LETTERS

An optical spectrum of the afterglow of a γ-ray burst at a redshift of $z = 6.295$

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The prompt γ-ray emission from γ-ray bursts (GRBs) should be detectable out to distances of $z > 10$ (ref. 1), and should therefore provide an excellent probe of the evolution of cosmic star formation, reionization of the intergalactic medium, and the metal enrichment history of the Universe[1–4]. Hitherto, the highest measured redshift for a GRB has been $z = 4.50$ (ref. 5). Here we report the optical spectrum of the afterglow of GRB 050904 obtained 3.4 days after the burst; the spectrum shows a clear continuum at the long-wavelength end of the spectrum with a sharp cut-off at around 9,000 Å due to Lyman α absorption at $z \approx 6.3$ (with a damping wing). A system of absorption lines of heavy elements at $z = 6.295 \pm 0.002$ was also detected, yielding the precise measurement of the redshift. The Si II fine-structure lines suggest a dense, metal-enriched environment around the progenitor of the GRB.

GRB 050904 was a long burst (duration $T_{90} = 225$ s) detected by the Swift γ-ray burst satellite on 4 September 2005, 01:51:44 UT (Universal time; refs 6, 7). Its position was immediately disseminated via the GRB Coordinates Network. Although the optical observations at the Palomar 60″ telescope carried out 3.5 hours after the trigger did not reveal a new source with upper limits of $R > 20.8$ mag and $I > 19.7$ mag (ref. 8), a relatively bright near infrared source with $J \approx 17.5$ mag was detected three hours after the burst in the Swift X-ray telescope error circle[9], which showed a temporal decay with an index of -1.20, fully consistent with being a typical GRB afterglow. Analysis of the near-infrared colours, combined with the non-detection in the optical bands, led to the suggestion that the burst originated at a high redshift[10], $5.3 < z < 9.0$. A refined photometric redshift of $z = 6.10^{+0.37}_{-0.12}$ was reported based on European Southern Observatory (ESO) Very Large Telescope (VLT) observations in the J, H, K and I bands[11].

We observed the field of GRB 050904 with the Faint Object Camera And Spectrograph (FOCAS)[12] on the 8.2-m Subaru Telescope on top of Mauna Kea, Hawaii, starting on the night of 6 September 2005. In the z' band image (600-s exposure, mid-epoch on 7 September, 8:04 UT), we detected the afterglow at $z'(\mathrm{AB}) = 23.71 \pm 0.14$ mag, but we failed to detect it in the I_C band even with a longer exposure (900 s), which implied that the Lyman break should be present around $\lambda \approx 8{,}500$–$9{,}000$ Å.

We then obtained a grism spectrum of the afterglow candidate, which exhibited a sharp cut-off at $\lambda \approx 9{,}000$ Å with strong depletion of the continuum at shorter wavelengths, strikingly similar to the spectra of quasars[13] at $z > 6$ except for the absence of a broad Lyα emission line. The emission is very weak in the wavelength range shorter than 8,900 Å. In particular, the flux is consistent with zero in the ranges 8,500–8,900 Å and 7,000–7,500 Å that extend shortward of the Lyα and Lyβ wavelengths for $z \approx 6.3$. This is a clear signature of absorption by neutral hydrogen in the intergalactic medium at $z > 6$, and marks the first detection of a Gunn–Peterson trough[14] from an object other than high-z quasars[15]. We also find weak emission features at ~7,500–8,300 Å which are presumably leakage flux from the continuum emission that is also found in quasar spectra at similar redshifts.

At the longer-wavelength end of the spectrum is a flat continuum with a series of absorption lines, which we identify as S II, Si II, O I, and C II lines at a common redshift of $z = 6.295 \pm 0.002$. We believe that this is the redshift of the GRB host galaxy, since no other absorption line system was observed at a redshift consistent with that of the Lyα break. This firm spectroscopic identification of the redshift breaks the previous record of GRB 000131 at $z = 4.50$ (ref. 5).

From a closer examination of the absorption lines, we find that they are not saturated and can be used to estimate the column densities of the heavy elements as shown in Table 1. Using the standard photospheric solar abundances[16] we obtain the metallicity of these elements as [C/H] $= -2.4$, [O/H] $= -2.3$, [Si/H] $= -2.6$, and [S/H] $= -1.0$, where $\log[N_{\mathrm{HI}}\,(\mathrm{cm}^{-2})] \approx 21.3$ is assumed from a damped Lyα system model for the Lyα damping wing presented below. These values may not represent the typical abundances in the GRB host galaxy for several reasons. First, they are derived using only a single ionization state for each element. Depletion due to dust condensation may modify the Si abundance in particular. And second, the spatial distribution of the heavy elements may be significantly different from that of hydrogen. It is possible that the heavy elements are distributed only locally around the GRB source in a metal-enriched circumstellar shell, while the neutral hydrogen is distributed on a larger scale in or outside the host galaxy.

