LETTER TO NATURE

A luminous quasar at a redshift of $z = 7.085$

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The intergalactic medium was not completely reionized until approximately a billion years after the Big Bang, as revealed[1] by observations of quasars with redshifts of less than 6.5. It has been difficult to probe to higher redshifts, however, because quasars have historically been identified[2–4] in optical surveys, which are insensitive to sources at redshifts exceeding 6.5. Here we report observations of a quasar (ULAS J112001.48+064124.3) at a redshift of 7.085, which is 0.77 billion years after the Big Bang. ULAS J1120+0641 had a luminosity of $6.3 \times 10^{13} L_{\rm Sun}$ and hosted a black hole with a mass of $2 \times 10^9\ M_{\rm Sun}$ (where $L_{\rm Sun}$ and $M_{\rm Sun}$ are the luminosity and mass of the Sun). The measured radius of the ionized near zone around ULAS J1120+0641 was 1.9 megaparsecs, a factor of three smaller than typical for quasars at redshifts between 6.0 and 6.4. The near zone transmission profile is consistent with a Ly α damping wing[5], suggesting that the neutral fraction of the intergalactic medium in front of ULAS J1120+0641 exceeded 0.1.

ULAS J1120+0641 was first identified in the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey[6] (UKIDSS) Eighth Data Release, which took place on 3 September 2010. The photometry from UKIDSS, the Sloan Digital Sky Survey[7] (SDSS) and follow-up observations on UKIRT and the Liverpool Telescope (listed in Fig. 1) was consistent[8] with a quasar of redshift $z \gtrsim 6.5$. Hence, a spectrum was obtained using the Gemini Multi-Object Spectrograph on the Gemini North Telescope on the night beginning 27 November 2010. The absence of significant emission blueward of a sharp break at $\lambda = 0.98\ \mu$m confirmed ULAS J1120+0641 as a quasar with a preliminary redshift of $z = 7.08$. Assuming a fiducial flat cosmological model[9] (that is, cosmological density parameters $\Omega_{\rm m} = 0.26$, $\Omega_{\rm b} = 0.024$, $\Omega_\Lambda = 0.74$ and current value of the Hubble parameter $H_0 = 72$ km s^{-1} Mpc^{-1}), ULAS J1120+0641 is seen as it was 12.9 billion years (Gyr) ago, when the Universe was 0.77 Gyr old. While three sources have been spectroscopically confirmed to have even higher redshifts, two are faint $J_{\rm AB} \gtrsim 26$ galaxies[10,11] and the other is a γ-ray burst which has since faded[12]. Indeed, it has not been possible to obtain high signal-to-noise ratio spectroscopy of any sources beyond the most distant quasars previously known: CFHQS J0210−0456[13] ($z = 6.44$), SDSS 1148+5251[3] ($z = 6.42$) and CFHQS J2329+0301[14] ($z = 6.42$). Follow-up measurements of ULAS J1120+0641 will provide the first opportunity to explore the 0.1 Gyr between $z = 7.08$ and $z = 6.44$, a significant cosmological epoch about which little is currently known.

Further spectroscopic observations of ULAS J1120+0641 were made using the FOcal Reducer/low dispersion Spectrograph 2 (FORS2) on the Very Large Telescope (VLT) Antu and the Gemini Near-Infrared Spectrograph (GNIRS) on the Gemini North Telecope and the results combined into the spectrum shown in Fig. 1. The spectrum of ULAS J1120+0641 is similar to those of lower redshift quasars of comparable luminosity, and comparison to a rest-frame template spectrum[15] over the wavelength range including the strong Si III]+C III] and Mg II emission features gives a accurate systemic redshift of $z = 7.085 \pm 0.003$. The most unusual feature of the spectrum is the 2800 ± 250 km s^{-1} blueshift of the C IV emission line, which is greater than that seen in 99.9 % of redshift $z \gtrsim 2$ quasars[16]. There is associated absorption (visible through the N V doublet at $\lambda = 0.999\ \mu$m and the C IV doublet at $\lambda = 1.249\ \mu$m), indicating the presence of material in front of the quasar flowing out at 1100 ± 200 km s^{-1}. There is also a narrow absorption line at the Ly α emission wavelength that is consistent with a cloud of H I close to the quasar. If ULAS J1120+0641 is not significantly magnified by gravitational lensing, the GNIRS spectrum gives an absolute magnitude (measured at 0.1450 μm in the rest-frame) of $M_{1450,\rm AB} = -26.6 \pm 0.1$ and, applying a fiducial bolometric correction[13] of 4.4, a total luminosity of $L = (6.3 \pm 0.6) \times 10^{13} L_{\rm Sun}$. ULAS J1120+0641 has not been detected at radio wavelengths, with a measured flux

