Direct detection of the bulk neutral IGM at reionization

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1 Scientific Justification

Observations of the CMB put the epoch of reionization of the intergalactic medium (IGM) at $z = 6.4$–9.7 (Planck Collaboration et al., 2016). There is compelling evidence for some IGM neutrality at these redshifts in the spectra of γ-ray bursts (GRBs) and quasars (e.g. Fan et al., 2006), which show the anticipated flux suppression of the Gunn-Peterson trough. But an unequivocal direct detection of the bulk neutral IGM gas itself still eludes us.

We propose to make this key observation of reionization by detecting the red damping wing of the IGM's hydrogen Lyα absorption across the foreground of a galaxy at $z > 7$.

Because the IGM was not uniformly reionised, we cannot use just any object at $z > 7$. We need a source that lies in a neutral IGM region at that redshift. To exclude the possibility of a small intervening cloud, we use a source extended over a large area, i.e. a resolved galaxy rather than a quasar. A galaxy that is both bright enough and in an IGM-neutral region at $z > 7$ is rare, since UV-bright sources will not only ionize an extended volume around them, but also lie in massive halos near other luminous sources. The characteristic signature of a galaxy with neutral IGM absorption is a large ($\sim$10000 km s^{-1}) red offset of the galaxy's Lyα break compared to its systemic redshift. Recently, we have found that the reionization-epoch galaxy, A1689-zD1, has this signature and a deep MOSFIRE observation would be able to detect the damping wing.

A1689-zD1 is a small (sub-L*), dusty galaxy. However, it is gravitationally-lensed by a factor of 9 (Bradley et al., 2008), making it bright enough to be spectroscopically accessible. The systemic redshift is $z = 7.132$ determined from detections of the C II 158 μm and CO(3–2) lines. However, the redshift determined from NIR spectroscopy with VLT/X-shooter of the Lyα spectral break is offset to the red by 14 000 km s^{-1}, i.e. X-shooter spectroscopy shows a break at about 1270 Å in the galaxy's restframe instead of 1216 Å, indicating an extremely high column density Lyα absorption line with a strong red damping wing. Measuring such a Lyα trough would be a clear detection of the bulk neutral IGM because the source is extended and the absorber must have a very high column density ($\log N_{\mathrm{H\,I}} \sim 23$). Our proposal seeks to measure the shape of this damping wing, and we need MOSFIRE on Keck to do it because it's the most sensitive spectrograph in the world at 1 μm. X-shooter's sensitivity is a factor of 4 lower in this region of the spectrum.

1.1 A1689-zD1 and the redshift discrepancy

A1689-zD1 was discovered as a HST z-band dropout () showing it to be a z = 7–8 galaxy, gravitationally lensed by the galaxy cluster Abell 1689. We analysed the results of Cycle 0, 1, and 2 ALMA and VLT/X-shooter observations (Watson et al., 2015; Knudsen et al., 2017) and found the galaxy to be dusty and evolved and we retrieved a coarse optical/NIR spectrum (Fig. 1) that confirmed spectroscopically the high redshift nature of the galaxy and located the break redshift at $z = 7.5 \pm 0.2$. The break can only be due to Lyα because of its depth and the relatively blue slope of the continuum. While the break is clearly visible in Fig. 1, the redshift uncertainty reflects that we needed to bin the spectrum substantially to recover the continuum emission and the break lies close to the region of least sensitivity for X-shooter—on the dichroic between the VIS and NIR arms. Our ALMA observations in bands 6 and 7 showed a clear detection of the source in dust continuum emission, with the HST and ALMA images of the galaxy co-spatial—there is no significant offset (Watson et al., 2015; Knudsen et al., 2017).

In the ALMA Cycle 3 data we find a strong emission line with significant velocity structure (Fig. 2). We infer this to be the C II 157.7 µm emission line at a redshift $z = 7.132$. The line is bright, with a flux of approximately 4 Jy km s^{-1}. The [C II] identification gives a flux consistent with expectations for this galaxy (De Looze et al., 2011). In our deep observations with GBT this year, we have detected a line at the expected frequency and luminosity (Stacey et al., 2010) for CO(3–2), confirming the systemic redshift, $z = 7.132$.

