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Spectroscopic confirmation of a galaxy at redshift $z = 8.6$

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Galaxies had their most significant impact on the Universe when they assembled their first generations of stars. Energetic photons emitted by young, massive stars in primeval galaxies ionized the intergalactic medium surrounding their host galaxies, cleared sightlines along which the light of the young galaxies could escape, and fundamentally altered the physical state of the intergalactic gas in the Universe continuously until the present day[1,2]. Observations of the cosmic microwave background[3], and of galaxies and quasars at the highest redshifts[4], suggest that the Universe was reionized through a complex process that was completed about a billion years after the Big Bang, by redshift $z \approx 6$. Detecting ionizing Lyman-α photons from increasingly distant galaxies places important constraints on the timing, location and nature of the sources responsible for reionization. Here we report the detection of Lyα photons emitted less than 600 million years after the Big Bang. UDFy-38135539 (ref. 5) is at a redshift of $z = 8.5549 \pm 0.0002$, which is greater than those of the previously known most distant objects, at $z = 8.2$ (refs 6 and 7) and $z = 6.96$ (ref. 8). We find that this single source is unlikely to provide enough photons to ionize the volume necessary for the emission line to escape, requiring a significant contribution from other, probably fainter galaxies nearby[9].

UDFy-38135539 was selected as a candidate $z \approx 8.6$ galaxy from deep Wide Field Camera 3 observations of the Hubble Ultra Deep Field[5]. Its red Y_{105}–J_{125} colour is one of the reddest in the parent sample of $z = 8$–9 candidates, and, together with the sensitive upper limits in the optical through to the Y_{105} band, make it the most plausible $z \approx 8.6$ galaxy[5,10]. To search for its Lyα emission, we obtained sensitive near-infrared integral-field spectroscopic observations of UDFy-38135539 using the SINFONI spectrograph at the ESO Very Large Telescope, with an integration time on the source of 14.8 h in the near-infrared J band (1.1–1.4 μm).

In our spectrum, we detect faint line emission at a wavelength of $\lambda = 11{,}615.6 \pm 2.4$ Å, corresponding to a redshift of $z = 8.5549 \pm 0.0002$ assuming that the line is Lyα (Fig. 1). This redshift is consistent with the redshift estimates made by comparing the photometry with models of spectral energy distributions[10]. We constructed a line image by spectrally summing a data volume containing the line (Fig. 2). Both the size of the emission and the spectral width of the line are what would be expected for a source of astrophysical origin. If the line were due to detector noise, this would generally lead to a linewidth and source size that are smaller than the resolution of the spectrograph and the smearing due to atmospheric turbulence (Supplementary Information).

The photometry from the Hubble Space Telescope allows for an alternative (but unlikely) redshift of $z = 2.12$, so we also investigate whether the emission line could be another emission line at lower redshift. In this case, the line may be the [O II] $\lambda = 3{,}726$ and $3{,}729$ Å emission doublet, but we rule this out because the [O II] doublet would be clearly resolved and, hence, the line would be intrinsically wider than observed (details are given in Supplementary Information).

For a standard Λ cold dark matter (ΛCDM) cosmology, the Hubble constant is 70 km s^{-1} Mpc^{-1}, the dark matter density is 0.3 and the dark energy density (cosmological constant) is 0.7, the luminosity distance is $d_l = 86.9$ Gpc, and the total flux of Lyα emission implies that the luminosity of the source is $5.5 \pm 1.0 \pm 1.8 \times 10^{42}$ erg s^{-1} (1σ uncertainty and systematic uncertainty). In comparison, currently known Lyα emitters over a wide range of redshifts ($z \approx 3$–7) have typical luminosities of $(3$–$10) \times 10^{42}$ erg s^{-1} without significant evolution[11,12]. Thus, UDFy-38135539 can be considered a typical Lyα-emitting galaxy.

