Astronomy & Astrophysics manuscript no.
(will be inserted by hand later)

Absorption systems in the spectrum of GRB 021004 ⋆

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

[1] European Southern Observatory, Karl-Schwarzschild-Straße 2, D-85748, Garching by München, Germany
[2] Department of Physics and Astronomy, Århus University, Ny Munkegade, DK-8000 Århus C, Denmark
[3] Astronomical Observatory, University of Copenhagen, Juliane Maries Vej 30, DK–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, D-14482 Potsdam, Germany
[6] Laboratorio de Astrofísica Espacial y Física Fundamental, P.O. Box 50727, E–28080 Madrid, Spain
[7] Department of Physics, University of Notre Dame, Notre Dame, IN 46556-5670, U.S.A.

Received ; accepted

Abstract. We report on a 3600 s spectrum of GRB 021004 obtained with the NOT telescope 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 GRB 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 DLA 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. We discuss whether line-locking in GRB absorbers and QSO absorbers could have a common origin.

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 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 12 OAs, namely GRB 970508 (Metzger al. 1998), GRB 980703 (Djorgovski et al. 1998), GRB 990123 (Andersen et al. 1999; Kulkarni et al. 1999), GRB 990510 (Vreeswijk et al. 2001), GRB 990712 (Vreeswijk et al. 2001), GRB 991216 (Vreeswijk et al. 1999), GRB 000301C (Smette et al. 2001; Jensen et al. 2001), GRB 000926 (Fynbo et al. 2002a; Castro et al. 2002), GRB 010222 (Jha et al. 2001; Salamanca et al. 2002a), GRB 011211 (Holland et al. 2002; Burud et al. in prep.), GRB 020124 (Hjorth et al. in prep.), and GRB 020813 (Price et al. 2002),

Until now absorption line spectra of GRBs have mostly been used to constrain the redshift of the burst but in the near future, as rapid response with high resolution spectroscopy becomes possible, GRB spectra may be used to gain insight into the nature of the burst, the gas phase of its host galaxy, and of its large scale environment (e.g. Mirabal et al. 2002). Furthermore, it is interesting to consider how the GRB absorption line systems compare with the properties of 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 the physical conditions in any of the various classes of QSO absorbers. In this *Letter* we present optical spectroscopy of the afterglow of GRB 021004, and discuss the similarity of its absorbers to QSO absorbers.

Here follows a brief summary of the GCN Circulars (GCNCs) pertaining to spectroscopy of this burst: GRB 021004 was detected by the HETE-II satellite on October 4.5043 2002 UT (Shirasaki et al. 2002). An optical afterglow was reported 10 minutes 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

Send offprint requests to: P. Møller
⋆ Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden.
Correspondence to: pmoller@eso.org & jfynbo@phys.au.dk

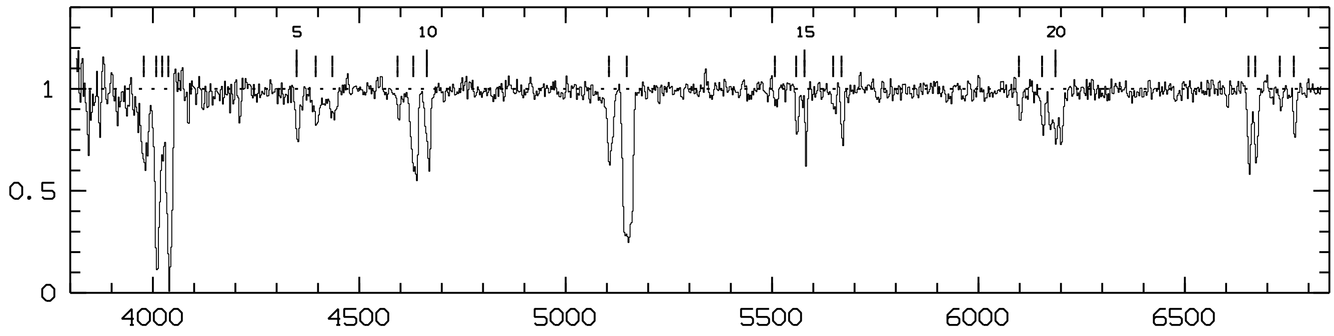

Fig. 1. Normalised spectrum of GRB 021004. Absorption lines are marked and numbered as in Table 1.

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. (2002), Sahu et al. (2002) and Castro-Tirado et al. (2002).

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 ALFOSC detector is a 2048^2 pixels thinned Loral CCD with a pixel scale of $0.''189$. We used Grism 7 and a slit of 1.3 arcsec which gave 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±0.03 and B=19.15±0.10. During the one hour exposure the OA faded by 0.08 magnitudes. 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.

