European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **100A**

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–8**

A new metallicity diagnostics of high-redshift galaxies from direct abundance measurements

2. Abstract / Total Time Requested

Total Amount of Time: 2 nights VM, 0 hours SM

The chemical enrichment of galaxies throughout the cosmic history is an important astrophysical investigation, which ultimately leads to a better understanding of galaxy evolution. High-z galaxy metallicities are determined through observations of strong optical emission lines with calibrations tied to the local universe. Recent debate has questioned if these calibrations are valid in the high-z universe, and what diagnostics, if any, are useful. We propose to settle this debate by observing gravitationally lensed, blue, low-mass galaxies at $z \sim 2.2$ in the CLASH and Frontier Fields surveys, measure their rest-frame UV and optical emission lines and derive direct (T_e) oxygen abundances. By doubling the number of direct metallicity measurements at $z > 2$, we will increase the dynamical range of metallicities to allow establishing a reference for several strong-line diagnostics. Such a reference is vital for deriving metallicities from the imminent *JWST* high-redshift galaxy spectra.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	100	XSHOOTER	2n	oct	d	0.8	CLR	v	
A/alt	100	XSHOOTER	17.6h	any	d	0.8	CLR	s	

4. Number of nights/hours

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

This re-submission addresses the remarks from the P99 OPC who questions the 'statistically valid sample sizes'. By doubling the number of direct metallicity measurements, we can verify existing R_{23} relations within 1σ confidence intervals from existing calibrations, where the current levels are at 2σ levels. For the *N2* and *O3N2* relations, there are currently too few direct metallicity measurements covering a too small dynamical range to derive a high-z strong-line diagnostics. The proposed observations will give new reference calibrations with a spread of ∼0.1–0.2 dex i.e. equivalent to the quality of the calibrations in the local universe.

6. Principal Investigator:

Lise Christensen, lise.christ@gmail.com, DK, Dark Cosmology Centre, Niels Bohr Institute

6a. Co-investigators:

R.	Canameras	Dark Cosmology Centre, Niels Bohr Institute,DK
C.	Grillo	Universita di Milano,Dipartimento di Fisica,I
I.	Balestra	INAF - Osservatorio Astronomico di Trieste,I
E.	Vanzella	INAF - Osservatorio Astronomico di Trieste,I

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

7. Description of the proposed programme

A – Scientific Rationale: Major observational efforts are invested in the study of galaxies in the $z \sim 2$ universe. Their chemical evolution is analysed through the mass-metallicity relation [1,2], which is mainly focused on the high stellar mass end, while average properties of faint, lower-mass galaxies are based on co-added spectra [3]. Investigations of individual high-redshift galaxies are limited by their faintness. To circumvent this problem we can take advantage of strong gravitational lensing, where massive foreground mass concentrations magnify the signal of the background galaxy. These cosmic telescopes can boost the signal from the background source by a factor of >10 allowing us to examine galaxies that are intrinsically fainter than those studied in flux-limited samples. Nevertheless, the strong lensed galaxies studied in detail to date are intrinsically luminous, have high star formation rates (SFRs), and high metallicities of 0.5–1 times solar [4,5].

Metallicities, reddening, densities and temperatures of the gas in the galaxies HII regions can be determined from a range of diagnostics tools applied to the observed emission lines [6]. An accurate method to derive metallicities is the direct temperature method (T_e), which relies purely on gas physics through detections of temperature sensitive emission lines such as [OIII] 4363 or [NII] 5755 [7,8]. These auroral lines become increasingly faint in lower-temperature regions present in high-mass ($\log M_* > 10.0$), high-metallicity ($Z/Z_\odot > 0.5$) galaxies, that are most frequently targeted in galaxy surveys. Conversely, low-mass galaxies have higher ionisation parameters, higher temperatures, and UV lines become increasingly bright. When auroral lines are not detected, we rely on strong-line diagnostics to determine metal abundances through strong-line diagnostics e.g. R_{23} [9] or *N2* [10]. However, to date all empirical abundance diagnostics are calibrated with respect to local and low-redshift galaxies, and it is unclear if those calibrations are also valid at higher redshifts where higher star-formation activity and higher densities give rise to higher ionisation parameters [11].

We demonstrated with X-shooter spectra of 4 lensed galaxies at $1.4 < z < 3.5$ that temperature sensitive lines were detected and T_e based abundances derived [12,13]. For these galaxies the T_e abundances were in agreement with the R_{23} diagnostics calibration in Pilyugin et al. [14] (Fig. 1). Other investigations of strong-line diagnostics have argued that the *N2* calibration is not an appropriate metallicity tool for high-z galaxies [15], because *N2* is primarily sensitive to the ionisation parameter. Similar problems arise for the *O3N2* ratio. Based on the high-z galaxies with prefix 'BX' in Fig. 1 alone it is indeed impossible to verify or dispute the validity of any relations, since the dynamical range of measured metallicities measured is low.