At $z = 8.55$, the observed H_{160}-band window samples around 1,700 Å in the rest-frame ultraviolet. The H-band magnitude implies a flux density of $\log(f_{1{,}700\text{Å}}\ (\text{erg s}^{-1}\text{ cm}^{-2}\text{ Hz}^{-1})) = -30.7 \pm 0.2$ and an intrinsic luminosity density of $\log(L_{1{,}700\text{Å}}\ (\text{erg s}^{-1}\text{ Hz}^{-1})) = 28.3 \pm 0.2$. The continuum luminosity density is about one magnitude fainter than M_{UV}*, the characteristic magnitude of the ultraviolet luminosity function, for galaxies with $z = 6$–7 (refs 13, 14). If the observed evolution of the luminosity function from $z \approx 3$ to $z \approx 7$ continues to $z \approx 8.6$, this would imply that UDFy-38135539 is a typical M_{UV}* galaxy[5].

Although we cannot derive the characteristics of the stellar population in UDFy-38135539, similarly selected galaxies at lower redshifts, $z \approx 5$–7, seem to be young (ages between 10 and 100 million years, Myr) and have both low metallicity and low extinction[15–17]. Plausible characteristics for the stellar population in UDFy-38135539 include low metallicity (10% of the solar metal abundance to essentially zero heavy elements), a mass distribution either similar to that of massive stars in local galaxies or with only very massive stars[18], and ages between 10 and 100 Myr (but perhaps as old as 300 Myr (ref. 19)). Considering this range of mass distributions, metallicities and ages, we estimate the star formation rate of UDFy-38135539, on the basis of the ultraviolet continuum luminosity, to be 2–$4 M_{\odot}$ yr^{-1}. On the basis of the Lyα luminosity, we estimate the star formation rate to be 0.3–$2.1 M_{\odot}$ yr^{-1}. However, we caution that, owing to the unknown absorption by the intergalactic or interstellar medium, the star formation rate estimated using this Lyα luminosity should be considered a lower limit.

Observing Lyα emission in a galaxy at $z = 8.55$ suggests that the surrounding intergalactic medium must be ionized beyond ~1 Mpc from the source to allow the emission to escape. We note that the mean recombination time at $z \approx 8.6$ is approximately a Hubble time at this redshift (~600 Myr). Thus, once a region of the intergalactic medium becomes ionized, we expect that it will be fossilized because the gas has insufficient time to recombine before the end of reionization. Moreover, because the time during which a source is a luminous emitter of ionizing photons is significantly less than a Hubble time, the sources that created any ionized bubble in the intergalactic medium may be very difficult to detect[20].

It is therefore instructive to investigate the possible size of the ionized region around UDFy-38135539. The total number of ionizing

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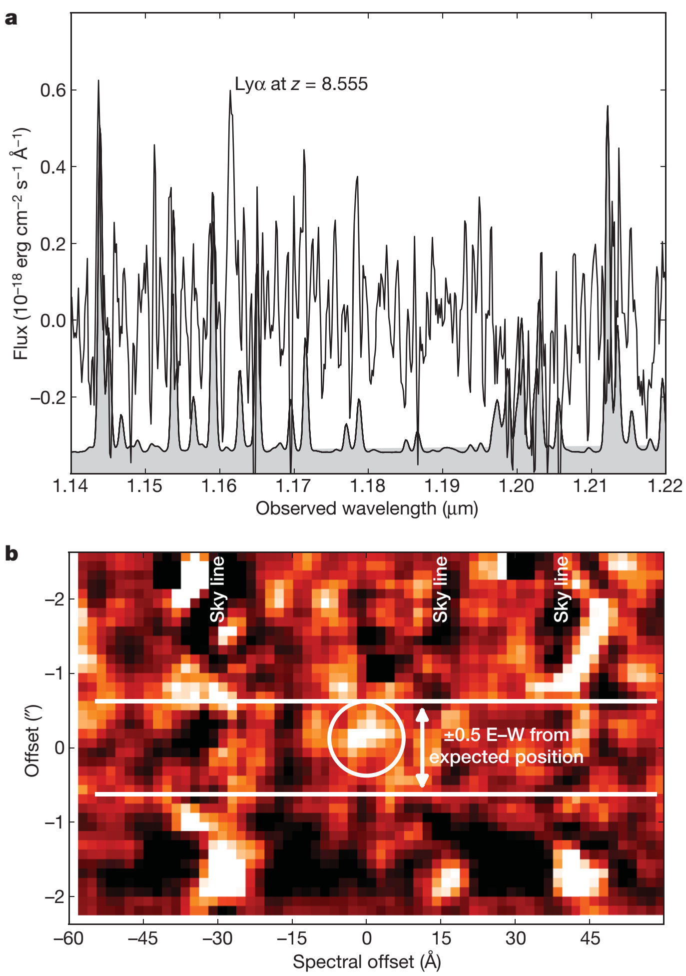