This redshift implies a Lyα break at 989 nm, strongly inconsistent with our observed Lyα break wavelength from VLT/X-shooter (Fig. 1), and lying about 14 000 km/s from the best fit. While the spectral break redshift has a conservative uncertainty of 0.2, the uncertainty space is highly non-linear and a redshift of 7.132 is excluded. This is because the dichroic region of the X-shooter spectrograph has particularly low signal-to-noise ratio, but 989 nm, where we expect Lyα at $z = 7.312$, is in the good part of the VIS arm and galaxy emission can be excluded there (Fig 1).

1.2 A unique opportunity to detect the bulk IGM

While modest velocity offsets with Lyα *in emission* are common due to the resonant scattering of the emission line, very large discrepancies with the absorption break are not expected and can only readily be explained except by a very large, damped absorption line. A line with $\log(N_{\rm H\,I}/{\rm cm}^2) \simeq 23$ at $z = 7.132$ would yield an apparent break in very low SNR data at $z \sim 7.5$. We believe this is the damping wing of the neutral IGM (the Gunn-Peterson damping wing; Miralda-Escudé, 1998). Such a column density is consistent with simulations of neutral gas densities in a reasonable fraction of lines of sight at this redshift (Kaurov & Gnedin 2015, ApJ 810, 154). The column cannot be associated with gas from the galaxy itself since the galaxy would be completely dust obscured ($A_V \sim 60$), given the dust-to-gas ratio for this galaxy (Watson et al., 2015), furthermore the column density is about two orders of magnitude larger than damped Lyα absorbers (DLAs) observed in galaxy spectra to date. To have such a large column DLA in this galaxy would require the DLA cloud to be pristine and to be foreground to essentially the entire galaxy and would require a H I cloud of at least the same mass as the galaxy gas mass. Such a cloud would be unstable to self-gravity and would collapse in only a few million years. The only credible explanation for the redshifting of the break is absorption by a large neutral IGM component.

Evidence of a damping wing has been seen in two $z > 7$ quasars (Mortlock et al., 2011; Bañados et al., 2018), but suffer from a number of caveats, most important of which is the possibility of a small local cloud intercepting the line-of-sight, a caveat noted by both Mortlock et al. and Bañados et al. This caveat also applies to GRBs (e.g. Tanvir et al., 2009), but is a possibility excluded in A1689-zD1 by the extended nature of the source.

A1689-zD1 represents a unique opportunity to detect the damping wing of the neutral IGM during reionization. We therefore request a MOSFIRE observation of the galaxy. The observation is designed to be deep enough to get a direct detection of the IGM damping wing. We have calculated the expected spectrum using the MOSFIRE ETC (Fig. 1) and we can clearly discriminate a damping wing compared to a sharp break and measure the column density in 16 hours exposure.

