Surveying the High-Redshift Universe with the VIMOS IFU

Matt J. Jarvis[1]
Caroline van Breukelen[1, 2]
Bram P. Venemans[2]
Richard J. Wilman[3]

[1] Astrophysics, Department of Physics, Oxford, United Kingdom
[2] Sterrewacht Leiden, The Netherlands
[3] Department of Physics, University of Durham, United Kingdom

We present results from a new method of exploring the distant Universe. We use 3-D (integral-field) spectroscopy to sample a large cosmological volume at a time when the Universe was less than 3 billion years old to investigate the evolution of star-formation activity in the Universe. Within this study we also discovered an obscured accreting black hole at high redshift which would not have been identified with imaging studies alone. This highlights the crucial role that integral-field spectroscopy may play in surveying the distant Universe in the future.

Hunting for high-redshift galaxies

The way in which galaxies form and evolve, along with the stars they contain, are crucial processes to investigate if we are to understand how the structure we see in the Universe today builds up over cosmic time. For many years this has been the forte of deep multi-colour imaging observations, which have been used to find and investigate galaxies in the distant Universe. This technique utilises the characteristic break in the continuum of a galaxy below the Hydrogen Lyα emission line at 121.6 nm and the Lyman-limit at 91.2 nm. Redward of these characteristic wavelengths, a galaxy will be observed to have a bright continuum, and observing the same patch of sky with a shorter wavelength filter, which lies below the continuum break wavelength, a galaxy will be much fainter and possibly not detected at all. Therefore large samples of candidate high-redshift galaxies can be constructed in this way over large areas. After catalogues of such objects have been built up, follow-up long-slit or multi-object spectroscopy is usually the next step to confirm redshifts and to gain a census of galaxies in the high-redshift Universe.

A further technique which has come to fruition over the past decade, with the onset of 8- and 10-metre-class telescopes, is that of narrow-band imaging. This method selects galaxies with strong emission lines at distinct distances, where the bright emission lines are redshifted into a filter which has a typical width of 5–10 nm. This essentially means that the imaging instrument acts as a very coarse spectrograph with 5–10 nm resolution. There are now many fields which have been targeted with this technique, most notably the deep narrow-band survey to target Lyα emitting galaxies at $z = 3.1$ (Steidel et al. 2000) which went on to find a new class of object – that of giant Lyα nebulae which are not associated with powerful active galactic nuclei. Other important surveys using the narrow-band technique have been those which target powerful radio sources at high redshift. These have yielded the detection of overdensities of Lyα emitting galaxies at redshifts above 2. Blank-field searches have also yielded the detection of large numbers of Lyα emitters at $z = 5.7$ (Ajiki et al. 2003) and one of the highest redshift galaxies known to date at $z = 6.6$ (Hu et al. 2002). However, similar to the multi-colour method highlighted above, this technique also requires follow-up spectroscopy to confirm the Lyα emitting candidates.

