Extremely metal–poor gas at a redshift of 7

Robert A. Simcoe1, Peter W. Sullivan1, Kathy L. Cooksey1, Melodie M. Kao1,2, Michael S. Matejek1 & Adam J. Burgasser1

In typical astrophysical environments, the abundance of heavy elements ranges from 0.001 to 2 times the solar value. Lower abundances have been seen in selected stars in the Milky Way’s halo1–3 and in two quasar absorption systems at redshift \( z = 3 \) (ref. 4). These are widely interpreted as relics from the early Universe, when all gas possessed a primordial chemistry. Before now there have been no direct abundance measurements from the first billion years after the Big Bang, when the earliest stars began synthesizing elements. Here we report observations of hydrogen and heavy-element absorption in a spectrum of a quasar at \( z = 7.04 \), when the Universe was just 772 million years old (5.6 per cent of its present age). We detect a large column of neutral hydrogen but no corresponding metals (defined as elements heavier than helium), limiting the chemical abundance to less than 1/10,000 times the solar level if the gas is in a gravitationally bound protogalaxy, or to less than 1/1,000 times the solar value if it is diffuse and unbound. If the absorption is truly intergalactic4,6, it would imply that the Universe was neither ionized by starlight nor chemically enriched in this neighbourhood at \( z \approx 7 \). It is gravitationally bound, the inferred abundance is too low to promote efficient cooling2,9, and the system would be a viable site to form the predicted but as yet unobserved massive population III stars.

We observed the recently discovered \( z = 7.085 \) quasar ULAS J1120+0641 (ref. 6) in January 2012 with the FIRE infrared spectrometer10 on the Magellan/Baade telescope. Our data provide a 12-fold increase in spectral resolution over the discovery spectrum at similar signal-to-noise ratio, enabling study of weak heavy-element absorption lines that are diluted by the instrumental profile at lower resolution.

Our spectrum (Fig. 1) confirms the presence of unusually strong Lyman \( \alpha \) (Ly\( \alpha \)) resonance absorption from neutral hydrogen (H\( \text{i} \)) in the immediate foreground of the quasar. This absorption is clearly visible in Fig. 1a, b as a contrast between the observed flux (black) and an intrinsic source spectrum model (red) at wavelengths \( \lambda < 0.98 \mu m \). However, the data also fall well below the source template at wavelengths redder than the Ly\( \alpha \) transition at the quasar’s systemic redshift (\( \lambda > 0.9829 \mu m \)). This has been interpreted6 as a Lorentzian damping wing of the H\( \text{i} \) Ly\( \alpha \) line at a redshift very close to that of the quasar, indicating a high neutral-hydrogen column density10. Such absorption could be caused by a long column of low-density, intergalactic hydrogen with a high neutral fraction in the vicinity of the quasar. Or, it could arise in compact, high-density gas gravitationally bound to an early galaxy. Such proximate damped Ly\( \alpha \) (DLA) absorption systems have numerous analogues at lower redshift.

At \( z = 5 \) and below, every known absorption system with sufficient neutral hydrogen to elicit damping wings also exhibits absorption from heavy-element lines11–13. However, we find no evidence of heavy-element absorption despite the sensitivity of the FIRE data, which is sufficient to detect metals (defined as elements heavier than helium) at abundance levels characteristic of lower-redshift DLAs. We do detect narrow metal absorption lines from highly ionized gas at the redshift of the quasar, manifested in C\( IV \) and N\( V \). However these are offset from the damped H\( \text{i} \) absorption by \( \Delta \nu = +711 \text{ km s}^{-1} \) (equivalent to 800 kpc in proper distance units if \( \Delta \nu \) is purely cosmological), and there is substantial flux transmission at the associated H\( \text{i} \) wavelength for these lines. The heavy-element lines are therefore most probably internal to the quasar host itself and not physically coincident with the neutral gas.

Quantitative chemical abundance estimates are usually impossible for \( z > 5.5 \) quasar absorbers because the benchmark neutral-hydrogen line is severely blended and saturated in the forest of neighbouring Ly\( \alpha \) systems. However the damping wing near the emission redshift of ULAS J1120 offers a unique opportunity to measure its H\( \text{i} \) column density. In conjunction with upper limits on the heavy-element column density, this yields a straightforward upper limit on the chemical abundance of metals.

