European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **101A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title

Category: **A–6**

Measurement of the damping wing of the neutral intergalactic medium at $z = 7.1$

2. Abstract / Total Time Requested

Total Amount of Time:

Reionisation took place around $z \sim 6.6 - 10$, and while the Gunn-Peterson trough is being detected regularly, the damping wing of the neutral intergalactic hydrogen has yet to be detected directly. We propose here to detect the neutral damping wing of the IGM for the first time. We have observed A1689-zD1, a modest SFR, lensed, reionisation-epoch galaxy at both NIR and mm wavelengths. The redshifts derived from these two are very different: we have 7.5 from the Lyα break observed in our low SNR NIR spectra, but $z = 7.13$ from our recently detected C^+ emission line with ALMA. The offset of the break is therefore 13 000 km/s to the red. This red offset would be characteristic of a very large ($\log(N_{\rm H\,I}/{\rm cm}^2) \simeq 23$) neutral damping wing. A deep KMOS spectrum will allow us to detect this damping wing – a direct signature of the reionization epoch.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	101	KMOS	21h	apr	g	0.8	PHO	s	

4. Number of nights/hours

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:	UT1	DDT 299.A-5004(A). See below.
b) still required to complete this project:	UT1	21h

5. Special remarks:

We got the ALMA data earlier this year and now have an emission line redshift to compare to the Lyα-break redshift. We request KMOS because KMOS-Iz is much more sensitive than X-shooter in the precise region of interest (990–1040 nm) because the dichroic of the X-shooter VIS/NIR arms lies in this range and the efficiency drops a factor of 2–3 here. This programme was approved as a DDT earlier this year, but only a small fraction of the time was executed. We therefore resubmit the request since the DDT allocation does not carry over.

6. Principal Investigator: DWATSON

6a. Co-investigators:

L.	Christensen	1227
J.	Selsing	1227
J.	Richard	1196
K.K.	Knudsen	8033

Following CoIs moved to the end of the document ...

7. Description of the proposed programme

A – Scientific Rationale: A significant prediction of our current cosmology is the existence of the epoch of reionisation, when the intergalactic medium (IGM), neutral since the emission of the cosmic microwave background, was ionised by luminous sources in the redshift interval now known to be $z = 6.6 - 10$ (Planck Collaboration, 2016, A&A 596, 108). While reionization epoch spectroscopy has made great strides in recent years, with increasing numbers of redshift confirmations via Lyα line emission (e.g. Zitrin et al. 2015, ApJL 810, 12; Oesch et al. 2015, ApJL 804, 30; Song et al. 2016, ApJ 826, 113; Stark et al. 2017, MNRAS 464, 469), the vast majority of candidate $z > 7$ galaxies do not have detectable Lyα lines (e.g. Finkelstein et al. 2013, Nature 502, 524, Watson et al. 2015, Nature 519, 327; Oesch et al. 2016, ApJ 819, 129), probably because even at $z \sim 7$, the IGM is significantly neutral. The spectra of high redshift galaxies, γ-ray bursts, and quasars, all show the expected flux suppression due to the Lyα forest, and at $z \gtrsim 6$, the complete suppression of flux due to intervening clouds of H I gas (the Gunn-Peterson trough). All of this evidence is compelling, though somewhat indirect. A key result for reionization would be the direct detection of the red damping wing of the general neutral IGM in a source during the epoch of reionization. To date, however, this has not been achieved because of the large Strömgren spheres of quasars and luminous galaxies, and the faintness of the continuum in sufficiently distant GRBs (Tanvir et al. 2009, Nature 461, 1254). In addition, even a quasar with high column density at this redshift is not enough to exclude the option of a local cloud; a sample would be needed. A GRB at this redshift would require extremely high SNR spectrum to differentiate between host galaxy absorbers and the IGM. A strongly-lensed, intrinsically faint galaxy with a systemic redshift from ALMA therefore seems our best option to detect the IGM directly, since it will have neither of these problems. It seems, serendipitously, that we have found such a galaxy with a very large IGM foreground.

