nature Vol 461|29 October 2009|doi:10.1038/nature08459

LETTERS

A γ-ray burst at a redshift of z ≈ 8.2

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Long-duration γ-ray bursts (GRBs) are thought to result from the explosions of certain massive stars[1], and some are bright enough that they should be observable out to redshifts of $z > 20$ using current technology[2–4]. Hitherto, the highest redshift measured for any object was $z = 6.96$, for a Lyman-α emitting galaxy[5]. Here we report that GRB 090423 lies at a redshift of $z \approx 8.2$, implying that massive stars were being produced and dying as GRBs ~630 Myr after the Big Bang. The burst also pinpoints the location of its host galaxy.

GRB 090423 was detected by the Burst Alert Telescope (BAT) on NASA's Swift satellite[6] at 07:55:19 UT on 23 April 2009. Observations with Swift's X-ray Telescope (XRT), which began 73 s after the trigger, revealed a variable X-ray counterpart and localized its position to a precision of 2.3 arcsec (at the 90% confidence level). Ground-based optical observations in the r, i and z filters starting within a few minutes of the burst revealed no counterpart at these wavelengths (Supplementary Information).

The United Kingdom Infrared Telescope (UKIRT), Hawaii, began imaging about 20 min after the burst, in response to an automated request, and provided the first infrared (2.15-μm) detection of the GRB afterglow. In parallel, observations in other near-infrared (NIR) filters using the Gemini North 8-m telescope, Hawaii, showed that the counterpart was only visible at wavelengths greater than about 1.2 μm (Fig. 1). In this range, the afterglow was relatively bright and exhibited a shallow spectral slope, $F_\nu \propto \nu^{-0.26}$, in contrast to the deep limit on any flux at 1.02 μm. Later observations from Chile using the MPI/ESO 2.2-m telescope, Gemini South and the Very Large Telescope (VLT) confirmed this finding. Such a sharp spectral break cannot be produced by dust absorption at any redshift, and is a textbook case of a short-wavelength 'drop-out' source. The full grizYJHK spectral energy distribution (SED) obtained ~17 h after burst gives a photometric redshift of $z = 8.06^{+0.21}_{-0.28}$, assuming a simple intergalactic medium (IGM) absorption model. Complete details of our imaging campaign are given in Supplementary Table 1.

Our first NIR spectroscopy was performed with the European Southern Observatory (ESO) 8.2-m VLT, starting about 17.5 h after the burst. These observations revealed a flat continuum that abruptly disappeared at wavelengths less than about 1.13 μm, confirming the origin of the break as being due to Lyman-α absorption by neutral

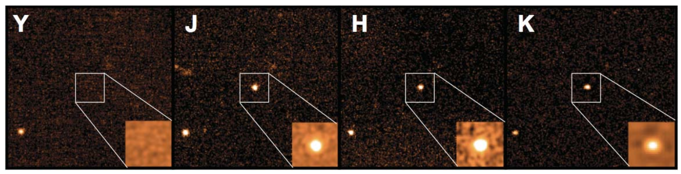

Figure 1 | Multiband images of the afterglow of GRB 090423. **The rightmost panel shows the discovery image made using the UKIRT Wide Field Infrared Camera with the K filter (centred at 2.15 μm) at a mid-time of about 30 min after the burst. The other three images (Y, 1.02 μm; J, 1.26 μm; H, 1.65 μm) were obtained approximately 1.5 h after the burst using Gemini North's Near Infrared Imager and Spectrometer (NIRI). The main panels are 40 arcsec to a side, oriented with north to the top and east to the left. Insets, regions around the GRB, smoothed and at higher contrast. The absence of any flux in Y implies a power-law spectral slope between Y and J steeper than $F_\nu \propto \nu^{-18}$ and, coupled with the blue colour at longer wavelengths ($J-H$(AB) ≈ 0.15 mag), immediately implies a redshift greater than about 7.8 for GRB 090423.**