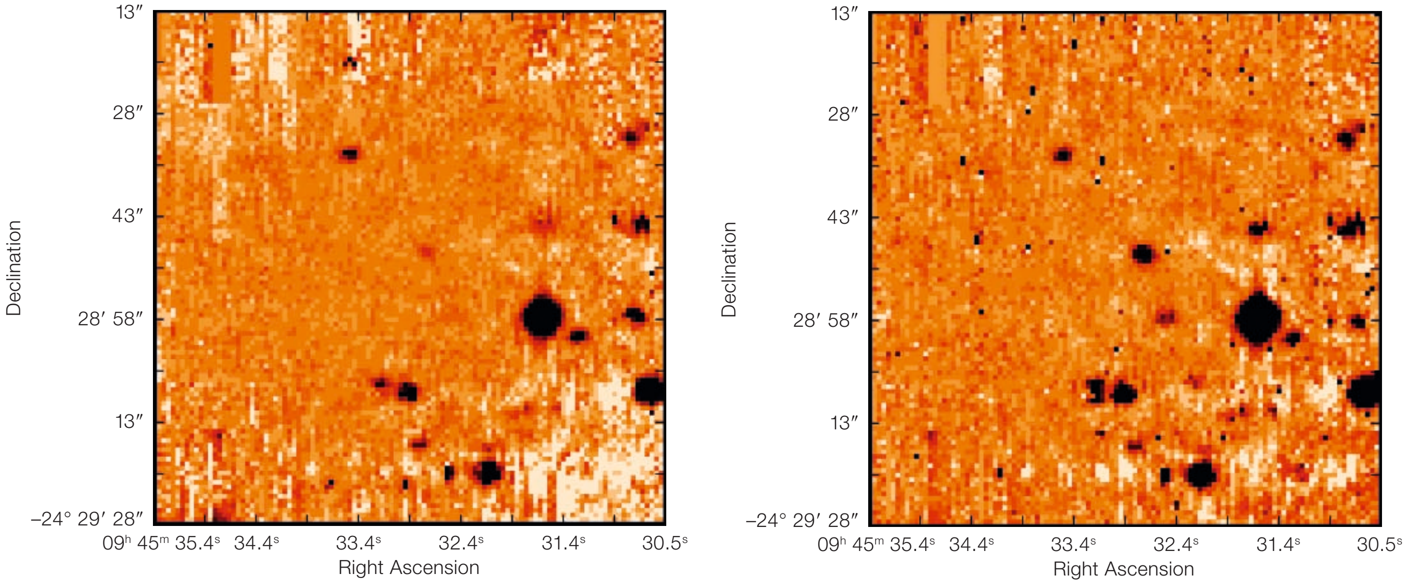
It would obviously be extremely useful if one could combine the imaging and spectroscopy into a single observation, which would not only overcome the various biases inherent to colour selected samples but would also expand on the narrow redshift ranges which one can probe with narrow-band searches. We are now entering an era in astronomy where this is achievable. In this article we describe the first results from a deep, large volume search for emission-line galaxies with the Visible Multi-Object Spectrograph (VIMOS) on the ESO-VLT (*http://www.eso.org/instruments/vimos/*).

As well as being a large multi-object spectrograph, VIMOS can also be used as a "large-area" integral-field unit (IFU). The idea behind an IFU is to obtain continuous coverage of a field in three dimensions, i.e. two spatial dimensions and a third spectral dimension. This is analogous to taking a number of long-slit spectra side-by-side all in one observation. Integral-field observations are therefore able to provide an immediate 3-dimensional view of structure in the Universe. The range of scales these IFUs may probe is from stellar populations in nearby galaxies to the furthest reaches of the observable Universe. In this article we highlight the intriguing possibilities that large-area IFUs offer with respect to volume-limited surveys of the high-redshift Universe.

A deep VIMOS IFU field and the star-formation history of the Universe

We initiated a pilot project with a deep, nine-hour, VIMOS observation centred on the high-redshift radio galaxy MRC0943-242 at a redshift of $z = 2.92$ in April 2003. The aims of this project were to probe the giant-Lyα emitting halo surrounding this source and the distribution of galaxies within the volume probed by the IFU. Figure 1a shows the reconstructed "broad-band" (i.e. with the spectral direction collapsed over all frequencies) image of the radio galaxy field. The central radio galaxy can easily be seen in the centre of the image. However, the only other sources visible in this broad-band representation are all relatively bright. Conversely, as can be seen in Figure 1b, if we now integrate over the spectral region where the Lyα line is seen in the radio galaxy spectrum [i.e. 121.6 nm $\times (1 + z)$], the radio galaxy becomes much brighter. This highlights the benefit of the integral-field approach when hunting for galaxies with bright emission lines at all redshifts. If we now split this data set up into finer bins in wavelength then we are able to detect all the galaxies with bright emission lines over the whole volume. For Lyα emission this range is $2.3 < z < 4.6$, and for [O II] emission at a rest-frame wavelength of $\lambda = 372.7$ nm, we probe $0.08 < z < 0.83$. Therefore we can search for emission-line galaxies over a large fraction of cosmic volume along the sightline of the IFU (e.g. for [O II] and Lyα emitters we probe ~ 50 % of cosmic time since the Big Bang over the 1.2 square arcminute field-of-view).

