The VIMOS VLT Deep Survey: Final Public Release of ~ 35 000 Galaxies and Active Galactic Nuclei Covering 13 Billion Years of Evolution

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The VIMOS VLT Deep Survey (VVDS) final and public data release offers an excellent opportunity to revisit galaxy evolution with a sample of 35 016 galaxies and active galactic nuclei covering the redshift range $0 < z < 6.7$. The VVDS includes three tiered surveys, the wide, deep and ultra-deep surveys, covering up to 8.7 square degrees, and each magnitude-selected with limits $i_{AB} = 22.5$, 24 and 24.75 respectively. The VVDS redshifts, spectra, and all associated multi-wavelength data are available at http://cesam.lam.fr/vvds. The highlights and scientific legacy of the VVDS are summarised.

Galaxy evolution is the result of a complex interplay between several fundamental physical processes. The underlying picture is that of hierarchical clustering, in which dark matter halos build up in mass along cosmic time with small halos merging to produce larger halos. Galaxies form with strong bursts of star formation, and appear as baryonic matter collapses in those halos, starting stellar lives that endure for millions to several billions of years. In galaxies, the stars evolve along their respective evolutionary tracks, the gas reservoir, possibly replenished by gas accretion, is gradually transformed into new stars, the environment leaves its imprint and spectacular galaxy mergers modify the morphology and content of galaxies. Simulations, which are becoming more and more sophisticated, seem (always!) to agree with observations. From a distance one would then say that most is understood, but we are still faced with major unknowns, particularly concerning which processes dominate in driving evolution for different galaxy types, and on which timescales.

Deep galaxy surveys are the key elements that enable progress in this understanding of galaxy evolution. A fundamental parameter is the knowledge of the redshift, linked to the distance and look-back time via the cosmological world model. With the redshift, we are able to probe back in cosmic time and compare galaxies at different times in their history. The advent of efficient multi-object spectrographs in the 1990s allowed, for the first time, truly representative samples of the high-redshift Universe to be assembled (e.g., the Canada France Redshift Survey [CFRS]; Le Fèvre et al., 1995), and demonstrated the rapid evolution of galaxy properties since $z \sim 1$, or about half the current age of the Universe. The statistical weight of large samples has become a major driver in all surveys, as one aims to know the average multivariate properties of a certain galaxy population as accurately as possible.

The VIMOS VLT Deep Survey

The VVDS was conceived with these considerations in mind. Originally based on guaranteed time to our consortium for the building of the Visible MultiObject Spectrograph (VIMOS) for the VLT under contract with ESO (Le Fèvre et al., 2003), the 50 guaranteed nights allocated to programme 070.A-9007, of which only 33 were under clear weather, were complemented by a 150-hour Large Programme (177.A-0837) for the ultra-deep part. The powerful VIMOS instrument and the observing strategy led to a competitive sample (Le Fèvre et al., 2004a; 2005a), comparable to the best programmes conducted at other facilities,

