

## LETTERS

GRB 090423 at a redshift of  $z \approx 8.1$ 

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Gamma-ray bursts (GRBs) are produced by rare types of massive stellar explosion. Their rapidly fading afterglows are often bright enough at optical wavelengths that they are detectable at cosmological distances. Hitherto, the highest known redshift for a GRB was  $z = 6.7$  (ref. 1), for GRB 080913, and for a galaxy was  $z = 6.96$  (ref. 2). Here we report observations of GRB 090423 and the near-infrared spectroscopic measurement of its redshift,  $z = 8.1_{-0.3}^{+0.1}$ . This burst happened when the Universe was only about 4 per cent of its current age<sup>3</sup>. Its properties are similar to those of GRBs observed at low/intermediate redshifts, suggesting that the mechanisms and progenitors that gave rise to this burst about 600,000,000 years after the Big Bang are not markedly different from those producing GRBs about 10,000,000,000 years later.

GRB 090423 was detected by NASA's Swift satellite on 23 April 2009 at 07:55:19 UT as a double-peaked burst of duration  $T_{90} = 10.3 \pm 1.1$  s. As observed by Swift's Burst Alert Telescope (BAT)<sup>4</sup>, it had a 15–150-keV fluence of  $F = (5.9 \pm 0.4) \times 10^{-7}$  erg cm<sup>-2</sup> and a peak energy of  $E_p = 48_{-6}^{+9}$  keV (errors at the 90% confidence level). Its X-ray afterglow was identified by Swift's X-ray Telescope (XRT), which began observations 73 s after the BAT trigger<sup>5</sup>. A prominent flare was detected at  $t \approx 170$  s in the X-ray light curve, which shows a typical 'steep decay/plateau/normal decay' behaviour (Fig. 1). Swift's Ultraviolet/Optical Telescope did not detect a counterpart even though it started making settled exposures only 77 s after the trigger<sup>6</sup>. A 2- $\mu$ m counterpart was detected with the United Kingdom Infra-Red Telescope, Hawaii, 20 min after the trigger<sup>7</sup>. Evidence that this burst occurred at high redshift was given by the Gamma-Ray Burst Optical/Near-Infrared Detector (GROND, Chile) multiband imager (from the g' band to the K band), which indicated a photometric redshift of  $z = 8.0_{-0.8}^{+0.4}$  (ref. 7).

We used the 3.6-m Telescopio Nazionale Galileo (TNG, La Palma) with the Near Infrared Camera Spectrometer (NICS) and the Amici prism to obtain a low-resolution ( $R \approx 50$ ) spectrum of GRB 090423  $\sim 14$  h after the trigger. NICS/Amici is an ideal instrument to detect spectral breaks in the continuum of faint objects because of its high efficiency and wide simultaneous spectral coverage (0.8–2.4  $\mu$ m).

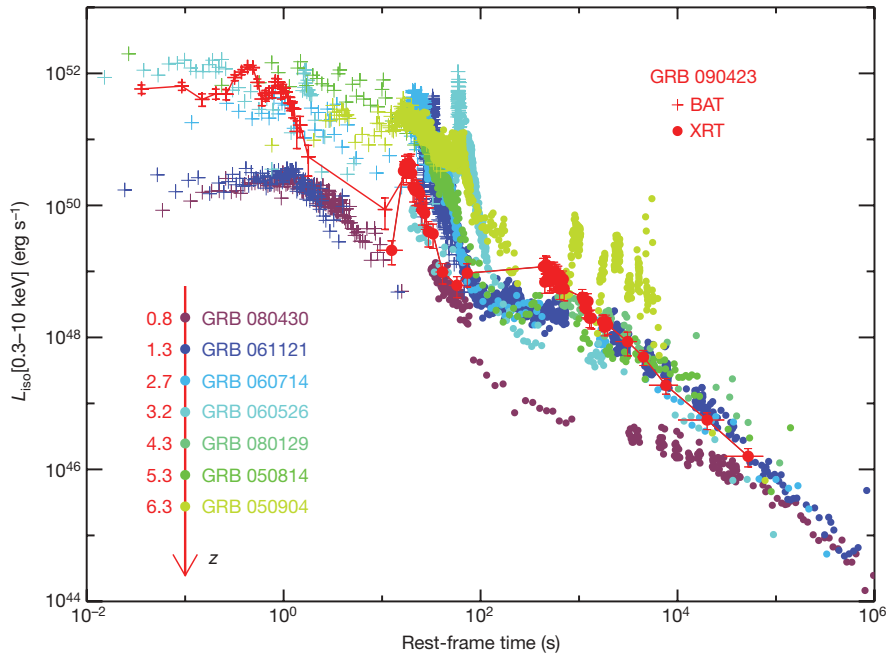
The spectrum (Fig. 2) reveals a clear break at a wavelength of 1.1  $\mu$ m (ref. 8). We derive a spectroscopic redshift for the GRB of  $z = 8.1_{-0.3}^{+0.1}$  (ref. 9; see Supplementary Information, section 3), interpreting the break as Lyman- $\alpha$  absorption in the intergalactic medium. No other significant absorption features were detected. This result is consistent, within the errors, with the measurement reported in ref. 7.

