European Organisation for Astronomical Research in the Southern Hemisphere

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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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–1**

"First Light" – the highest redshift galaxies

2. Abstract

We propose to use integrated JHK spectroscopy on the ELT (in GLAO mode) to identify the first UV emitting sources in the Universe responsible for reionization at $z > 6$. The galaxy candidates will be identified via the Lyman-break technique with upcoming deep space-based and groundbased near-IR surveys (with HST/WFC3, Spitzer, VISTA, and JWST). The source densities at $z \sim 8$ are about 1 arcmin^{-2} at $H_{AB} = 28.5$, for which an ELT spectrograph equipped with a GLAO or LTAO/MOAO system will be necessary to obtain redshifts and to understand their physical properties. These observations will probe an era of a few hundreds million years right at the end of the "dark ages", will identify the sources of reionization and yield their luminosity function. Such a program will give the first insight of the crucial early stages of galaxy formation process.

3. Run

Run	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	79Multi-IFU	300h	any	d	$\leq 0.4''$	PHO	v
B	79Multi-IFU	250h	any	d	$\leq 0.4''$	PHO	v
C	79Multi-IFU	250h	any	d	$\leq 0.4''$	PHO	v

4. Principal Investigator:

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CoI(s): Marijn Franx (Leiden University, NL), Bram Venemans (ESO, ESO)

5. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

6. Description of the proposed programme

A) Scientific Rationale: **I. The First Galaxies** When and where did the first galaxies form? From very general considerations, the critical mass scale at which the "first galaxies" likely formed is in $\sim 5 \times 10^7$ $M_\odot$ halos assembled at z$\sim$10. At this scale, the virial temperature of the halo exceeds 10^4 K and atomic cooling becomes the dominant cooling mechanism. Halos above this mass can retain photoionized gas and therefore likely maintained a self-regulated multi-phase ISM sustained by the energy due to star-formation (e.g., Mac Low & Ferrara 1999; Madau et al., 2001; Ricotti et al., 2002). These are the "first galaxies".

Many other questions surround the formation of the first galaxies. What was the shape of the IMF, if such a designation even makes sense for the first galaxies? The IGM is likely to have been heavily enriched (Becker et al. 2009), the radiation fields may have been intense and the turbulence high during this epoch. The balance between metalicity, turbulence generated by collapsing gas and mechanical energy injection from the stars, and the strength of the radiation is not at all academic as it determines whether the star-formation is regulated by cooling through molecular or atomic lines. These two cooling mechanisms could lead to substantially different IMFs (Bromm et al. 2003; Greif et al. 2007; Wise & Abel 2008; Greif & Bromm 2006). Moreover, the accretion of cold gas from filaments in combination with a softened equation of state drives strong shocks and turbulence (e.g., Keres et al. 2005) which might lead to vigorous fragmentation and the formation of the first star clusters. Such a situation would be an important early step towards conditions that are similar to star-formation in the local Universe and hence a "normal" IMF.

However, to know whether or not any of our modeling represents reality, and to solve this "tension" in the models of the first galaxies, observers must find the first galaxies and then confirm that they are indeed in the early Universe. To overcome the problem of discovering galaxies at high redshift, regardless of their properties, we should use selection methods which rely on extrinsic rather than intrinsic galaxy properties and which, if possible, can be applied over the entire history of the Universe. The dropout technique, which selects galaxies according to the strength of their Lyman break (so-called Lyman break galaxies) is such a selection method. LBGs have been the benchmark against which other samples of high z galaxies have been compared since their discovery by Steidel and collaborators and they allow us to study galaxies selected in a consistent manner over z=0-7 and now perhaps even up to z=8.5 (Bouwens et al. 2009). So, while LBGs can in principle select every type of galaxy, we inherently add a bias which is that they must be actively star-forming with little reddening to "clean" the samples of "interlopers". At higher and higher redshifts it becomes difficult to remove interlopers as data of sufficient depth at longer wavelengths (i.e., beyond 2.5μm) are difficult to obtain. However, despite this, it is the simplicity of selection of the LBG technique, its robustness, and wide redshift span probed that makes the LBG selection technique unrivaled for (comparative) galaxy evolution studies.