Metallicity diagnostics vary widely and different diagnostics differ by up to 0.7 dex [16]. When studying the redshift evolution of the galaxy mass-metallicity relation, one often has to rely on various types of calibrations, since not all strong emission lines are accessible within the given redshift range. If we could choose a single diagnostic, the systematic shifts between the metallicity calibrations applied to the low- and high-redshift universe can be eliminated. It is therefore crucial to determine the best way to measure metallicities of high-z galaxies. A calibration of the diagnostics for galaxies at $z \sim 1$ is currently in progress [17], and it is timely to expand the metallicity diagnostics calibration to even higher redshifts. This will place solid foundations for galaxy metallicities at $z \sim 2$, which currently rely on calibrations from the local universe [15,18].

B – Immediate Objective: We propose to observe 11 lensed galaxies at $z \sim 2.2$ detected in CLASH and *HST*/Frontier Fields (HFF) surveys. The large wavelength range of X-shooter is essential in order to cover UV lines, in particular the OIII]1661,1666 doublet and simultaneously the optical lines: [OII] 3727, Hβ, [OIII] 5007, Hα, and [NII], with which we can infer the gas temperature, electron density and derive direct oxygen abundances and metallicity of the gas [12,13] and derive relations with the line flux ratios R_{23}, *N2* and *O3N2*.

We chose lensed galaxies that are spectroscopically confirmed by VIMOS and MUSE follow-up of CLASH and HFF clusters [19]. We require the galaxies to lie at $2 < z < 2.5$, and check that all the relevant emission lines are detectable within the X-shooter wavelength coverage, so that the redshifted emission lines are not absorbed by telluric lines or severely affected by sky lines. The selected targets either show (Fig. 2) or are very likely to have strong UV emission lines. The redshift range $z = 2.0 - 2.5$ is also widely used by large flux-limited surveys [15,18], and we therefore have a large sample available for comparison.

The galaxies are required to be relatively bright (F814W$\lesssim$24 mag) and with magnifications that ensure that we select galaxies with low intrinsic stellar masses. Magnification factors lie in the range 1.3–7, resulting in intrinsic absolute magnitudes at restframe 2500Å between –22.2 and –19.1. The galaxies must lie uncontaminated regions in the clusters such that sky-subtraction by nodding along the X-shooter slit is possible. We require that the galaxies have a blue continuum. Galaxies with detected CIII] lines are known to have blue continua with colours F814W–F125W < 0 [12], or steep UV slopes ($f \propto \lambda^\beta$) with $\beta < -2$ [20], and typically show Lyα emission (Fig. 2). Weaker UV lines such as OIII] 1666 are often not detected in low-resolution VIMOS spectra which smooths out faint, narrow lines due to the resolution [21], but in cases (Fig. 2) several lines can be seen. These criteria are fulfilled by 11 among the CLASH and HFF lensed galaxies.

With ancillary HST imaging data, we have derived physical properties via standard SED fits. Stellar masses for the chosen targets lie in the range $M_* = 10^{8.8} - 10^{10.0}$ M$_\odot$ and SFRs=1–70 M$_\odot$ yr^{-1} *after* correcting for magnifications. These high SFRs ensure clearly detectable strong emission lines from Hβ, [OIII] and UV lines. From the mass-metallicity relation at $z = 2$ [25], we will cover a 0.9 dex range in metallicity (12+log(O/H)=7.5–8.4).

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

Since metallicity diagnostics rely on emission-line ratios, they are independent on magnification uncertainties. Differential magnification is not a concern given the galaxies position relative to the critical lines of the cluster. With the proposed data we will examine the low-mass end of the fundamental mass-metallicity-SFR relation [22], as lensing reaches beyond conventional surveys. While previous studies have used strong-line diagnostics to derive metallicities, an exploration of the fundamental metallicity relation based solely on the direct metallicity for high-z galaxies is critically needed before the imminent JWST surveys of high-redshift galaxy metallicities.