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hydrogen, with a redshift of $z \approx 8.2$. The spectrum and broadband photometric observations, plotted over model data, are shown in Fig. 2. To obtain a more quantitative estimate of the redshift, we fit the spectra in redshift versus $\log[N_{\mathrm{H\,I}}(\mathrm{cm}^{-2})]$ space, assuming a flat prior likelihood value for $\log[N_{\mathrm{H\,I}}(\mathrm{cm}^{-2})]$ of between 19 and 23, which is broadly consistent with the distribution observed for lower-redshift GRB hosts[7–9]. We take the neutral fraction of the IGM to be 10%, although our conclusions depend only weakly on this assumption. We find the redshift from ISAAC spectroscopy to be $z = 8.19^{+0.03}_{-0.06}$. An additional spectrum, recorded ~40 h after the burst using the VLT's Spectrograph for INtegral Field Observations in the Near Infrared confirms this analysis, yielding $z = 8.33^{+0.06}_{-0.11}$ (Supplementary Information). Fitting simultaneously to both spectra and the photometric data points gives our best estimate of the redshift, $z = 8.23^{+0.06}_{-0.07}$. The low signal-to-noise ratio means we that are unable to detect metal absorption features in either spectrum—which would provide a more precise value of the redshift—and prevents a meaningful attempt to measure the IGM H I column density in this instance. Our three independent redshift measures are consistent with that reported from a low-resolution spectrum obtained with the Telescopio Nazionale Galileo, La Palma[10].

The X-ray and NIR light curves of GRB 090423 (Fig. 3) show a broken power-law decay, with evidence of flares in both the X-ray and the infrared bands. The spectral energy distribution is consistent with the presence of the cooling break between the X-ray and optical bands. Apart from the unusually shallow spectral slope of the continuum at wavelengths greater than 1.2 μm, its afterglow properties in general appear to be consistent with the bulk GRB population (see Supplementary Information for further discussion).

With the standard cosmological parameters (Hubble parameter, $H_0 = 71\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$; total matter density, $\Omega_{\mathrm{M}} = 0.27$; dark-energy density, $\Omega_{\Lambda} = 0.73$) a redshift of $z = 8.2$ corresponds to a time of only 630 Myr after the Big Bang, when the Universe was just 4.6% of its current age. GRB 090423's inferred isotropic equivalent energy, $E_{\mathrm{iso}} = 1 \times 10^{53}$ erg (8–1,000 keV)[11], indicates that it was a bright, but not extreme, GRB. Thus, we find no evidence of exceptional behaviour that might indicate an origin in a population III progenitor. First-generation stars are thought more likely to collapse into particularly massive black holes, which in turn may produce unusually long-lived GRBs[12]; this seems not to be the case for GRB 090423.

Indeed, we note that the γ-ray duration of GRB 090423, $t_{90} = 10.3$ s, corresponds in the rest frame to only 1.1 s, and the peak energy measured by BAT, 49 keV, is moderately hard in the rest frame. Two other GRBs with $z > 5$ (GRB 060927 and GRB 080913) had similarly short rest-frame durations, leading to some debate[13] as to whether their progenitors were similar to those of the 'short-hard' class of GRBs, which are not thought to be directly related to core collapse. However, in the case of GRB 090423, a more careful extrapolation of the observed γ-ray and X-ray light curves to lower redshifts shows that its duration would have appeared significantly longer than suggested by naive time-dilation considerations[14]. In any event, short GRBs probably have their origins in compact objects that are themselves the end products of massive stars, so the above conclusions will hold irrespective of the population from which GRB 090423 derives.

