Observing the high redshift universe using the VIMOS-IFU

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Abstract. We describe the advantages of using Integral Field Spectroscopy to observe deep fields of galaxy. The VIMOS Integral Field Unit is particularly suitable for this kind of studies thanks to its large field-of-view (∼ 1 arcmin²). After a short description of the VIMOS-IFU data reduction, we detail the main scientific issues which can be addressed using observations of the Hubble Deep Field South with a combination of Integral Field Spectroscopy and broad band optical and Near-Infrared imaging.

Key words: instrumentation: spectrographs - cosmology: observations – galaxies: evolution – large-scale structure of universe

1. Introduction

Studying high redshift galaxies is one of the main topics that will help in constructing a coherent picture of the physical processes that led to galaxy evolution.

Within the framework of large-scale structure formation, in which small fluctuations of matter density grow under the influence of gravity to form large-scale structures and galaxy halos, physically motivated prescriptions have been used to describe the main processes involved in galaxy formation and evolution (e.g. White & Frenk [1991]; Cole et al. [2000]). Furthermore, perturbation theory and numerical simulations provide useful predictions which can be compared with observations. However, comparing these models to available observations has not been straightforward, and any discrepancy between the predictions and observations could have important impacts on our understanding of some fundamental processes. It is therefore important to perform those comparisons at intermediate and high redshift, as here is where the physical processes of galaxies formation are more visible.

In this paper, we report on the advantages of using Integral Field Spectroscopy (IFS) associated to broad band imaging (optical and near infrared) to observe deep fields compared to classical photometric and spectroscopic observations. It is organised as follows: in section 2 we shortly raise the limitations of the photometric and spectroscopic surveys; in section 3 we describe the advantages of using IFS; in section 4 we describe the VIMOS Integral Field Unit (IFU) and detail the data reduction process; in section 5 we describe the use of VIMOS-IFU to observe the Hubble Deep Field South and the main issues which will follow from those observations. Finally, conclusions are summarised in section 6.

2. Photometric and spectroscopic surveys

As a statistically large number of intermediate and high redshift galaxies is needed to perform comparison between models and observations, some large galaxy surveys were accomplished during the last decade or are under acquisition (e.g. CFRS – Lilly et al. [1995]; CNOC – Carlberg et al. [2000]; DEEP – Davis et al. [2003]; VIRMOS – Le Fèvre et al. [2003b]).

Two complementary kind of surveys exists: the deep multi-colour photometric surveys, such as the VIMOS Deep Imaging Survey (VDIS – Le Fèvre et al. [2003b]; McCracken et al. [2003]) – 4 fields of 4 deg² covered in BVRI bands and a sub-fraction in U and JK’ – and the spectroscopic surveys, such as the VIMOS-VLT Deep Survey (VVDS – Le Fèvre et al. [2003a]) – around 150,000 redshifts acquired on the 4 fields of 4deg² of the VDIS using the VIMOS spectrograph at VLT. Photometric surveys allow to access to a very large amount of objects (more than 2,000,000 for $J_{AB} < 25$ in the case of the VDIS) but with colour informations only ($UBVRI$, plus $JK'$ for a small fraction, in the
case of the VDIS). Those photometric surveys can then be used as reference catalogues for spectroscopic surveys, but even with the new generation of Multi-Object Spectrograph (like VIMOS) only a fraction of the objects can have a spectroscopic follow-up (in the case of the VVDS around 150,000 spectra are acquired).

A way to have all redshifts for those galaxies is to use photometric methods, as the photometric redshifts technique (e.g. Fontana et al., 2000; Bolzonella et al., 2000; Arnouts et al., 2002) or the Lyman-break technique (e.g. Steidel et al., 1999; Ouchi et al., 2001; Foucaud et al., 2003) which are using the multi-colour information to estimate the redshift and the nature of the galaxies. Those techniques can be considered as very low resolution spectroscopy.

To summarise, the large photometric and spectroscopic surveys allow to gather large galaxy samples, but in one case with a poor spectral information and in the other case a poor spatial sampling.