References: [1] Tremonty, C. et al. 2004, ApJ, 613, 898 [2] Maiolino, R. et al. 2008, A&A, 488, 463 [3] Shapley, A. et al. 2000, ApJ, 528, 96; [4] Quider, A. et al. 2009, MNRAS, 398, 126; [5] Dessauges-Zavadsky, M. et al. 2010, A&A, 510, 26; [6] Kewley, L. & Dopita, M. 2002; ApJS, 142, 35; [7] Osterbrock, D. 1989, 'Active Galactic Nuclei'; [8] Izotov, Y.I et al. 2006, A&A, 448, 955; [9] Pagel, B.E.J. et al. 1979, MNRAS, 189, 95; [10] Pettini, M. & Pagel, B.E.J. 2004, MNRAS, 348, L59; [11] Kewlew, L. et al. 2015, ApJ, 812, 20 [12] Christensen, L. et al. 2012, MNRAS, 427, 1973; [13] James, B. et al. 2014, MNRAS, 440, 1794; [14] Pilyugin, L.S. 2005, A&A 436, 1; [15] Steidel, C. et al. 2014, ApJ, 795, 165; [16] Kewley, L. & Ellison, S. 2008, ApJ, 681, 1183; [17] Ly, C. et al. 2016, ApJ, 828, 67; [18] Wisnioski, E. et al. 2015, ApJ, 799, 209; [19] Grillo, C. et al 2015, ApJ, 800, 38; [20] Stark, D.P. et al. 2014, MNRAS, 445, 3200; [21] Vanzella, E. et al. 2016, ApJ, 821, 27; [22] Mannucci, F. et al. 2011, MNRAS, 414, 1263; [24] Belli, S. et al. 2013, ApJ, 772, 141; [25] Wuyts, E. et al. 2012, ApJ, 755, 73; [26] Sanders, R. et al. 2016, ApJ, 825, 23

Attachments (Figures)

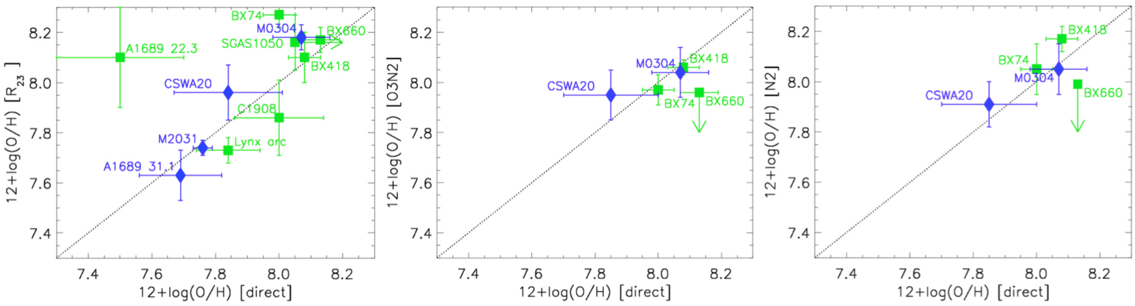

Fig. 1: Comparison of direct T_e based metallicities with those of strong-line diagnostics from our study of lensed galaxies at $z > 1.4$ (blue diamonds [12,13]), combined with literature measurements (green squares)[e.g. 15,26]. Left panel shows R_{23}, middle *O3N2*, and right *N2*. Some lensed galaxies show reasonable agreements with calibrations [12], when including a correction for the ionisation parameter of R_{23}. In order to re-calibrate the diagnostics it is important to span a large dynamic range by including the low-metallicity end, beyond what is reached in most luminosity-limited surveys. Here, CSWA20 and Lyman break galaxies with prefix 'BX' [15] are representative for massive systems (log $M_* > 10.0$) at their redshifts. A careful investigation of the numerous distinct calibrations [16] will be done with the expanded sample, which allows us to explore all three major diagnostics over a 0.9 dex dynamical range in metallicity. Given the mass-metallicity relation at $z = 2$ [25], the lensed low-mass galaxies (log M_*=8.8–10) ensure that we cover the low-metallicity end (12+log(O/H) $\sim$ 7.5–8.4). Expanding the dynamical range of the *N2* and *O3N2* calibrations is essential, and by doubling the number we can derive a new reference R_{23} calibration with a 1σ spread of $\sim$0.1–0.2 dex i.e. equivalent to the quality of the calibration in the local universe.