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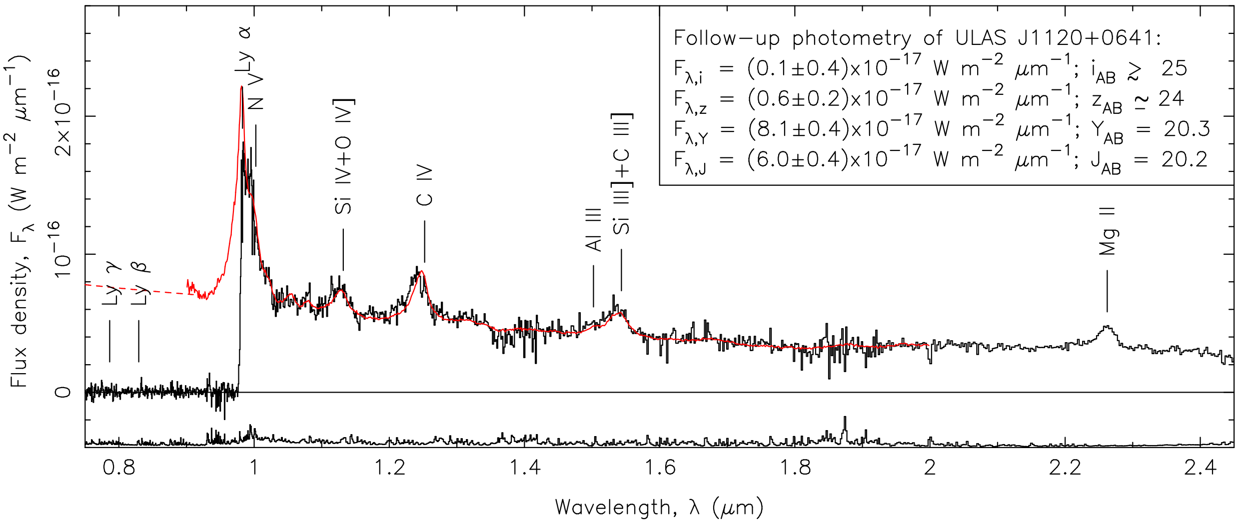


Figure 1. | Spectrum of ULAS J1120+0641 compared to a composite spectrum derived from lower-redshift quasars. Blueward of 1.005 μm the spectrum was obtained with the FORS2 on the Very Large Telescope (VLT) Antu using a 1.″0 wide longslit and the 600z holographic grism, which has a resolution of 1390; the resultant dispersion was 1.6×10^{-4} μm per pixel and the spatial scale was 0.″25 per pixel. The full FORS2 spectrum covers the wavelength range 0.75 μm $\leq \lambda \leq$ 1.03 μm. Redward of 1.005 μm the data were obtained using the GNIRS on the Gemini North Telecope. The GNIRS observations were made in cross-dispersed mode using a 32 lines per mm grating and the short camera with a pixel scale of 0.″15 per pixel; with a 1.″0 slit this provided a resolution of 500. The full GNIRS spectrum covers the wavelength range 0.90 μm $\leq \lambda \leq$ 2.48 μm. The data are binned by a factor of four and are shown in black; the 1 σ error spectrum is shown below the observed spectrum. The wavelengths of common emission lines, redshifted by $z = 7.085$, are also indicated. The solid red curve shows a composite spectrum constructed by averaging the spectra of 169 SDSS quasars in the redshift interval $2.3 \lesssim z \lesssim 2.6$ that exhibit large C IV emission line blueshifts. Absorption lines in the SDSS spectra were masked in forming the composite. The composite is a strikingly good fit to the spectral shape of ULAS J1120+0641 and most of its emission lines, although it was not possible to match the extreme C IV blueshift. The Ly α and C IV equivalent widths of the SDSS quasars are strongly correlated; the fact that the equivalent width of C IV from the composite spectrum is similar to that of ULAS J1120+0641 implies that the Ly α line is also correctly modelled. The dashed red curve shows the power-law ($F_\lambda \propto \lambda^{-0.5}$) used to estimate the quasar's ionizing flux and the follow-up photometry of ULAS J1120+0641 is also listed.

