



## 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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APPLICATION FOR OBSERVING TIME

LARGE PROGRAMME

PERIOD: **81A**

### 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: <b>A-7</b>						
A Spectroscopic Survey for Ultra-Faint $z \sim 3$ Lyman $\alpha$ Emitters in the Hubble Ultra Deep Field								
2. Abstract / Total Time Requested								
Total Amount of Time:				Total Number of Semesters:				
<p>We propose to perform an ultra-deep spectroscopic survey for Ly<math>\alpha</math> emitting galaxies in the Hubble Ultra Deep Field (HUDF). Our recently completed FORS2 longslit blank field survey has demonstrated that we can detect starforming galaxies by their Ly<math>\alpha</math> line radiation to the depth of the HUDF with <i>ground-based</i> telescopes. We discovered 27 faint, extended, single-line emitters likely to be dominated by Ly<math>\alpha</math> at <math>z \sim 3</math>, a population more than 20 times more numerous than Lyman-break-selected galaxies. These new sources may correspond to the hosts of damped Ly<math>\alpha</math> systems, and possibly represent the majority of star-forming galaxies at that redshift. An unambiguous identification of the emitters, and an understanding of their emission mechanism, star formation history, and gas dynamics depends on observing the Ly<math>\alpha</math> line <i>and</i> the broad band continuum radiation for each object, but the faintness of the detected line emission requires broad band imaging to depths currently attained only in the HUDF. Therefore, we propose to obtain a 120h long-slit exposure with FORS2 centered on the HUDF, allowing us to finally solve the mystery of the elusive host galaxies of damped Ly<math>\alpha</math> systems and would constitute a breakthrough in our understanding of the formation of present-day galaxies. Due to the extended nature of the emitters <b>this proposal can take advantage of poor seeing periods in VLT service mode.</b></p>								
3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	81	FORS2	60h	any	d	n	CLR	s
B	82	FORS2	60h	any	d	n	CLR	s
4. Principal Investigator: <b>M. Haehnelt</b> (Institute of Astronomy, Cambridge, UK, <a href="mailto:haehnelt@ast.cam.ac.uk">haehnelt@ast.cam.ac.uk</a> )								
Col(s): L. Barnes (IoA Cambridge, UK), G. Becker (OCIW, USA), A. Bunker (Exeter, UK), S. Cristiani (Trieste, I), J. Graham (UC Berkeley, USA), M. Jarvis (Oxford, UK), C. Lacey (Durham, UK), F. Marleau (Caltech, USA), C. Peroux (Marseille, F), M. Rauch (OCIW, USA), H. Röttgering (Leiden, NL), T. Theuns (Durham, UK)								

## 5. Description of the proposed programme

### A) Scientific Rationale:

#### Searches for young galaxies

The search for and discovery of young galaxies at high redshift has involved a number of unexpected twists and turns. Early predictions of young galaxies shining brightly in Ly $\alpha$  line radiation (Partridge & Peebles 1967) have not been borne out by reality. The first detections of an entire population of ordinary (i.e., non-AGN) high redshift galaxies came from the observations of damped Ly $\alpha$  systems (DLAS) seen in absorption against background QSOs (e.g., Wolfe et al 1986). Detections of substantial numbers of high redshift galaxies in emission had to wait for another decade and larger telescopes, and came to rely not on emission lines but on broad band continuum ("Lyman break") features (e.g. Steidel & Hamilton 1995), yielding massively star forming galaxies where, ironically, the expected Ly $\alpha$  emission was highly suppressed because of dust absorption. With the advent of 10m class telescopes narrow-band surveys for Ly $\alpha$  line emission finally reached sufficient depth as well, discovering considerable numbers of galaxies with large Ly $\alpha$  equivalent widths (e.g., Cowie & Hu 1998). The relation between the galaxy populations selected by these three different methods has so far remained obscure. Galaxies selected by Lyman  $\alpha$  line emission (down to typical narrow-band limiting fluxes of a few  $\times 10^{-17}$  erg s $^{-1}$ cm $^{-2}$ ), though similar in numbers to Lyman break selected galaxies, appear different from these because of their much larger line-to-continuum ratios. Both emitter populations appear more metal-rich and have star formation rates larger than compatible with the low metallicity and low dust contents of DLAS.

