Tracing the Ancestry of Galaxies (on the land of our ancestors)
Proceedings IAU Symposium No. 277, 2010
C. Carignan, F. Combes & K.C. Freeman, eds.

doi:10.1017/S1743921311022605

Large High Redshift Spectroscopic Surveys

Olivier Le Fèvre[1]

[1]Laboratoire d'Astrophysique de Marseille, CNRS-Université de Provence, Marseille, France
email: `olivier.lefevre@oamp.fr`

Abstract. Deep spectroscopic redshift surveys have become an important tool for observational cosmology, supported by a new generation of wide field multi-object spectrographs. They bring high redshift accuracy and a wealth of spectral features necessary for precision astrophysics and have led to the outstanding progress in our understanding of the different phases of galaxy evolution. The measurement of the evolution of volume quantities like the luminosity and mass functions or the correlation function, has enabled a deep insight into galaxy evolution since redshifts $z \simeq 7$. The redshift distribution N(z,m) is a basic property but is still difficult to be reproduced by models. We have now a global perspective on the history of star formation with a peak at $z = 1 - 2$ but the decline in SFRD at higher redshifts is still to be confirmed. The evolution of the stellar mass density with a fast growth in red passive galaxies between $z = 2$ and $z = 1$ is well established. The contribution to galaxy mass assembly of key physical processes like merging or cold accretion is now well documented. However, the pioneer measurements at the high redshift end $z >> 1$ remain to be consolidated with robust sample selection and statistical accuracy from large spectroscopic redshift surveys, a challenge for the years to come.

Keywords. galaxies: distances and redshifts, galaxies: high-redshift, galaxies: evolution, galaxies: formation, large-scale structure of universe

1. Introduction

With a theoretical frame describing the formation and evolution of galaxies, the challenge of the past two decades has been to bring forward observational evidence for a direct confrontation with theoretical expectations and large numerical simulations, leading to a coherent scenario. Deep spectroscopic redshift surveys, made possible by instrumentation development, have been the core provider of observational facts, pushing in look-back time all the way to $z \sim 7$. I describe below the principles driving deep spectroscopic surveys and the methods used to conduct them. I then review recent and on-going surveys and present the main results that have been obtained, focusing on the main challenges to the galaxy formation and evolution models. I then give some perspectives for the future.

2. Goals and principles

In observational cosmology, deep spectroscopic surveys are used for different aspects:

- *Cartography:* mapping the distribution of galaxies in 3D space. Exploring large volumes is necessary to avoid to be sensitive to cosmic variance effects.
- *Population surveys:* studying the properties of galaxies as a function of key parameters like type or environment. Spectroscopy enables the measurement of a number of key parameters including absolute total luminosity, emission lines strength, continuum breaks, and derived quantities like stellar mass, star formation rate, etc.
- *Discovery surveys:* pushing the observational frontier to higher redshifts, fainter galaxies, or towards higher spatial or spectral resolution.

In addition, deep redshift surveys produce reference catalogs which form the statistical basis necessary to conduct more detailed follow-up studies (e.g. 3D integral field spectroscopy observations discussed elsewhere in these conference proceedings).

A key aspect is the need for spectroscopic samples to be truly representative of the galaxy population. This calls for surveys in large volumes and with large numbers of galaxies to provide statistical robustness in the measurements of global volume quantities. Surveys need to be unbiased, meaning that they have to be complete towards the selection imposed on the data, whether it is a selection in luminosity or mass, in type or environment. In order to really be useable to discuss galaxy evolution, samples need to be statistically robust and provide a complete census based on a well controlled selection function. The control of the selection function is a tough condition which imposes a deep understanding of a-priori hypotheses used to pre-select galaxies prior to a spectroscopic survey. A-priori selection using magnitude, color, morphological type, environment, may translate into incompletness and carry the risk of biasing a sample following one's prefered scenario. Simple selection based on magnitude or line flux is prefered, although a combination of magnitude and color selection is used extensively to select the highest redshift populations (Lyman break galaxies, extremely red galaxies, BzK-selected galaxies, etc.). One has to note that whatever the selection, the photometric catalogs need to be at least one magnitude deeper than the spectroscopic limit to avoid imposing biases from the photometric selection itself.

