fox, D. W. 2002, GCNC #1564
Fox, D. W., Barth, A. J., Soderberg, A. M., et al. 2002, GCNC #1569
Fynbo, J. P. U., Holland, S. T., Andersen, M. I., et al. 2001, ApJL, 542, L89
Fynbo, J. P. U., Møller, P., Thomsen, B., et al. 2002, A&A, 388, 42
Jensen, B. L., Fynbo, J. U., Gorosabal, J., et al. 2001, A&A, 370, 909
Kudritzki, R.-P. 2002, ApJ, 577, 389
Lazzati, D., Rossi, E., Covino, S., Ghisellini G., & Malesani, D. 2002, A&A, 396, L5
Lucy, L. B., & Abbott, D. C. 1993, ApJ, 405, 738
Matheson, T., Garnavich, P. M., et al. 2002, ApJ, submitted
Mirabal, N., Halpern, J. P., Kularni, S. R., et al. 2002, ApJ, 578, 818
Møller, P. 2000, The Messenger, 99, 31
Møller, P., & Kjærgaard, P. 1992, A&A, 258, 234
Møller, P., Jakobsen, P., & Perryman, M. A. C. 1994, A&A, 287, 719
Møller, P., Warren, S. J., Fall., S. M., Fynbo, J. U., & Jakobsen, P. 2002, ApJ, 574, 51
Sahu, K., Fruchter, A., Burud, I. & Sembach, K. 2002, GCNC #1608
Salamanca, I., et al. 2002a, MNRAS, submitted
Salamanca, I., Rol, E., Wijers, R., et al. 2002b, GCNC #1611
Savaglio, S., D'Odorico, S., & Møller, P. 1994, A&A, 281, 331
Savaglio, S., Fall, S. M., & Fiore, F. 2002a, ApJ, submitted
Savaglio, S., Fiore, F., Israel, G. L., et al. 2002b, GCNC #1633
Shirasaki, Y., Graziani, C., Matsuoka, M., et al.2002, GCNC #1565
Srianand, R., Petitjean, P., Ledoux, C., & Hazard, C. 2002, MNRAS, in press
Vietri, M., & Stella, L. 1998, ApJL, 507, L45
Vilkoviskij, E. Y., & Irwin, M. J. 2001, MNRAS, 321, 4
Vilkoviskij, E. Y., Efimov, S. N., Karpova, O. G., & Pavlova, L. A. 1999, MNRAS, 309, 80
Vreeswijk, P. M., Fruchter, A., Kaper, L., et al. 2001, ApJ, 546, 672
Weymann, R. J., Williams, R. E., Turnshek, et al. 1979, ApJ, 234