Table 1. Absorption lines in GRB 021004

No.	$\lambda_{\rm vac}$ (Å)	$W_{\rm obs}$ (Å)	σ_W (Å)	line ID (system)	$z_{\rm abs}$
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	AlII (B)	1.6048
6	4398.21	2.95	0.35	CII (C)	2.2957
7	4438.65	2.57	0.34	CII (D+E)	
8	4596.82	1.26	0.21	SiIV (C)	2.2982
9	4634.89	7.97	0.29	SiIV (C+D+E)	
10	4667.64	4.95	0.28	SiIV (D+E)	
11	5108.88	5.96	0.26	CIV (C)	
12	5152.16	19.56	0.26	CIV (D+E)	
13	5511.21	0.84	0.20	AlII (C)	2.2986
14	5562.56	1.99	0.19	AlII (E)	2.3293
[a]15	5582.76	2.41	?	FeII (A)	
16	5652.16	1.32	0.19	FeII (A)	1.3804
17	5672.26	2.38	0.17	FeII (A)	1.3805
18	6102.42	1.64	0.23	FeII (B)	1.6032
19	6158.50	2.41	0.23	FeII (A)	1.3809
20	6190.76	7.58	0.33	complex (Fig. 2)	
21	6658.57	4.19	0.22	MgII (A)	1.3812
22	6675.02	3.83	0.21	MgII (A)	1.3809
[b]23	6734.36	0.84	?	FeII (B)	
24	6768.53	2.00	0.18	FeII (B)	1.6031

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

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

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 3 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.

Table 2. Absorption redshift constraints from line fitting

System	FeII	CIV	AlII	SiIV	Total
A	1.3806	-	-	-	1.3806 ± .0005
B	1.6030	-	1.6048	-	1.6039 ± .0009
C	-	2.2980	2.2990	2.2982	2.2983 ± .0004
D	-	2.3220	-	2.3240	2.3230 ± .0010
E	-	2.3290	2.3290	2.3296	2.3292 ± .0004

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.

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 HI column. The total HI column actually used in the fit of systems C, D, and E was 5.7×10^{19}.

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, 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 $2.46 \pm 0.50 \times 10^{-16}$ erg s^{-1} cm^{-2} consistent with other reported measurements within 1–1.5σ. The inferred redshift (2.3351) is 530 km s^{-1} higher than that of the E system.

4. Discussion

4.1. Properties of Lyα absorption and emission lines

A shift of several hundred km s^{-1} between redshifts determined from absorption and Lyα emission is commonly seen for DLAs (Møller et al. 2002) and for Lyman-Break galaxies (e.g. Adelberger at al. 2002, their Fig. 2 and Fig. 3). Several effects can contribute to the observed velocity shift: the absorbing gas may be in a galactic wind moving towards us, and the Lyα emitting gas may be redshifted relative to the systemic redshift by a combination of dust absorption and resonant scattering. However, *i)* a spread in absorption redshifts similar to that for systems C–E, more than 3000 km s^{-1}, has never been seen in Lyman-Break Galaxy spectra, and *ii)* equation 2 from Adelberger et al. (2002) show that the velocity shift of the Lyα emission line is typically small when the equivalent width is large (as it must be in this case). This suggests that the large velocity range spanned by systems C–E and the Lyα emission line cannot be naturally explained in terms of host galaxy properties, but has to be explained by an unusually fast outflow.