#### DLAS and the general population of star-forming galaxies

The key to a full understanding of the *general* population of galaxies at high redshift (which is likely to be less actively star-forming and, at least according to the CDM paradigm, far more numerous than either of the two bright classes of objects) must lie with the DLAS. Unfortunately, DLAS host galaxies have remained largely elusive at high redshift. The attempt to identify individual DLAS with galaxy counterparts has usually been frustrated by the difficulty of detecting an extremely faint object (the DLAS host) next to an extremely bright object (the QSO). Searches (e.g., Warren et al 2001, Fynbo et al 2003; Kulkarni et al 2000,2001; Christensen et al 2006) have so far produced only a handful of confirmed detections of the underlying galaxies. Such efforts indicated that DLAS hosts at high redshift are generally drawn from the very faint end (Fynbo, Møller, & Warren 1999; Bunker et al 1999) of the general galaxy population at high redshift (Møller et al 2002) giving support to the idea that DLA host galaxies have rather low masses (Haehnelt Steinmetz & Rauch 2000), albeit with a considerable gas cross-section.

#### A search for faint Ly $\alpha$ emitters and a surprising discovery

We recently completed a deep spectroscopic blind survey for low level Ly $\alpha$  fluorescence, using FORS2 on the VLT (LP 173.A-0440). The original motivation was to search for Ly $\alpha$  emission from the optical thick part of the gaseous cosmic web (Lyman Limit systems (LLS) and DLAS), induced by the general UV background (Hogan & Weymann 1987; Gould & Weinberg 1996). Line emission in response to recombinations caused by the impinging UV photons would cause any patches of optically thick gas to exhibit a universal "glow" of Ly $\alpha$  photons. Our experiment consisted of a long-slit spectrum with a  $7' \times 2''$  large slit, of a blank piece of sky, exposed for 92 hours (120 hours including overheads). The resulting  $1\sigma$  surface brightness detection limit for line photons,  $8 \times 10^{-20}$  erg cm $^{-2}$  s $^{-1}$   $\square''^{-1}$  was close to the sensitivity needed to detect the effect, but in the course of the project, theoretical estimates of the UV background intensity had gone down, and so we were somewhat short of the signal-to-noise-ratio required. However, instead of the expected  $\sim 30$  optically thick patches fluorescing at very low light levels in Ly $\alpha$  patches we found 27 single line emitters on the slit (see Fig. 1), with fluxes typically a factor ten stronger (a few  $\times 10^{-18}$  erg s $^{-1}$ cm $^{-2}$ ) than the expected signal from fluorescence alone. Many of the objects (Fig 2.) are extended, with detectable Ly $\alpha$  emission out to 4 arcsec.

In a publication submitted to ApJ (Rauch et al 2007) we argue that most of the emitters are likely to be Ly $\alpha$  at redshift  $z \sim 3.2$ , and find that they are probably powered by star-formation as opposed to other processes like fluorescence or cooling radiation. The large comoving number density  $3 \times 10^{-2}$  h $_{70}^3$  Mpc $^{-3}$  (more than 20 times the number density of Lyman Break galaxies; see Figs. 3 and 4), the large covering factor  $dN/dz \sim 0.2 - 1$  (Fig. 5), the low star-formation rates (a few tenths of  $M_{\odot}\text{yr}^{-1}$ ) implied formally by the line luminosities, and the spatially extended Ly $\alpha$  emission suggest that the emitters be identified with the elusive host population of damped Ly $\alpha$  systems and high column density Lyman limit systems. Moreover, DLAS are known to dominate the neutral hydrogen contents of the universe and thus the raw material for star formation, so if our objects are more or less identical to DLAS host galaxies they are also likely to correspond to the bulk of the star-forming galaxies as well, a suggestion consistent with the large comoving density.

#### The elusive continuum

The essential, but missing piece of evidence in this puzzle is clearly the rest frame UV continuum radiation of the objects. A knowledge of the continuum will not only allow the unambiguous identification in each individual case as high redshift galaxy, but it will also give a more reliable measure of the star-formation rate, and clues as to the stellar composition and provide constraints on the morphology of these galaxies - it will

## 5. Description of the proposed programme (continued)

tell us what these objects really are. Unfortunately, as the line emission is very faint, the expected continuum emission, assuming that both line and continuum are largely unextinguished, mutually consistent indicators of star-formation (corresponding to an equivalent width of 70 Å for a Kennicutt (1998) Ly $\alpha$  to star-formation conversion, and a Madau, Pozzetti & Dickinson (2000) conversion from star-formation to UV luminosities), is even considerably fainter, such that we need the broad band sensitivity of the Hubble Ultra Deep Field ( $M_{AB} \sim 29$  in V) to detect the corresponding UV rest frame continua (see Fig. 4). When our original project was started, our target field was selected to add signal to an existing pilot project, the HUDF was not yet on the horizon, and the possibility of such a large number of star-forming objects on the slit was frankly unexpected. After our surprise discovery of the faint emitters, it is clear now that that a knowledge of the continuum emission is of utmost importance. As we obviously cannot obtain imaging with the depth and quality of the HUDF of our original field from the ground we would like to perform a spectroscopic observation similar to our original one in the HUDF.