Further analysis of the Si lines allows us to constrain the scale of the absorbing metals. Using the equivalent width ratio of the fine-structure transition lines Si II* $\lambda = 1{,}264.7$ Å and Si II $\lambda = 1{,}260.4$ Å, the electron density n_e can be constrained[17] as $\log[n_e(\mathrm{cm}^{-3})] = 2.3 \pm 0.7$ for a reasonable temperature range of $10^3\,\mathrm{K} < T < 10^5\,\mathrm{K}$. Combined with the column density and the abundance of Si derived

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Table 1 | Absorption lines detected in the spectrum of the optical afterglow of GRB 050904

Observed wavelength (Å)	Equivalent width (Å)	Column density log (cm^{-2})	Line identification (element, Å)	Redshift, z
9,041.0 ± 0.8	4.5 ± 1.0	$14.44^{+0.14}_{-0.16}$	C IV, λ = 1,548.2	4.840 ± 0.001
		–	(N V, λ = 1,238.8)	(6.298 ± 0.001)
9,055.9 ± 1.7	1.7 ± 1.0	$14.21^{+0.25}_{-0.46}$	C IV, λ = 1,550.8	4.840 ± 0.001
		–	(N V, λ = 1,242.8)	(6.287 ± 0.001)
9,146.4 ± 1.8	3.8 ± 1.1	$15.60^{+0.14}_{-0.17}$	S II, λ = 1,253.8	6.295 ± 0.001
9,188.7 ± 2.6	6.1 ± 3.7	$16.20^{+1.87}_{-0.92}$	S II, λ = 1,259.5	6.295 ± 0.002
9,195.9 ± 1.2	8.3 ± 2.7	$14.29^{+0.57}_{-0.39}$	Si II, λ = 1,260.4	6.296 ± 0.001
9,225.8 ± 1.8	3.9 ± 1.1	$13.63^{+0.13}_{-0.16}$	Si II*, λ = 1,264.7	6.295 ± 0.001
9,499.1 ± 0.9	10.3 ± 1.9	$15.85^{+0.39}_{-0.28}$	O I, λ = 1,302.2	6.295 ± 0.001
9,737.2 ± 1.1	12.3 ± 2.4	$15.41^{+0.30}_{-0.26}$	C II, λ = 1,334.5	6.296 ± 0.001

The wavelengths and equivalent widths were derived by fitting a single gaussian. The column densities of lines were estimated by the standard curve of growth analysis[25]. The equivalent widths in the table are observed ones, that is, not converted to the rest-frame. The quoted uncertainties are 1σ statistical errors. Most of the absorption lines are consistent with being at a single redshift of $z = 6.295 \pm 0.002$ within the statistical uncertainties. The absorption lines at $\lambda = 9{,}041.0$ Å and 9,055.9 Å could be identified as N V $\lambda = 1{,}238.8$ Å, $\lambda = 1{,}242.8$ Å, if they are at a redshift similar to that of the other absorption lines. However, the derived redshifts of these two lines are significantly inconsistent with each other. Another possible identification is C IV $\lambda = 1{,}548.2$ Å, $\lambda = 1{,}550.8$ Å in an intervening system at $z = 4.840$, which we think is more likely.

above and assuming a hydrogen ionization fraction of 0.1, we obtain the physical depth of the absorbing system to be 0.4 pc with an uncertainty of a factor of ~10, reflecting the statistical errors and the possible temperature range. These fine-structure lines have been found in GRB afterglow spectra[18–20], whereas they have never been clearly detected in quasar damped Lyα systems[18]. This is consistent with a local origin for the absorption such as a metal-enriched molecular cloud in the star-forming region or a dense metal-enriched shell nebula swept-up by a progenitor wind prior to the GRB onset suggested for GRB 021004 (refs 21, 22) and GRB 030226 (ref. 23). The column density of C II is also consistent with the calculation for a carbon-rich Wolf–Rayet wind[24].

As shown in Fig. 1, the Lyα cut-off exhibits the signature of a damping wing redward of the Lyα wavelength. To our knowledge, this is the first detection of significant neutral hydrogen absorption at $z \gtrsim 6$, allowing us to explore the distribution of neutral hydrogen in the vicinity of a GRB, in the host galaxy, and/or in intergalactic space at very high redshifts. Such a study is difficult with high-z quasars owing to their enormous ultraviolet flux, which ionizes the surrounding environment, and owing to the presence of a strong Lyα emission line.