Luminosity Function and Correlation Lengths: One of the most important parameters that we would like to know is the spatial distribution and clustering properties of the galaxies as a function of magnitude. From such studies we can determine the halo mass and the likely evolutionary outcomes for this first galaxies. In order to accomplish this, we need to:

1. measure the redshifts, confirm that the galaxies are at high redshift; give the redshift distribution for the population as a function of magnitude. From this, we can determine their 3-D spatial correlation and their likely halo masses.

2. determine the luminosity function of the galaxies at a variety of wavelengths. From this combined with thier spatial distributions will allow us to begin guage their impact on the IGM and their integral mass to light ratios - useful for constraining the IMF.

The Violent ISM of Young Galaxies at z>6: All the of the most distant galaxies known have properties suggesting that they are in their formative phases and are sites of intense star-formation. The star-formation intensities are well above the threshold for galaxies driving winds in the local universe (0.05 $M_\odot$ yr^{-1} kpc^{-2}) and LBGs at lower redshifts have strong evidence for driving winds from rest-frame UV spectroscopy (e.g., Shapley et al. 2001; Vanzella et al. 2009). Studies of starburst-driven outflows in nearby galaxies have determined that these flows are a multiphase phenomenon where each phase reveals important details about the ionization state of the ISM and the distribution of mass, energy, and thermal and ram pressure. Without constraining all of these characteristics, it is difficult to know what the ultimate fate of the gas may be. How much is retained in the halo and how much is likely ejected? For example, in starbursts, the observed outflow velocities of the optical emission line gas are much lower than the expected terminal velocity of the wind (i.e., Lehnert & Heckman 1996). In contrast, line widths and offset velocities of the *absorption* line gas seem to trace the terminal velocities and correspond to the wind velocities estimated from the X-ray emission (Heckman et al. 2000). The absorption line gas also has the advantage that it probes the gas between us and the UV/optical continuum emission. Thus if we see the gas blueshifted relative to systemic it is outflowing. With emission line gas, there is not this sense of direction - all velocities can be seen. In addition, the absorption line gas probes

6. Description of the proposed programme (continued)

large ranges of temperature and ionization state (T$\sim10^4$ to 10^6 K and many ionization states, for example CI to CIV).
By determining the properties of the rest-frame UV emission and absorption lines, we can:

1. Determine if the warm/hot ISM will escape the galaxy and halo potential.
2. Determine the metallicity of the galaxy and the rate at which metals are ejected into the halo and/or IGM by the outflowing gas. Are their sufficient baryons to account for the metallicity of the early IGM?
3. Determine the velocity and total energy in the outflowing gas. Is there sufficient energy and velocity (to estimate how far the outflow reaches) to explain the topology of the IGM as determined through absorption line studies from background QSOs (if any), GRBs, and supernovae. Is the energy per baryon sufficient to explain the phase of the early IGM?
4. What is the covering fraction of neutral and highly ionized gas? What is the topology of the ISM in these early galaxies? What is the escape fraction? Combined with the luminosity function, is it sufficiently high given the number of sources to account for reionization?
5. Combined with observations with infrared/submm/mm facilities such as ALMA and JWST/MIRI (CO and H_2 lines) how much of the mechanical energy of the star-formation dissipated in the warm/cold molecular gas or advected out of the system through winds? How much mass is in each phase of the ISM in these early galaxies? Is the ISM turbulent?
6. Observations with infrared/submm/mm facilities such as ALMA and JWST/MIRI (CO and H_2 lines) and direct detection of stellar photospheric lines with E-ELT we can ask: How efficient is the star-formation in these early galaxies?
7. Combined with rest-frame optical and near-infrared imaging and a direct detection of the UV stellar photospheric lines which form in the atmospheres of O and B stars, we can determine the age and number of O and B-stars. This will allow us to determine the shape of the IMF. Was it top heavy? These lines will also allow us to estimate the metallicity of the young stars. HeII emission might be seen which in combination with the UV absorption lines may tell us what fraction of Population III stars these galaxies may host.
8. Galaxies at high redshifts are often multi-modal (Douglas et al. 2009) similar to low-z LBGs (Overzier et al. 2009). What is the nature of these components, velocity differences, internal properties? Are these mergers or clumpy star forming complexes (see Overzier et al. 2009)?