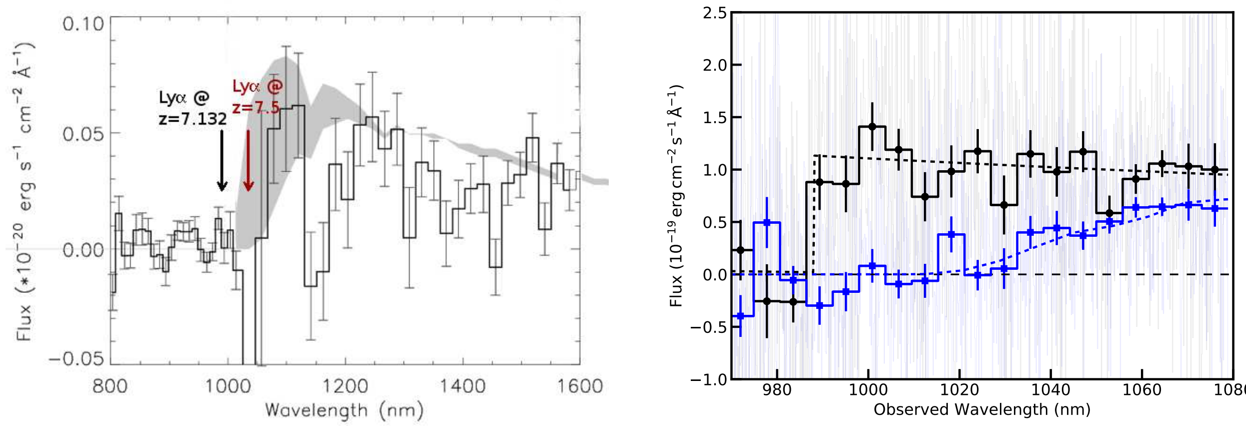

Figure 1: *Left*: VLT/X-shooter spectrum of Abell 1689-zD1. A break at $z \sim 7.5$ is apparent. The location of a simple Lyα break if it were at the redshift of the [C II] 158 μm line, $z = 7.132$, is indicated and is excluded by these X-shooter data. The shaded area indicates the allowed 1σlimits for the spectrum due to absorption by a DLA system fixed at $z = 7.132$ that would be required to explain the UV/FIR redshift discrepancy. The NIR spectrum is strongly affected by atmospheric absorption bands. *Right*: Simulation of the spatially integrated MOSFIRE spectrum based on galaxies absorbed by a $\log(N_{\rm HI}/{\rm cm}^2) = 23.1$ cloud (blue) and a standard IGM cut-off model (Meiksin 2006, MNRAS 365, 807, black). The simulation uses the MOSFIRE ETC and accounts for sky emission and absorption lines as well as instrumental noise. The lighter, thin lines are the unbinned spectra. The heavy histograms are these same spectra binned. We can clearly distinguish with these data between a sharp break and a large Lyα absorber both at the systemic redshift, $z = 7.132$ (models shown as dotted black and blue lines respectively) and we will be able to measure the effective column density.

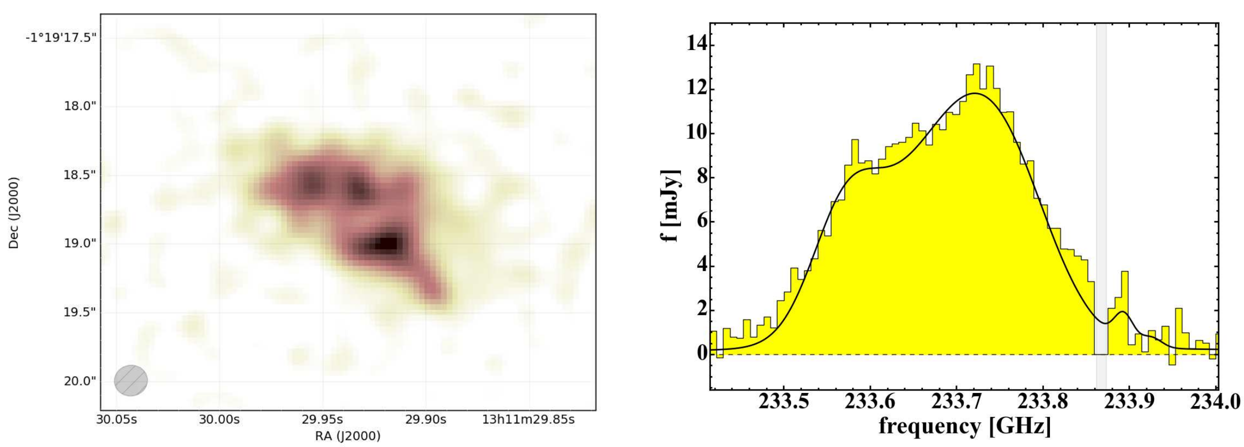

Figure 2: ALMA Cycle 3 data in band 6 showing an image (*left*) and the spectrum (*right*) in the emission line [C II] 157.7 μm. The redshift is $z = 7.132$. (The light grey box indicates flagged channels.)

References

Bañados, E., Venemans, B. P., Mazzucchelli, C., et al. 2018, Nature, 553, 473

Bradley, L. D., Bouwens, R. J., Ford, H. C., et al. 2008, ApJ, 678, 647

De Looze, I., Baes, M., Bendo, G. J., Cortese, L., & Fritz, J. 2011, MNRAS, 416, 2712

Fan, X., Strauss, M. A., Becker, R. H., et al. 2006, AJ, 132, 117

Knudsen, K. K., Watson, D., Frayer, D., et al. 2017, MNRAS, 466, 138

Miralda-Escudé, J. 1998, ApJ, 501, 15

Mortlock, D. J., Warren, S. J., Venemans, B. P., et al. 2011, Nature, 474, 616

Planck Collaboration, Adam, R., Aghanim, N., et al. 2016, A&A, 596, A108

Stacey, G. J., Hailey-Dunsheath, S., Ferkinhoff, C., et al. 2010, ApJ, 724, 957

Tanvir, N. R., Fox, D. B., Levan, A. J., et al. 2009, Nature, 461, 1254

Watson, D., Christensen, L., Knudsen, K. K., et al. 2015, Nature, 519, 327

2 Technical Remarks (2 pages max)

2.1 The need for Keck/MOSFIRE

There are very few instruments in the world capable of detecting the wing at this redshift. We require an 8–10 m-class telescope because the target is so faint, and we require an efficient detector at 1000 nm. We have deep X-shooter data for this target, but in this specific band $990 - 1030$ nm, where the X-shooter dichroic lies, X-shooter has a factor of 2–3 dip in efficiency due to the low sensitivity of first and last spectral orders of the NIR and VIS arms respectively. However, MOSFIRE'S Y grating has the sensitivity to make this observation.