3. Advantages and disadvantages of the 3D spectroscopy

Thanks to Integral Field Spectroscopy (IFS), it is now possible to gain both spectroscopic and photometric information in a given field of view. The IFS is based on a new kind of instrument (Integral Field Unit – IFU) that provide a spectrum for each spatial element (spaxel) thanks to optical fibres and/or micro-lenses and a dispersive element (e.g. Bacon et al., 1995).

The IFU configuration presents a lot of advantages for observing high redshift galaxies. Their identification is free from any selection criteria, such as the a priori selection applied in the photometric and spectroscopic surveys. It does not impose any particular geometry on object sampling and allows to extract spectra over the full object extension, avoiding the slit loss problem faced with conventional spectrographs. Finally IFUs are particularly sensitive to faint slightly extended objects, like low surface brightness galaxies which are difficult to detect and observe with conventional photometry and spectroscopy.

Current generation IFUs are still only able to cover a small field of view, their area coverage being below 1 arcmin$^2$ (c.f. section 4.1). In order to increase the field of view, it is possible mosaicking multiple pointings, but it is still unconceivable to cover areas of the same order as photometric and spectroscopic surveys. Another disadvantage of these instruments is its smaller total efficiency compared to ordinary spectroscopy, which implies a longer integration time to reach the same depth of the ordinary spectroscopic surveys. Anyway these instruments are particularly suited to observe small deep pointings like for instance the Hubble Deep Fields (c.f. section 4.1), even if it is still to be demonstrated that IFUs can produce scientifically relevant results for cosmology and high redshift galaxies.

4. VIMOS Integral Field Unit

4.1. Description of the VIMOS-IFU

The VIMOS instrument installed at the VLT-Paranal telescope U3 works with two configurations: a spectro-imaging multi-object mode and an integral field mode (Le Fevre et al., 2003c). The four spectrographs that compose VIMOS are in common to those two different modes. Each spectrograph is a classical focal reducer imaging spectrograph, with a collimator, a parallel beam where dispersive grisms are inserted, followed by a camera focusing onto a 2048 × 4096 15µm pixels CCD that produce an image for one quadrant. The Mask Support Unit placed at the entrance focal plane of VIMOS allows to position either four Invar masks in the case of the multi-object mode or the four masks of the IFU and then switch from one mode to the other (Bonneville et al., 2003).

The field of the IFU is sampled thanks to a 6400 fibres/lenslets matrix. The output of the fibres are distributed on the four spectrographs through the masks and coupled to each spectrograph thanks to micro-lenses and curved prisms. Two possible spatial resolutions are available thanks to a removable focal elongator placed in front of the IFU head. To obtain high spectral resolution, a motorised shutter can be used to select only the central part of the field in purpose to avoid spectra superposition. The characteristics of the VIMOS-IFU are summarised in table I.

4.2. Reduction of VIMOS-IFU data

The huge amount of data (6400 spectra from each exposure) provided by VIMOS-IFU and the complexity of IFU data, require a fully dedicated automatic data reduction pipeline. In this section we will quickly describe the different steps of the data reduction (part of the data reduction is also developed in Scodeggio et al., 2001).

As 4 images are acquired during each VIMOS exposure (one image for each quadrant), the data reduction is done on single quadrants up to Data Cube reconstruction.

For each frame the first usual steps of bias and flat field corrections are applied. Using those corrected frames the next step is to extract the 2D spectra. As the gap between the fibres is known, this extraction is accomplished automatically starting from a first guess. Wavelength calibration is then applied on each individual 2D spectrum. 1D spectra are then obtained from the 2D spectra by adding together the flux collected by the corresponding optical fibres. As the different fibres have different transmission efficiencies, a fibre relative transmission correction is computed using the spectrum continuum and sky lines. A standard way to compute this correction is to first fit the continuum (by a 2 degrees polynomial) either on a spectrum of twilight sky or better on an image obtained adding the set of images taken within a jitter offset sequence. A further finer calibration can be done after the 1D extraction this time fitting the sky lines (by a gaussian). From those fitted lines their flux is determined and a refined relative normalisation is computed. Then the 1D spectra are to be sky subtracted. To build an estimate of the sky background intensity, it is necessary to identify the pure sky spectra from
the whole spectra set. Using the distribution of total light intensities registered in the various spectra, pure sky spectra are identified as those that have an intensity around the mode of the distribution. Sky spectra are median-averaged together and this spectrum is subtracted from all the 1D spectra.