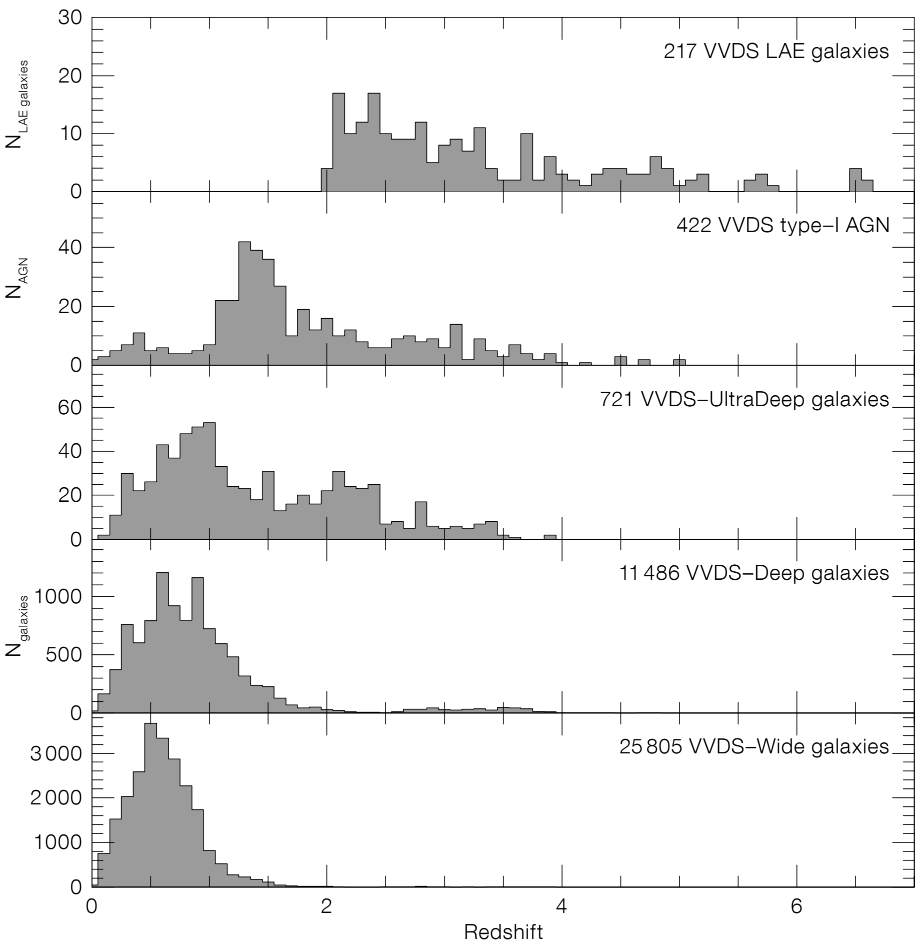

Figure 1. The redshift distribution and sample numbers for the VVDS wide ($i_{AB} \leq 22.5$), deep ($i_{AB} \leq 24$) and ultra-deep ($23 \leq i_{AB} \leq 24.75$) surveys, as well as for the AGN and Lyman-α emitter (LAE) populations are shown from bottom to top.

like the DEEP2 survey with the DEIMOS spectrograph on the Keck Telescope (Davis et al., 2003).

In total more than 58 000 targets have been observed. While the original goal of obtaining 100 000 redshifts in 16 square degrees could not be reached with this time allocation, more than 34 594 galaxies, 422 Type I active galactic nuclei (AGN) and 12 430 Galactic stars have been identified. Redshift measurements however failed for another ~ 10 000 objects; thus the spectroscopic incompleteness represents ~ 20% of all sources. The Galactic stars mainly come from the VVDS-Wide, as no attempt was made to exclude stars from the photometric sample prior to selecting spectroscopic targets in order to keep all compact objects, in particular AGN, as possible targets.

The redshift distribution of the different VVDS surveys is presented in Figure 1. The median redshift increases from $z \sim 0.5$ to $z \sim 1.2$ from the wide to ultra-deep samples, and a high-redshift tail of bright galaxies extends to $z \sim 5$ for the magnitude-limited surveys and up to $z \sim 6.7$ for the Lyman-α emitter (LAE) serendipitous sample. From one single survey with a well-defined selection function, the VVDS therefore allows coverage of about 13 billion years of evolution and traces quantitatively the evolution of galaxy populations and large-scale structures. Another great strength of the VVDS is the wealth of ancillary data. First and foremost deep multi-band photometry was obtained with the Canada France Hawaii Telescope (CFHT), first with the CFH12K wide-field CCD mosaic camera (McCracken et al., 2003; Le Fèvre et al., 2004b), then with the 1-square-degree MegaCam, processed at Terapix in Paris (Cuillandre et al., 2012). Multi-wavelength data include near-infrared photometry (Bielby et al., 2012), Very Large Array (VLA; Ciliegi et al., 2005), Spitzer-SWIRE (Spitzer Space Telescope Wide-area Infrared Extragalactic Survey; Lonsdale et al., 2003), XMM (X-ray Multi-Mirror Mission; Pierre et al., 2004), GALEX (Galaxy Evolution Explorer; Arnouts et al., 2005) and Herschel (Lemaux et al., 2013) measurements. Due to the pressure on the Hubble Space Telescope (HST) to observe many of the extragalactic fields under study by different groups, we have not yet succeeded in getting HST high spatial resolution imaging on the VVDS-02h 0226-04 field, which is quite unfortunate given the immediate science return to be reaped from the more than 12 000 galaxies with spectroscopic redshifts. This opportunity remains open.

