LETTERS

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

N. R. Tanvir[1], D. B. Fox[2], A. J. Levan[3], E. Berger[4], K. Wiersema[1], J. P. U. Fynbo[5], A. Cucchiara[2], T. Krühler[6,7], N. Gehrels[8], J. S. Bloom[9], J. Greiner[6], P. A. Evans[1], E. Rol[10], F. Olivares[6], J. Hjorth[5], P. Jakobsson[11], J. Farihi[1], R. Willingale[1], R. L. C. Starling[1], S. B. Cenko[9], D. Perley[9], J. R. Maund[5], J. Duke[1], R. A. M. J. Wijers[10], A. J. Adamson[12], A. Allan[13], M. N. Bremer[14], D. N. Burrows[2], A. J. Castro-Tirado[15], B. Cavanagh[12], A. de Ugarte Postigo[16], M. A. Dopita[17], T. A. Fatkhullin[18], A. S. Fruchter[19], R. J. Foley[4], J. Gorosabel[15], J. Kennea[2], T. Kerr[12], S. Klose[20], H. A. Krimm[21,22], V. N. Komarova[18], S. R. Kulkarni[23], A. S. Moskvitin[18], C. G. Mundell[24], T. Naylor[13], K. Page[1], B. E. Penprase[25], M. Perri[26], P. Podsiadlowski[27], K. Roth[28], R. E. Rutledge[29], T. Sakamoto[21], P. Schady[30], B. P. Schmidt[17], A. M. Soderberg[4], J. Sollerman[5,31], A. W. Stephens[28], G. Stratta[26], T. N. Ukwatta[8,32], D. Watson[5], E. Westra[4], T. Wold[12] & C. Wolf[27]

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
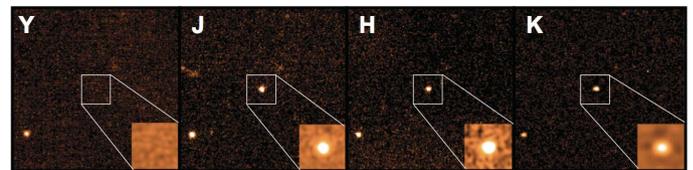

Figure 1 | Multiband images of the afterglow of GRB 090423. The right-most panel shows the discovery image made using the UKIRT Wide Field Infrared Camera with the K filter (centred at 2.15 μm) at a mid-time of about 30 min after the burst. The other three images (Y, 1.02 μm; J, 1.26 μm; H, 1.65 μm) 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 ($J-H(AB) \approx 0.15$ mag), immediately implies a redshift greater than about 7.8 for GRB 090423.

[1]Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK. [2]Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, Pennsylvania 16802, USA. [3]Department of Physics, University of Warwick, Coventry CV4 7AL, UK. [4]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA. [5]Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark. [6]Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße 1, 85740 Garching, Germany. [7]Universe Cluster, Technische Universität München, Boltzmannstrasse 2, 85748 Garching, Germany. [8]NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. [9]Department of Astronomy, University of California, Berkeley, California 94720-3411, USA. [10]Astronomical Institute "Anton Pannekoek", University of Amsterdam, PO Box 94249, 1090 GE Amsterdam, The Netherlands. [11]Centre for Astrophysics and Cosmology, Science Institute, University of Iceland, Dunhagi 5, 107 Reykjavík, Iceland. [12]Joint Astronomy Centre, 660 North A'ohoku Place, University Park, Hilo, Hawaii 96720, USA. [13]School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK. [14]H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK. [15]Instituto de Astrofísica de Andalucía del Consejo Superior de Investigaciones Científicas, PO Box 03004, 18080 Granada, Spain. [16]European Southern Observatory, Casilla 19001, Santiago 19, Chile. [17]Research School of Astronomy & Astrophysics, The Australian National University, Cotter Road, Weston Creek, Australian Capital Territory 2611, Australia. [18]Special Astrophysical Observatory, Nizhnij Arkhyz, Karachai-Cirkassian Republic, 369167, Russia. [19]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218, USA. [20]Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany. [21]CRESST and NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. [22]Universities Space Research Association, 10211 Wincopin Circle, Suite 500, Columbia, Maryland 21044, USA. [23]Department of Astronomy, California Institute of Technology, MC 249-17, Pasadena, California 91125, USA. [24]Astrophysics Research Institute, Liverpool John Moores University, Birkenhead CH41 1LD, UK. [25]Department of Physics and Astronomy, Pomona College, Claremont, California 91711, USA. [26]ASI Science Data Center, Via Galileo Galilei, 00044 Frascati, Italy. [27]Department of Physics, Oxford University, Keble Road, Oxford OX1 3RH, UK. [28]Gemini Observatory, Hilo, Hawaii 96720, USA. [29]Physics Department, McGill University, 3600 Rue University, Montreal, Quebec H3A 2T8, Canada. [30]The UCL Mullard Space Science Laboratory, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK. [31]The Oskar Klein Centre, Department of Astronomy, Stockholm University, 106 91 Stockholm, Sweden. [32]The George Washington University, Washington DC 20052, USA.

