Hunting for the Building Blocks of Galaxies like our own Milky Way with FORS

Martin G. Haehnelt[1]
Michael Rauch[2]
Andrew Bunker[3]
George Becker[2]
Francine Marleau[4]
James Graham[5]
Stefano Cristiani[6]
Matt J. Jarvis[7]
Cedric Lacey[8]
Simon Morris[9]
Celine Peroux[10]
Huub Röttgering[11]
Tom Theuns[9]

[1] Institute of Astronomy, Cambridge, United Kingdom
[2] Observatories of the Carnegie Institution of Washington, Pasadena, USA
[3] Anglo-Australian Observatory, Epping, Australia
[4] Spitzer Science Center, Caltech, Pasadena, USA
[5] University of California, Berkeley, USA
[6] Osservatorio Astronomico di Trieste, INAF, Italy
[7] Centre for Astrophysics, Science & Technology Research Institute, University of Hertfordshire, Hatfield, United Kingdom
[8] Institute for Computational Cosmology, Department of Physics, University of Durham, United Kingdom
[9] Department of Physics, University of Durham, United Kingdom
[10] Observatoire Astronomique de Marseille-Provence, France
[11] Leiden Observatory, the Netherlands

We report results from our ultra-deep spectroscopic survey for low surface brightness Lyα emitters at redshift $z \sim 3$. A 92-hour-long exposure with the ESO VLT FORS2 instrument has yielded a sample of 27 faint line emitters with fluxes of a few times 10^{-18} erg s^{-1} cm^{-2} which we argue are likely to be dominated by Lyα. The large comoving number density, the large covering factor, $dN/dz \sim 0.2$–1, and the spatially extended surface brightness of the emission suggest that the emitters can be identified with the elusive host population of damped Lyα systems (DLAS) and high column density Lyman limit systems. The finding suggests that most Lyman limit systems and DLAS are part of the same low-mass galaxies.

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 Lyα 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 Lyα systems 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 broadband continuum ('Lyman break') features (e.g. Steidel & Hamilton, 1995). These searches yielded massively star forming galaxies where, ironically, the expected Lyα emission was often highly suppressed because of dust absorption. With the advent of 10-m-class telescopes, narrowband surveys for Lyα line emission finally reached sufficient depth, discovering considerable numbers of galaxies with large Lyα 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 Lyα line emission (down to typical narrowband limiting fluxes of a few × 10^{-18} 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 damped Lyα systems (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, 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, DLA host galaxies have remained largely elusive at high redshift. The attempt to identify individual DLA with galaxy counterparts has usually been frustrated by the difficulty of detecting an extremely faint object (the DLA host) next to an extremely bright object (the QSO). Searches (e.g. Warren et al., 2001, Christensen et al., 2006) have so far produced only a handful of confirmed detections of the underlying galaxies. Such efforts indicated that DLA hosts at high redshift are generally drawn from the very faint end of the general galaxy population at high redshift (Møller et al., 2002), giving support to the idea that DLAS host galaxies have rather low masses (Haehnelt, Steinmetz & Rauch, 2000), albeit with a considerable gas cross-section.

A search for faint Lyα emitters and a surprising discovery

We report here on the results of an ultra-deep, spectroscopic blind survey for low-level Lyα emission using FORS2 on the VLT (Large Programme 173.A-0440). The original motivation was to search for fluorescent Lyα emission from the optically thick part of the gaseous cosmic web (Lyman Limit systems 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 Lyα photons. For this purpose we obtained a FORS2 spectrum of a basically blank piece of sky with the 7′ × 2″ slit exposed for 92 hours (120 hours including overheads).

The field contained a moderately bright QSO and was observed during 2004–2006 with the volume-phased holographic grism 1400 V on FORS2. The resulting 2-dimensional spectrum is shown in Figure 1 with the spatial direction shown vertically and the spectral direction shown horizontally. The spectrum ranges from 4457 to 5776 Å. Despite the long exposure time we were able to reach the sky noise limit and the surface brightness detection limit for line photons of our spectrum is an unprecedented 8×10^{-20} erg cm^{-2} s^{-1} arcsec^{-2}.