Figure 1: (a) The two-dimensional image of our IFU field of view, integrated from 405–680 nm. (b) The same image integrated from 470–500 nm. The noisier regions in the corners of the images are due to a dither pattern used in the observations to enable accurate sky subtraction and bad pixel rejection, therefore the corners have had slightly less exposure time than the central, least noisy, region.



In order to achieve this we construct a sensitivity map across the whole field and search for peaks in the clean parts of the optical spectrum, i.e. those regions devoid of bright sky lines and also where characteristic problems associated with the optics within the IFU are at a minimum. This is carried out by fitting a polynomial to the spectra at all points over the field and detecting all of those peaks in the spectra which deviate significantly from the noise estimates in each spectrum and each region within that spectrum.

This process enabled us to detect 17 emission-line objects over the volume probed with the IFU. These are predominantly single line objects, and for 14 all of the characteristics point to them being hydrogen Lyα emission-line galaxies (two others are [O II] emitters and the third is the type-II quasar discussed later in this article), we will now concentrate on these Lyα emitters. Lyα emission is produced by massive stars photoionsing hydrogen gas. By using some simple assumptions it is possible to estimate the star-formation rate in galaxies which exhibit Lyα emission by measuring the luminosity of the emission line. Although undoubtedly crude, this does at least produce a lower limit for the star-formation activity in distant galaxies. If we now bin all of the Lyα luminosities in the volume then we are able to construct the Lyα emitter luminosity function, i.e. the number density of emitters at a given luminosity per unit volume. Construction of the luminosity function is a non-trivial task for this type of data because those galaxies with bright emission lines can be seen to much greater distance in the volume covered in our data, thus the volume probed is a strong function of the luminosity of the emission lines. Therefore, the luminosity-dependent volume is measured using the sensitivity function of the data cube.

Figure 2 shows the Lyα luminosity function derived from this study compared to the luminosity function measured from narrow-band studies and multi-colour selection. One can see that our luminosity function, which probes the redshift range $2.3 < z < 4.6$ extends the work of the narrow-band searches to fainter luminosities where the luminosity function keeps the same Schechter function form over redshifts up to $z \sim 6$. This implies that there is little evolution in the star-formation rate density over this redshift range, although small number statistics preclude strong statements regarding any evolution.

As stated above, knowledge of the luminosity of the Lyα emission line in these galaxies gives information on the total star-formation rate. Using typical assumptions of hydrogen recombination the star-formation rate is given by,

$$\mathrm{SFR} = 9.1 \times 10^{-36}\,(L_{(\mathrm{Ly}\alpha)} / \mathrm{W})\ M_{\odot}\mathrm{year}^{-1}.$$

By integrating over the Lyα luminosity function we are therefore able to measure the star-formation rate at the redshifts covered by our data. This plot, along with the star-formation rate density derived by other methods, is shown in Figure 3, for $0 < z < 6$. Due to the fact that Lyα can be resonantly scattered and absorbed by neutral hydrogen around the source, the measured SFR from studies using Lyα are hard lower limits. Also, the presence of dust preferentially extinguishes the UV continuum emission, therefore even multi-colour searches are prone to biases which work to reduce the estimated SFR. Therefore, we also show the estimated star-formation rate corrected for obscuration. With this correction in place it is apparent that our IFU search is in line with previous studies conducted in a number of different ways. However, the benefit of using the integral-field approach is that we select sources at all redshifts in our volume in precisely the same way, thus reducing the biases involved in comparing studies at different redshifts from different surveys, which may utilise different techniques.

