Afterglow spectrum of a $\gamma$-ray burst with the highest known redshift $z=6.295$

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Gamma-ray bursts (GRBs) and their afterglows have been proposed as an excellent probe to study the evolution of cosmic star formation, the reionization of the intergalactic medium, and the metal enrichment history of the universe \(^{1-4}\), since the prompt \(\gamma\)-ray emission of GRBs should be detectable\(^3\) out to distances \(z > 10\). Hitherto, the highest measured redshift for a GRB has been \(z = 4.50\)^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 cutoff at around 9000 Å due to Ly\(\alpha\) absorption at a redshift of 6.3 with a damping wing. Little flux is present in the waveband shortward of the Ly\(\alpha\) break. A system of absorption lines of heavy elements at redshift \(z = 6.295 \pm 0.002\) were also detected, yielding a precise measurement of the largest known redshift of a GRB. Analysis of the Si II fine structure lines suggest a dense metal-enriched environment around the GRB progenitor, providing unique information on the properties of the gas in a galaxy when the universe was younger than one billion years.

GRB 050904 was a long burst (duration \(T_{90} = 225\) s) detected by the Swift \(\gamma\)-ray burst satellite on 4 September 2005, 01:51:44 UT\(^6,7\). Its position was immediately disseminated via the GRB Coordinates Network (GCN). While 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\(^8\), a relatively bright near infrared source with \(J \sim 17.5\) 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 colors, 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
$z = 6.10^{+0.37}_{-0.12}$ was reported based on ESO VLT observations in the $J$, $H$, $K$, and $I$ bands\textsuperscript{11}.

We observed the field of GRB 050904 with the Faint Object Camera And Spectrograph (FOCAS)\textsuperscript{12} on the 8.2m Subaru Telescope atop Mauna Kea starting on the night of 6 September. In the $z'$ band image (600 s exposure, mid-epoch 7 September, 8:04 UT), we detected the afterglow at $z'(AB) = 23.71 \pm 0.14$ 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 $\lambda \approx 8500–9000$ Å.

We then obtained a grism spectrum of the afterglow candidate, which exhibited a sharp cutoff at $\lambda \approx 9000$ Å with strong depletion of the continuum at shorter wavelengths, strikingly similar to the spectra of quasars\textsuperscript{13} at $z > 6$ except for the absence of a broad Ly$\alpha$ emission line. The emission is very weak in the wavelength range shorter than 8900 Å. In particular the flux is consistent with zero in the ranges 8500–8900 Å and 7000–7500 Å that extend shortward of the Ly$\alpha$ and Ly$\beta$ wavelengths for $z \sim 6.3$. 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\textsuperscript{14} from an object other than high-$z$ quasars\textsuperscript{15}. We also find weak emission features at $\sim 7500–8300$ 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 Ly$\alpha$ break. This firm spectroscopic identification of the redshift breaks the previous record of GRB 000131 at $z$=4.50\textsuperscript{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\(^\text{16}\) we obtain the metallicity of these elements as \([\text{C/H}]=-2.4, [\text{O/H}]=-2.3, [\text{Si/H}]=-2.6, \text{and [S/H]}=-1.0\), where \(\log N_{\text{HI}}(\text{cm}^{-2}) \sim 21.3\) is assumed based on a DLA (damped Lyman \(\alpha\) system) model for the Ly\(\alpha\) 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* \(\lambda 1264.7\) and Si II \(\lambda 1260.4\), the electron density can be constrained\(^\text{17}\) as \(\log n_e(\text{cm}^{-3}) = 2.3 \pm 0.7\) for a reasonable temperature range of \(10^3 \text{ K} < T < 10^5 \text{ K}\). Combined with the column density and the abundance of Si derived 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 \(\sim 10\), reflecting the statistical errors and the possible temperature range. These fine structure lines have been found in GRB afterglow spectra\(^\text{18–20}\), whereas they have never been clearly detected in QSO-DLAs\(^\text{18}\). 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\(^\text{21,22}\) and GRB 030226\(^\text{23}\). The column density of C II is
also consistent with the calculation for a carbon-rich Wolf-Rayet wind\textsuperscript{24}.