We had expected to detect about 30 optically thick patches fluorescing at very low light levels in Lyα with a median

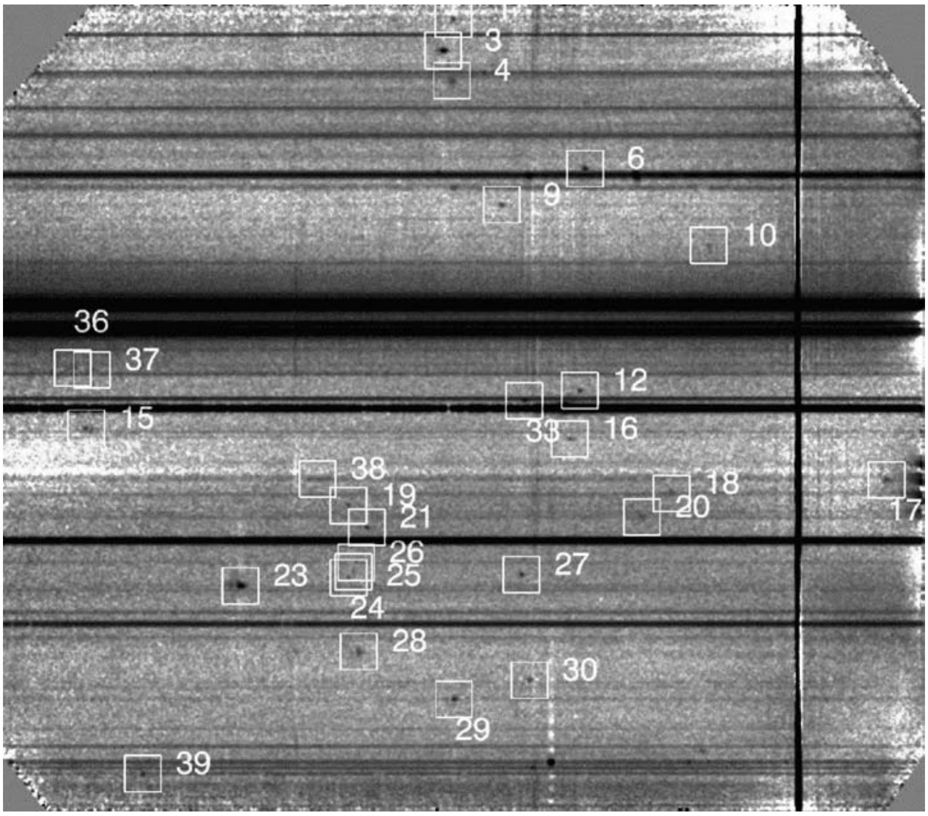

Figure 1. Two-dimensional spectrum obtained in 92 hours of exposure time with FORS2 at the VLT. The line emitter candidates for H I Lyα are enclosed by the numbered boxes. The dispersion direction is horizontal, with blue to the left and red to the right; the spatial direction along the slit is vertical. The figure is adapted from Rauch et al. (2008).

diameter of 5 arcsec. The expected large spatial extent meant that we could accept observing time in periods of moderate seeing for which there is substantially less demand.

However, as we will describe below, theoretical estimates of the UV background intensity had gone down during the project, and so we were probably somewhat short of the signal-to-noise ratio required to detect the fluorescent (re-) emission of the meta-galactic UV background from optically thick regions in a blank field. We nevertheless found 27 single-line emitters on the slit, however with total fluxes typically a factor five to ten higher than our revised expectations for the signal from fluorescence alone. We also detected a number of low-redshift line-emitting interlopers by their [O II], [O III], and H I Balmer series emission.