Further it is also worth mentioning that the choice of field, i.e. one containing a powerful radio galaxy at $z = 2.92$, does not bias the results in any way. Our data contains only one Lyα emitter at the redshift of the radio galaxy. This is principally due to the small area probed by the IFU. However we can quantify how many we would expect in our data at this redshift, given the typical overdensities of emitters found in narrow-band searches around powerful radio galaxies. In their study of Lyα emitters around the powerful radio galaxy TN J1338-1942 at $z = 4.1$, Venemans et al. (2002) showed that the overdensity of emitters was a factor of ~ 15 more than one would expect in a blank-field search. Using this fact we would expect to find of order one object within $\Delta z = 0.004$ of the radio galaxy. In the IFU data cube we find one object at a distance of $\Delta z = 0.002$. Thus although in agreement with the expected overdensity for a protocluster, the poor number statistics arising from the relatively small field-of-view of the IFU, precludes any strong statement about the clustering of Lyα emitters around the radio source. However, we do find what seems to be an excess of Lyα emitters at $z \sim 2.5$, where there are three emitters within $\Delta z = 0.04$ of each other. This leads us to believe there may be a probable high-redshift cluster at this redshift, although there is no known powerful AGN in the vicinity. However, deep, wider-field observations are needed to confirm this.

Discovery of a type-II quasar in the IFU deep field

In this section we discuss the way in which our integral-field data has also led to the discovery of two Active Galactic Nuclei (AGN) in the volume probed, in addition to the radio galaxy which was targeted. One of these is a "normal" unobscured type-I quasar with broad emission lines and an unresolved morphology on optical images at a redshift of $z = 1.79$. However, the other AGN exhibits only narrow-emission lines (Figure 4) and has a resolved morphology in the optical image.

From radio surveys we know that there are at least two populations of powerful radio-loud AGN, radio-loud quasars (RLQs) and radio galaxies (RGs). Under the model for the unification of AGN, this difference is dictated solely by the orientation of the AGN with respect to our line-of-sight, where the presence of a dusty torus surrounding an accreting supermassive black hole may obscure our view to the nucleus. RLQs are the unobscured type-I population where our view to the nucleus is through the opening in the torus, and we see the unresolved nucleus and the high-velocity clouds (v > 2 000 km/s) of gas which surround it. Whereas for radio galaxies, the torus lies along our line of sight obscuring our view to the central engine, these are type-II AGN and we only see the low-velocity, narrow forbidden (v < 2 000 km/s) emission lines. Moreover, there is also a population of radio-quiet quasars which outnumber their radio-loud counterparts by a factor of ~ 10. These are relatively easy to find due to the fact they exhibit a characteristically very blue continuum and appear as unresolved point sources in imaging surveys. By simple methodology there should also be a large population of radio-quiet obscured AGN. This can also be inferred from models of the X-ray background, where the universal hard X-ray emission cannot be accounted for unless there is a large population of obscured AGN at high redshift.

These type-II AGNs are relatively difficult to find compared to the type-I counterparts. This is principally due to the fact that type-II AGN look like normal galaxies, and it is only by looking for other signatures of AGN activity, which do not suffer from extinction due to the torus, they can be found, e.g. X-rays from the central engine which penetrate the torus, radio emission from powerful jets or reprocessed dust emission in the mid-infrared from the torus itself. However, with the integral-field approach we are sensitive to the bright narrow-emission lines that are characteristic of an obscured AGN, as we obtain the spectrum of any object in the IFU field immediately.