It has long been recognized that GRBs have the potential to be powerful probes of the early Universe[15]. Their association with individual stars means that they serve as a signpost of star formation, even if their host

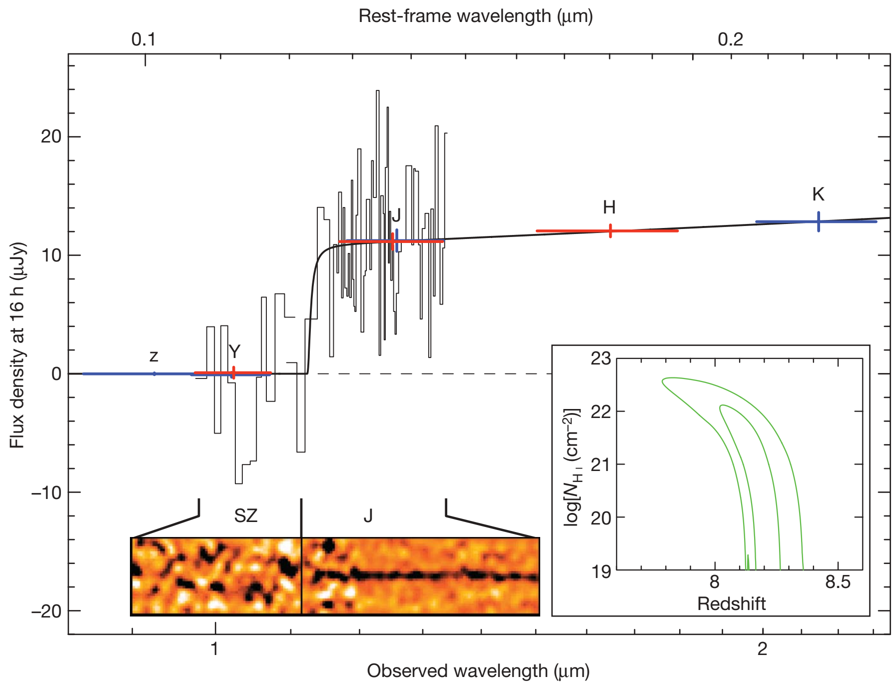

Figure 2 | The composite infrared spectrum of the GRB 090423 afterglow. SZ-band (0.98–1.1 μm) and J-band (1.1–1.4 μm) one- and two-dimensional spectra obtained with the VLT using the Infrared Spectrometer And Array Camera (ISAAC). Also plotted are the sky-subtracted photometric data points obtained using Gemini North's NIRI (red) and the VLT's High Acuity Wide field K-band Imager and Gemini South's Gemini Multi-Object Spectrograph (blue) (scaled to 16 h after the burst and expressed in microjanskys; $1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$). The vertical error bars show the 2σ (95%) confidence level, and the horizontal lines indicate the widths of the filters. The shorter-wavelength measurements are non-detections, and emphasize the tight constraints on any transmitted flux below the break. The break itself, at an observed wavelength of about 1.13 μm, is seen to occur close to the short-wavelength limit of the J-band spectrum, below which, although noisy, the spectrum shows no evidence of any detected continuum. Details of the data-reduction steps and adaptive binning used to construct these spectra are given in Supplementary Information. A model spectrum showing the H I damping wing for a host galaxy with a hydrogen column density of $N_{\mathrm{H\,I}} = 10^{21}\ \mathrm{cm^{-2}}$ at a redshift of $z = 8.23$ is also plotted (solid black line), and provides a good fit to the data. Inset, allowing for a wider range in possible host $N_{\mathrm{H\,I}}$ values gives the 1σ (68%) and 2σ confidence contours shown. The fact that no deviation is seen from a power-law spectrum at wavelengths greater than 1.2 μm, together with its shallow spectral slope, suggests that there is little or no dust along the line of sight through the GRB host galaxy (unless it is 'grey'), consistent with the galaxy being relatively unevolved, and having a low abundance of metals.