of $F_\nu = -0.08 \pm 0.13$ mJy in the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey[17]. Assuming an unabsorbed continuum blueward of Ly α of the form $L_\lambda \propto \lambda^{-0.5}$ (as appropriate for a radio-quiet quasar[18]) implies ULAS J1120+0641 was emitting ionizing photons at a rate of $\Gamma_{\rm ion} = 1.3 \times 10^{57}$ s^{-1}.

Quasars are believed to be powered by accretion onto their central black holes. The black hole's mass can be estimated from the quasar's luminosity and its Mg II line width[19]. ULAS J1120+0641 has $L_\lambda = (1.3 \pm 0.1) \times 10^{40}$ W μm^{-1} at a rest-frame wavelength of $\lambda = 0.3$ μm and the Mg II line has a full width at half-maximum of 3800 ± 200 km s^{-1}, implying $M_{\rm BH} = (2.0^{+1.5}_{-0.7}) \times 10^9 M_{\rm Sun}$ (where the uncertainty is dominated by the empirical scatter in the scaling relationship). The Eddington luminosity for ULAS J1120+0641 is hence $L_{\rm Edd} = (5.3^{+3.9}_{-1.8}) \times 10^{13} L_{\rm Sun}$, which is comparable to the above bolometric luminosity and implies an Eddington ratio of $\lambda_{\rm Edd} = 1.2^{+0.6}_{-0.5}$. Assuming Eddington-limited accretion with an efficiency of $\epsilon \simeq 0.1$, a black hole's mass would grow as[20] $M_{\rm BH} \propto \exp(t/(0.04 \text{ Gyr}))$; this implies that all other known high-redshift quasars (for example, SDSS J1148+5251 at $z = 6.42$, with an estimated[21] black hole mass of $M_{\rm BH} \simeq 3 \times 10^9 M_{\rm Sun}$) would have had $M_{\rm BH} \lesssim 5 \times 10^8 M_{\rm Sun}$ at 0.77 Gyr after the Big Bang. The existence of $\sim 10^9 M_{\rm Sun}$ black holes at $z \simeq 6$ already placed strong limits on the possible models of black hole seed formation, accretion mechanisms and merger histories[20,22]; the discovery that a $2 \times 10^9 M_{\rm Sun}$ black hole existed just 0.77 Gyr after the Big Bang makes these restrictions even more severe.

Aside from its existence, the most striking aspect of ULAS J1120+0641 is the almost complete lack of observed flux blueward of its Ly α emission line, which can be attributed to absorption by H I along the line of sight. The transmission, T, was quantified by dividing the observed spectrum of ULAS J1120+0641 by the power-law shown in Fig. 1. Converting from observed wavelength to Ly α absorption redshift yields the transmission spectrum shown in Fig. 2. The effective optical depth, defined in the absence of noise as $\tau_{\rm eff} \equiv -\ln(T)$, was measured in redshift bins of width $\Delta z_{\rm abs,Ly\,\alpha} = 0.15$ in the range $5.9 \lesssim z_{\rm abs,Ly\,\alpha} \lesssim 7.1$. In all eight bins the 2σ lower limit is $\tau_{\rm eff} > 5$. The overall implication is that the neutral hydrogren density at redshifts of $z \gtrsim 6.5$ was so high that it cannot be probed effectively using continuum Ly α absorption measurements.

The inability of Ly α forest absorption measurements to probe high optical depths is generic, but quasars differ from other high-redshift sources in that they have a strong effect on the intergalactic medium in their vicinity, ionizing megaparsec-scale near zones around them. Ultraviolet photons can propagate freely through these ionized regions, resulting in significant transmission just blueward of the Ly α