Science highlights

The science exploitation of the VVDS has led to numerous new results detailing the evolution of galaxies, such that it is hard to single out only a few highlights. The characterisation of the survey using classical statistical functions has been performed, describing the time evolution of luminosity functions, stellar mass functions and correlation functions. The complete census of star-forming galaxies, enabled by the magnitude selection, led to our claim that magnitude-selected surveys identify more galaxies at redshifts $z \sim 2$–3 than colour-selected surveys (Le Fèvre et al. 2005b); a claim confirmed with the full dataset (Le Fèvre et al., 2013b).

While the expected $N(z)$ distributions down to $i_{AB} = 24$, based on mid-1990s basic knowledge of the high-z galaxy population, were predicting almost no detections at $z > 2$, the VVDS-Deep has unveiled an unexpectedly large galaxy population at $2 < z < 5$ (Le Fèvre et al., 2005b). With its three surveys, the VVDS provides a robust counting of galaxies with reference redshift distributions $N(z)$ at increasing depth. Comparing the VVDS to state-of-the art simulations, we find that these under-predict the number of luminous high-redshift galaxies and over-predict the number of lower luminosity galaxies at low redshifts (de la Torre et al., 2011; Le Fèvre et al., 2013b).

The luminosity function of different galaxy types from the VVDS showed that most of the luminosity evolution (Ilbert et al., 2005) comes from late-type irregular-like galaxies, while early-type elliptical-like galaxies were already mostly in place at $z \sim 1$ (Zucca et al., 2006). The stellar mass function showed that galaxies with elliptical-like evolved spectral types were already in place at $z \sim 1$ (Pozzetti et al., 2007). The stellar mass density showed a striking behaviour with the first evidence of the rapid build-up of elliptical–red galaxies at the epoch $1 < z < 2$ (Arnouts et al., 2007); the stellar mass density of these galaxies was increasing by a factor ~ 10 over this period, a trend which has been confirmed by several subsequent studies.

One surprising result is the evidence for a strong evolution of the colour (morphology)–density relation, which tells us that in the local Universe early-type galaxies reside preferentially in the densest environments, while late types are located in lower density neighbourhoods. Using a finely sampled galaxy density field enabled by the spectroscopic redshift coverage, we find that this relation is flattening and even tentatively inverting at redshifts beyond $z \sim 0.8$–1 (Cucciati et al., 2006); the implication is that at half the current age of the Universe galaxies of different types were equally distributed in different density environments.

The ultraviolet (UV) restframe luminosity functions from the VVDS data led to a remarkable account of the evolution of the star formation rate density (SFRD) derived from the integrated luminosity density over 12 billion years of evolution. First reported in Tresse et al. (2007), the SFRD, corrected for dust, is well established from $z \sim 4$ to $z \sim 0.2$ with unsurpassed robustness (Cucciati et al., 2012). We find that the SFRD rose mildly from early times to a peak or plateau at $z \sim 2$, before decreasing strongly to the present time by about one order of magnitude. The contribution of galaxies of different types to the SFRD history showed a downsizing pattern, with the most luminous galaxies contributing mostly at high-z, while less luminous galaxies dominate the SFRD at lower redshifts. We derived for the first time the evolution of the mean dust attenuation A_{FUV} of the observed galaxy population: it rises up to $z \sim 1$ followed by a plateau to $z \sim 2$ and a fast decrease to $z \sim 4$. The VVDS revealed the first evidence for a delayed dust attenuation peak, appearing ~ 2 Gyr after the SFRD peak (Cucciati et al., 2012); a result later confirmed with Herschel data.