B) Immediate Objective: Our immediate objective is a low spectral resolution study (R=1000-3000) to obtain redshifts followed by a detailed investigation of the nature of the stellar and interstellar absorption lines in the most distant galaxies known. All galaxies are taken from our large sample of galaxies drawn from the deep surveys with HST/WFC3, JWST/NIRCam, and ultra deep surveys with the VLT and other 10m class telescopes. Some fields already have a substantial number of galaxies which have been spectroscopically confirmed by JWST/NIRSpec.
Moderate resolution spectroscopy of the most distant galaxies with a high multiplex spectrometer will provide:
• A wide variety of absorption lines in the UV and blue optical. These include the important interstellar lines of: Lyα, NV$\lambda\lambda$1239, 1243, SiII$\lambda\lambda$1260,1265 OI/SiII$\lambda\lambda$1302,1305, SiII$\lambda\lambda$1304, 1309, CII$\lambda\lambda$1334,1336, SiIV$\lambda\lambda$1393, 1402, SiII$\lambda\lambda$1527,1533 CIV$\lambda\lambda$1548, 1550, MgII$\lambda\lambda$2796, 2803, FeII lines, etc. as well as several strong stellar absorption lines (e.g, SVλ1502, CII$\lambda\lambda$1426,1428; some of the lines listed have contributions from both). Such a line list will allow us to probe gas ranging from 10^4 to 10^6 K.
•A wide variety of strong emission lines including: Lyα,NV, CIV, HeII, etc.
Specifically, with these intermediate resolution spectra, we will:
(1) measure the relative velocity offsets of the various UV absorption lines as a function of ionization to Lyα HeIIλ1640,etc. This will uniquely and quantitatively show whether they are driving winds. Blueshifted absorption lines relative to recombination lines will be strong evidence for winds and allow to quantify their

terminal velocities. From ionization calculations, covering fraction estimates (see next point), and column density measurements, we can estimate the mass/energy outflow rates.
(2) estimate the covering fractions of low-ionization and high-ionization absorption line gas. The lines are resolved, which means that the covering fraction can be estimated from the residual core intensity of the line. Our spectra will contain both low and high ionization UV lines, hence we can estimate the covering fraction of various gas phases. This will give us clues on the distribution of the ISM in this galaxies and help constrain the outflow rates.
(3) estimate the escape fraction of ionizing photons. An HI column depth of only 1.6×10^{17} cm^{-2} produces $\tau \sim 1$ at the Lyman edge. Since the mean columns of galaxies are much greater ($\sim10^{21}$ cm^{-2}), the leakage of photons from any system must be determined by its topology. We expect to resolve the UV absorption lines, hence if we know the velocity widths, we can derive the line depth from absorption line modeling. CIIλ1335 is produced in the same regions as HI; thus the core residual intensity of CII will yield direct constraints on the areal coverage of optically thick, neutral gas.
(4) measure the photospheric lines. From the photospheric and stellar wind lines we will derive the main properties of the UV-emitting stellar population (composition, age, metallicity). If any of these galaxies have H_2 mass determinations, we can estimate the star-formation efficiency. The UV absorption lines in comparison with emission lines such as HeII will allow us to constrain the metallicity and ionization state of the gas. Can we find evidence for population III stars?

C) Telescope Justification: Only the large light grasp and high spectral and spatial resolution of the E-ELT can think about accomplishing this experiment.

D) Strategy for Data Reduction and Analysis: The strategy for this proposal depends on a number of factors. The main one is the competitiveness with JWST. At resolutions greater than about 3000, a 42m E-ELT is about a factor of 3 faster in integration time to each the same depths. For example, in 10^5 s, JWST/NIRSpec can reach K_{AB}=24 at 10σ which E-ELT can reach this depth in about 3.5×104s. The number of Y-J break galaxies is about 0.5 arcmin^2 down to H_{AB}=28.5 (Bouwens et al. 2009). In the field of view of an E-ELT, assumed to be about 30-40 arcmin^2. Thus, if a spectrograph with deployable IFUs has a multiplex of about 20, its effective multiplex is larger than JWST/NIRSpec because of the larger field of view. The E-ELT can actually obtain redshifts faster at these resolutions. At R=1000, the situation is reversed and JWST is much faster (about a factor of 5 in integration time). R=1000 is sufficient for redshifts and characterizing the absorption line EQWs but not anything more. Also, if JWST stays on schedule, they would have a headstart of a few years for obtaining redshifts, stacking analyses, clustering amplitude determinations, metallicity/age estimates, etc - albeit on relatively small numbers of galaxies (perhaps 10s). The niche of the E-ELT is then in the physics of the ISM and the topology of the IGM. If JWST does not fly, then even a R=3000-5000 multi-object spectrometer will be a capable redshift machine. It is not clear if lower resolutions will be able to get redshifts if there are not strong emission lines.