Spectroscopic redshift surveys are often being questioned in terms of efficiency while photometric redshift measurements have been regularly gaining in reliability and require photometry only. There are two basic differences which make these two techniques highly complementary: while photometry provides a broad overview of the spectral energy distribution (SED), spectroscopy provides accurate measurements of spectral features like lines or continuum breaks, and redshift accuracy is still about 2 orders of magnitude better for spectroscopic redshifts. Photometric redshifts methods apply to fainter objects but they need spectroscopic samples to get trained. One important aspect is the different nature of incompleteness and catastrophic failures: spectroscopic incompleteness is related to the lack of spectral features and is traceable to specific objects on which the redshift measurement has failed, while catastrophic failures in photometric redshifts are a statistical behavior which cannot be traced to specific objects. Given the shape of the redshift distribution on faint samples ($mag_{AB} \simeq 24-25$) which is peaked at $z \sim 1$ (see section 4), a 1% catastrophic error on photometric redshifts at $z \sim 1$ can translate into a 30-50% error on the population of galaxies at $z \sim 3-4$.

With the large range of possibilities that they enable, large redshift surveys have become a tool of choice, a backbone, to establish the secure facts that we need to discuss a robust scenario for galaxy formation and evolution.

3. Recent and on-going surveys

Spectroscopic surveys of galaxies started when Hubble and Humason measured the redshifts of galaxies and established the basis for the Hubble diagram. Galaxies were painfully measured one by one for several decades. The technique which has revolutionarized the field is multi-object spectroscopy, starting from the simple idea that multiplying the number of objects observed is equivalent to multiplying the collecting power or the number of telescopes. Pionnier spectroscopic redshift surveys started in the early 90s with a first generation of powerful multi-slit spectrographs like MOS-SIS on the CFHT (Le Fèvre *et al.*, 1994), which was used for the Canada-France Redshift survey (CFRS,

Table 1. Recent or on-going spectroscopic redshift surveys (non-exhaustive)

Survey	Instrument	redshift	# of galaxies	Ref.
CFRS - 1995	CFHT-MOS	$0 < z < 1.2$	600	Lilly *et al.* (1995)
LBG - 1996	Keck-LRIS	$2.5 < z < 4.5$	1,000	Steidel *et al.* (1996)
DEEP2 - 2005	Keck-DEIMOS	$0.7 < z < 1.4$	50,000	Faber *et al.* (2007)
VVDS - 2005	VLT-VIMOS	$0 < z < 5$	50,000	Le Fèvre *et al.* (2005)
GDDS - 2005	Gemini-GMOS	$0 < z < 1.2$	500	Abraham *et al.* (2004)
GOODS - 2006	VLT-FORS2/VIMOS	$0 < z < 7.1$	2,000	Vanzella *et al.* (2006)
zCOSMOS - 2007	VLT-VIMOS	$0 < z < 1.2$ $1.4 < z < 3$	20,000 5,000	Lilly *et al.* (2007)
VIPERS - 2009	VLT-VIMOS	$0.5 < z < 1.2$	100,000	in progress
VUDS - 2010	VLT-VIMOS	$2.5 < z < 7$	10,000	in progress
PRIMUS - 2010	Magellan-IMACS	$0 < z < 1.2$	100,000	in progress

Lilly *et al.*, 1995), or LDSS on the AAT (Glazebrook *et al.*, 1995). The total number of objects observed simultaneously for the CFRS was about 80.

The new generation of multi-object spectrographs which have appeared on 8-10m class telescopes in the first years of the 21^{st} century, like DEIMOS on the Keck (Faber *et al.*, 2003) or VIMOS on the VLT (Le Fèvre *et al.*, 2003), have multiplex gains of several hundred, up to ~ 1000 on VIMOS. This is strictly equivalent to observing with 1000 8m telescopes and single slit spectrographs in parallel. Now, multi-slit spectrographs have become the workhorse instrument for faint object work (in addition to DEIMOS and VIMOS: IMACS on Magellan, FORS2 on the VLT, GMOS on GEMINI,...), while multi-fiber spectrographs have been efficiently working in larger fields at lower redshifts $z < 1$ (SDSS, Abazajian *et al.*, 2003; 2dFGRS Colless *et al.*, 2001).