Figure 2 shows a mosaic of the 27 single-line emitters. Many emitters are considerably extended in wavelength and real space, suggesting the importance of radiative transfer in shaping the appearance of the objects and thus an identification as Lyα line. The detectable emission often extends to 'radii' as large as 4 arcsec.

What are the faint spatially extended line emitters?

For the 27 single-line emitters – at least in principle – [O II], [O III] and Lyα are all possible identifications. Obviously the different interpretations differ drastically in the inferred range of redshift, luminosity and star formation and most crucially in the inferred space density (see Table 1).

In a publication to appear in the ApJ (Rauch et al., 2008), we argue in considerable detail that most of the emitters are likely to be Lyα at redshift $z \sim 3.2$. Our main argument concerns the inferred space densities. With an identification as Lyα, the inferred space density is approaching the total space density of local dwarf galaxies as faint as $M_R = -13$. If the emission were instead due to [O II] or [O III], the corresponding space density would be larger than the space density of local dwarf galaxies by factors 6 and 100, respectively. From a statistical point of view, most of the 27 single-line emitters should thus indeed be Lyα. This interpretation is supported by the typical asymmetric shape of many of the emitters and the fact that we have also detected the expected number of [O II] emission line doublets.

A steeply rising faint end of the luminosity function of Lyα emitters

Even though the inferred space densities are smallest if the line emission is identified as Lyα, the resulting space density still implies a significant steepening of the luminosity function of Lyα emitters below flux levels reached by previous surveys. In Figure 3 we compare the cumulative luminosity function inferred from our 27 line emitters (neglecting slit losses) with the luminosity function from published surveys. Due to the spectroscopic nature of our survey and the long exposure time, we reach more than a factor 10 lower flux levels. There is good agreement in the overlap region at the bright end. Towards fainter magnitudes the luminosity function appears to steepen significantly.

Physical origin of the line emission

An identification of the emission as Lyα raises the question of the potential emission mechanisms. We will briefly consider three possibilities here: fluorescent (re-) emission of the meta-galactic UV background; gas cooling; and emission due to the formation of (massive) stars. As already discussed, the original aim of our project was to detect fluorescent emission from optically thick regions. For this purpose we further increased our sensitivity by stacking the individual spectra of our emitters. In Figure 4 we compare the result of this stacking analysis to our expectation for the fluorescent emission (see Rauch et al. (2008) for more details). The points with error bars and open squares show our measurements of the mean and median surface brightness