B – Immediate Objective: This very ambitious programme aims to use a strongly lensed galaxy at $z \sim 7$ to directly detect the damped Lyα signature of the IGM during reionization. In 2014, we completed our analysis of ALMA and VLT/X-shooter data on a $z = 7 - 8$ galaxy candidate, gravitationally lensed by the galaxy cluster Abell 1689. With only very low SNR, we obtained a coarse optical/NIR spectrum (Fig. 1) that confirmed the high redshift nature of the galaxy and pinned the redshift to $z = 7.5 \pm 0.2$. The break can only be due to Lyα and is not a 4000 Å break because of its depth and the 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. This galaxy, because of the lensing magnification of a factor of 9 (Bradley et al. 2008), is relatively low luminosity, with an intrinsic absolute magnitude of $M_{\rm UV} \sim -20$. It is a magnitude below $L*$ at these redshifts. Our Cycle 0, 1, and 2 ALMA observations in bands 6 and 7 showed a clear detection of the source in dust continuum emission with about $2 \times 10^7\,{\rm M}_\odot$ of dust and an infrared-measured SFR of $\sim 12\,{\rm M}_\odot\,{\rm yr}^{-1}$ (Watson et al. 2015; Knudsen et al. 2017, MNRAS 466, 138). Its modest SFR and dustiness make this a good candidate for a galaxy with a small Strömgren sphere.

In the ALMA Cycle 3 data that we are currently analysing, 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 $4\,{\rm Jy\,km\,s^{-1}}$. (The only other possible line ID consistent with the X-shooter break is [O I] 2060.07 GHz. However, this is very unlikely because the line would be at least an order of magnitude brighter than expected for this galaxy (Cormier et al. 2015, A&A 587, 53), and we would expect to detect CO(3–2) easily in our existing data from the Green Bank Telescope (GBT) and we do not (Knudsen et al. 2017). Very high-J CO transitions are excluded. The [C II] identification gives a flux consistent with expectations for this galaxy (De Looze et al. 2011, MNRAS 416, 2712) and the expected $L_{\rm CO(3-2)}/L_{\rm [C\,II]}$ ratio (Stacey et al. 2010, ApJ 724, 957) is also consistent with our GBT spectrum.

A redshift $z = 7.13$ is strongly inconsistent with our Lyα break redshift from VLT/X-shooter (Fig. 1), and lies more than 13000 km/s from the best fit. A $\log(N_{\rm H\,I}/{\rm cm}^2) \simeq 23$ at $z = 7.13$ 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 observed for the first time. 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. This is very unlikely, requiring a H I cloud of at least the same mass as the entire galaxy gas mass to be gravitationally infalling and in its foreground. Column densities approaching this value have been observed in about a percent of γ-ray burst (GRB) afterglow DLAs (Tanvir et al. in prep.), however, GRB-DLAs are pencil beams directly out of young star-forming regions with a covering fraction of the galaxy light of at most a few percent, and again, those sightlines are always significantly dust extinguished. We conclude that the red shifting of the break away from the systemic redshift is due to a large neutral IGM component. This represents a unique opportunity to detect the damping wing of the neutral IGM during reionization.

We request a KMOS observation of the galaxy to investigate the redshift discrepancy. The observation is designed to be deep enough to get a direct detection of the IGM damping wing. We have calculated the

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

expected spectrum using the KMOS ETC (Fig. 1) and we can clearly discriminate a damping wing compared to a sharp break and measure the column density in 10 hours exposure. This wavelength range (990–1030 nm) is particularly unfavourable for X-shooter since it lies right in the region of the dichroic between the VIS and NIR arms.

We submitted this proposal earlier this year as a DDT request which was approved. However, only 3 hours were observed. In those observations, the in-frame dither pattern requested in the OB was not executed correctly, and only half of the data were usable.

Attachments (Figures)