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 $\log[N_{H\,I}\,(cm^{-2})]$ space, assuming a flat prior likelihood value for $\log[N_{H\,I}\,(cm^{-2})]$ 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).
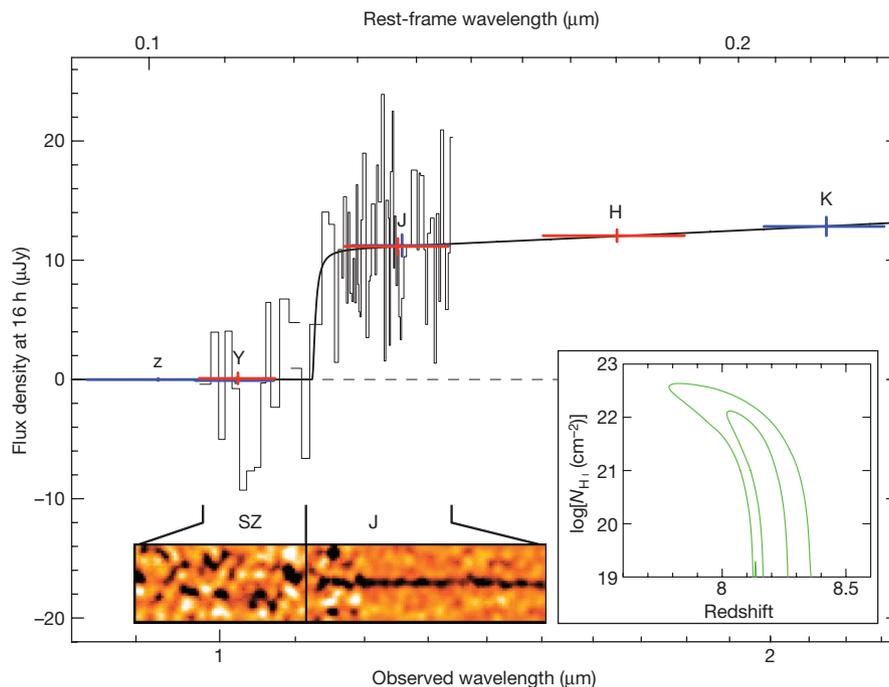
With the standard cosmological parameters (Hubble parameter, $H_0 = 71\ km\ s^{-1}\ Mpc^{-1}$; total matter density, $\Omega_M = 0.27$; dark-energy density, $\Omega_\Lambda = 0.73$) a redshift of $z = 8.2$ corresponds to a time of only 630 Myr after the Big Bang, when the Universe was just 4.6% of its current age. GRB 090423's inferred isotropic equivalent energy, $E_{iso} = 1 \times 10^{53}$ 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 Jy = 10^{-26} 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 $N_{H\,I} = 10^{21}\ cm^{-2}$ 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 $N_{H\,I}$ 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.
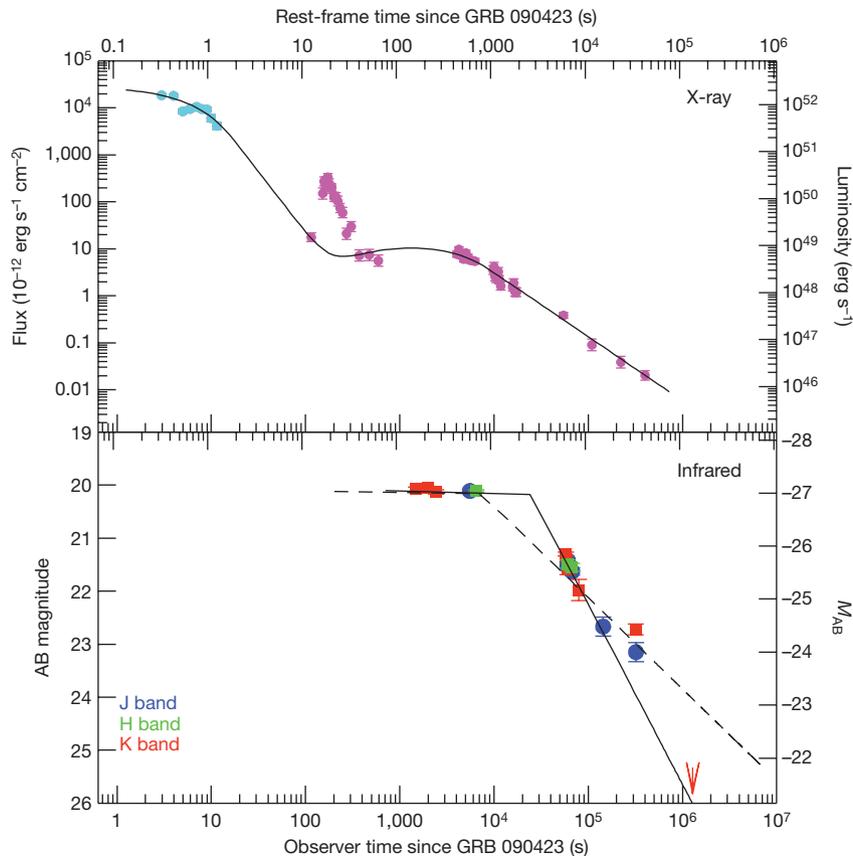
Figure 3 | The X-ray and infrared light curves of GRB 090423. The axes show both observed (left-hand and bottom axes) and rest-frame (right-hand and top axes) quantities. The X-ray light curve was obtained using Swift's BAT (cyan) and XRT (magenta), where the BAT observations have been extrapolated into 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 $\sim$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.

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