The H\( \text{i} \) column density estimate is sensitive to the detailed shape of the damping profile, which is fitted to the ratio of emitted to observed flux (the ratio of the red to black lines in Fig. 1). This ratio depends

![Figure 1](https://example.com/figure1.png)

**Figure 1** Infrared spectrum of ULAS J1120+0641, compared to our estimate of the intrinsic quasar spectrum without foreground absorption.

* a. The unabsorbed continuum is shown in red, and the blue curve includes the absorption. The continuum template is constructed from a composite of quasars in the Sloan Digital Sky Survey14,15, shifted to a redshift of \( z_{\text{mod}} = 7.07 \). C\( IV \) absorption intrinsic to the quasar host galaxy is seen to the red of the labelled C\( IV \) emission peak. However, the C\( IV \) emission line is anomalously blueshifted\(^2\) in ULAS J1120, so we compute the redshift distance between the absorber and quasar host using its Mg\( \text{II} \) (ref. 6) or [C\( \text{II} \)] (ref. 25) redshift.

* b. Magnified view of the Ly\( \alpha \) region of the spectrum with unabsorbed continuum model (red) and absorbed continuum (blue). The vertical arrow marks the location of Ly\( \alpha \) absorption at \( z_{\text{abs}} = 7.04 \). c. Detail of the damping wing with best-fit H\( \text{i} \) absorption model (solid line) centred on \( z_{\text{abs}} \) with \( \log(N_{\text{HI}}) = 20.6 \text{ cm}^{-2} \). Dotted and dashed lines indicate the \( \pm 1\sigma \) fit uncertainty. The quasar’s emission redshift\(^6\) is indicated with the vertical dashed line.

---

1MIT-Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Avenue, Building 37, Room 664L, Cambridge, Massachusetts 02139, USA.
2Department Of Astronomy, California Institute of Technology, 1200 East California Boulevard, MC 249-17, Pasadena, California 91125, USA.
3Center for Astrophysics and Space Science, University of California San Diego, MC 0424, 9500 Gilman Drive, La Jolla, California 92037, USA.

©2012 Macmillan Publishers Limited. All rights reserved
critically on how the intrinsic (that is, unabsorbed) shape of the quasar’s Ly\(\alpha\) emission line is modelled, including both its absolute flux density and its redshift, which fixes the location of the emission peak. The details of this procedure are described in Supplementary Information, but to summarize, we experimented with several different prescriptions, including four different quasar composite spectra generated from low-redshift surveys\(^{14–17}\), and additionally a principal-component analysis fit\(^{18}\) extrapolated over the Ly\(\alpha\) region. For each of these continua, we calculated the H\(\text{I}\) column density required to produce the damping wing redshift of the systemic Ly\(\alpha\) line via Voigt profile model fitting, finding a best-fit value of \(\log(N_{\text{H}I}) = 20.60 \text{ cm}^{-2}\). For any one continuum model, the formal fit error for \(\log(N_{\text{H}I})\) was of the order of 0.02–0.03 dex, but the true error is much more likely to be dominated by systematic uncertainty in the continuum. By experimenting with different choices of continuum and absorber redshift, we estimated the range of allowable \(\log(N_{\text{H}I})\) as 20.45–21.0, at a best-fit absorption redshift of \(z = 7.04 \pm 0.03\) (95% confidence).

We estimated upper limits to the metal line column densities (Fig. 2) both by curve-of-growth analysis and by direct Voigt profile fitting (Table 1, see also Supplementary Information). For systems with \(\log(N_{\text{H}I}) > 20.3\), the transitions in Table 1 represent the predominant ionization states for their respective elements\(^{19,20}\). The one exception to this is C\(\text{IV}\), which is secondary to C\(\text{II}\) but which we include as an ionization constraint (discussed below). We therefore follow the usual practice for DLA systems and do not apply ionization corrections when estimating abundances\(^{19,20}\).