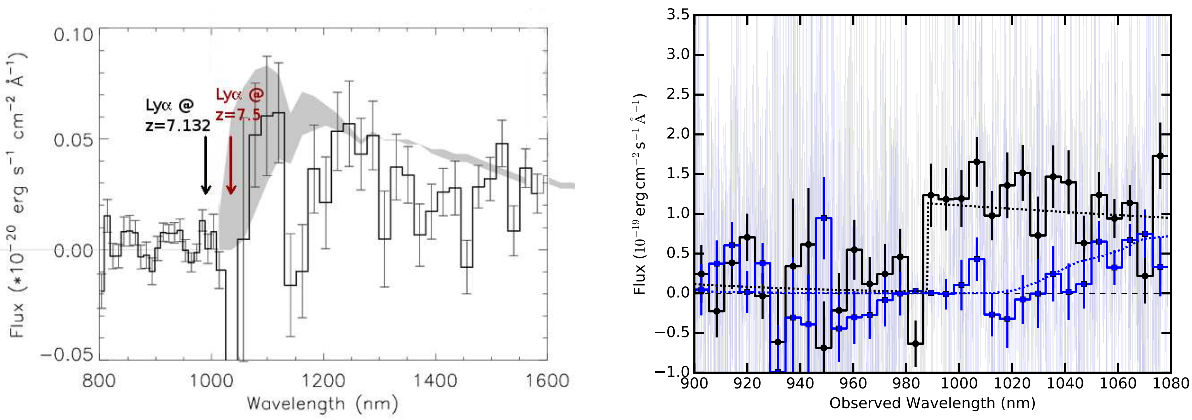

Fig. 1: *Left*: VLT/X-shooter spectrum of Abell 1689-zD1. A break at $z \sim 7.5$ is apparent. The location of a simple Lyα break if it were at the redshift of the [C II] 158 μm line, $z = 7.13$, is indicated and is excluded by these X-shooter data. The shaded area indicates the allowed 1σ limits for the spectrum due to absorption by a DLA system fixed at $z = 7.13$ 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 KMOS spectrum based on galaxies absorbed by a $\log(N_{\rm H\,I}/{\rm cm}^2) = 23.1$ cloud (blue) and a standard IGM cut-off model (Meiksin 2006, MNRAS 365, 807, black). The simulation uses the KMOS 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, $z = 7.13$ (models shown as dotted black and blue lines respectively) and we will be able to measure the effective column density.

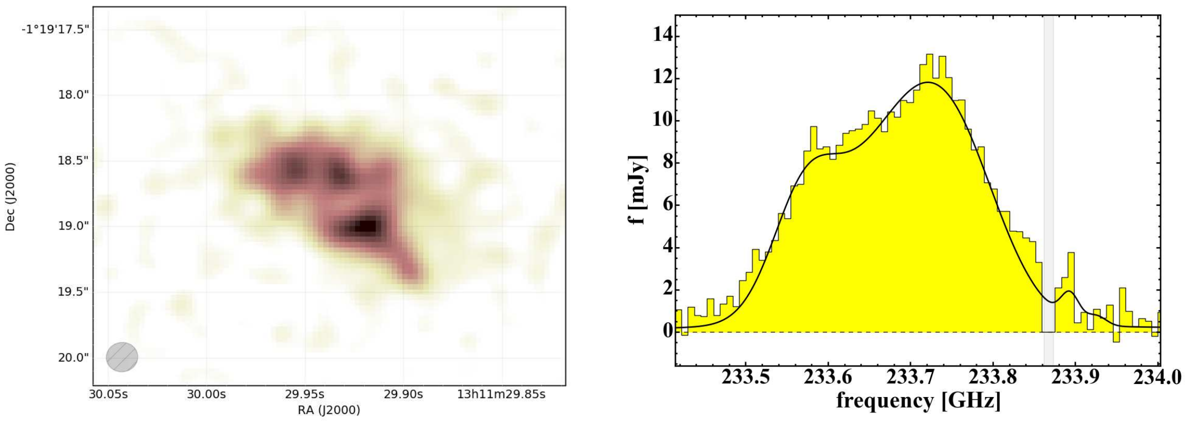

Fig. 2: ALMA Cycle 3 data in band 6 showing an image (*left*) and the spectrum (*right*) in the emission line [C II] 157.7 μm. The redshift is $z = 7.132$. (The light grey box indicates flagged channels.)

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: Very faint target, but NIR observations only, so grey time is acceptable.

Time Justification: (including seeing overhead) 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 of ~ 3. The KMOS ETC gives for a $J_{\rm AB} = 25.0$ mag source (the HST F125W detection was 25.0 ± 0.13), extended over 1 square arcsecond area (Watson et al. 2015). The number of pixels in the reference area is 25. A SNR=0.54/pixel is found the integrated source and 0.143 nm/pixel spectral dispersion in a 21 hour observation (16 hours exposure time) with 300 s DIT and NDIT=192, at a reference wavelength of 1025 nm. This corresponds to a SNR over a 4 nm bin of ~ 2.9 taking into account that approximately half of the spectral band is heavily affected by sky emission lines. Closer to the middle of the trough, the SNR will drop giving a lower SNR in the wing. We used the KMOS ETC with model galaxies, one cutoff at $z = 7.13$ (Meiksin 2006) and one with a $\log(N_{\rm H\,I}/{\rm cm}^2) = 23.1$ DLA, to represent the IGM, at $z = 7.13$, and determined the signal-to-noise ratio 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. Our DDT observations were affected by a problem with the requested telescope dither, removing half of the usable exposure time (just 1.2 hours on source of usable data) and rendering our sky subtraction strategy worse than expected.
To remove the background and optimize the SNR on our high-redshift object we will adopt the following strategy. We allocate 2 IFUs per target separated by 20–40 arcsec and use a telescope nodding sequence ABAB with 300sec exposure each, to move the target from A to B position (similar to a nodding along the slit). This will optimize the sky subtraction (i.e. one of the 2 IFUs is always monitoring the sky background) and maximize the science exposure, since the science target is observed 100% of the time. Twenty minutes overhead per OB inferred directly from P2PP gives a total of 21 hours. The remaining IFUs will be used to observe photometrically selected lensed galaxies at typically $z = 1 - 1.5$. At those redshifts we will target [OII], [OIII] and $H\beta$. 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.

