A galaxy rapidly forming stars 700 million years after the Big Bang at redshift 7.51

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Of several dozen galaxies observed spectroscopically that are candidates for having a redshift (z) in excess of seven, only five have had their redshifts confirmed via Lyman α emission, at z = 7.008, 7.045, 7.109, 7.213 and 7.215 (refs 1–4). The small fraction of confirmed galaxies may indicate that the neutral fraction in the intergalactic medium rises quickly at z > 6.5, given that Lyman α is resonantly scattered by neutral gas3,5–8. The small samples and limited depth of previous observations, however, makes these conclusions tentative. Here we report a deep near-infrared spectroscopic survey of 43 photometrically-selected galaxies with z > 6.5. We detect a near-infrared emission line from only a single galaxy, confirming that some process is making Lyman α difficult to detect. The detected emission line at a wavelength of 1.0343 micrometres is likely to be Lyman α emission, placing this galaxy at a redshift z ≈ 7.51, an epoch 700 million years after the Big Bang. This galaxy’s colours are consistent with significant metal content, implying that galaxies become enriched rapidly. We calculate a surprisingly high star-formation rate of about 330 solar masses per year, which is more than a factor of 100 greater than that seen in the Milky Way. Such a galaxy is unexpected in a survey of our size6, suggesting that the early Universe may harbour a larger number of intense sites of star formation than expected.

We obtained near-infrared (NIR) spectroscopy of galaxies originally discovered in the Cosmic Assembly Near-infrared Extragalactic Legacy Survey (CANDELS)9,11 with the newly commissioned NIR spectrograph MOSFIRE10 on the Keck I 10-m telescope. From a parent sample of over 100 galaxy candidates at z > 7 in the GOODS-North field selected via their Hubble Space Telescope (HST) colours through the photometric redshift technique11,12–16, we observed 43 candidate high-redshift galaxies over two MOSFIRE pointings with exposure times of 3.5 and 4.5 h, respectively. Our observations covered Lyman α (Lyα) emission at redshifts of 7.0–8.2. We visually inspected the reduced data at the expected slit positions for our 43 observed sources and found plausible emission lines in eight objects, with only one line detected at >5σ significance. The detected emission line is at a wavelength of 1.0343 μm with an integrated signal-to-noise ratio of 7.8 (Fig. 1) and comes from the object designated z8_GND_5296 in our sample (right ascension 12 h 36 min 37.90 s, declination 62° 18′ 8.5″, 2000). On the basis of arguments outlined below (and discussed extensively in the Supplementary Information), we identify this line as the Lyγ transition of hydrogen at a line-peak redshift of z ≈ 7.5078 ± 0.0004; this is consistent with our photometric redshift 95% confidence range of 7.3 < z < 8.1 for z8_GND_5296.

As expected for a galaxy at z ≈ 7.51, z8_GND_5296 is undetected in the HST optical bands, including an extremely deep 0.8 μm image (Fig. 2). The galaxy is bright in the HST NIR bands, becoming brighter with increasing wavelength, implying that the Lyman break lies near 1 μm and that the galaxy has a moderately red rest-frame ultraviolet colour. The galaxy is well-detected in both Spitzer/IRAC bands (3.6 μm and 4.5 μm wavelength) and is much brighter at IRAC 4.5 μm than at IRAC 3.6 μm. The strong break at observed 1 μm restricts the observed emission line to be either Lyα at z ≈ 7.51 (near the Lyman break) or [O II] 3726 and 3729 Å (a doublet) at z = 1.78 (near the rest-frame Balmer/4000 Å break). We investigated these two possibilities by comparing our observed photometry to a suite of stellar population models at both redshifts (Fig. 3). A much better fit to the data is obtained when...
This very high \([\text{O} \text{ III}]\) equivalent width constrains the abundance of metals in this galaxy, as highly enriched stars do not produce hard-enough ionizing spectra, and very low-metallicity systems do not have enough oxygen to produce strong emission lines. Of the metallicities available in our models (0.02, 0.2, 0.4 and 1.0 times solar), only models with a metal abundance of about 20–40% of solar have [O III] equivalent widths \(>300\,\text{Å}\). Thus, even at such early times, a moderately chemically enriched galaxy could form. However, because of the discreteness of the model metallicities, further analysis is needed to draw more quantitative conclusions about the metallicity—particularly its lower limit. We note that at \(z = 7.51\) [O II] is in the 3.6 \(\mu\text{m}\) band, but it is predicted to be about five times fainter than [O III] and thus does not significantly affect the 3.6 \(\mu\text{m}\) flux.

The galaxy z8_GND_5296 is forming stars at a very high rate, with a 'mass-doubling' time of at most 4 Myr. The most recent estimates\(^{17}\) at \(z \approx 7\) find that galaxies with stellar masses of \(5 \times 10^{10} \text{M}_\odot\) typically have specific SFRs (that is, SFR divided by stellar mass) of \(\sim 10^{-8} \text{yr}^{-1}\). This galaxy is a factor of five less massive, yet its specific SFR is a factor of 30 greater at \(3 \times 10^{-7} \text{yr}^{-1}\), implying that z8_GND_5296 is undergoing an enormous starburst.