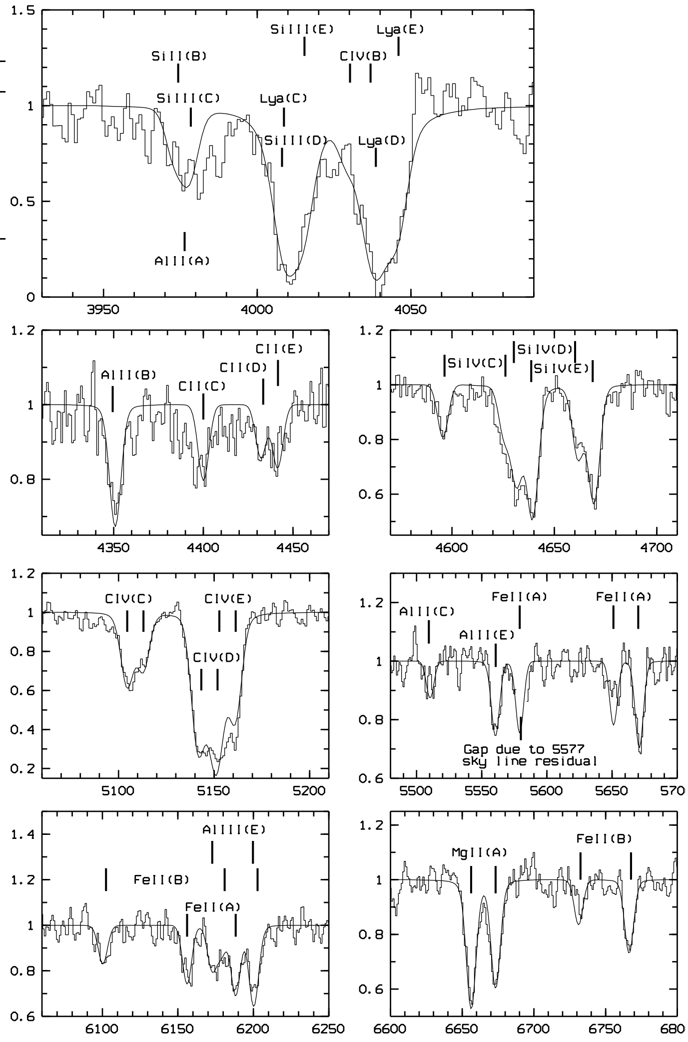

Fig. 2. Profile fits

4.2. GRB vs. QSO absorbers

In Fig. 2 we show a combined fit of 42 absorption lines. Of those, 28 are found in complex blends while only 14 are found as single lines. Yet, inspection of Fig. 1 shows that large parts of the spectrum is free of absorption lines. It appears that absorption lines have a tendency to "group". This is not a new phenomenon but has long been known in the study of QSO absorption lines where it is often referred to as "line-locking".

Any absorption seen in the spectra of high-redshift objects 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

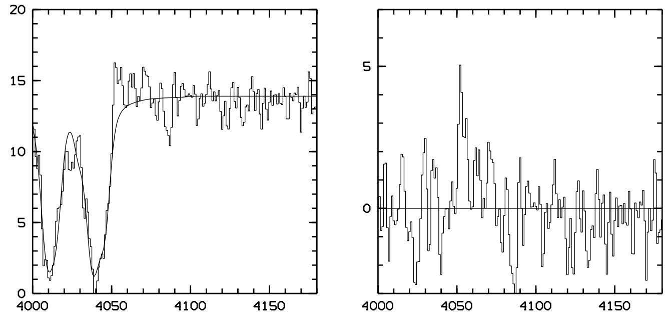

Fig. 3. Left: Section of the spectrum with Lyα absorption lines. Note the poor fit to the extreme right wing of the second line. Right: Residual after subtraction of the fit shown to the left. A narrow Lyα emission line is now clearly visible. The vertical scale in both plots is in units of 10^{-17}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

redshift lower than that of the source. "Local systems" will have the same redshift as the source to within $\pm$ the velocity dispersion of the local cluster or filament. Finally, "associated systems" (physically closest) can be radiatively accelerated to large velocities (up to 0.04c has been observed), and can therefore inhabit a large span of redshifts lower than the source. This makes it particularly difficult to uniquely determine if a system is physically associated rather than intervening or local.

For QSOs there is some help to be found. The associated systems are often seen as BALs (P-Cygni type broad absorption line systems) and/or as line-locked systems (Foltz et al. 1987; Vilkoviskij & Irwin 2001). They 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 clouds 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. This line-locking is thought to take some time to be set up because the clouds must first be accelerated.

The spectrum of GRB 021004 is the first GRB spectrum to exhibit what appears to be line-locking. The probability of this happening in a single case by chance is not vanishing, so no major conclusions should be drawn at this time. Nevertheless, if the reality of this phenomenon can be confirmed in other GRB spectra, then a very interesting question poses itself: "Is the source of the line-locking phenomenon in GRBs and QSOs the same, or is the same effect caused by two different processes?"

At a first glance it would seem unlikely that there is enough time during the GRB itself to establish line-locking. Alternatively, GRBs and QSOs obtain the same observed characteristics because they sample the same gas. One may choose between two conclusions. Either GRBs with line-locked absorption systems are located inside the central engine region of recently deceased QSOs, or the line-locked absorbers seen in QSO spectra are not located as close to the central engine as the currently favored models stipulate. Rather they would be spread much farther, such that they cover a significant fraction of the star-forming regions of the host galaxy. The first conclusion is not as unlikely as it seems. It fits well with the observation that many GRBs are found at redshifts close to or just below redshift 2, the redshift which marks the peak of the QSO population and the start of its downfall. At this epoch the number of recently deceased QSOs must be high and these are likely located in starburst galaxies.

The continued rapid spectroscopic pursuit of GRB OAs, and especially the comparison of those spectra to the large databases of high-quality QSO spectra, clearly holds promises for insight which could not be gained from the study of any one single of those two classes of objects.

Acknowledgements. The data presented here have been taken using ALFOSC, which is owned by the Instituto de Astrofisica de Andalucia (IAA) and operated at the Nordic Optical Telescope under agreement between IAA and the NBIfAFG of the Astronomical Observatory of Copenhagen. 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).

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