Considering first the DLA scenario, our strongest abundance limit is derived from Si\(\text{II}\), which yields a \(1\sigma\) (2\(\sigma\)) upper bound of 1/20,000 (1/10,000) times the solar metallicty. With such unusual abundances, one must consider the possible effects of ionization, particularly given the proximity of the brightest known object in the \(z = 7\) Universe. However, prior studies of other proximate DLA systems indicate that ionization plays only a minor role and may be counterbalanced by a tendency for such systems to have higher than average metallicities\(^{1,21}\). Additionally, our spectrum places strong constraints on the lack of ionized gas seen in C\(\text{IV}\), which would yield a tenfold lower abundance limit than C\(\text{II}\) if it dominated the ionization balance (on account of its higher signal-to-noise ratio and larger atomic cross-section). This rules out an ionized phase as a major source of missing metals in this absorber.

The limits presented above assume that the absorbing gas resides in a compact structure that is well-represented by a discrete line or cloud, which is appropriate for DLAs at lower redshift. However at \(z = 7\) the absorption could also result from the integrated contribution of diffuse intergalactic gas if the neighbourhood of ULAS J1120 has not yet been ionized by starlight. Using Monte Carlo simulations of intergalactic H\(\text{I}\) and heavy-element absorption (described in Supplementary Information), we find that for physical conditions leading to an intergalactic damping wing our spectrum still restricts heavy element absorption to the \(<10^{-3}\) times the solar level, even with no DLA.

These chemical abundance limits have significant implications for either of the two physical scenarios considered. If the diffuse absorption model is correct, then at \(z = 7\) the intergalactic medium must be both metal-poor and substantially neutral, even in the neighbourhood of a bright quasar. Such intergalactic material would not yet have mixed with the chemically polluted interstellar by-products of galaxies, so it should not be surprising for its heavy-element content to be small. At later epochs (\(z = 2–4\)), heavy elements are actually observed in intergalactic space, with abundances distributed log-normally between 1/300 and 1/3,000 times solar\(^{22,23}\). Our \(z = 7\) limit excludes the upper half of this distribution, but enrichment at the low end could elude detection in the FIRE data. Nevertheless, if this one object proves to be representative of the Universe at these epochs, it is plausible that \(z = 7\) pre-dates both the radiative feedback and the chemical feedback thought to be hallmarks of reionization.

---

**Figure 2** | Continuum-normalized transmitted flux in spectral regions where expected heavy-element transitions would appear for a DLA at redshift \(z = 7.041\). a. Spectral regions with transition given; \(1\sigma\) error contours are shaded grey, and the extraction aperture is indicated with horizontal bars. A Voigt profile with \(b = 10 \text{ km s}^{-1}\) and \(N\) set by our column-density upper limit is shown in red for each panel. Velocity offsets are relative to the rest frame of the H\(\text{I}\) absorber. b. Composite stack of all heavy-element transitions, generated using an inverse-variance weighted mean and solar relative abundances. Each transition is scaled to the cross-section and relative abundance of \(\text{O I}\). Overlaid curves show predicted metal absorption profiles for a DLA of \(\log(N_{\text{HI}}) = 20.6\) and varying metallicity levels. The stack shows no statistically significant absorption, though there is a fluctuation at the \(1\sigma\) level, corresponding to an effective \([\text{O}/\text{H}] < -4\).
DLA gas is commonly said to be a fuel supply for star formation, but our limits on the abundance in this geometry are sufficiently low that normal gas cooling channels for population I and II star formation would be suppressed. Theoretical calculations suggest that below an abundance of \([\mathrm{C}/\mathrm{H}] \approx -3.5\) (see Table 1 footnote for a definition of this nomenclature), the normal fine-structure atomic cooling mechanisms lose their effectiveness, and the predominant mode of star formation occurs through molecular \(\mathrm{H}_2\) cooling, resulting in high-mass population III stars\(^7,8\). Taken together with its high redshift, this fact renders the \(z = 7.04\) absorber in ULAS J1120 a viable site for population III star formation if the neutral gas is organized into a bound halo.

We warn that many more observations of \(z > 7\) absorption systems will be required to establish whether the trends of large neutral-hydrogen column and low metal content are representative of the entire Universe at this early epoch. Indeed, the existence of heavy elements in both emission and absorption in the background quasar host indicates that local enrichment is underway in some environments. However, the confluence of neutral gas and extremely low chemical abundance, taken together with the young age of the Universe (772 Myr) at this redshift, suggests that current observations may already be reaching the era corresponding to the onset of star formation and cosmic chemical enrichment.

Received 20 March; accepted 19 September 2012.