Figure 1 | Two representations of the spectrum of UDFy-38135539 showing its significance. **a**, The spectrum shows a faint emission line detected at 6σ significance at a wavelength of 11,615.6 Å, corresponding to a redshift of $z = 8.5549 \pm 0.0020$ for Lyα. The integrated spectrum was extracted from a square aperture of 5×5 pixels, corresponding to $0.625'' \times 0.625''$, which is approximately the size of the seeing disk. The measured line full-width at half-maximum is 9.2 ± 1.2 Å, which is about 1σ greater than the instrumental resolution. The line flux is $(6.1 \pm 1.0) \times 10^{-18}$ erg cm^{-2} s^{-1}, detected at 6σ significance. All of the line parameters (redshift, width, flux and significance) were estimated with a Monte Carlo simulation assuming a Gaussian line and randomly generated Gaussian noise similar to that estimated for the observed spectrum. We note that the absolute flux calibration may have a significant systematic uncertainty of up to 30–40%, but this does not affect the estimate of the significance of the line detection. The night sky spectrum, scaled arbitrarily, is shown in grey. Regions of particularly deviant values in the spectrum correspond to strong night sky lines. The emission line from the source lies fortuitously in a region relatively free of night sky contamination. We estimate that the percentage of regions in the night sky with a background as low as that near the detected line is approximately 50% for 1.15–1.35 μm and is generally lower over the rest of the SINFONI J passband. **b**, The sky-subtracted two-dimensional spectrum shows the projection of the spectrum along the spectral and right-ascension axes of the data cube. It corresponds to a two-dimensional long-slit spectrum obtained with a slit width of $0.625''$ positioned along right ascension on the sky. The object is indicated by the white circle, the regions affected by the night sky lines are labelled and the range in the expected position of the source is marked.

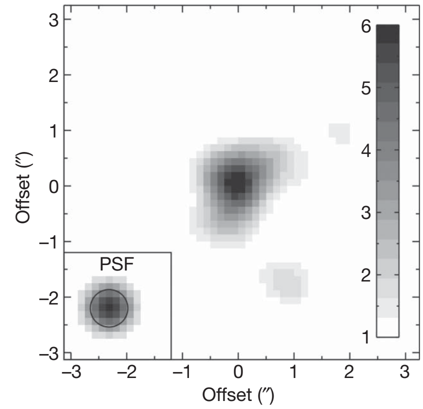

Figure 2 | Lyα line image of UDFy-38135539. The line image was constructed by summing the region containing the emission in the wavelength direction. The inset shows the expected morphology of a point source with the same signal-to-noise ratio in its centre as that of the source, and the circle shows the size of the point spread function (PSF). The colour bar shows the significance relative to the root mean squared noise in the data set. The image has been smoothed using a Gaussian with the same width as the point spread function. The size of the line image is consistent with the expected size of an intrinsically unresolved source whose image is smeared out by the turbulence in the Earth's atmosphere and distortions induced by the telescope and instrument optics.