Additionally, estimates of the SFR functions\(^{9}\) show
that a typical galaxy at $z \approx 7$ has SFR = 10 $M_\odot$ yr$^{-1}$; the measured SFR of z8_GND_5296 is a factor of more than 30 times greater. If this SFR function is accurate, the expected space density per co-moving Mpc$^3$ for this galaxy would be $< 10^{-3}$. The implied rarity of this galaxy could be that it is the progenitor of some of the most massive systems in the high-redshift Universe. However, the $z = 7.213$ galaxy GN 108036 (ref. 3), also in the GOODS-North field, also has an implied SFR $> 100 M_\odot$/yr. Although the current statistics are poor, the presence of these two galaxies in a relatively small survey area suggests that the abundance of galaxies with such high SFRs may have previously been underestimated. If the high SFR of z8_GND_5296 continues down to $z = 6.5$, it is interesting that these galaxies in the local Universe—perhaps through blowing holes in the interstellar medium (ISM), allowing both Lyα and ionizing photons to escape. An outflow in the ISM of 200–300 km s$^{-1}$ could clear a hole in this galaxy in about 3–5 Myr, or perhaps even sooner if the galaxy is undergoing a merger, which could preferentially clear some lines of sight for Lyα to escape. Finally, we examine the lack of detected Lyα lines in our full data set. If the Lyα equivalent width distribution continues its observed increase$^{19}$ from $3 < z < 6$ out to $z = 7–8$, we should have detected Lyα emission from six galaxies. Our single detection rules out this equivalent width distribution at 2.5σ significance. This confirms previous results at $z \approx 6.5$ (refs 3, 5, 6 and 8), but here we probe $z > 7$. The lack of detectable Lyα emission is unlikely to be due to sample contamination, as contamination by lower-redshift interlopers is probably not dominant at $z = 7$ given the low contamination rate at $z = 6$ (ref. 8). To explain the low detection rate of Lyα, a neutral fraction in the intergalactic medium (IGM) at $z = 6.5$ as high as 60–90% has been proposed$^{14}$, implying a rapid increase from $z = 6$ (ref. 20). However, most other observations are consistent with an IGM neutral fraction $\leq 10\%$ at $z = 7$ (refs 21, 22), thus alternative explanations for the dearth of Lyα emission need to be explored.

One alternative explanation for at least part of the Lyα deficit may be gas within galaxies. A high ratio of gas mass to stellar mass may be consistent with the very high SFR of z8_GND_5296, as galaxies should not have SFRs (for long periods) exceeding their average gas accretion rate from the IGM (which is set by the total baryonic mass). For the inferred stellar mass and redshift, z8_GND_5296 must have a gas reservoir of about 50 times the stellar mass to give an accretion rate comparable to the SFR$^{15}$. If true, this galaxy would have a gas surface density similar to the most gas-rich galaxies in the local Universe, and its SFR would be consistent with local relations between the gas and SFR surface densities$^{16}$.

The large gas-to-stellar mass ratio could be due to low metallicities at earlier times which may initially inhibit star formation, allowing the formation of such a large gas reservoir$^{17}$. If such high gas-to-stellar mass ratios are common amongst $z > 7$ galaxies, it could explain the relative paucity of Lyα emission in our observations. Direct observations of the gas properties of distant galaxies are required to make progress in understanding both the fuelling of star formation and the escape of Lyα photons.

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Table 1 | Lyα spectroscopically confirmed galaxies at $z > 7$

| ID* | $z_{\text{Ly}a}$ | $M_{\text{UV}}$ (mag) | Rest equiv. width of Lyα (Å) | SFR (M$_\odot$/yr$^{-1}$) | log($M_\ast$) |
|-----|-----------------|----------------------|-----------------------------|--------------------------|---------------|
| z8_GND_5296 | 7.508 | −21.2 | 8 | 330 | 9.0 |
| SXDF-NB1006-2 (ref. 4) | 7.215 | −22.4 | 15 | 56 | NA |
| GN 108036 (ref. 3) | 7.213 | −21.8 | 33 | 100 | 8.8 |
| BDF-3299 (ref. 1) | 7.109 | −20.6 | 50 | 9 | NA |
| A1703_3D2A (ref. 2) | 7.045 | −19.4 | 65 | 4 | NA |
| BDF-521 (ref. 1) | 7.088 | −20.6 | 64 | 4 | NA |
| IOK-1 (refs 3, 6) | 6.965 | −21.4 | 43 | 10 | NA |
| HFLS3 (ref. 26) | 6.337 | NA | NA | 2.900 | 10.6 |

NA, not available in the literature.

* Currently known galaxies with $z_{\text{Ly}a} > 7$. We include IOK-1 for comparison, as it was the highest-redshift spectroscopically confirmed galaxy for several years, and HFLS3, which has the most extreme SFR known, and may represent the z ~ 6 evolution of z8_GND_5296.

† We compute ultraviolet absolute magnitudes ($M_{\text{UV}}$) for BDF-3299 and BDF-512 using the Lyα-corrected Y-band magnitudes, and for A1703_3D2A using the de-lensed J-band magnitude.

‡ The SFR for z8_GND_5296 and GN 108036 were both calculated via SED fitting. The SFR for IOK-1 was measured from Lyα emission, which is likely to be a lower limit, owing to unknown absorption. The SFRs for BDF-3299, BDF-512, A1703_3D2A and SXDF-NB1006-2 were calculated from the ultraviolet luminosity, which are also likely to be lower limits, as the ultraviolet luminosity was not corrected for dust attenuation, and the scaling relation was defined for a stellar population with an age of 100 Myr (ref. 27). The SFR for HFLS3 was derived via the infrared luminosity.

§ SXDF-NB1006-2 was only photometrically detected in a narrow band which encompassed Lyα emission. The corresponding ultraviolet absolute magnitude, and subsequent SFR, are thus highly uncertain, with published uncertainties of $M_{\text{UV}} = −24.2^\pm1.6$ (ref. 4).
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Supplementary Information is available in the online version of the paper.

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