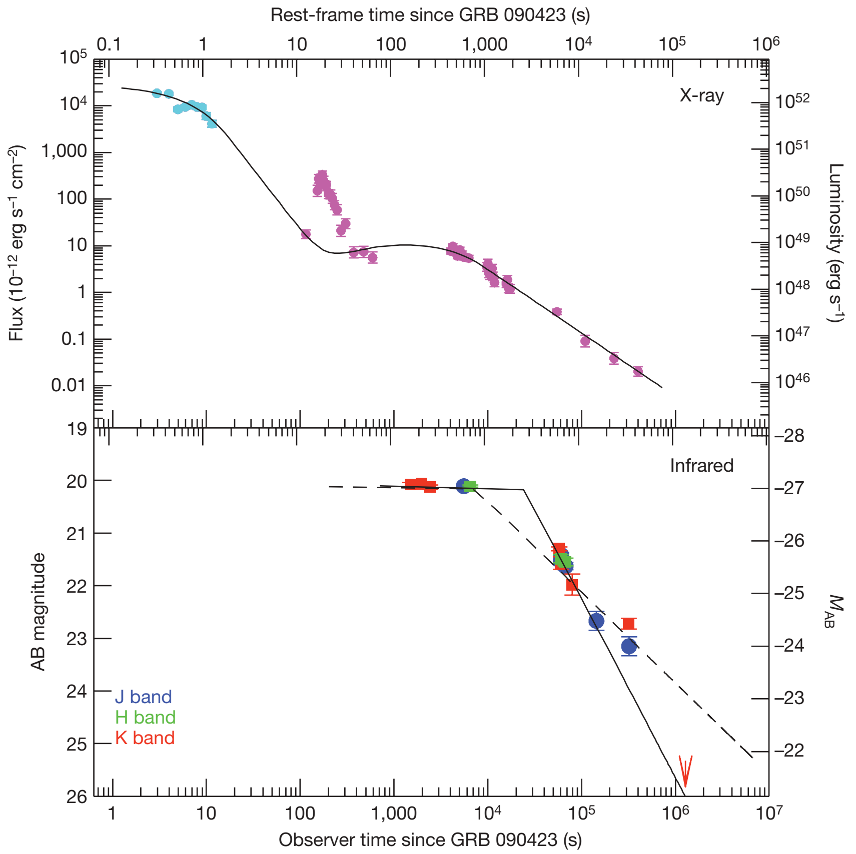

Figure 3 | The X-ray and infrared light curves of GRB 090423. The axes show both observed (left-hand and bottom axes) and rest-frame (right-hand and top axes) quantities. The X-ray light curve was obtained using Swift's BAT (cyan) and XRT (magenta), where the BAT observations have been extrapolated into the X-ray band. The fitted function represents a phenomenological model[28] of the prompt and afterglow components. The infrared light curve was obtained using UKIRT, Gemini North, the MPI/ESO 2.2-m telescope and the VLT. For consistency, although individual bands are plotted, they have been transformed into absolute magnitudes in the J band by means of the best-fitting SED ($F_\nu \propto \nu^{-0.26}$). We show two illustrative fits to the infrared light curve. The solid line shows a plateau, breaking at 24,000 s to a steeper slope proportional to $\sim t^{-1.4}$. This underestimates the late time points, which must then be interpreted as a flare. The dashed line shows an alternative model, in which mid-time points at ~60,000 s are instead interpreted as a flare; this is more consistent with the later time points and the X-ray break time at the end of the plateau. However, in this case the post-break slope, proportional to $\sim t^{-0.7}$, is much slower than the X-ray decay at comparable times, and it further requires a additional break in the light curve to accommodate the late-time upper limit. Error bars are 1σ (68% confidence level) and the absolute magnitude scale corresponds to absolute AB magnitudes at 0.136 μm. See Supplementary Information for further details.

galaxies are too faint to detect directly. Equally important, precise determination of the hydrogen Lyman-α absorption profile can provide a measure of the neutral fraction of the IGM at the location of the burst[16–20]. With multiple GRBs at redshifts of $z > 7$, and the associated information about the IGM, we could therefore trace the process of reionization from its early stages[21].