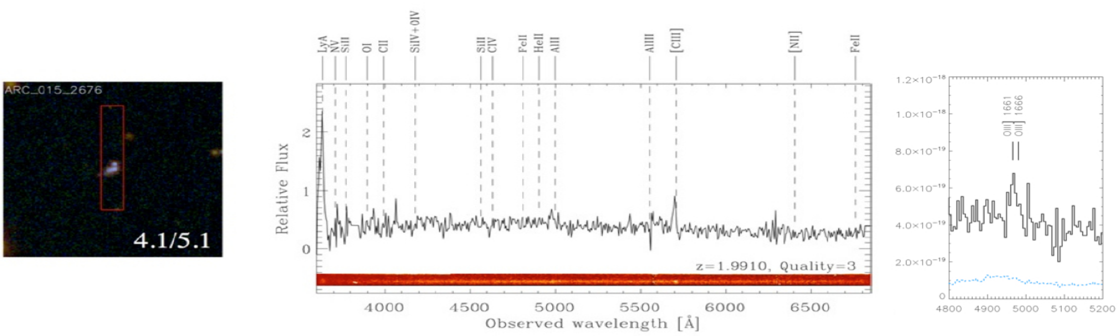

Fig. 2: HST image of one of the lensed galaxies in the sample (from [19]). Although the sample is selected from the CLASH and HST Frontier Fields arc catalogues, all galaxies are compact or dominated by a single compact knot, and will appear as point sources from ground. The low-resolution VIMOS spectra often prevents detection of weaker lines [21]. However, OIII] 1661,1666 is detected here (in 3 hours integration time) with a flux of 3.5×10^{-18} erg/s/cm^2 (right panel). Among the 11 targets, Lyα is detected in 8, CIII] 1909 in 5, and OIII] 1666 in 3, but these numbers are expected to increase in higher-resolution X-shooter spectra which more efficiently detects fainter and narrow emission lines.

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: We are interested in capturing the UV lines of faint (mag$\lesssim$24) distant galaxies. In particular the O III] 1661,1666 doublet is critical to detect, and it will fall around 5000–5800 Å. Good observing conditions are needed, and therefore we ask for dark time.

Time Justification: (including seeing overhead) The requested integration time is driven by the wish to observe faint rest-frame UV emission lines which at $z \sim 2$ fall in the UVB and VIS arms.

Fig. 2 illustrates a 3 hour VIMOS spectrum where O III] 1666 is detected with a flux of 3.5×10^{-18} erg/s/cm^2. Other objects may show even fainter lines as they are not clearly detected in low-resolution VIMOS data. We calculate the needed exposure times given the following criteria: An emission-line flux of 2×10^{-18} erg/s/cm^2 around 5000 Å, a line width (velocity dispersion) around 100 km/s giving a FWHM$\sim$0.4-0.5 nm. In dark-time, and with a seeing of 0.8 arcsec at a representative airmass of 1.4, the ESO ETC gives that in $4 \times 1200s$, we can achieve a S/N=4 for the line detection.

Rest-frame optical lines (Hβ,[O II],[O III],Hα,[N II]) are expected to be significantly brighter (around a few times 10^{-17} erg/s/cm^2 and will be detected at S/N$\gtrsim$ 10 (e.g. [12]). Previous experience with X-shooter data showed that in very good seeing (0.7 arcsec) we can achieve a S/N = 8 for a line-flux of 3×10^{-18} erg/s/cm^2 (Christensen et al. 2012a,b) in similar integration times.

We ask for 1.6 hours per target including 12 minutes overhead per OB. With 11 targets we therefore need 17.6 hours. In visitor mode, we need observations of hot stars prior or after the science exposures to remove telluric features in the spectra. For this an additional 2 hours is needed in total. In total we therefore ask for 2 nights in visitor mode or 17.6 hours in service mode.

8a. Telescope Justification:

The observations require simultaneous observations of rest-frame UV and optical lines for galaxies at $z \sim 2.2$. X-shooter is the only instrument that allows us to do that.

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

Since the targets have unknown UV line fluxes, visitor mode observations will allow us to effectively use the observing time should the lines be detectable in shorter than expected integration times. The targets are spread in RA such that full nights in Oct. 2017 are useful. Alternatively, service mode allows the data to be obtained at the optimal seeing conditions.

8c. Calibration Request:

Standard Calibration

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

098.A-0665(A) - Xshooter - PI: Vanzella “Pushing X-Shooter high-resolution spectroscopy to the faintest limits: unveiling the physical properties of L < 0.1 L* redshift >3 Lyα emitters”.
096.A-0650(C)+098.A-0182(B) - UT1/FORS2 - PI: Vanzella ”State-of-the-art cosmic telescopes call for deep spectroscopy: imaging of faint (0.05L*)” 15hr allocated on MACSJ0329.
096.B-0212(A) - UT4/MUSE PI: James ”Exploring Primordial Star-Formation in a Newly Uncovered Population: Blue Diffuse Dwarf Galaxies” - Observations were taken early 2016. Data have been reduced and analysis of the data is currently underway.