A number of deep spectroscopic surveys have been produced or are now on-going using these instruments, as identified in Table 1. Taken together, a few hundred thousand spectra have been obtained, bringing an unprecedented view of the distant Universe.

4. Observational results

Spectroscopic redshift surveys have delivered a number of fundamental quantities that need to be reproduced by any galaxy formation and evolution scenario:

- Accurate measurement of the redshift distribution N(z) for different magnitude and color selected samples.
- The evolving shape of luminosity functions, luminosity densities, and the star formation history.
- The evolving shape of the stellar mass function, hence the knowledge of the global stellar mass density evolution.
- The past history of mergers, and their contribution to galaxy mass assembly.
- The evolving relationship between the environment and global galaxy properties.
- The clustering strength of different galaxy populations and their relation to underlying dark matter halos.

4.1. *The redshift distribution N(z)*

The redshift distribution for different magnitude limits N(z,m) is a simple yet important statitics because it results from the combined evolution of different galaxy types. The

VIMOS VLT Deep Survey (VVDS, Le Fèvre *et al.*, 2005) has assembled a large number of galaxies. The redshift distribution of 20,000 galaxies in the VVDS-Wide survey selected down to $i_{AB} = 22.5$ is shown in Fig. 1 (see also Garilli *et al.*, 2008). It peaks at a median z=0.58 with a redshift tail going somewhat beyond z = 1.5. Going to fainter magnitude limits has the effect of boosting the number of high redshift galaxies beyond z = 1, as about half of the galaxies with $23 \leqslant i_{AB} \leqslant 24.75$ are at redshifts beyond 1.3 (Fig. 2; Le Fèvre *et al.*, in preparation). Color selection like BzK (Daddi *et al.*, 2004) or Lyman-break techniques (Steidel *et al.*, 1996) attempt to pre-select galaxies in this high redshift tail to improve on the efficiency of high redshift galaxies identification, with the need to carefuly monitor the effects of a-priori selection.

The current best N-body simulations coupled to semi-analytic models do not seem to be able to fully reproduce the shape of these N(z), as shown in Fig. 2 by the red continuous line with the Millenium simulation (Springel *et al.*, 2005) and the Munich semi-analytic model (De Lucia & Blaizot, 2007), as shown by de la Torre *et al.* (2011). The models seem to produce too many faint galaxies at redshifts below $z \sim 1$ and not enough bright galaxies at $z > 2$.

4.2. *Luminosity functions and the global star formation history*

The global star formation history is derived from the volume average of star formation in galaxies as measured by star formation tracers. While there are some 'ideal' star formation indicators (e.g. $H\alpha$), they are not readily accessed at all redshifts, and hence a combination of different indicators is used in the latest versions of the Madau diagram (Madau *et al.*, 1996). The luminosity in the UV is often used as a tracer of star formation which can be followed accross a large redshift range to produce integrated star formation. This method has several limitations, including the need to use complete samples or

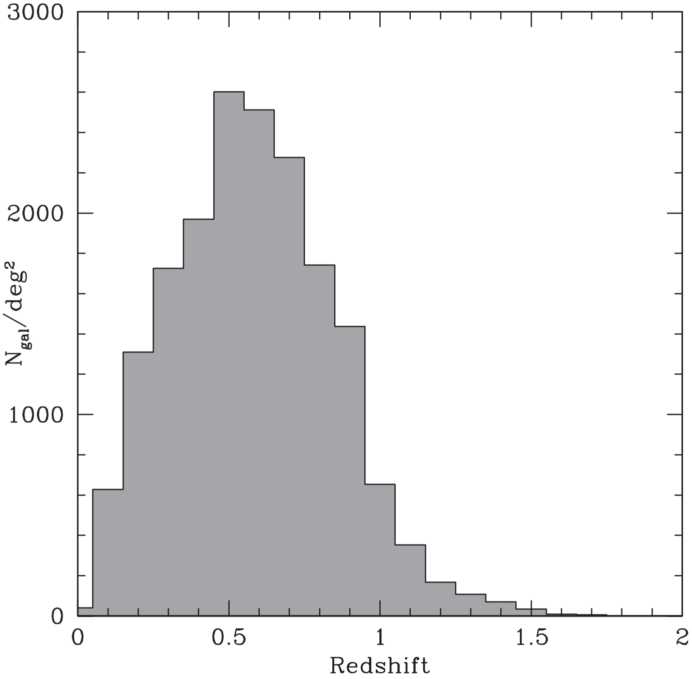

Figure 1. Redshift distribution N(z) of $\sim 20,000$ VVDS galaxies selected with $17.5 \leqslant i_{AB} \leqslant 22.5$.