The high redshift of GRB 090423 has several crucial implications. Predictions based on extrapolating the global star-formation-rate density suggest that the observed rate of GRBs at $z \approx 8$ should be about 40% of that at $z \approx 6$ (ref. 12). Given the extra difficulty of identifying afterglows at higher redshifts, our finding is broadly consistent with these predictions. This is extremely encouraging for the prospects of future initiatives aimed at finding high-redshift GRBs and using them to locate and study primordial galaxies and measure the history of star formation at early times[22–24]. Furthermore, it is close to the redshift range in which the bulk of the cosmic reionization is thought to have taken place[25–27]. Very high-redshift GRBs for which infrared spectroscopy was possible earlier, or which had brighter afterglows, would provide a direct probe of the progress of reionization. Finding such events is not an unreasonable hope: the most extreme GRBs have had afterglows that were intrinsically significantly brighter than that of GRB 090423 at the same rest-frame time[3,4], and our first spectra were recorded more than 15 h after the burst. Spectroscopy with a high signal-to-noise ratio would also provide a measure of the metallicity of the host galaxy, which potentially offers important clues to the nature of any earlier generations of stars. Because the massive stars that yield GRBs are also likely to belong to the same population that is responsible for reionization, this suggests that GRBs will ultimately be used to constrain both sides—supply and demand—of the cosmic ionization budget in the early Universe.

Received 3 June; accepted 19 August 2009.

1. Woosley, S. E. & Bloom, J. S. The supernova gamma-ray burst connection. *Annu. Rev. Astron. Astrophys.* **44,** 507–556 (2006).
2. Lamb, D. Q. & Reichart, D. E. Gamma-ray bursts as a probe of the very high redshift universe. *Astrophys. J.* **536,** 1–18 (2000).
3. Racusin, J. L. *et al.* Broadband observations of the naked-eye γ -ray burst GRB 080319B. *Nature* **455,** 183–188 (2008).
4. Bloom, J. S. *et al.* Observations of the naked-eye GRB080319B: implications of nature's brightest explosion. *Astrophys. J.* **691,** 723–737 (2009).
5. Iye, M. *et al.* A galaxy at a redshift $z = 6.96$. *Nature* **443,** 186–188 (2006).
6. Gehrels, N. *et al.* The Swift Gamma-Ray Burst Mission. *Astrophys. J.* **611,** 1005–1020 (2004).
7. Jakobsson, P. *et al.* H I column densities of $z > 2$ Swift gamma-ray bursts. *Astron. Astrophys.* **460,** L13–L17 (2006).
8. Chen, H.-W., Prochaska, J. X. & Gnedin, N. Y. A new constraint on the escape fraction in distant galaxies using γ-ray burst afterglow spectroscopy. *Astrophys. J.* **667,** L125–L128 (2007).
9. Fynbo, J. P. U. *et al.* Low-resolution spectroscopy of gamma-ray burst optical afterglows: biases in the Swift sample and characterization of the absorbers. Preprint at ⟨http://arxiv.org/abs/0907.3449⟩ (2009).
10. Salvaterra, R. *et al.* GRB 090423 at a redshift of $z \approx 8.1$. *Nature* doi:10.1038/nature08459 (this issue).