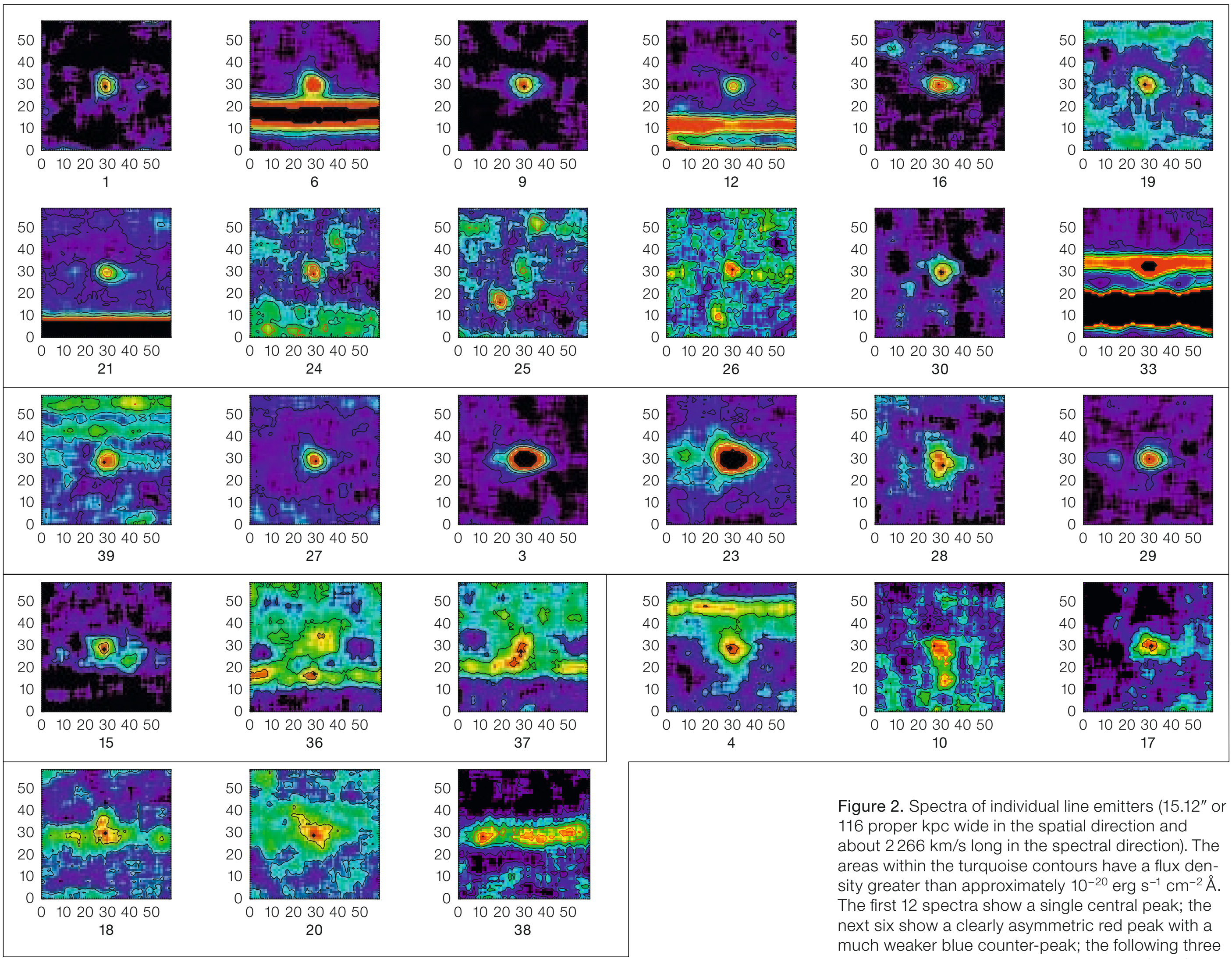

Figure 2. Spectra of individual line emitters (15.12″ or 116 proper kpc wide in the spatial direction and about 2 266 km/s long in the spectral direction). The areas within the turquoise contours have a flux density greater than approximately 10^{-20} erg s^{-1} cm^{-2} Å. The first 12 spectra show a single central peak; the next six show a clearly asymmetric red peak with a much weaker blue counter-peak; the following three either have a stronger blue than red peak (ID 15) or emission features blueward of an absorption line (36, 37); the remaining six spectra are unclassifiable. The figure is adapted from Rauch et al. (2008).

as a function of angular distance from the centre of emission along the slit, respectively. The dotted curves give the range of the expected surface brightness for the fluorescent (re-) emission of the metagalactic UV background based on recent measurements of photo-ionisation rate of the Intergalactic Medium at $z \sim 3$. The predictions for the Lyα fluorescence are a factor two to four lower than the measured surface brightness of our line emitters in the stacking analysis.

The spectral line shapes and sizes of our emitters suggest that the Lyα photons have been processed by radiative transfer through an optically thick medium. In principle, the Lyα radiation could be produced by the cooling of gas in galactic haloes. However, as we argue in detail in Rauch et al. (2008), this may be true for a few of our objects but not for the majority. The reason is that the observed Lyα luminosity is too high to be consistent with the observed high space density and the implied low masses of the underlying haloes. This leaves Lyα radiation from centrally concentrated formation of (massive) stars, resonantly scattered in an optically thick galactic halo, as the most

	[O III]	[O II]	Lyα
Redshift [z]	0–0.15	0.2–0.55	2.67–3.75
Luminosity [h_{70}^{-2} erg s^{-1}]	2×10^{36} -3×10^{38}	3.7×10^{38} -2×10^{40}	7.9×10^{40} -1.6×10^{42}
Star-formation rate [h_{70}^{-2} $M_{\odot}$ yr^{-1}]		5×10^{-3} -0.3	7×10^{-2} -1.5
Space density [h_{70}^{3} Mpc^{-3}]	9	0.5	3×10^{-2}

Table 1. Properties of line emitters for different possible identifications.

promising remaining emission mechanism.