orhterwise risk missing some of the star forming population, the correction of UV fluxes for dust absorption, or the large uncertainty in the measurement of the faint-end slope of the luminosity function when going to the highest redshifts. Some of these difficulties are discussed in the VVDS account of the star formation rate evolution since $z \simeq 5$ (Tresse *et al.*, 2007). Galaxies go through different phases in terms of star formation, with the bright galaxies producing a lots of star formation early in the life of the Universe, followed by intermediate then fainter galaxies (Tresse *et al.*, 2007). A peak in star formation seems to hold at $z \sim 2$ (Wilkins *et al.*, 2008), as confirmed by the deepest spectroscopic surveys like the ultra-deep VVDS (Cucciati *et al.*, 2011, in prep.). At higher redshifts there seems to be a decrease in the SFRD (Bouwens *et al.*, 2009), however with large remaining uncertainties because of the sample selection and small samples.

4.3. *Stellar mass functions and the global stellar mass density history*

The evolution of the distribution of galaxies versus stellar mass is giving an integrated story on the growth of stellar mass in galaxies, independantly of its origin. The massive end of the mass function is stable since $z \sim 1$ or above, but the shape of the MF has been changing quite dramatically as e.g. observed from the COSMOS survey (Ilbert *et al.*, 2010). There is a strong change in the stellar mass growth at $z \sim 1$: from $z = 1$ to the present, stellar mass density has been growing steadily but slowly with an increase of about 50%, while earlier times $1 < z < 2$ have witnessed a fast build-up of stellar mass in passive red galaxies by a factor 10 or more (Arnouts *et al.*, 2007; Ilbert *et al.*, 2010).

Different mechanisms can be invoked to assemble mass in galaxies, including major and minor mergers or steady accretion of gas along cosmic web filaments transforming into stars, subject to feedback (AGN, SNe), quenching, etc. Today, it is fair to say that there is no single galaxy formation and evolution scenario able to reproduce the observed evolution of the mass function and the global stellar mass density reported above. This remains a major challenge for those models. A complementary line of investigation has recently opened tracking the growth of mass in dark matter halos using the shape of the correlation function and Halo Occupation Distribution models (Abbas *et al.*, 2010). Following, for the same galaxies, the growth of the DM halo they are in and the growth of stellar mass inside the galaxies could bring some new insight into this problem.

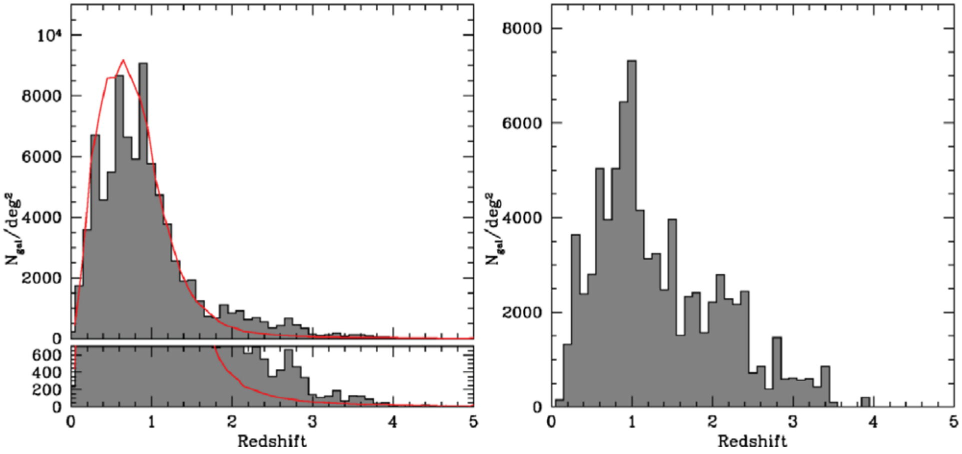

Figure 2. Redshift distribution N(z) of $\sim 10,000$ VVDS galaxies selected with $17.5 \leqslant i_{AB} \leqslant 24$, the red line has been extracted from the Millenium simulation (left), and ~ 1000 galaxies with $23 \leqslant i_{AB} \leqslant 24.75$ (right).