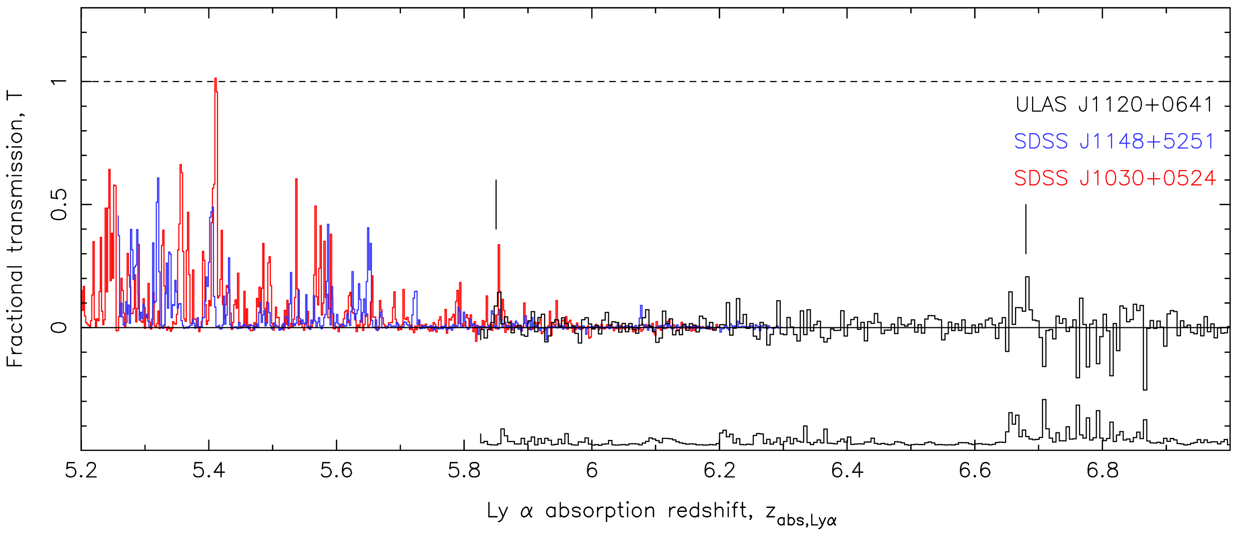


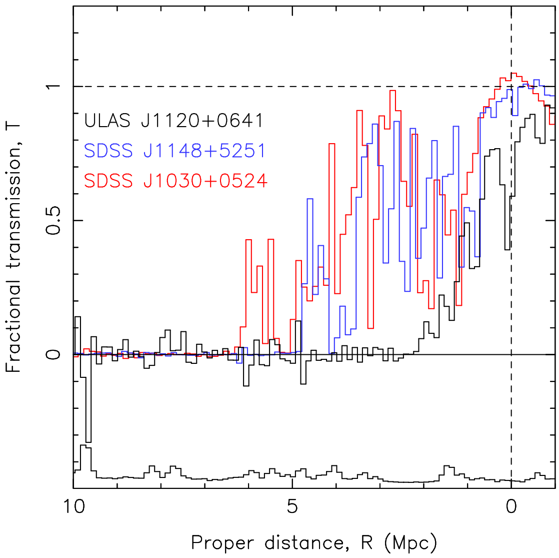
Figure 2. | The observed Ly α absorption measured towards ULAS J1120+0641 and two lower-redshift quasars. For ULAS J1120+0641, SDSS J1148+5251[3] ($z = 6.42$) and SDSS J1030+0524[2] ($z = 6.31$) the transmission was calculated by dividing the measured spectrum by a power-law continuum of the form $F_\lambda \propto \lambda^{-0.5}$; the Ly α absorption redshift is given by $z_{\rm abs,Ly\,\alpha} = \lambda/\lambda_{\rm Ly\,\alpha} - 1$, where $\lambda_{\rm Ly\,\alpha} = 0.12157$ μm. The three transmission curves are shown as far as the edges of the quasars' near zones, just blueward of Ly α; the transmission towards ULAS J1120+0641 is only shown redward of its Ly β emission line, which corresponds to $z_{\rm abs,Ly\,\alpha} = 5.821$. The transmission spectrum of ULAS J1120+0641 is binned by a factor of four and the one 1 σ uncertainty in each pixel is shown below the data. The measurements[23] of the other two quasars have a signal-to-noise ratio sufficiently high that the errors can be ignored. Comparing the three transmission curves reveals a clear trend: the numerous transmission spikes at $z \simeq 5.5$ give way to increasingly long Gunn–Peterson[24] troughs at $z \simeq 6$ and, finally, to almost complete absorption beyond $z \simeq 6.3$. The most significant transmission spikes identified towards ULAS J1120+0641 are indicated by the vertical lines: the feature at $z_{\rm abs,Ly\,\alpha} = 5.85$ is detected at $\sim 5.8\sigma$ over three pixels; the feature at $z_{\rm abs,Ly\,\alpha} = 6.68$ is detected at $\sim 3.8\sigma$ over three pixels. Although the spectrum of ULAS J1120+0641 has a higher noise level than those of the two lower-redshift quasars, transmission spikes of the strength seen at $z_{\rm abs,Ly\,\alpha} \lesssim 5.8$ would have been clearly detected at $z_{\rm abs,Ly\,\alpha} \gtrsim 6$ towards ULAS J1120+0641 if present.