Have we discovered the host galaxies of DLAS?

As discussed above the difficulties in finding the host galaxies of DLAS, as well as theoretical models within the ΛCDM paradigm for structure formation, suggest that DLA host galaxies are fainter and more numerous than typical Lyman break galaxies. Unfortunately, absorption line studies only constrain the total incidence rate, which depends on the product of space density and cross section for absorption. With our spectroscopic survey we have measured the space density and the size of the objects. We can thus predict the expected rate of incidence for absorption by the emission regions of our putative population of faint spatially extended Lyα emitters. In Figure 5 we show this incidence rate as a function of the measured 'radius' of our emitters. The cumulative rate of incidence is very similar to that of DLAS, suggesting that we may indeed have discovered a substantial part of the elusive population of DLA host galaxies.

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 would allow us to unambiguously identify each individual case as a high redshift galaxy. Knowledge of the continuum will also give us a more reliable measure of the star-formation rate and provide constraints on the morphology of these galaxies – it will tell us what these objects really are. Unfortunately, the expected continuum emission is very faint. In Figure 6 we compare the cumulative UV continuum luminosity function of Lyman break galaxies in the Hubble Ultra-Deep Field (HUDF) with those predicted for our line emitters assuming a rest-frame EW of 70 Å. The space density of our line emitters is similar to those of the faintest Lyman break galaxies in the HUDF (Bouwens et al., 2007).

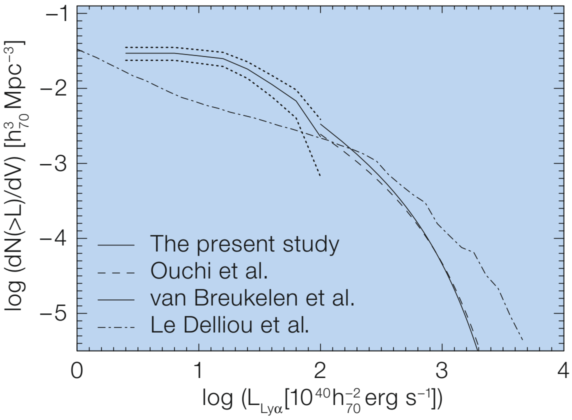

Figure 3. Observed cumulative luminosity function at $z = 3.1$ from Ouchi et al. (2007; dashed curve), $z = 2.9$ from van Breukelen et al. (2005; dash-triple dotted curve) and our sample (solid curve, dotted curves represent 1σ error contours). The dot-dashed curves are theoretical predictions. From Rauch et al. (2008).

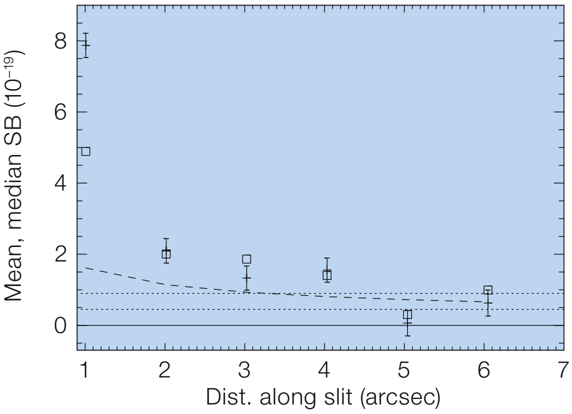

Figure 4. Mean (points with error bars) and median (open squares) surface brightness measurements in units of 10^{-19} erg cm^{-2} s^{-1} arcsec^{-2} for the combined surface brightness profiles, as a function of angular distance in arcsecs from the centre of emission along the slit. The dotted curves give the range of the expected surface brightness based on the photo-ionisation rate of the $z \sim 3$ Intergalactic Medium. The upper dotted curve is for a QSO type UV spectrum, the bottom curve for a spectrum where 50 % of the flux is contributed by galaxies. The dashed curve is the 4σ surface brightness detection threshold for individual objects. From Rauch et al. (2008).