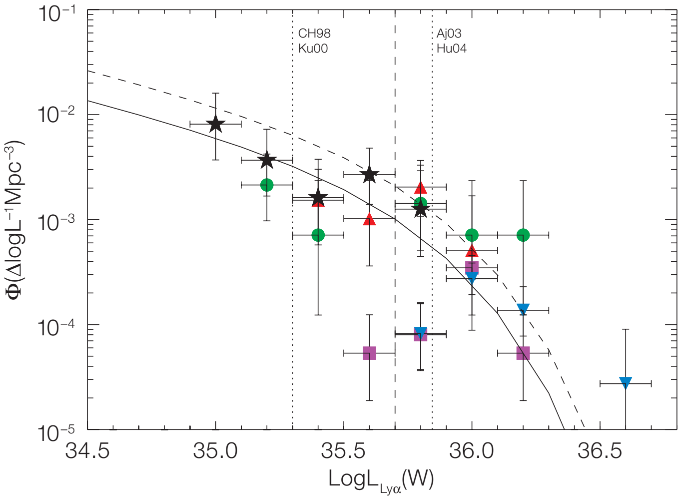
J094531-242831 (hereafter J0945-242) exhibits these bright narrow-emission lines, in the C IV doublet ($\lambda\lambda$ = 154.8 nm, 155.1 nm), He II (λ = 164.0 nm) and C III] (λ = 190.9 nm), all characteristic of a type-II AGN. The radio map shows that there is no radio emission down to a radio flux limit of 0.15 mJy at 5 GHz. At a redshift of $z = 1.65$ this is significantly below the typical luminosity of a radio galaxy, thus we confirm that this is a genuine radio-quiet type-II quasar. The line luminosity ratios of the C IV, He II and C III] lines are also consistent with the ratios for radio galaxies, and not the generally lower-luminosity Seyfert-I galaxies and the unobscured quasars. Using these line luminosities it is possible to estimate the lower mass limit of the accreting black hole in the centre of this galaxy. We assume the typical line ratios of radio galaxies to convert the He II luminosity to a line luminosity in [O II], which is correlated with the total bolometric luminosity of the AGN. Under the assumption that the quasar is accreting at its maximum rate, i.e. the Eddington limit, then this bolometric luminosity equates to a black-hole mass of 3×10^8 $M_{\odot}$.

In the local Universe there is now a well-known correlation between the mass of black holes and the luminosity of their host galaxy (see e.g. Magorrian et al. 1998). The near-infrared *K*-band (2.2 μm) magnitude of J0945-242 is very faint, with K = 20.5. Radio galaxies at $z = 1.65$ typically have host galaxy luminosities of K ~ 18. Thus the host galaxy of J0945-242 appears to be 2.5 mag (or a factor of 10) fainter than that for a typical radio-loud type-II AGN. If this faintness of the host galaxy is caused by extinction from dust then we would expect the blue end of the galaxy spectrum to be fainter, as dust attenuates the blue light more readily than at red wavelengths. However, the host galaxy of J0945-242 is extremely blue, indicative of ongoing star formation. Therefore, the faintness in the *K*-band light indicates that the host galaxy has a dearth of old, massive stars, which in turn implies that the galaxy is not yet fully formed at $z = 1.65$. Whereas the black hole has already grown, presumably by accretion of matter, close to its final mass due to the fact that the low-redshift black-hole mass function shows that supermassive black holes appear to have a maximum mass of around 10^{10} $M_{\odot}$.

This relatively large black-hole mass associated with a host galaxy approximately a factor of 10 fainter than what would be expected from the local relation implies that supermassive black holes at high redshift may essentially be fully grown before the host galaxy has fully formed. This is in qualitative agreement with what we already see in high-redshift radio galaxies, where the small, young, radio sources appear to have extremely bright sub-millimetre luminosities. This extremely luminous sub-millimetre emission is due to reprocessed UV light from young stars which has been absorbed by the

Figure 2: The number density of Lyα emitters plotted against luminosity. The filled symbols mark surveys with an average redshift similar to ours (triangles and circles) and the open symbols stand for surveys at redshift $z = 5.7$ (squares and inverted triangles). Overplotted are two Schechter luminosity functions: the solid line is the fit to all our data points and the dashed line is the fit to our two highest luminosity data points and those of the surveys at similar redshift with L > 5 × 1035 W (dashed horizontal line) to ensure completeness. The dotted horizontal lines mark the detection limits of the surveys.