11. von Kienlin, A. *et al.* GRB 090423: Fermi GBM observation (correction of isotropic equivalent energy). *GCN Circ.* **9251** (2009).
12. Bromm, V. & Loeb, A. High-redshift gamma-ray bursts from population III progenitors. *Astrophys. J.* **642,** 382–388 (2006).
13. Zhang, B. *et al.* Physical classification scheme of cosmological gamma-ray bursts and their observational characteristics: on the nature of z=6.7 GRB 080913 and some short/hard GRBs. *Astrophys J.* (in the press); preprint at ⟨http://arxiv.org/abs/0902.2419v1⟩ (2009).
14. Zhang, B.-B. & Zhang, B. GRB 090423: pseudo burst at z=1 and its relation to GRB 080913. *GCN Circ.* **9279** (2009).
15. Wijers, R. A. M. J. *et al.* Gamma-ray bursts from stellar remnants - probing the universe at high redshift. *Mon. Not. R. Astron. Soc.* **294,** L13–L17 (1998).
16. Miralda-Escude, J. Reionization of the intergalactic medium and the damping wing of the Gunn-Peterson Trough. *Astrophys. J.* **501,** 15–22 (1998).
17. Barkana, R. & Loeb, A. Gamma-ray bursts versus quasars: Lyα signatures of reionization versus cosmological infall. *Astrophys. J.* **601,** 64–77 (2004).
18. Totani, T. *et al.* Implications for cosmic reionization from the optical afterglow spectrum of the gamma-ray burst 050904 at z = 6.3. *Publ. Astron. Soc. Jpn* **58,** 485–498 (2009).
19. Greiner, J. *et al.* GRB 080913 at redshift 6.7. *Astrophys. J.* **693,** 1610–1620 (2009).
20. Faucher-Giguere, C.-A., Lidz, A., Hernquist, L. & Zaldarriaga, M. Evolution of the intergalactic opacity: implications for the ionizing background, cosmic star formation, and quasar activity. *Astrophys. J.* **688,** 85–107 (2008).
21. McQuinn, M. *et al.* Probing the neutral fraction of the IGM with GRBs during the epoch of reionization. *Mon. Not. R. Astron. Soc.* **388,** 1101–1110 (2008).
22. Grindlay, J. in *Gamma-Ray Burst: Sixth Huntsville Symposium* (eds Meegan, C., Kouveliotou, C. & Gehrels, N.) 18–24 (AIP Conf. Ser. 1113, American Institute of Physics, 2009).
23. Tanvir, N. R. & Jakobsson, P. Observations of GRBs at high redshift. *Phil. Trans. R. Soc. A* **365,** 1377–1384 (2007).
24. Berger, E. *et al.* Hubble Space Telescope and Spitzer observations of the afterglow and host galaxy of GRB 050904 at z = 6.295. *Astrophys. J.* **665,** 102–106 (2007).
25. Komatsu, E. *et al.* Five-year Wilkinson Microwave Anisotropy Probe observations: cosmological interpretation. *Astrophys. J.* **180** (suppl.), 330–376 (2009).
26. Malhotra, S. & Rhoads, J. E. Luminosity functions of Lyα emitters at redshifts z=6.5 and z=5.7: evidence against reionization at $z\leq6.5$. *Astrophys. J.* **617,** L5–L8 (2004).
27. Becker, G. D., Rauch, M. & Sargent, W. L. W. The evolution of optical depth in the Lyα forest: evidence against reionization at z∼6. *Astrophys. J.* **662,** 72–93 (2007).
28. Willingale, R. *et al.* Testing the standard fireball model of gamma-ray bursts using late X-ray afterglows measured by Swift. *Astrophys. J.* **662,** 1093–1110 (2007).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank Ph. Yock, B. Allen, P. Kubanek, M. Jelinek and S. Guziy for their assistance with the BOOTES-3 YA telescope observations (Supplementary Information). This work was partly based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the US National Science Foundation on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), the Ministério da Ciência e Tecnologia (Brazil) and SECYT (Argentina). This work was also partly based on observations made using ESO telescopes at the La Silla or Paranal observatories by G. Carraro, L. Schmidtobreick, G. Marconi, J. Smoker, V. Ivanov, E. Mason and M. Huertas-Company. The UKIRT is operated by the Joint Astronomy Centre on behalf of the UK Science and Technology Facilities Council. R.J.F. acknowledges a Clay Fellowship.

Author Contributions Triggering observations: N.R.T., D.B.F., A.J.L., E.B., J.S.B., D.P., J. Greiner, A.J.C.-T., A.d.U.P.; analysis of ground-based data: N.R.T., D.B.F., A.J.L., E.B., K.W., J.P.U.F., A.C., J.S.B., J.F., J.D., J. Gorosabel, B.C., D.P., J.R.M., T. Krühler, A.J.C.-T., A.d.U.P., C.G.M.; Swift analysis: P.A.E., R.L.C.S., K.P., R.W., A.J.L., N.R.T., N.G., D.W., P.S., T.S.; observations at various observatories and their automation to accept GRB overrides: A.J.A., A.A., T. Kerr, T.N., A.W.S., K.R., T.W. All authors made contributions through their involvement in the programmes from which the data derive, and contributed to the interpretation, content and discussion presented here. Writing was led by N.R.T., A.J.L., D.B.F. and E.B.

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