### The present proposal

We thus propose here a 120h longslit-exposure with FORS2 centered on the HUDF. The scientific value of such an observation is obvious; simultaneous spectra (emission line) (from FORS2) and broad band (continuum) information (from the HUDF) on a population of galaxies 20 times as numerous and 10-1000 times fainter than existing ground based samples of galaxies, will afford us the opportunity of studying, for the first time, the bulk of the star-forming galaxy population at high  $z$ . The  $\sim 120h$  of spectroscopy are not inordinately expensive (when compared to traditional galaxy surveys, and certainly relative to space-based missions) especially since we are prepared, as in the earlier project, to take advantage of bad seeing periods in service mode. Aside from its immediate scientific objective it is clear that observations of this kind (targeting the line emission of faint galaxies in long, untargeted, spectroscopic exposures) reach the same number density of objects as continuum (drop-out) surveys from space (Fig. 5), making 8m telescopes directly competitive with space missions, as far as optical searches for faint galaxies are concerned.

**B) Immediate Objective:**      **Long-slit spectroscopy with FORS:** We propose to obtain a 120h (including overheads) FORS2 long-slit exposure with the 1400V grism centered on the HUDF. Figure 1 shows such an exposure for a different field which we obtained under the program LP173.A-0440(A) in which we have detected 27 faint mostly spatially extended emission line objects with fluxes of a few  $\times 10^{-18}$  erg s $^{-1}$ cm $^{-2}$ . We expect to detect a similar sample of faint emission line objects for which, however, because of our targeting the HUDF, we will have imaging information of unrivalled depth (down to  $M_{AB} \sim 29$  in V and 28.7 in B). About half of the sample is expected to be part of the HUDF B-dropout sample. The HUDF data will allow us to confirm the emission as being Lyman $\alpha$  radiation. Establishing the equivalent width we will be able to decide which objects if any are dominated by cooling radiation. We will further significantly improve our estimates of the star formation rates and will be able to investigate the spatial distribution of the star formation relative to the resonantly scattered Lyman  $\alpha$  radiation. We will the significantly improve our upper limits on the amplitude of the meta-galactic UV background which are currently limited by confusion with emission from star formation when stacking the spectra of objects with low star formation rate. **Note that because of the extended nature of the emission this proposal can take advantage of times of poor seeing and the flexibility of the VLT queue schedule.**

**C) Telescope Justification:**      The faint nature of the emitters makes the use of a telescope of the size of the VLT essential. We note that other large telescopes (e.g. Keck) do not have the same flexibility of scheduling as the VLT. Hence, a program such as this (which requires a large amount of telescope time but can tolerate bad seeing) would not be scheduled on a classically-operated telescope. The HUDF is best observed from the southern hemisphere.

**D) Observing Mode Justification (visitor or service):**      Due to the extended nature of the Ly $\alpha$  fluorescence emission (median diameter  $\sim 8''$ ) we are not sensitive to bad seeing. Our previous program LP173.A-0440 where we have observed a different field with the same instrumental set-up has served successfully as a back-up program for bad seeing in periods 73/74 and 76/77, and did not run into any scheduling difficulties.

## 5. Attachments (Figures)

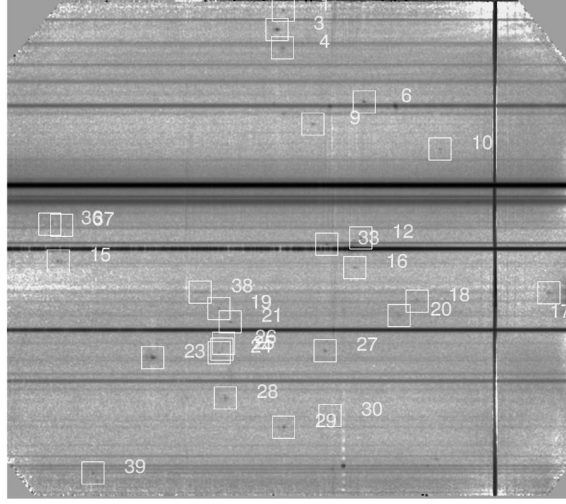


Fig. 1: Two-dimensional spectrum obtained in 92 hours of exposure time with FORS2 under program LP173.A-0440 showing the line emitter candidates for HI Ly $\alpha$  (boxes). The dispersion direction is horizontal, with blue to the left and red to the right; the spatial direction along the slit is vertical. The large majority of the continuum traces are foreground lower redshift galaxies and stars.