6. Attachments (Figures)

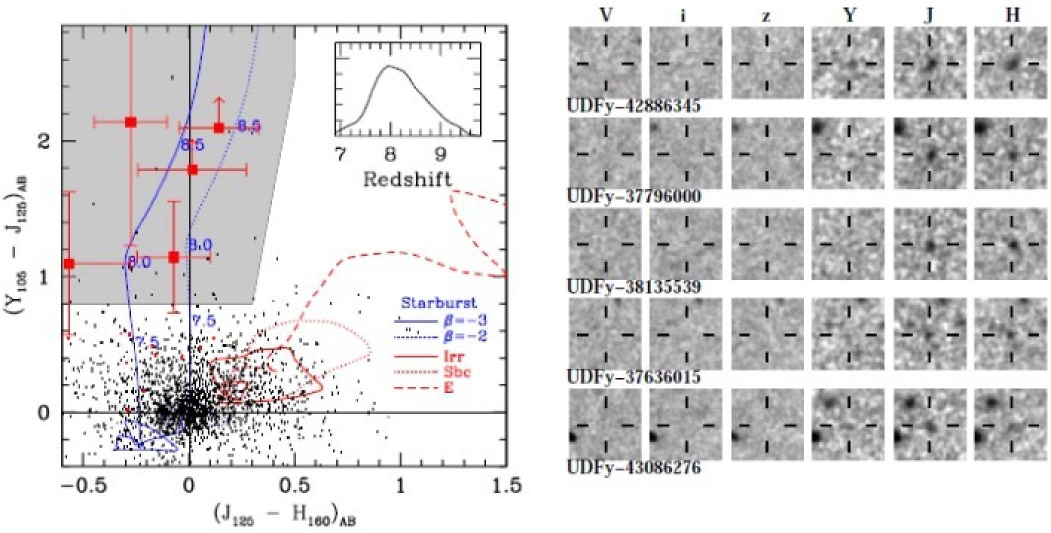

Fig. 1: *(left)* The source color selection, J_{125}-H_{160} versus Y_{105}-J_{125}, used by Bouwens et al 2009 to select very high redshift galaxies. The red squares represent the distant galaxies and the numbers are the best fit photometric redshift for each source. *(right)* Postage stamps of the images of the 5 candidate z∼8 galaxies. The surface density of z∼8 candidates is about 0.5 arcmin^2 at H_{AB}∼28.5.

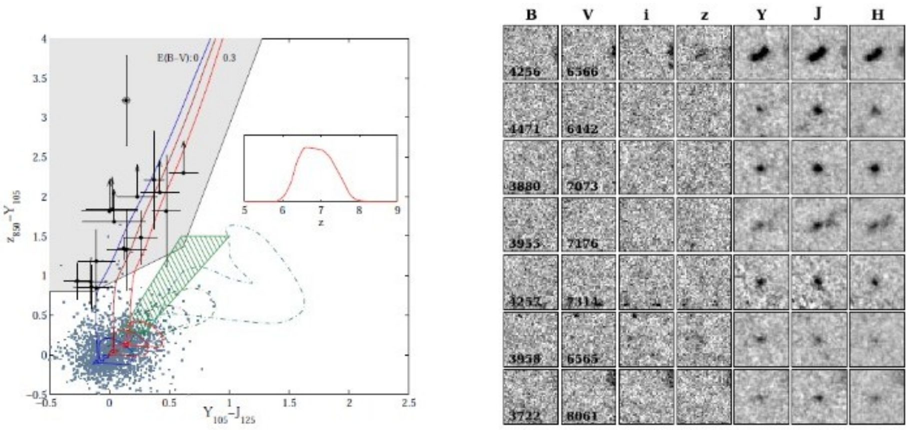

Fig. 2: *(left)* The source color selection, Y_{105}-J_{125} versus z_{850}-Y_{105}, used by Oesch et al. 2009 to select z∼7 galaxies. The black circles represent the distant galaxies with galaxies of various redshifts with different reddenings are shown by the lines. The shaded area in the color-color diagram is the selection region. *(right)* Postage stamps of the images of some of the candidate z∼7 galaxies (see Oesch et al. for the rest).