In the case of several exposure per pointing, jitter offsets are applied between exposures in order to better determine the relative transmission (see above) and ameliorate the combination. Those offsets between exposures are typically of around 4 fibres, i.e. ∼ 2.7 arcsec. Thanks to jitter sequences it is also possible to remove part of the fringing present in the red part of the spectra. This fringing is due to reflection of the sky emission inside the detector and a sigma-clipping medianshing combination of the exposures, without having previously shifted them, helps to eliminate this effect.

The combinations of the final spectra are obtained by medianshing the spectra from the various frames. Usage of the median instead of the mean helps in the case of over-correction for fibre transmission or of sky over-subtraction, as well as with cosmics removal.

To reconstruct a data cube from the 1D spectrum, the correspondence between fibre position on IFU head – which, coupled with world coordinate system, gives fibre position on sky – and spectrum position on detection head is stored in a so-called “IFU table”. After reduction procedures, this table contains also informations about fibre relative transmission measured by calibration procedures and the fibre profile parameters (X and Y FWHM of the spectrum on the CCD). When all the four quadrants have been reduced, the fully calibrated 1D spectra are rearranged in a data cube according to the IFU table, to allow a spatially coherent reconstruction of the observed sky region.

From the final data cube, 2D reconstructed images can be re-extracted by collapsing the data cube in the wavelength direction using the whole grism spectral range or an user-selected range. Interpolation or drizzling techniques can then be used to better display the 2D reconstructed images.

### Table 1. Characteristics of the VIMOS Integral Field Unit. The wavelength coverage is obtained thanks to two type of grisms: a red (∼ 0.6 – 1µm) and a blue (∼ 0.37 – 0.7µm).

| Spectral resolution | Wavelengths (µm) | Field (arcsec²) | Spatial resolution (arcsec) | Spatial elements | Spectral elements |
|---------------------|-----------------|-----------------|-----------------------------|-----------------|------------------|
| R = 250 (low)       | 0.37 – 1        | 54 × 54         | 0.67                        | 6400            | 600              |
| R = 2500 (high)     | 0.37 – 1        | 27 × 27         | 0.33                        | 1600            | 4096             |
|                     |                 |                 |                             |                 |                  |

5. Observing the Hubble Deep Field South

The Hubble Deep Field South (HDF-S) is one of the best field observed up-to-date in term of depth, multicolour extension and high spatial resolution. This field was originally observed using the HST-WFPC2 camera in four wide bandpasses ($F300W$, $F450W$, $F606W$ and $F814W$) (Casertano et al. 2000). Very deep Near-Infrared ISAAC images are also available in three wide bandpasses ($J$, $H$ and $K$), and a complete multicolour catalogue of galaxies is selected down to $K_{AB} = 25$ (Fontana et al. 2003; Vanzella et al. 2001). A spectroscopic analysis of faint galaxies in that field was done using the VLT-FORS spectrograph but it is limited by the multiplexing capabilities of the spectrograph. Therefore a deeper spectroscopic sample of galaxies in that field is needed.

Given the small size of the HDF-S field (∼ 4.9 arcmin²), the use of the VIMOS-IFU is perfectly suitable as only 7 IFU pointings are requested to cover that field. Such observations will provide for the first time the full spectroscopic coverage of galaxies with $I_{AB} < 26$ of the HDF-S (PI E. Giallongo). A total time of 120h have been allocated by ESO to observe this field using the VIMOS-IFU – half of it being already allocated this year. For one pointing the total observation time requested in low resolution mode is of 20h with the red grism, i.e. a jitter sequence with exposures of 40min each, and of 13h with the blue grism, i.e. a jitter sequence with exposures of 40min each. Indeed, an exposure time of $T_{exp} = 12h$ is needed with the red grism in low resolution mode to reach at $I_{AB} = 26$ a $S/N = 4 \times 8$ per spectral resolution element at $\lambda = 7800 \ (5800)$Å for point sources, and after integration over all the fibers covering the source. With the blue grism in low resolution mode, the same $S/N$ is obtained with an exposure time of $T_{exp} = 8h$ at $\lambda = 3700 \ (5500)$Å.