At  $z \approx 8.1$ , GRB 090423 has a prompt-emission rest-frame duration of only  $T_{90,rf} = 1.13 \pm 0.12$  s in the redshifted 15–150-keV energy band, an isotropic equivalent energy of  $E_{iso} = (1.0 \pm 0.3) \times 10^{53}$  erg in the redshifted 8–1,000-keV energy band<sup>10</sup> and a peak energy of  $E_{p,rf} = 437 \pm 55$  keV. The short duration and the high peak energy are consistent both with the distribution of long bursts, linked to massive stellar collapse, and with the population of short bursts, thought to arise from the merger of binary compact stars<sup>11,12</sup>. Although the analysis of the spectral lag between the high- and low-energy channels in the BAT band is inconclusive about the classification of GRB 090423, the high  $E_{iso}$  argues in favour of a long GRB. The fact that GRB 090423 matches the  $E_{iso}-E_{p,rf}$  correlation of long GRBs within  $0.5\sigma$  further supports this classification<sup>13</sup> (Supplementary Fig. 2).

The rest-frame  $\gamma$ -ray and X-ray light curves of GRB 090423 are remarkably akin to those of long GRBs at low, intermediate and high redshifts (Fig. 1), suggesting similar physics and interaction with the circumburst medium. The near-infrared light curve of GRB 090423  $\sim 15$  h after the trigger shows a temporal decay with a power-law index of  $\alpha_0 \approx 0.5$ , which is markedly different from the decay observed at X-ray energies during the same time interval, which has a power-law index of  $\alpha_{X,2} \approx 1.3$  (Supplementary Fig. 3 and Supplementary Information, section 2). As for other lower-redshift GRBs, this behaviour is difficult to reconcile with standard afterglow models, although the sampling of the near-infrared light curve is too sparse for any firm conclusion to be drawn.

The spectral energy distribution of near-infrared afterglow is well fitted by a power law with an index of  $\beta = 0.4_{-1.4}^{+0.2}$  and an equivalent interstellar extinction of  $E(B-V) < 0.15$ , assuming dust reddening

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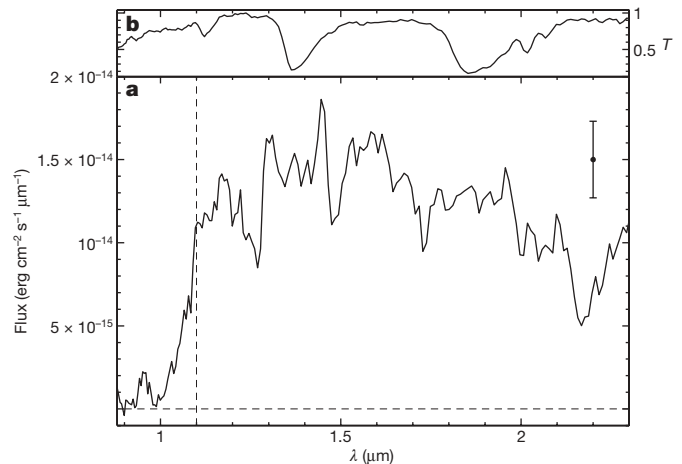
**Figure 1 | Rest-frame  $\gamma$ -ray and X-ray light curves for bursts at different redshifts.** BAT and XRT light curves of GRB 090423 (red data) in the source rest frame. Errors in luminosity,  $L_{\text{iso}}$ , are at the  $1\sigma$  level; horizontal bars refer to the integration time interval. The XRT 0.3–10-keV light curve shows a prominent flare at a rest-frame time of  $t_{\text{rf}} \approx 18$  s (also detected by BAT), and a flat phase (with a power-law index of  $\alpha_{X,1} = 0.13 \pm 0.11$ ) followed by a typical decay with a power-law index of  $\alpha_{X,2} = 1.3 \pm 0.1$ . We compare the light curves of GRB 090423 with those of seven GRBs in the redshift interval

0.8–6.3. The bursts are selected from among those showing a canonical three-phase behaviour (steep decay/plateau/normal decay) in the X-ray light curve and without a spectral break between BAT and XRT, allowing the spectral calibration of the BAT signal into the 0.3–10-keV energy band. The light curves of GRB 090423 do not have any distinguishing features relative to those of the lower-redshift bursts, suggesting that the physical mechanism that causes the GRB and its interaction with the circumburst medium are similar at  $z \approx 8.1$  and at lower redshifts.