As shown in Fig 1, the Ly\textsubscript{α} cutoff exhibits the signature of a damping wing redward of the Ly\textsubscript{α} wavelength. This is the first detection of significant neutral hydrogen absorption at $z \gtrsim 6$, and offers the first case for which one can explore the distribution of neutral hydrogen in the vicinity of a GRB, in the host galaxy, and/or in intergalactic space at such high redshifts. Such a study is difficult with high-$z$ quasars due to their enormous UV flux which ionizes the surrounding environment, and due to the presence of a strong Ly\textsubscript{α} emission line.

There are two possibilities for the nature of the absorber. It may be a DLA associated with the host galaxy, which has been observed in the afterglows of several GRBs at lower redshifts\textsuperscript{18–20}. The other possibility is the neutral hydrogen in the intergalactic medium (IGM) left over from the pre-reionization era\textsuperscript{2}. If the latter is the case, we can measure the neutral fraction of the IGM at $z \gtrsim 6$ for the first time, giving crucially important information on the reionization history of the universe. We find that the wing shape can be reproduced either by DLA absorption (see inset of Fig. 1) or by the IGM. A comprehensive 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 one would detect the metal absorption lines even from GRBs originating from the metal-free first generation stars, as their environment may be self-polluted by pre-burst winds as suggested by the present observation. One 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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| Observed Wavelength (Å) | Equivalent Width (Å) | Column Density log (cm$^{-2}$) | Line Identification | Redshift |
|-------------------------|----------------------|-------------------------------|---------------------|----------|
| 9041.0 ± 0.8            | 4.5 ± 1.0            | 14.44$^{+0.14}_{-0.16}$       | C IV λ1548.2        | 4.840 ± 0.001 |
|                         |                      | (N V λ1238.8)                 |                     | (6.298 ± 0.001) |
| 9055.9 ± 1.7            | 1.7 ± 1.0            | 14.21$^{+0.25}_{-0.46}$       | C IV λ1550.8        | 4.840 ± 0.001 |
|                         |                      | (N V λ1242.8)                 |                     | (6.287 ± 0.001) |
| 9146.4 ± 1.8            | 3.8 ± 1.1            | 15.60$^{+0.14}_{-0.17}$       | S II λ1253.8        | 6.295 ± 0.001 |
| 9188.7 ± 2.6            | 6.1 ± 3.7            | 16.20$^{+1.87}_{-0.92}$       | S II λ1259.5        | 6.295 ± 0.002 |
| 9195.9 ± 1.2            | 8.3 ± 2.7            | 14.29$^{+0.57}_{-0.39}$       | Si II λ1260.4       | 6.296 ± 0.001 |
| 9225.8 ± 1.8            | 3.9 ± 1.1            | 13.63$^{+0.13}_{-0.16}$       | Si II* λ1264.7      | 6.295 ± 0.001 |
| 9499.1 ± 0.9            | 10.3 ± 1.9           | 15.85$^{+0.39}_{-0.28}$       | O I λ1302.2         | 6.295 ± 0.001 |
| 9737.2 ± 1.1            | 12.3 ± 2.4           | 15.41$^{+0.30}_{-0.26}$       | C II λ1334.5        | 6.296 ± 0.001 |

Table 1: List of the absorption lines detected in the spectrum of the optical afterglow of GRB 050904. 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, i.e., 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 $\lambda = 9041.0$ and 9055.9 Å could be identified as N V λλ1238.8,1242.8 if they are at a similar redshift as the other absorption lines. However, the derived redshifts of these two lines are significantly inconsistent with each other. Another possible identification is C IV λλ1548.2, 1550.8 in an intervening system at $z = 4.840$, which we think is more likely.
Figure 1  Spectrum of the afterglow of GRB 050904 covering wavelengths 7000–10000 Å with a resolution $R = \lambda/\Delta \lambda \sim 1000$ at 9000 Å. It was taken with Subaru/FOCAS at mid-epoch 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 $R = \lambda/\Delta \lambda \sim 600$ at 9000 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 Ly$\alpha$ and Ly$\beta$ 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, we show a model for the damping wing of Ly$\alpha$ absorption with a neutral hydrogen column density $\log N_{\text{HI}}(\text{cm}^{-2}) = 21.3$ at a redshift $z = 6.3$ by the solid line, overlaid on the observed spectrum in the wavelength range of 8700–9500 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. Note that only the red wing is relevant to the fit, since the emission blueward of Ly$\alpha$ is absorbed by the IGM.