6. Attachments (Figures)

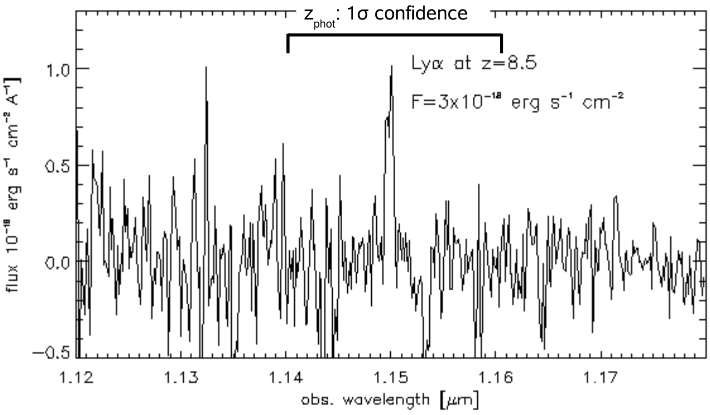

Fig. 3: Artificial (Gaussian) Lyα line with observed FWHM=200 km s^{-1} and flux 3×10^{-18} erg s^{-1} cm^{-2} at z$\sim$8.5 superimposed on a real SINFONI J-band spectrum. The cube is was scaled such that it represents 12 hrs of integration time. The spectrum was extracted from a box aperture of 5×5 pixels ($0.625'' \times 0.625''$) and smoothed by 3 pixels along the spectral axis. Note that there are several bright night sky lines near 1.15μm which we were able to subtract robustly with our routines (which is a strong factor in determining whether this experiment is even feasible in the first place). The black bar shows the 1σ confidence interval of the photometric redshift given by Bouwens et al. (2009). Such a line would imply equivalent widths of more than about 150Å in the rest-frame for H$_{AB}$=28.2. An equivalent integration with a E-ELT would push this a factor of 5 deeper or down to 30Å. Most distant lyman break galaxies have EQWs higher than this.

7. Justification of requested observing time and lunar phase

Lunar Phase Justification: The spectrograph will be used in the near-infrared and so we have no lunar phase requirement.

Time Justification: (including seeing overhead) The ETC indicates that H_{AB} 27 can be reached in 30 hours. Hence the ULTRA VISTA galaxies require integration time of that amount. This assumes that the galaxies convolved with the psf have a half-light radius of 200mas. This is unknown ofcourse, but hopefully reachable with GLAO. The surface density of these galaxies is approximately 0.38 / sq arcmin; and we wish to cover 2600 sq arcmin. Obviously, wide field access is critical. If the effective field is 10 arcmin, we can do this program in approximately 30 pointings, hence 300 hours. Deeper observations will be done on a bright subsample to give better physical information.
The galaxies with Hab=28 will be done in approximately 100 hours per integration. Their surface density is expected to be higher by about a factor of 6 - about 2 per sq arcmin. This number is of course quite uncertain - it should be measured. Working over a field of 10x10 arcmin, this would give 200 galaxies per 100 hours. In 500 hours, 1000 galaxies can be measured, yielding a meaning full sample.

Calibration Request: Special Calibration - Regular observations of standard star fields (!)

8. Instrument requirements

AO-fed multi-IFU spectrograph (Multi-IFU)
Wavelength range required: 10000Å to 14000Å.
Spectral resolution: 4 000 –10 000

9. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	COSMOS	10	+2:12	300	26-28	45	90	COSMOS FIELD
B	CDFS	03 32 28	-27 48 30	250	26-28	45	90	CDF-south
C	HDFS	22 32 56.22	-60 33 02.69	250	26-28	45	90	HDF-south

Target Notes: These are typical targets. Cosmos field will likely happen; other fields are more uncertain, they depend on what JWST will do.