consistent with the Small Magellanic Cloud<sup>9</sup>. On the other hand, the analysis of the XRT data in the time interval 3,900–21,568 s suggests the presence of intrinsic absorption (in excess of the Galactic value) with an equivalent hydrogen column density of  $N_{\text{H}}(z) = 6.8^{+5.6}_{-5.3} \times 10^{22} \text{ cm}^{-2}$  (90% confidence level; Supplementary Information, section 1). The low value of the dust extinction coupled with a relatively high value of  $N_{\text{H}}$  suggests that GRB 090423 originates from a region with low dust content relative to those of low- $z$  GRBs<sup>14</sup>, but one similar to that of the high- $z$  GRB 050904, for which  $z = 6.3$  (ref. 15). Because the absorbing medium must be thin from the point of view of ‘Thomson’ scattering, the metallicity of the circumburst medium can be constrained to be  $>4\%$  of the solar value,  $Z_{\odot}$ . The implication is that previous supernova explosions have already enriched the host galaxy of GRB 090423 to more than the critical metallicity,  $Z \approx 10^{-4} Z_{\odot}$  (ref. 16), that prevents the formation of very massive stars (population III stars). Therefore, the progenitor of GRB 090423 should belong to a second stellar generation. Its explosion injected fresh metals into the interstellar medium, further contributing to the enrichment of its host galaxy. Its existence empirically supports the cosmological models<sup>17,18</sup> in which stars and galaxies, already enriched in metals, are in place only  $\sim 600,000,000$  yr after the Big Bang. Long GRBs are mostly associated with star-forming dwarf galaxies, which are thought to be the dominant population of galaxies in the early Universe<sup>19</sup>. The fact that GRB 090423 appears to have exploded in an environment similar to that of low- $z$  GRB hosts<sup>20</sup> is in agreement with this.

The occurrence of a GRB at  $z \approx 8$  has important implications for the cosmic history of these objects<sup>21–24</sup>. In a first, simple, approach, we can assume that GRBs trace the cosmic star formation history, given the well-known link between long GRBs and the deaths of massive stars<sup>25</sup>, and that GRBs are well described by a universal luminosity function. However, under these assumptions the expected number of bursts at  $z \geq 8$  with an observed photon peak flux larger than or equal to that of GRB 090423 is extremely low:  $\sim 4 \times 10^{-4}$  in  $\sim 4$  yr of Swift operation (Supplementary Fig. 6 and Supplementary Information, section 4). Hence, one or both of the above assumptions may be an

oversimplification<sup>24,26</sup>. The detection of a very high- $z$  burst such as GRB 090423 could be accommodated if the GRB luminosity function were shifted towards higher luminosities according to  $(1+z)^{\delta}$  with



**Figure 2 | TNG spectrum of the near-infrared afterglow.** **a**, Spectrum of GRB 090423 obtained using the Amici prism on the TNG. The sharp break at wavelength  $\lambda \approx 1.1 \mu\text{m}$ , which is due to H I absorption in the intergalactic medium at the wavelength of the Lyman- $\alpha$  line, implies that  $z = 8.1^{+0.1}_{-0.3}$ . The spectrum has been smoothed with a boxcar filter of width  $\Delta = 25$  pixels (where one pixel corresponds to  $\sim 0.006 \mu\text{m}$  at  $\lambda = 1.1 \mu\text{m}$ ). The absolute flux calibration was obtained by matching the almost simultaneous GROND photometric measurements<sup>7</sup>. The wavelength calibration was obtained from the TNG archive and adjusted to the wavelengths of the main atmospheric bands. The error bar corresponds to  $1\sigma$  uncertainty as measured on the smoothed spectrum. The confidence level of the Lyman- $\alpha$  break detection is  $\approx 4\sigma$ . See also Supplementary Information, section 3. **b**, Plot of transmittance,  $T$  (the atmospheric transparency convolved with the instrumental response). The system has a significant sensitivity down to  $0.9 \mu\text{m}$ , and no instrumental or atmospheric effect could explain the abrupt flux break observed in the spectrum of GRB 090423.

$\delta \gtrsim 1.5$ , or if the GRB formation rate were strongly enhanced in galaxies with  $Z \lesssim 0.2Z_{\odot}$ . The requirement for evolution may be mitigated if we assume a very high star formation rate at  $z > 8$ . However, we note that the need for evolution is strongly supported by both the large number of Swift detections at  $z > 2.5$  (ref. 24) and the number of bursts with peak luminosities in excess of  $10^{53} \text{ erg s}^{-1}$  (ref. 26). A possible explanation is that high-redshift galaxies are characterized by a top-heavy (bottom-light) stellar initial mass function with a higher incidence of massive stars than in the local Universe<sup>27</sup>, providing an enhanced number of GRB progenitors. Such objects could be the main agents responsible for completing the reionization of the Universe<sup>19,28–30</sup>.

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**Supplementary Information** is linked to the online version of the paper at [www.nature.com/nature](http://www.nature.com/nature).

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