emission wavelength. The scale of the near zone can be characterised by[1] $R_{\rm NZ}$, the (proper) radius at which the measured transmission drops to $T = 0.1$, and then corrected to $R_{\rm NZ,corr} = 10^{0.4\,(27+M_{1450,\rm AB})/3}\,R_{\rm NZ}$ to compare quasars of different luminosities. The near zone transmission profile of ULAS J1120+0641, shown in Fig. 3, implies that $R_{\rm NZ} = 1.9 \pm 0.1$ Mpc and $R_{\rm NZ,corr} = 2.1 \pm 0.1$ Mpc. This is considerably smaller than the near zones of other comparably luminous high-redshift quasars, which have been measured[25] to have $R_{\rm NZ,corr} = (7.4 - 8.0(z - 6))$ Mpc on average. The considerable scatter about this trend notwithstanding, these observations of ULAS J1120+0641 confirm that the observed decrease in $R_{\rm NZ,corr}$ with redshift continues at least to $z \simeq 7.1$.

The observed transmission cut-offs of $z \simeq 6$ quasars have been identified with their advancing ionization fronts, which grow as[26,27] $R_{\rm NZ,corr} \propto T_{\rm q}^{1/3}(1+z)^{-1}\Delta^{-1/3} f_{\rm HI}^{-1/3}$, where $T_{\rm q}$ is the quasar age and Δ is the local baryon density relative to the cosmic mean. Assuming a fiducial age of $T_{\rm q} \simeq 0.01$ Gyr has led to the claim[28] that $f_{\rm HI} \gtrsim 0.6$ around several redshift $6.0 \lesssim z \lesssim 6.4$ quasars. Given that the above $R_{\rm NZ,corr}$-z fit gives an average value of $R_{\rm NZ,corr} = 5.8$ Mpc at $z = 6.2$, the measured near zone radius of ULAS J1120+0641 then implies that the neutral fraction was a factor of ~ 15 higher at $z \simeq 7.1$ than it was at $z \simeq 6.2$. The fundamental limit that $f_{\rm HI} \leq 1$, makes it difficult to reconcile the small observed near zone of ULAS J1120+0641 with a significantly neutral Universe at $z \simeq 6$. It is possible that ULAS J1120+0641 is seen very early in its luminous phase or that it formed in an unusually dense region, but the most straightforward conclusion is that observed near zone sizes of $z \simeq 6$ quasars do not correspond to their ionization fronts[27].

An alternative explanation for the near zones of the $z \simeq 6$ quasars is that their transmission profiles are determined primarily by the residual H I inside their ionized zones[27,29]. If the H I and H II are in equilibrium with the ionizing radiation from the quasar then the neutral fraction would increase with radius as $f_{\rm HI} \propto R^2$ out to the ionization front. The resultant transmission profile would have an approximately Gaussian envelope, with $R_{\rm NZ}$ being the radius at which[27] $f_{\rm HI} \simeq 10^{-4}$, and not the ionization front itself. The envelopes of the measured profiles of the two $z \simeq 6.3$ quasars shown in Fig. 3 are consistent with this Gaussian model, although both have sharp cut-offs as well, which could be due to Lyman limit systems along the line of sight[30].