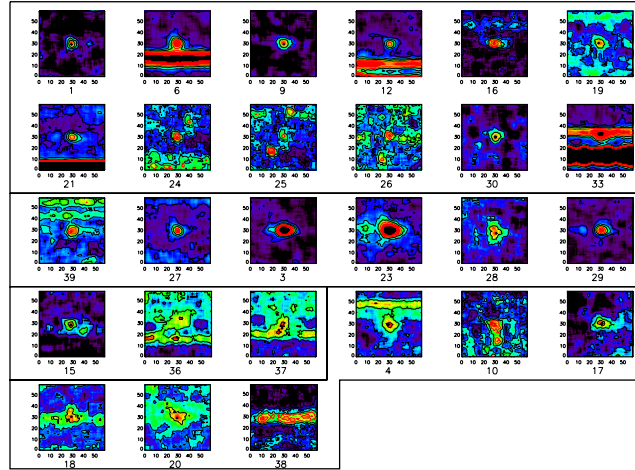


Fig. 2: Individual spectra for the single line emitters. The coordinates are in pixel units ( $0.252'' \times 0.67\text{\AA}$ ). The sections of the spectra shown here are  $15.12''$  or  $116$  proper kpc wide in the spatial direction and about  $2266 \text{ km s}^{-1}$  long in the spectral direction (i.e., horizontally). The spectra have been heavily smoothed with a  $7 \times 7$  pixel boxcar filter. The areas within the turquoise (light grey) contours have a flux density greater than approximately  $1.5 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{\AA}$ . At least ten of the objects clearly show emission line asymmetries characteristic of known high redshift galaxies.

## 5. Attachments (Figures)

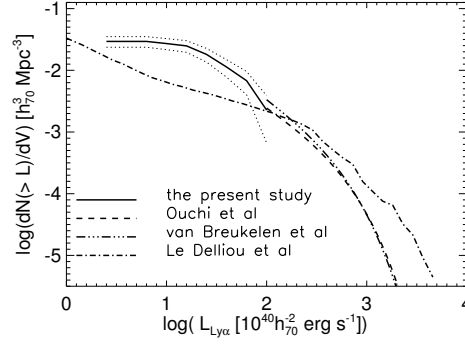


Fig. 3: Comoving number density of emitters with a luminosity exceeding  $L_{Ly\alpha}$ , as a function of  $Ly\alpha$  luminosity, compared to existing  $Ly\alpha$  surveys (Ouchi et al, van Breukelen et al) and theoretical predictions (LeDelliou et al).

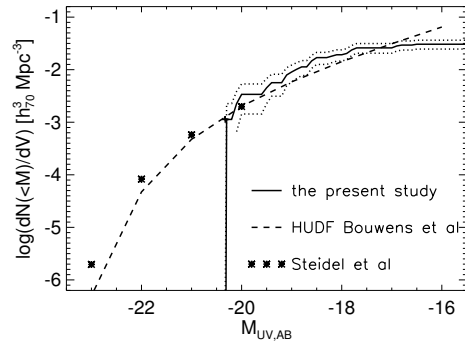


Fig. 4: Comparison between the HUDF luminosity function for B-band dropouts (Bouwens et al 2007), the Steidel et al luminosity function for Lybreak galaxies, and the population of faint  $Ly\alpha$  emitters, with a projected "continuum magnitude" based on the (debatable) assumption that the  $Ly\alpha$  luminosity is a faithful measure of star formation, together with the Madau et al 2000 calibration for the star formation rate as a function of UV luminosity. Our faint emitters are roughly as numerous as the B-dropouts in the HUDF.

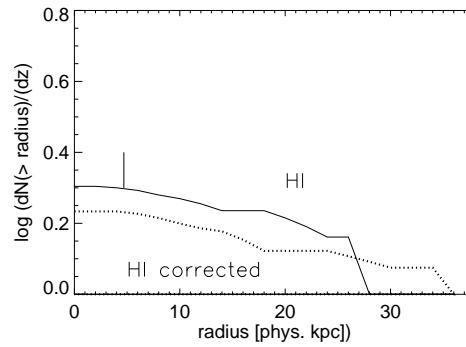


Fig. 5: Contribution of objects of different sizes to the rate of incidence per unit redshift,  $dN/dz$ , for HI (solid line). The cumulative value, corrected for slit losses and finite sizes, is similar to the  $dN/dz = 0.26$  for DLAS at the same redshift.