There are two possibilities for the nature of the absorber. It may be a damped Lyα system associated with the host galaxy, which has been observed in the afterglows of several GRBs at lower redshifts[18–20]. The other possibility is the neutral hydrogen in the intergalactic medium (IGM) left over from the pre-reionization era[2]. If the latter is the case, we can now measure the neutral fraction of the IGM at $z \gtrsim 6$, giving important information on the reionization history of the Universe. We find that the wing shape can be reproduced either by a damped Lyα system (see inset of Fig. 1) or by the IGM. A comprehensive

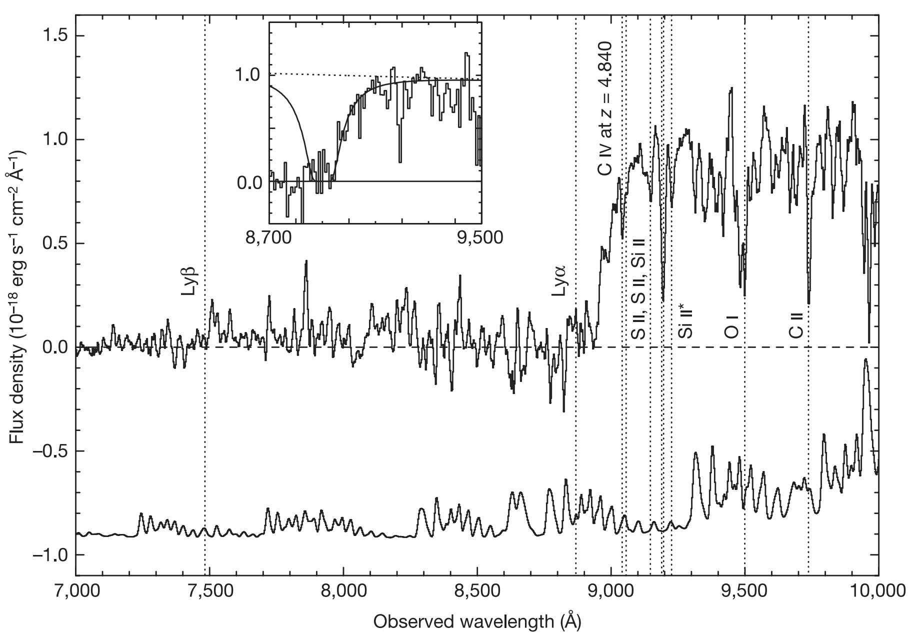

Figure 1 | The spectrum of the afterglow of GRB 050904. It covers the wavelengths 7,000–10,000 Å with a resolution $R = \lambda/\Delta\lambda \approx 1{,}000$ at 9,000 Å. It was taken with Subaru/FOCAS at mid-epoch on 7 September, 12:05 UT, 3.4 days after the burst, for a total exposure of 4.0 hours. The abscissa is the observed wavelength converted to that in vacuum. The spectrum is smoothed to a resolution $R = \lambda/\Delta\lambda \approx 600$ at 9,000 Å. The locations of the identified absorption lines (see Table 1) at $z = 4.840$ and $z = 6.295$, as well as the wavelengths of Lyα and Lyβ at $z = 6.295$, are shown with vertical dotted lines. The one-sigma errors are shown with an offset of -1.0 at the bottom of the panel. In the inset, the solid line shows a model for the damping wing of Lyα absorption with a neutral hydrogen column density $\log[N_{\mathrm{HI}}$ (cm^{-2})] = 21.3 at a redshift of $z = 6.3$, overlaid on the observed spectrum in the wavelength range of 8,700–9,500 Å. The dotted line indicates the unabsorbed continuum model following a power-law ($f_\nu \propto \nu^{-1}$) function as typically observed for GRB afterglows. We note that only the red wing is relevant to the fit, because the emission blueward of Lyα is absorbed by the IGM.

spectral fitting analysis is necessary to examine these possibilities, which is beyond the scope of this Letter.

With the detection of metal absorption lines, we have shown that GRBs are found in metal-enriched regions even at such an early phase of the Universe as $z > 6$. It is, therefore, possible that we would detect the metal absorption lines even from GRBs originating from the metal-free first-generation stars, because their environment may be self-polluted by pre-burst winds, as suggested by the present observation. We can expect to obtain afterglow spectra with much higher quality for GRBs at even higher redshifts in the immediate future, considering that Swift is constantly localizing faint GRBs, and that our spectrum was taken when the afterglow had faded by more than an order of magnitude since its first detection in the *J* band. Such future data will give us even better opportunities to probe the formation of stars and galaxies in the early Universe.