In contrast, the measured transmission profile of ULAS J1120+0641, shown in Fig. 3, is qualitatively different from those of the lower redshift quasars, exhibiting a smooth envelope and significant absorption redward of the Ly α wavelength. The profile has the character of a Ly α damping wing, which would indicate that the intergalactic medium in front of ULAS J1120+0641 was substantially neutral. It is also possible that the absorption is the result of an interven-



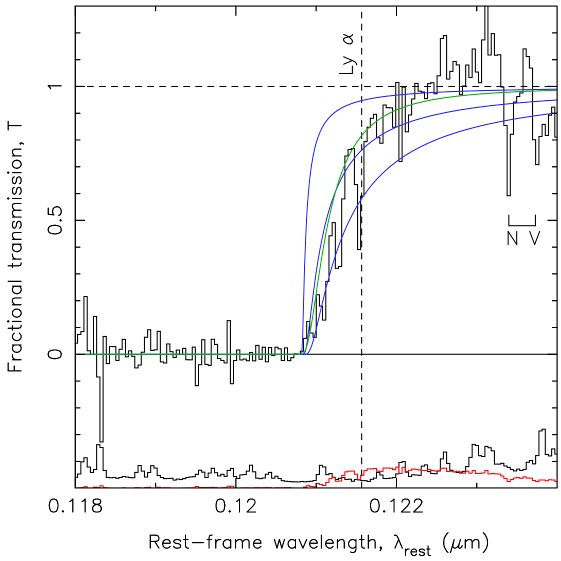


Figure 3. | The inferred Ly α near zone transmission profile of ULAS J1120+0641 compared to those of two lower-redshift quasars. The near zone transmission profile of ULAS J1120+0641 was estimated by dividing the observed spectrum by the composite spectrum shown in Fig. 1. The transmission profiles towards the two SDSS quasars were estimated by dividing their measured[23] spectra by parameterised fits based on the unabsorbed spectra of lower-redshift quasars. The transmission profile of ULAS J1120+0641 is strikingly different from those of the two SDSS quasars, with a much smaller observed near zone radius, $R_{\rm NZ}$, as well as a distinct shape: whereas the profiles of SDSS J1148+5251 and SDSS J1030+0524 have approximately Gaussian envelopes out to a sharp cut-off, the profile of ULAS J1120+0641 is much smoother and also shows absorption redward of Ly α. The 1 σ deviation error spectrum for ULAS J1120+0641 is shown below the data.

Figure 4. | Rest-frame transmission profile of ULAS J1120+0641, in the region of the Ly α alpha emission line, compared to several damping profiles. The transmission profile of ULAS J1120+0641, obtained by dividing the spectrum by the SDSS composite shown in Fig. 1, is shown in black. The random error spectrum is plotted below the data, also in black. The positive residuals near 0.1230 μm in the transmission profile suggest that the Ly α emission line of ULAS J1120+0641 is actually stronger than average, in which case the absorption would be greater than illustrated. The dispersion in the Ly α equivalent width at fixed C IV equivalent width of 13 % quantifies the uncertainty in the Ly α strength; this systematic uncertainty in the transmission profile is shown in red. The blue curves show the Ly α damping wing of the IGM for neutral fractions of (from top to bottom) $f_{\rm HI} = 0.1$, $f_{\rm HI} = 0.5$ and $f_{\rm HI} = 1.0$, assuming a sharp ionization front 2.2 Mpc in front of the quasar. The green curve shows the absorption profile of a damped Ly α absorber of column density $N_{\rm H\,I} = 4 \times 10^{20}$ cm^{-2} located 2.6 Mpc in front of the quasar. These curves assume that the ionized zone itself is completely transparent; a more realistic model of the H I distribution around the quasar might be sufficient to discriminate between these two models[27,29]. The wavelength of the Ly α transition is shown as a dashed line; also marked is the N V doublet of the associated absorber referred to in the text.

ing high column density ($N_{\rm H\,I} \gtrsim 10^{20}$ cm^{-2}) damped Ly α system[5], although absorbers of such strength are rare. Both models are compared to the observed transmission profile of ULAS J1120+0641 in Fig. 4. Assuming the absorption is the result of the IGM damping wing, the shape and width of the transmission profile require $f_{\rm HI} > 0.1$, but are inconsistent with $f_{\rm HI} \simeq 1$, at $z \simeq 7.1$. These limits will be improved by more detailed modelling, in particular accounting for the distribution of H I within the near zone[27,29], and deeper spectroscopic observations of ULAS J1120+0641. Given the likely variation in the ionization history between different lines of sight, it will be important to find more sources in the epoch of reionization. However, there are only expected[4] to be $\sim 10^2$ bright quasars with $z \gtrsim 7$ over the whole sky, ULAS J1120+0641 will remain a vital probe of the early Universe for some time.

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