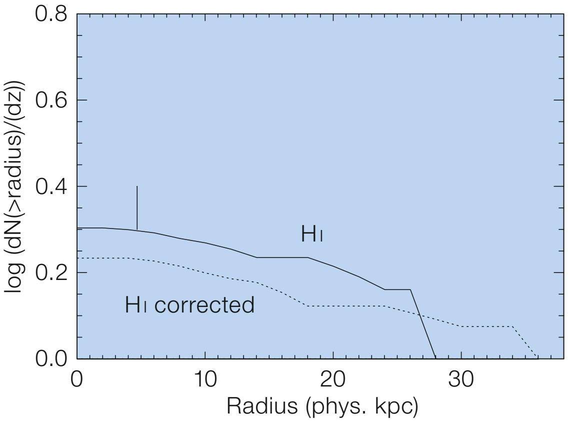

Figure 5. Contribution of objects of different sizes to the predicted rate of incidence per unit redshift, dN/dz for H I with (dotted line) and without (solid line) correction for the extended sizes and our underestimating the radius. The short vertical line on top of the uncorrected curve indicates the spatial resolution limit along the slit. From Rauch et al. (2008).

The next step

The similarity of the space density of our emitters to that of the Lyman break galaxy population at the faint end of the UV continuum luminosity function in the HUDF is tantalising, but circumstantial, evidence that these may be the same objects, once seen by their centrally concentrated continuum and once by their spatially extended Lyα emission. The most efficient way for testing this hypothesis, and for constraining further the fractions of true Lyα emitters and interlopers, would be to repeat our ultra-deep spectroscopic survey in the HUDF. This should be considered a modest investment of (moderate seeing!) observing time in return for substantial progress in understanding the formation of typical present-day galaxies like our Milky Way.

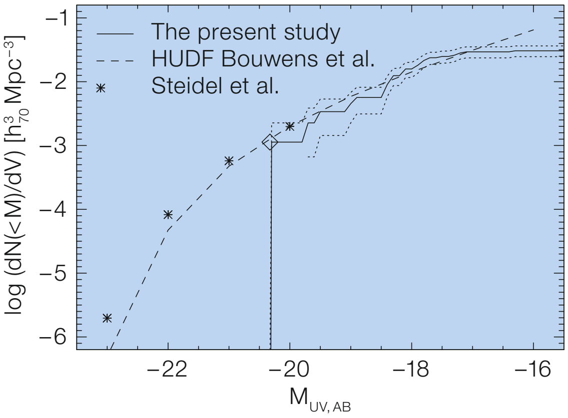

Figure 6. Cumulative UV continuum luminosity functions of Lyman break galaxies and the cumulative distribution of our survey (solid line; dotted lines are ±1σ errors). The emitters are assumed to have a continuum magnitude predicted by their Lyα line flux assuming a rest-frame equivalent width of 70 Å. From Rauch et al. (2008).

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Colour-composite image of a triplet of galaxies which make up part of the Hickson Compact Group HCG 90. The galaxies in the image are NGC 7173 (north), 7174 (south-east) and 7176 (south-west); the image orientation is north up, east to the left and the size is about 5.3 arcminutes. The image is based on data obtained with VLT FORS1 with *B*, *V*, and *R* filters. NGC 7173 and 7176 are elliptical galaxies, while NGC 7174 is a spiral galaxy with a disturbed dust lane. See ESO PR Photo 02/08 for more details. Image processing by Henri Boffin (ESO).