Thanks to this new deep sample associated with the deep Near-Infrared photometry, a better assessment of the star light distribution in a wavelength range where it is little affected by dust absorption will be possible.

The detection and confirmation of very high redshift galaxies ($z = 5 – 6$) should be one of the first issues. Several recent studies have shown that high redshift Ly-$\alpha$ emitters can be selected thanks to specially dedicated narrow and broad band filters (e.g. Hu et al. 2002; Cuby et al. 2003). But some galaxies, with strong emission line and a continuum too faint for colour selection, can only be detected thanks to IFUs. Including the contribution of such objects, a better estimation of the cosmologic evolution of average star formation rate at high redshift should be obtained.

Some recent results point towards the presence in the range of redshift $z = 2 – 3$ of an excess of bright star forming galaxies in the rest frame blue luminosity function – excess with respect to CDM models predictions (see e.g. Poli et al. 2003). The presence of such an excess could be assessed by the spectroscopic confirmation of galaxies with $K_{AB} < 25$ at $z = 2 – 3$. This study should bring strong informations on the star formation activity and relative age of the bright high redshift galaxies. The detailed study of morphology of those galaxies in rest frame Ultraviolet bands (HST optical bands) and in rest frame optical bands (ISAAC NIR bands) could also provide informations about spatial varia-
tion in the star population and relative fraction of high redshift galaxies with red nuclei.

Using VIMOS blue grism, redshift and spectral properties for galaxies with \( z = 1-2 \) will also be accessible through detection of interstellar lines (for instance the line \( C IV\ [1549\AA] \) at \( z > 1.4 \) is shifted to \( \lambda > 3700\AA \)). This intermediate range of redshift is particularly interesting as some studies indicate the star formation rate tend to be at its maximum in that range (Madau et al. 1996, Connolly et al. 1997). The spatial resolution reached by the VIMOS-IFU would also be able to probe emission and absorption properties of substructures in bright \( z = 1-2 \) galaxies.

Thanks to observations in multicolour broad band imaging extended to the Near-Infrared wavelengths and comparisons with spectral synthesis model, the galactic stellar mass can be estimated for a wide redshift range in a given sample (Fontana et al. 2000). This technique allows to gather physical informations on the properties of high redshift galaxies. Furthermore main physical quantities of each galaxy in the sample can also be estimated thanks to that technique, as for instance the age of the last major starburst, the stellar mass or the dust content. For instance, Fontana et al. (2003) were able to constraint the stellar masses of galaxies in the HDF-S to within of factor of two with \( U - K \) band imaging over a wide redshift range (0.5 < \( z < 3 \)). This study suffer anyway of a lack of spectroscopic redshifts, which would help in decreasing the uncertainties on the mass estimation. As a depth of \( I_{AB} \sim 26 \) is reached at a \( S/N \sim 5 \) with \( \sim 10h \) of integration time using VIMOS-IFU, and as according to Vanzella et al. (2001) the mean color of the galaxies is \( (I - K)_AB \sim 1 \) when the Extremely Red Objects are excluded, the IFU survey will gather a complete spectroscopic sample and allow to determine the stellar mass for Near-Infrared galaxies down to \( K_{AB} = 25 \). Of course the accuracy of this method is not comparable to kinematical observations but it is enough to study the relative evolution of the stellar mass function at different redshifts.

6. Summary

In this paper, we have described how suitable is the use of the VIMOS Integral Field Unit to observe small deep fields, like the Hubble Deep Field South. IFU observations allow to bypass the limitations of conventional spectrographs, like mainly their multiplexing capabilities. Furthermore the large size of the VIMOS-IFU is particularly suitable for deep field observations, as only mosaic of few pointings is required.

After a short description of the data reduction, we detailed the main scientific issues which could be done thanks to observations of the Hubble Deep Field South with IFU and broad band imaging extended to the Near-Infrared wavelengths. For instance, those observations should lead to the detection of high redshift galaxies (\( z = 5-6 \)), help to confirm the excess of star forming galaxies in the redshift range \( z = 2-3 \), understand some of the spectral properties of galaxies in the redshift range \( z = 1-2 \) and allow an analysis of stellar mass distribution for faint Near-Infrared selected galaxies. All those studies will bring important informations to better understand the physical processes which are underlying to the galaxy evolution.

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