2.2 Targets and Exposures:

The target is A1689-zD1, R.A. 13 11 29.93, Dec. -01 19 18.7. It has a $M_{J_{\rm AB}} = 25$ Source extent is $1''$. The requested exposure time is 16 hours.

The required time is calculated based on detecting the shape of a Lyα damping wing with a width of ~ 40 nm. We require 10 bins across the wing, i.e. 4 nm per bin, with a SNR ~ 3. The MOSFIRE ETC for a $Y_{\rm AB} = 25.0$ mag source (the HST F125W detection was 25.0 ± 0.13 and the spectrum is flat in F_ν), extended over 1 square arcsecond area (Watson et al. 2015) with a slit width of $0.7''$ gives a time required of about 50000 s. A SNR=0.6/pixel is found for the integrated source and 0.109 nm/pixel spectral dispersion in a 16 hour total exposure time with 1200 s integrations. This corresponds to a SNR over a 4 nm bin of ~ 3.6 taking into account that approximately half of the spectral band is heavily affected by sky emission lines. We used the MOSFIRE ETC with model galaxies, one cutoff at $z = 7.132$ (Meiksin 2006) and one with a $\log(N_{\rm H\,I}/{\rm cm}^2) = 23.1$ DLA, to represent the IGM, at $z = 7.132$, and determined the SNR spectrum, which includes instrument and sky emission and absorption contributions.

From these SNR spectra we simulated the output spectra and we show these simulations in Fig. 1 (right). Based on these simulations we can clearly discriminate between a break and a damping wing at $z = 7.13$ with 16 hours on source exposure. We can also fit the damping wing to measure the column density.

To remove the background and optimize the SNR on our high-redshift object we will adopt the following strategy. We will nod along the slits, using a telescope nodding sequence ABAB with 1200 s exposure each. This will optimize the sky subtraction and maximize the science exposure, since the science target is observed 100% of the time.

The remaining slits will be used to observe photometrically selected lensed galaxies at typically $z = 1 - 1.5$. At those redshifts we will target [O III], [O II] and Hβ. Given the significant exposure time for many of them we will be able not only to determine redshift but also to derive meaningful spatially resolved information and dynamical properties.

Lunar phase: This is a very faint target, but NIR observations only are required, so grey time is acceptable.

2.3 Backup Program:

If conditions are too poor to target very faint galaxies at $z > 7$, we will instead observe brighter, relatively low-redshift galaxies in the CANDELS UDS, GOODS-S and COSMOS fields, which are available in a similar range of right ascensions. We we will observe Hα + [NII] (and if possible also [SII] for galaxies at $0.4 < z < 1$, where we already have [OIII]+Hβ measurements from existing optical spectra, in order to measure line excitation diagnostics (BPT diagrams). These will be used to calibrate alternate methods, such as the Mass-Excitation (MEx) diagram of Juneau et al. 2011, that can be applied at high redshift without the need for infrared spectroscopy. Other programs, such as measuring nebular line extinction from the Balmer decrement for infrared-luminous galaxies with detections in deep Herschel and Spitzer data, will also be pursued to the extent that we can assess the relative Hα to Hβ flux calibration, using continuum detections of the galaxies to compare with HST photometry (and morphology to assess slit losses).

2.4 Supplementary Observations:

No other observations are required.

2.5 Status of Previously Approved Keck Programs (B. Mobasher):

- "The MOSDEF Survey" (co-PIs Shapley/Kriek/Reddy/Siana/Coil/Mobasher): This LMAP program was allocated 45.5 nights. Data from all the runs have been reduced and analyzed and used. Early data are included in MOSDEF publications. Because of this, B. Mobasher did not submit proposals in 2013A-2015A.

- Search for $z \sim 7.7$ and 8.8 galaxies in the DAWN fields—Mobasher 1.5 nights 2015B MOSFIRE: lost 1 night to weather, need more exposure on the sources to publish.

- Nature and Dynamics of Kpc-scale Clumps in star forming disk galaxies at $1 < z < 2$—Mobasher OSIRIS 1.5 nights: Lost one night to weather. Found no signature of Hα/Hβ lines we were looking for in the two target galaxies.