1. Christlieb, N. et al. A stellar relic from the early Milky Way. Nature 419, 904–906 (2002).
2. Frebel, A. et al. Nucleosynthetic signatures of the first stars. Nature 434, 871–873 (2005).
3. Caffau, E. et al. An extremely primitive star in the Galactic halo. Nature 477, 67–69 (2011).
4. Fumagalli, M., O’Meara, J. M. & Prochaska, J. X. Detection of pristine gas two billion years after the Big Bang. Science 334, 1245–1249 (2011).
5. Bolton, J. S. et al. How neutral is the intergalactic medium surrounding the redshift \(z = 7.085\) quasar ULAS J1120? Mon. Not. R. Astron. Soc. 416, L70–L74 (2011).
6. Mortlock, D. J. et al. A luminous quasar at a redshift of \(z = 7.085\). Nature 474, 616–619 (2011).
7. Bromm, V., Ferrara, A., Coppi, P. S. & Larson, R. B. The fragmentation of pre-enriched primordial objects. Mon. Not. R. Astron. Soc. 328, 969–976 (2001).
8. Frebel, A., Johnson, J. L. & Bromm, V. Probing the formation of the first low-mass stars with stellar archaeology. Mon. Not. R. Astron. Soc. 380, L40–L44 (2007).
9. Simcoe, R. A. et al. FIRE: a near-infrared cross-dispersed echellelette spectrometer for the Magellan telescopes. Proc. SPIE 7014, 27–37 (2008).
10. Miralda-Escude, J. & Reionization of the intergalactic medium and the damping wing of the Gunn-Peterson trough. Astrophys. J. 501, 15–22 (1998).
11. Prochaska, J. X. et al. The UCSD/Keck damped Ly\(\alpha\) abundance database: a decade of high-resolution spectroscopy. Astrophys. J. Suppl. Ser. 171, 29–60 (2007).
12. Cooke, R., Pettini, M., Steidel, C. C., Rudie, G. C. & Nissen, P. E. The most metal-poor damped Ly\(\alpha\) systems: insights into chemical evolution in the very metal-poor population II. Mon. Not. R. Astron. Soc. 406, 1435–1459 (2010).
13. Richards, G. T. et al. Unification of luminous type 1 quasars through C IV emission. Astron. J. 141, 167–183 (2011).
14. Vanden Berk, D. E. et al. Composite quasar spectra from the Sloan Digital Sky Survey. Astron. J. 122, 549–564 (2001).
15. Hewett, P. C. & Wild, V. Improved redshifts for SDSS quasar spectra. Mon. Not. R. Astron. Soc. 405, 2302–2316 (2010).
16. Zheng, W., Kriss, G. A., Telfer, R. C., Grimes, J. P. & Davidsen, A. F. A Composite HST spectrum of quasars. Astrophys. J. 475, 469–478 (1997).
17. Yip, C. W. et al. Spectral classification of quasars in the Sloan Digital Sky Survey: eigenspectra, redshift, and luminosity effects. Astron. J. 128, 2630–2630 (2004).
Venemans, B. P. et al. Detection of atomic carbon [CII] 158 μm and dust emission from a z~7.1 quasar host galaxy. Astrophys. J. 751, L25 (2012).

Supplementary Information is available in the online version of the paper.

Acknowledgements We thank J. O’Meara and A. Frebel for comments during the preparation of this Letter. M. Haehnelt also provided advice on methods for modelling the quasar near-zone, and G. Richards shared his composite QSO spectra in electronic form. This work includes data gathered with the 6.5-m Magellan Telescopes located at Las Campanas Observatory, Chile. R.A.S. acknowledges support from the NSF under awards AST-0908920 and AST-1109115. K.L.C. is supported by the NSF Astronomy and Astrophysics Postdoctoral Fellowship programme.

Author Contributions R.A.S. constructed the FIRE instrument, and together with P.W.S. designed and executed the observations, performed the analysis and prepared the manuscript. K.L.C. prepared observations and edited the manuscript. M.S.M. assisted with the pipeline software used to reduce the spectroscopic data, and M.M.K. wrote the software to perform eigenspectrum continuum fits. A.J.B. contributed to the spectrograph construction, and executed observations for the program. All authors helped with the scientific interpretations and commented on the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to R.A.S. (simcoe@space.mit.edu).