6. Experience of the applicants with telescopes, instruments and data reduction

The applicants have had observational experience with all major telescopes worldwide and have comprehensive skills in spectroscopic data analysis. Co-I Rauch is a former support astronomer for FORS and UVES. We have recently successfully analyzed observations of a different field with the same instrumental set-up and to similar depth, demonstrating that the approach works, and that we can indeed obtain and reduce data limited largely by the photon noise from the sky background. We have shown that the technique can find large numbers of emission line objects at unprecedentedly faint flux levels. Figures 1 and 2 show the results for such an analysis for a different field with the same instrumental set-up requested here.

7. Resources available to the team, such as: computing facilities, research assistants, etc.

Within the collaboration sufficient resources and expertise to deal with all aspects of the data analysis, interpretation and modelling of the results are available. We have recently successfully analysed observations of a different field with the same instrumental set-up and submitted the results of the analysis for publication within twelve months of the end of data acquisition.

8. Special remarks:

Due to the extended nature of the Ly $\alpha$  emission (median diameter  $\sim 6''$ ) we can tolerate bad seeing. Our previous program LP173.A-0440 where we have observed a different field with the same instrumental set-up has served successfully as a back-up program for bad seeing in periods 73/74 and 76/77.

## 9. Justification of requested observing time and lunar phase

**Lunar Phase Justification:** Dark time is essential. We are sky-background limited and try to see ultrafaint objects at a surface brightness never reached before by spectroscopic observations prior to our previous project.

**Time Justification: (including seeing overhead)** During our previous deep survey 120 hours in total yielded about 95 hours (92 hours of useful non-fragmented exposures) of on-source exposure time, and gave a surface brightness detection limit of  $8 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ . That value resulted in 27 emitters with a rate of incidence per unit redshift  $dN/dz$  similar to that of damped Ly $\alpha$  systems. To probe a similar  $dN/dz$  again in the HUDF, given the steeply rising luminosity function, and to make the fields useful as mutual control fields, we need at least the same number of hours.

**Calibration Request:** Standard Calibration

## 9b. Convert to a normal programme?

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

We have conducted a long slit search for low-surface brightness Lyman  $\alpha$  emitters at redshift  $2.67 < z < 3.75$ , which has been completely reduced and analyzed. A paper describing the analysis of the data and the interpretation of the newly discovered population of 27 faint emission line objects is submitted to ApJ. Further papers describing the analysis of the faint objects showing continuum emission and on the improved limits on the amplitude of the metagalactic UV background are in preparation.

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

Rauch M., Haehnelt M.G., Bunker A., Becker G., Marleau F., Graham J., Cristiani S., Jarvis M.J., Lacy C., Morris M., Peroux C., Theuns T. : A population of Faint Extended Line Emitters and the Host Galaxies of Optically Thick QSO Absorption Systems, 2007, ApJ, submitted will appear on astro-ph once accepted, submitted version available at <http://www>.

Bunker A., Stanway E., Ellis R., McMahon R., Eyles L., Lacy M.: Galaxies in the First Billion Years: Implications for Reionization and the Star Formation History at  $z \leq 6$ , 2006, NewAR, 50, 422

Peroux C., Dessauges-Zavadsky M., D'Odorico S., Kim T.-S., McMahon, R.G.: A homogeneous sample of sub-damped Lyman  $\alpha$  - III. Total gas mass  $\Omega_{HI+HeII}$  at  $z > 2$ , 2005, MNRAS, 363, 479

Le Delliou M., Lacey C., Baugh C. M., Guiderdoni, B., Bacon R., Courtois H., Sousbie T., Morris, S. L.: The abundance of Ly $\alpha$  emitters in hierarchical models, 2005, MNRAS, 356, 1191

Haehnelt, M. G., Steinmetz, M., Rauch, M.: Damped Lyman  $\alpha$  Absorber and the Faint End of the Galaxy Luminosity Function at High Redshift, 2000, ApJ, 534, 594

## 12. List of targets proposed in this programme

Run	Target/Field	$\alpha$ (J2000)	$\delta$ (J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	HUDF	03 32 39	-27 47 29.1	60.0	-			
B	HUDF	03 32 39	-27 47 29.1	60.0	-			

**Target Notes:** We are targeting the HUDF to take advantage of the deepest existent broad band continuum imaging data. The precise location and orientation of the slit will be chosen such as to minimize bright objects on the slit.



12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (<http://archive.eso.org>)? If yes, explain why the need for new data.

No

### 13. Scheduling requirements

### 14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
81	FORS2	A	LSS	1400V
82	FORS2	B	LSS	1400V