- Evidence for Population III Light from a Galaxy at z=6.6: 2 nights of DEIMOS: time 2015B. Clear weather. Results published in Sobral et al. 2016.

- Spectroscopic Observations of Galaxies in the Cosmic web: 1.5 nights DEIMOS: December 2016 weathered out.

3 Optional, but highly recommended, subsections (2 pages max)

3.1 Path to Science from Observations:

The observations will be carried out by Mobasher or Nayyeri. The data will be reduced and analyzed by our team, led by Mobasher, Watson, and Nayyeri. The analysis and reduction of the other targets in the field, which are primarily multiply-imaged systems, will be done by Johan Richard and Kirsten Knudsen. An improved mass model for Abell 1689 will be derived from these data, and constraints determined on background SMGs.

3.2 Technical Concerns:

The observations proposed here, while very deep, are not complex, and should be achievable with a straightforward observing strategy. The most important thing is to get a good sky subtraction. The simple ABBA nodding scheme proposed here should be good enough to achieve an accurate subtraction.

3.3 Publications by the Principal Investigator:

Some publications relevant to the present proposal (work based on Keck data is marked with *):

1. Nayyeri H., Mobasher B., et al. 2014 “A Study of Massive and Evolved Galaxies at High Redshift”, ApJ 794, 68;

2. * Mobasher B., et al. 2015, “A Critical Assessment of Stellar Mass Measurement Methods”, ApJ 808, 101;

3. * Sobral D., Matthee J., Darvish B., Schaerer D., Mobasher B., et al. 2015 “Evidence for PopIII-like Stellar Populations in the Most Luminous Lyman-Emitters at the Epoch of Reionization: Spectroscopic Confirmation”, ApJ 808, 139;

4. * Khostovan A. A., Sobral D., Mobasher B., et al. 2016 “The nature of Hβ+[OIII] and [OII] emitters to z = 5 with HiZELS: stellar mass functions and the evolution of EWs”, MNRAS 463, 2363;

5. * Faisst, A. L., [. . .], Mobasher B. et al. 2016 “Rest-UV Absorption Lines as Metallicity Estimator: The Metal Content of Star-forming Galaxies at z 5”, ApJ 822, 29;

6. * Darvish B., Mobasher B., et al. 2016 “The Effects of the Local Environment and Stellar Mass on Galaxy Quenching to $z \sim 3$”, ApJ 825, 113; 7

7. * Nayyeri H., Hemmati S., Mobasher B., Ferguson H. C. et al. 2017 “CANDELS Multi-wavelength Catalogs: Source Identification and Photometry in the CANDELS COSMOS Survey Field”, ApJS 228, 7;

8. * Khostovan A. A., Sobral D., Mobasher B., et al. 2018 “The clustering of Hβ+[OIII] and [OII] emitters since $z \sim 5$: dependencies with line luminosity and stellar mass”, MNRAS 478, 2999.

Co-Is Watson and Knudsen have been leading ESO observations of this galaxy and published the first spectroscopic redshift and ALMA detections.

Watson D. et al., 2015, Nature, 519, 327: A dusty, normal galaxy in the epoch of reionization

Knudsen K. K. et al., 2017, MNRAS 466, 138: A merger in the dusty, z = 7.5 galaxy A1689-zD1?

3.4 Resources and Publication Timescale:

The primary result—the detection of the Gunn-Peterson damping wing, will be written up rapidly in the first instance for publication in a high impact journal without extensive modelling. Watson and Nayyeri will be available to do this, with a first draft quickly, about two months after the observations since the observations will likely be performed in March–May, after the main teaching season. A follow-up paper will be written, modelling the IGM neutral fraction constraints with assistance from J. Zavala. The timescale for this is longer, about 6 months after the first publication. The publication of the revised mass constraints on Abell 1689 and the sub-mm galaxies depends on the level of improvement that can be derived from the data, but are likely to be part of a larger publication within 18 months of the observations.

3.5 Service to UCO (new since 2017B):

The PI is the IRMS instrument scientist on the TMT. He has developed preliminary exposure time calculator for the IRMS and performed a study of the capabilities of this instrument. The PI is also PI of a $4.5M grant from NASA to perform research and training in Big Data. This will provide the funding for a graduate student to work on the project proposed here. The PI has been supporting a significant number of undergraduate students from different UC campuses as well as a number of graduate students at UCR through his NASA-MIRO grant.