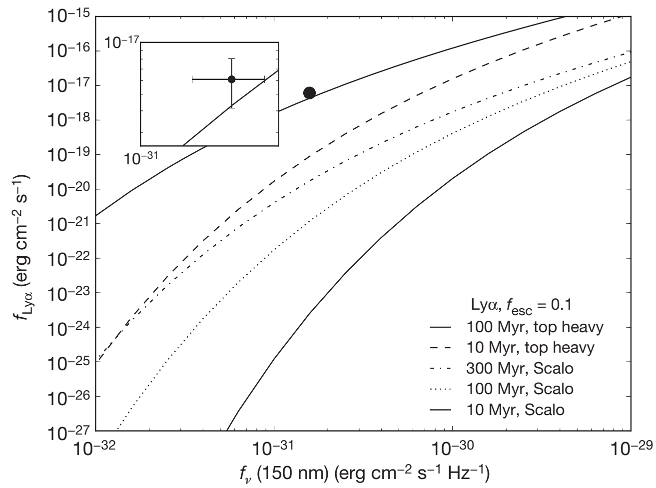

Figure 3 | The predicted Lyα flux for a given ultraviolet flux density. The Lyα flux, $f_{Ly\alpha}$, is predicted assuming a range of characteristics for the stellar population within UDFy-38135539. The characteristics — age, metallicity and distribution of stellar masses — determine the relationship between the non-ionizing ultraviolet continuum at 1,500 Å (with flux density f_ν) and the ionizing continuum with $\lambda < 912$ Å. We adopted a range of ages from 10 to 300 Myr for a metal-poor stellar population given by a Scalo initial mass function[26]. Our other initial mass function is the one that only contains massive stars, $>100 M_\odot$, which have zero metallicity[18]. For this top-heavy initial mass function, we only considered ages of 10 and 100 Myr because it is unrealistic for metal-free star formation to persist after the first supernova explosions, which are expected after a few to a few tens of megayears. For all the calculations, we have assumed an escape fraction of ionizing photons of 10%. Estimates of the escape fraction in the local Universe up to about $z \approx 3.3$ suggest modest fractions of ~10% or less[27–29]. The black circle represents the ultraviolet continuum flux density and Lyα flux of UDFy-38135539. The uncertainties in this data are shown in the inset (the 1σ random uncertainty and the systematic uncertainty added in quadrature). The uncertainty in the Lyα flux is dominated by the systematic uncertainties, which are included in the error bars. Under our assumptions, the Lyα flux of UDFy-38135539 is greater than that expected if it alone was responsible for ionizing its local volume. Because the recombination time is long at $z \approx 8.6$, ~600 Myr, many of the sources responsible for ionizing this region could have easily faded or may simply be of lower luminosity.

photons that UDFy-38135539 has produced allows us to estimate the size of the bubble it has ionized[9]. Adopting the star formation rate derived from the ultraviolet continuum flux density, and assuming the range of characteristics discussed above, we estimate that UDFy-38135539 will ionize a region between $\sim 0.1(f_{esc}/0.1)^{1/3}$ and $0.5(f_{esc}/0.1)^{1/3}$ Mpc in radius where f_{esc} is the escape fraction of ionizing photons. With such a small radius, the neutral intergalactic medium surrounding the bubble will significantly suppress the intrinsic Lyα emission from the source[21,22] (Fig. 3). Outflows of gas driven by the star formation within the source may help the escape of Lyα radiation[23]. However, for the line emission to be highly redshifted relative to the systemic velocity of the sources, the optical depth to Lyα must be high, further suppressing the emission.

Given the difficulty of ionizing the surrounding medium sufficiently, the most likely explanation for the relatively strong Lyα emission from UDFy-38135539 is that other sources within a few megaparsecs of this source may also have contributed to ionizing this volume. Indeed, the likelihood that many sources contribute to the ionization of bubbles during reionization has been discussed previously[20,24]. As the intergalactic medium is potentially 30–50% ionized at this redshift[25], it would not be surprising that multiple ionizing sources exist in the vicinity of UDFy-38135539 that may also be responsible for ionizing a significant fraction of the entire volume of the intergalactic medium.

Thus, the luminous Lyα emission of UDFy-38135539 implies that it is probably surrounded by other sources that contributed to the reionization of the Universe, but which have not yet been discovered or characterized. With the current capabilities of the Wide Field Camera 3 and sensitive spectrographs in the near-infrared on 8–10-m-class telescopes such as SINFONI (and, in the near future, the KMOS spectrometer, also at the Very Large Telescope), it may be possible directly to detect and characterize the galaxies during the epoch of reionization, helping us to understand how galaxies reionized the Universe. However, the biggest breakthroughs in our understanding of galaxies responsible for reionization will come with observations using the European Extremely Large Telescope and the James Webb Space Telescope over the next decade.

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

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