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1. Lamb, D. Q. & Reichart, D. E. Gamma-ray bursts as a probe of the very high redshift Universe. *Astrophys. J.* **536,** 1–18 (2000).
2. Miralda-Escude, J. Reionization of the Intergalactic Medium and the damping wing of the Gunn-Peterson trough. *Astrophys. J.* **501,** 15–22 (1998).
3. Totani, T. Cosmological gamma-ray bursts and evolution of galaxies. *Astrophys. J.* **486,** L71–L74 (1997).
4. Ciardi, B. & Loeb, A. Expected number and flux distribution of gamma-ray burst afterglows with high redshifts. *Astrophys. J.* **540,** 687–696 (2000).
5. Andersen, M. I. *et al.* VLT identification of the optical afterglow of the gamma-ray burst GRB 000131 at z = 4.50. *Astron. Astrophys.* **364,** L54–L61 (2000).
6. Cummings, J. *et al.* GRB050904: Swift-BAT detection of a probable burst. *GCN Circ.* **3910** (2005).
7. Sakamoto, T. *et al.* GRB 050904 BAT refined analysis of complete data set. *GCN Circ.* **3938** (2005).
8. Fox, D. B. & Cenko, S. B. GRB050904: P60 observations. *GCN Circ.* **3912** (2005).
9. Haislip, J. *et al.* GRB 050904: SOAR/PROMPT observations. *GCN Circ.* **3913** (2005).
10. Haislip, J. *et al.* GRB 050904: possible high-redshift GRB. *GCN Circ.* **3914** (2005).
11. Antonelli, L. A. *et al.* GRB 050904: photometric redshift. *GCN Circ.* **3924** (2005).
12. Kashikawa, N. *et al.* FOCAS: The Faint Object Camera and Spectrograph for the Subaru Telescope. *Publ. Astron. Soc. Jpn.* **54,** 819–832 (2002).
13. White, R. L., Becker, R. H., Fan, X. & Strauss, M. A. Probing the ionization state of the Universe at $z > 6$. *Astron. J.* **126,** 1–14 (2003).
14. Gunn, J. E. & Peterson, B. A. On the density of neutral hydrogen in intergalactic space. *Astrophys. J.* **142,** 1633–1641 (1965).
15. Becker, R. H. *et al.* Evidence for reionization at $z \sim 6$: Detection of a Gunn-Peterson trough in a z = 6.28 quasar. *Astron. J.* **122,** 2850–2857 (2001).
16. Grevesse, N. & Sauval, A. J. Standard solar composition. *Space Sci. Rev.* **85,** 161–174 (1998).
17. Silva, A. I. & Viegas, S. M. Physical conditions in quasi-stellar object absorbers from fine-structure absorption lines. *Mon. Not. R. Astron. Soc.* **329,** 135–148 (2002).
18. Vreeswijk, P. M. *et al.* The host of GRB 030323 at z = 3.372: A very high column density DLA system with a low metallicity. *Astron. Astrophys.* **419,** 927–940 (2004).
19. Chen, H.-W., Prochaska, J. X., Bloom, J. S. & Thompson, I. B. Echelle spectroscopy of a GRB afterglow at z = 3.969: A new probe of the interstellar and intergalactic media in the young Universe. *Astrophys. J. Lett.* (in the press); preprint at ⟨http://arXiv/astro-ph/0508270⟩ (2005).
20. Berger, E. *et al.* Spectroscopy of GRB 050505 at z = 4.275: A logN(HI) = 22.1 DLA host galaxy and the nature of the progenitor. *Astrophys. J.* (submitted); preprint at ⟨http://arXiv/astro-ph/0511498⟩ (2005).
21. Mirabal, N. *et al.* GRB 021004: A possible shell nebula around a Wolf-Rayet star gamma-ray burst progenitor. *Astrophys. J.* **595,** 935–949 (2003).
22. Schaefer, B. E. *et al.* GRB 021004: A massive progenitor star surrounded by shells. *Astrophys. J.* **588,** 387–399 (2003).
23. Klose, S. *et al.* Probing a gamma-ray burst progenitor at a redshift of z = 2: A comprehensive observing campaign of the afterglow of GRB 030226. *Astron. J.* **128,** 1942–1954 (2004).
24. van Marle, A.-J., Langer, N. & Garcia-Segura, G. Constraints on gamma-ray burst and supernova progenitors through circumstellar absorption lines. *Astron. Astrophys.* (in the press); preprint at ⟨http://arXiv/astro-ph/0507659⟩ (2005).
25. Spitzer, L. *Physical Processes in the Interstellar Medium* 51 (Wiley-Interscience, New York, 1978).

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