4.4. *The contribution of mergers to the mass assembly in galaxies*

To identify the relative contribution of different physical phenomena to the stellar mass growth, it is now possible to directly measure the contribution of mergers. Using spectroscopic redshift measurements of two galaxies in a pair, it is possible to infer their probability to merge into one single object. This has been done for both major merger events with a mass or luminosity ratio $< 1/4$ (de Ravel *et al.*, 2009; Lin *et al.*, 2008; Conselice *et al.*, 2007) and minor mergers with a ratio 1/10 to 1/4 (Lopez-san Juan *et al.*, 2011). The picture emerging is that merger events contribute about 25% of the total mass growth of L_* galaxies (40% for early-types) since $z \sim 1$, with 75% of this being due to major mergers and 25% to minor mergers. Mergers alone are therefore not enough to account for all the observed stellar mass density growth. The next challenge is to extend these measurements to earlier epochs, making the few attempts so far more robust, and several on-going surveys should be able to tackle this up to $z \sim 3$ or more.

5. Prospects for the near future

Larger and deeper spectroscopic surveys will remain a central goal for observational cosmologists in order to clarify the galaxy formation and evolution scenario. Efforts are focusing on the epoch of the peak in star formation $1 < z < 3$ which is also a time of fast change in the global stellar mass density. Pushing the mean redshift of spectroscopic surveys much beyond $z \sim 3$ will be necessary to provide secure measurements of global quantities like the star formation rate or stellar mass density, and to probe physical mechanisms like merging, following the pioneering efforts of measurements based on color-selected or photometric redshifts sample.

References

Abazajian, K., *et al.* 2003, *AJ*, 126, 2081
Abraham, R., *et al.*, 2004, *AJ*, 127, 2455
Arnouts, S., *et al.*, 2007, *A&A*, 476, 137
Abbas, U., *et al.*, 2010, *MNRAS*, 406, 1306
Bouwens, R., *et al.*, 2009, *ApJ*, 705, 936
Colless, M., *et al.*, 2001, *MNRAS*, 328, 1039
Conselice, C., *et al.*, 2007, *MNRAS*, 381, 862
Daddi, E., *et al.*,, 2004, *ApJ*, 617, 746
de la Torre, S., *et al.*, 2011, *A&A*, 525, 125
de Ravel, L., *et al.*, 2009, *A&A*, 498, 379
De Lucia, G., & Blaizot, J., 2007, *MNRAS*, 375, 2
Faber, S., *et al.*, 2003, *SPIE*, 4841, 1657
Faber, S., *et al.*, 2007, *ApJ*, 665, 265
Garilli, B., Le Fèvre, O., Guzzo, L., *et al.*,, 2008, *A&A*, 486, 683
Glazebrook, K. *et al.*, 1995, *MNRAS*, 273, 157
Ilbert, O., *et al.*,, 2010, *ApJ*, 709, 644
Le Fèvre, O., *et al.*, 1994, *A&A*, 282, 325
Le Fèvre, O., *et al.*, 2003, *SPIE*, 4841, 1670
Le Fèvre, O., Vettolani, G., Garilli, B., & Tresse, L., *et al.*, 2005, *A&A*, 439, 845
Lilly, S. J., Le Fèvre, O., Crampton, D., Hammer, F., & Tresse, L., 1995, *ApJ*, 455, 50
Lilly, S. J., Le Fèvre, O., & Renzini, A., *et al.*, 2007, *ApJSupp*, 172, 70
Lin, L., *et al.*,, 2008, *ApJ*, 681, 232

Lopez-SanJuan, C., *et al.*, 2011, *A&A*, in press, arXiv:1009.5921
Madau, P., *et al.*, 1996, *MNRAS*, 283, 1388
Springel, V., *et al.*, 2005, *Nature*, 435, 629
Steidel, C. C., *et al.*, 1996, *ApJ*, 462, 17
Vanzella, E., *et al.*, 2006, *A&A*, 454, 423
Wilkins, *et al.*, 2008, *MNRAS*, 385, 687