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.

None of the targets are observed with X-shooter. Existing VIMOS data is insufficient because of low-spectral resolution, and that NIR data is required.

9b. GTO/Public Survey Duplications:

N/A

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

Balestra, I. et al., 2016, ApJS, 224, 33: “CLASH-VLT: Dissecting the Frontier Fields Galaxy Cluster MACS J0416.1-2403 with 800 Spectra of Member Galaxies”

Grillo, C. et al. 2016, ApJ, 822, 78; “The Story of Supernova Refsdal Told by Muse”

Grillo, C. et al. 2015, ApJ, 800, 38: CLASH-VLT: Insights on the Mass Substructures in the Frontier Fields Cluster MACS J0416.1-2403 through Accurate Strong Lens Modelling

Patricio, V. et al. incl. Christensen: 2016, MNRAS, 456, 4191: A young star-forming galaxy at z = 3.5 with an extended Lyman α halo seen with MUSE

Vanzella, E. et al. 2016, ApJ, 825, 41, “Hubble Imaging of the Ionizing Radiation from a Star-forming Galaxy at $z = 3.2$ with f_{esc} >50%”

Vanzella, E. et al. 2016, ApJ, 821, 27: High-resolution Spectroscopy of a Young, Low-metallicity Optically Thin L = 0.02L* Star-forming Galaxy at $z = 3.12$

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

Vanzella, E. et al. 2015, A&A, 576, 116: “Peering through the holes: the far-UV color of star-forming galaxies at z $\sim$ 3-4 and the escaping fraction of ionizing radiation”

S. Schulze, et al. incl. L. Christensen 2017, MNRAS submitted, “Cosmic evolution and metal aversion in super-luminous supernova host galaxies”

Karman, W.; Caputi, K. I.; Grillo, C.; Balestra, I.; Rosati, P.; Vanzella, E.; Coe, D.; Christensen, L. et al., 2015 A&A, 574, 11, “MUSE integral-field spectroscopy towards the Frontier Fields cluster Abell S1063. I. Data products and redshift identifications”

G. Leloudas, et al. incl L. Christensen 2015 MNRAS, 449, 917: “Spectroscopy of superluminous supernova host galaxies. A preference of hydrogen-poor events for extreme emission-line galaxies”

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	Abell209 4378	1:31:50.355	-13:37:34.15	1.6	23.11		z=2.331	
A	Abell209 1957	1:31:54.172	-13:36:09.09	1.6	23.65		z=2.255	
A	Abell209 1326	1:31:52.119	-13:35:35.17	1.6	23.30		z=2.464	
A	Abell383 2099	2:48:02.145	-3:31:05.71	1.6	23.80		z=2.186	
A	MACS2129 3320	21:29:21.756	-7:41:03.37	1.6	23.07		z=2.271	
A	MS2137 4247	21:40:19.185	-23:39:32.18	1.6	23.28		z=2.486	
A	MS2137 3128	21:40:12.723	-23:38:49.45	1.6	23.20		z=2.243	
A	RXJ2248 2134	22:48:37.106	-44:31:21.20	1.6	23.67		z=2.062	
A	RXJ2129 1611	21:29:39.560	+0:06:45.94	1.6	23.85		z=2.403	
A	MACS0416 8.1	04:16:06.246	-24:04:37.76	1.6	24.5		z=2.304	
A	MACS0416 4.1/5.1	04:16:07.385	-24:04:01.62	1.6	23.8		z=1.990	

Target Notes: All selected targets have spectroscopic redshifts based on low-resolution VIMOS data. The additional info lists the observed aperture F814W magnitudes (AB) of the galaxies. Some arcs are slightly extended (1 arcsec), but their flux is dominated by single bright knots in all cases. Magnification maps are derived for all CLASH clusters (e.g. Grillo et al. 2015, Zitrin et al. 2015), and the galaxies magnification factors lie in the range between 1.3 – 7. MACS0416 8.1 is fainter than the required limit, but has a clear CIII] 1909 detection already in VIMOS data [19].

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
100	XSHOOTER	A	300-2500nm	SLT
100	XSHOOTER	A	SLT	1.0,0.9,0.9
100	XSHOOTER	A	SLT	100k-1x2,100k-1x2,NDR

6b. Co-investigators:

...continued from Box 6a.

B.	James	Space Telescope Science Institute,US
P.	Rosati	Universita di Ferrara,Dipartimento di Fisica,I
A.	Mercurio	INAF - Osservatorio Astronomico di Capodimonte,I