▲ Cowie and Hu 1998
● Kudritzki et al. 2000
■ Ajiki et al. 2003
▼ Hu et al. 2004
★ This project



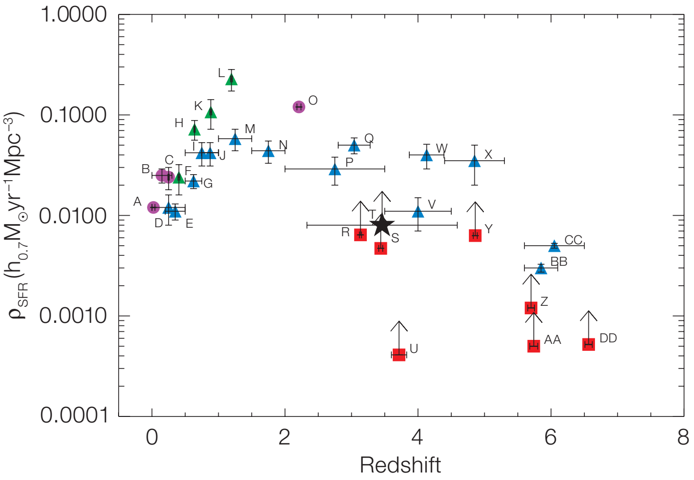


Figure 3 (above): Star-formation-rate densities as derived by various types of surveys. The result from this work is denoted by the filled star derived from integrating over the luminosity function fit to our data alone. The different types of surveys are marked with different symbols: the open circles are Hα searches, the open triangles are surveys aimed at oxygen emission lines, the filled triangles are multicolour surveys, and the open squares are Lyα searches.

● Hα emitters
▲ O-lines
▲ Multi-colour
■ Lyα emitters
★ This paper

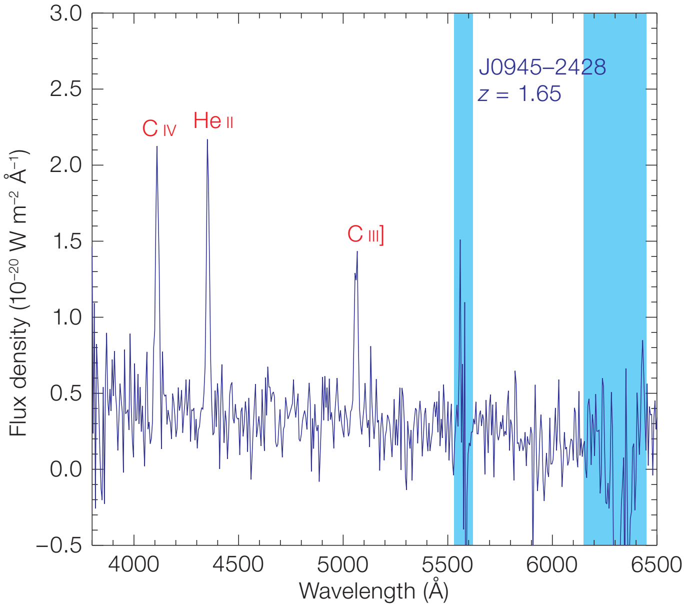


Figure 4 (left): The 1-D spectrum of the type-II quasar, J0945-2428 at $z = 1.65$. The spectrum was extracted over the whole galaxy (seven IFU fibres). The shaded regions show the wavelengths affected by sky-line emission.

large amounts of dust associated with star-forming regions, and re-radiated in the far-infrared. In order to produce these sub-millimetre luminosities, star-formation rates of up to 1000 $M_{\odot}yr^{-1}$ are needed, typical of a galaxy undergoing its first major bout of star-formation activity.

Conclusions

The new method of detecting emission-line galaxies at high redshift along with the serendipitous discovery of an obscured quasar at $z = 1.65$, highlights the way in which relatively wide-area integral-field units on large telescopes can open up a unique window on the Universe. VIMOS is currently the only instrument which has the capability of large spectral coverage coupled with a ~ 1 square arcminute field-of-view. However, future instruments, such as the Multi-Unit Spectroscopic Explorer (MUSE; *http://muse.univ-lyon1.fr*), will expand the initial work taking place in this field with VIMOS. Furthermore, volumetric surveys with IFUs may begin to find types of objects we have yet to discover in traditional surveys, and thus offer a whole new view of the Universe.

Full details of the work presented in this article can be found in van Breukelen, Jarvis & Venemans (2005) and Jarvis, van Breukelen & Wilman (2005).

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