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Rotation in [C II]-emitting gas in two galaxies at a redshift of 6.8

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The earliest galaxies are thought to have emerged during the first billion years of cosmic history, initiating the ionization of the neutral hydrogen that pervaded the Universe at this time. Studying this 'epoch of reionization' involves looking for the spectral signatures of ancient galaxies that are, owing to the expansion of the Universe, now very distant from Earth and therefore exhibit large redshifts. However, finding these spectral fingerprints is challenging. One spectral characteristic of ancient and distant galaxies is strong hydrogen-emission lines (known as Lyman-α lines), but the neutral intergalactic medium that was present early in the epoch of reionization scatters such Lyman-α photons. Another potential spectral identifier is the line at wavelength 157.4 micrometres of the singly ionized state of carbon (the [C II] $\lambda = 157.74\,\mu$m line), which signifies cooling gas and is expected to have been bright in the early Universe. However, so far Lyman-α-emitting galaxies from the epoch of reionization have demonstrated much fainter [C II] luminosities than would be expected from local scaling relations[1–5], and searches for the [C II] line in sources without Lyman-α emission but with photometric redshifts greater than 6 (corresponding to the first billion years of the Universe) have been unsuccessful. Here we identify [C II] $\lambda = 157.74\,\mu$m emission from two sources that we selected as high-redshift candidates on the basis of near-infrared photometry; we confirm that these sources are two galaxies at redshifts of $z = 6.8540 \pm 0.0003$ and $z = 6.8076 \pm 0.0002$. Notably, the luminosity of the [C II] line from these galaxies is higher than that found previously in star-forming galaxies with redshifts greater than 6.5. The luminous and extended [C II] lines reveal clear velocity gradients that, if interpreted as rotation, would indicate that these galaxies have similar dynamic properties to the turbulent yet rotation-dominated disks that have been observed in Hα-emitting galaxies two billion years later, at 'cosmic noon'.

Using the Atacama Large Millimetre Array (ALMA) in Chile, we obtained spectroscopy at 241–245 GHz for two Lyman-break galaxies (LBGs)—COS-3018555981 and COS-2987030247—at an estimated photometric redshift of just less than 7, corresponding to roughly 800 million years after the Big Bang. These two sources are luminous in the rest-frame ultraviolet (UV; L_{UV} is roughly $2 \times L^*_{z=7}$ (this latter value being obtained from ref. 6)), but are representative of 'normal' star-forming galaxies at redshifts of around 7, with a UV-based star-formation rate (SFR) of (19–23)$M_\odot$ yr^{-1} (L, luminosity; $M_\odot$, mass of the Sun). We selected these sources on the basis of the blue rest-frame optical colours measured in the 3.6-μm and 4.5-μm photometric bands by the Spitzer Space Telescope[7]; these rest-frame colours strongly constrain the photometric redshift probability distribution to the range $6.6 < z < 6.9$. The two sources are among the most extreme [O III] + Hβ emitters known at redshifts of around 7 (refs 7, 8). We observed them using a 36-antennae ALMA configuration (angular resolution $1.1'' \times 0.7''$, equivalent to 5.8 kpc $\times$ 3.7 kpc at $z = 6.8$), with 24 minutes of source-integration time for each target. Using this spectral scan, we searched for [C II] lines in the redshift range $z_{[C\,II]} = 6.74$–6.90. Our results are summarized in Extended Data Table 1.

We detected a line at 241.97 ± 0.01 GHz and at 243.42 ± 0.01 GHz for COS-3018555981 and COS-2987030247, respectively, in both one-dimensional spectra and spectral-line-averaged maps (Fig. 1; more than 5σ significance). We thereby derived spectroscopic redshifts of $z_{[C\,II]} = 6.8540 \pm 0.0003$ and $z_{[C\,II]} = 6.8076 \pm 0.0002$, respectively, in excellent agreement with the photometric redshift estimates of 6.76 ± 0.07 and 6.66 ± 0.14 for COS-3018555981 and COS-2987030247; we also derived line-widths of 232 ± 30 km^{-1} and 124 ± 18 km^{-1}, respectively. Although successful line searches have previously confirmed far-infrared lines in submillimetre-selected star-bursting galaxies at redshifts of more than 6 (refs 9, 10), and a few tantalizing 'blind' candidate [C II] emitters (with no optical or near-infrared counterpart) have been detected with a significance of around 4σ (ref. 11), this is the first time that normal star-forming galaxies in this early epoch—selected at optical or near-infrared wavelengths—have confidently been spectroscopically confirmed with ALMA.

We furthermore obtained upper limits to the far-infrared dust-continuum emission from the ALMA data. We found infrared SFRs of less than (16–19)$M_\odot$ yr^{-1}—rates that are consistent with 'normal' star-forming galaxies in the local Universe[12], and which rule out the presence of a dusty starburst in these sources. Figure 2 shows that, given the colour of the UV-continuum slopes of these sources (this slope, β_{UV}, is roughly -1.2), a higher dust content (measured by the infrared excess, L_{IR}/L_{UV}) would be expected if the sources obeyed the Meurer dust law, which is observed to apply for local starburst galaxies[13]. Scatter in the IRX–β_{UV} relation could be due to the geometry of the dust, the age of the population of galaxies, or the shape of the attenuation curve. However, for blue galaxies (where β_{UV} is less than around -0.5) that scatter below the Meurer[13] relation—such as our selected galaxies—the most likely way to reproduce the low observed values of IRX is through a steeper attenuation curve, such as that derived for the Small Magellanic Cloud[14] (consistent with our measurements to within 3σ), in combination with a potential increase in dust temperature at higher redshifts.

In Fig. 2 we present the measured flux of the [C II] lines as a function of the SFR, which is consistent with the SFR–$L_{[C\,II]}$ relation for galaxies in the local Universe (ref. 15), and consistent with data for similarly bright galaxies observed at redshifts of about 5–6 (refs 16, 17). By contrast, [C II] observations from the epoch of reionization so far have shown

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