8a. Telescope Justification:

There are very few instruments in the world capable of detecting the wing at this redshift. We require an 8 m-class telescope because the target is so faint, and we require an efficient detector at 1000 nm. X-shooter has a factor of 2–3 dip in efficiency at precisely this wavelength range due to using the low sensitivity first and last spectral orders of the NIR and VIS arms respectively. The FORS detector has too low sensitivity at these wavelengths. However KMOS's Iz grating has the sensitivity to do this in a reasonable integration time.

8b. Observing Mode Justification (visitor or service):

N/A. Service mode is preferred due to the good observing conditions required, however visitor mode is acceptable.

8c. Calibration Request:

Standard Calibration

9. Report on the use of ESO facilities during the last 2 years

VLT: 299.A-5004(A) this proposal as a DDT (PI: Watson)

ALMA: 2015.1.01406.S (PI: Watson): The ALMA data presented in this proposal (Fig. 2). Just received, currently being analysed.

099.A-0292, 098.A-0502, 097.A-0269, 096.A-0496 (PI: Richard) MUSE/GTO observations of lensing clusters. Data has been published in Bina et al. (2016), Patricio et al. (2016), Mahler et al. (2017) and Lagattuta et al. (2017).

ALMA: 2016.1.00329.S (PI: Michałowski): the data have been reduced and are being analysed.

APEX: 096.D-0280, 096.F-9302, 097.F-9308 (PI: Michałowski): the data have been reduced and analysed. The results for one galaxy is published in Michałowski et al. (2014, A&A, 562, 70). The survey paper is being written.

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

We have deep X-shooter data for this target, but as explained above, in this specific band $990 - 1030$ nm, where the X-shooter dichroic is, only KMOS has the sensitivity to make this detection. We have 3 hours of KMOS data observed, but with only about half of it usable, as explained above.

9b. GTO/Public Survey Duplications:

No duplications.

10. Applicant's publications related to the subject of this application during the last 2 years

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?

Michałowski, M. J., 2015, A&A, 577, 80: Dust production 680-850 million years after the Big Bang

Mahler, G., Richard, J., Clément, B., Lagattuta, D., Schmidt, K., et al. 2017, MNRAS submitted, astro-ph/1702.06962: Strong lensing analysis of Abell 2744 with MUSE and Hubble Frontier Fields images

Lagattuta, D., Richard, J., Clément, B., Mahler, G., et al. 2017, MNRAS submitted, astro-ph/1611.01513: Lens Modeling Abell 370: Crowning the Final Frontier Field with MUSE

Bina, D., Pello, R., Richard, J., et al., 2016, A&A, 590, 14: MUSE observations of the lensing cluster Abell 1689

Patrício, V., Richard, J., et al., 2016, MNRAS, 456, 4191: A young star-forming galaxy at z = 3.5 with an extended Lyman halo seen with MUSE

Richard, J., Patricio, V., Martinez, M. et al., 2015, MNRAS 446, 16: MUSE observations of the lensing cluster SMACSJ2031.8-4036: new constraints on the mass distribution in the cluster core

Stark, D., Richard, J., et al. 2015, MNRAS, 450, 1846, Spectroscopic detections of CIII]1909 at $z \sim$6-7: A new probe of early star forming galaxies and cosmic reionisation

Alavi, A., Siana, B., Richard, J. et al., 2014 ApJ 780, 143: Ultra-faint ultraviolet galaxies at $z \sim 2$ behind the lensing cluster A1689: The luminosity function, dust extinction and star formation rate density

Vanzella E., et al., incl. Christensen, 2017, ApJ submitted: Magnifying the Early Episodes of Star-Formation: A pair of low-metallicity super-star clusters at z=3.2222

Tilvi V., et al., incl. Christensen, 2016, ApJ, 827, 14: First results from faint infrared grism survey: first simultaneous detection of Lyman-a emission and Lyman break from a galaxy at z = 7:51

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	A1689-zD1	13 11 29.93	-01 19 18.7	10	25 (J_{AB})	$1''$		

Target Notes: This is a note about targets.

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
101	KMOS	A	IFU	IZ

6b. Co-investigators:

...continued from Box 6a.

M.	Michalowski	1366
J.	Zavala	9287
A.	Gallazzi	1335
O.	Turner	1366
M.	Cirasuolo	1258