The volumes of 0.5×10^6 to 2×10^7 h^{-3} cubic Mpc probed by the VVDS enabled the distribution of galaxies in large-scale structures to be quantified, and this was employed to infer some useful constraints on cosmology. The apparent evolution of the clustering length r_0 is relatively mild, which translates into an important intrinsic evolution since $z \sim 1$ (Le Fèvre et al., 2005c). We demonstrated that "red" galaxies are already more clustered at $z \sim 1$ than "blue" galaxies (Meneux et al., 2006), a classical property in local surveys never before observed at a time when the Universe was half of its present age. At these redshifts more luminous galaxies are more clustered than fainter galaxies (Pollo et al., 2006) and the dependence of clustering on galaxy mass (Meneux et al., 2008) has been established. The evolution of the galaxy to dark matter halo bias (Marinoni et al., 2005) and the growth of dark matter halos (Abbas et al., 2010) were also reported.

The usefulness of high-redshift surveys to constrain the origin of the apparent accelerated expansion of the Universe was demonstrated using the redshift space distortions (RSD) measured in the clustering of VVDS galaxies (Guzzo et al., 2008). The RSD is one of the only cosmological probes capable of identifying whether our current understanding of gravity in the framework of general relativity is accurate or needs further refinement in modified gravity models that might eliminate the need for dark energy. Since the VVDS proof of concept, RSD at high redshift is much in focus, as exemplified by the recent VIPERS measurements with VIMOS (Guzzo et al., 2013a,b; de la Torre et al., 2013), and is at the heart of large experiments like the Euclid European Space Agency mission (Laureijs et al., 2011).

Thanks to the VVDS sample size and observing strategy, several interesting populations could be studied in detail, including Lyman-α emitters, He II 1640 Å emitters and Type 1 AGN. A large spectroscopic sample of LAEs with $2 < z < 6.7$ was identified, found serendipitously in the observed VIMOS slit masks of the main survey targets — a nice bonus. The total sample of 217 LAEs, still the largest to date, was used to identify that the LAE luminosity function at these redshifts has a steep slope $\alpha = -1.7$, and to show that the ratio of the luminosity density (LD) from LAE to the LD of the general population is increasing with redshift, becoming more than half of the total LD by $z \sim 6$ (Cassata et al., 2011). A peculiar population of He II 1640 Å emitters was identified, with half of these showing properties compatible with residual Population III star formation in pockets of leftover pristine gas from the original reservoir, or from recently accreted gas, down to redshifts $z \sim 3$ (Cassata et al., 2013).The VVDS sample of Type 1 AGN (Gavignaud et al., 2006) was used to measure the faint end of their luminosity function and to better constrain their cosmological evolution (Bongiorno et al., 2007), finding, for the first time in an optically-selected AGN sample, clear evidence of AGN cosmic downsizing.

In the hot debate about galaxy assembly, the VVDS accurately quantified the amount of mass assembled by galaxies in merger events. From the fraction of pairs identified from their concordant spectroscopic redshifts, we have established that 40–50% of the mass of a galaxy today went through a merger event since $z \sim 3$, either from major mergers (de Ravel et al., 2009) or minor mergers (Lopez-Sanjuan et al., 2011). Contrary to what is often assumed from the current cold accretion picture, having a large fraction of the mass of galaxies assembled in mergers is not in contradiction with cold accretion driving star formation, and the two processes are likely to act together in building up galaxies. Mergers are a powerful means to accumulate stellar mass, with major mergers producing galaxies with as much as twice the mass of the progenitors, while often producing only a small and temporary increase in star formation. The VVDS established that merging is a most

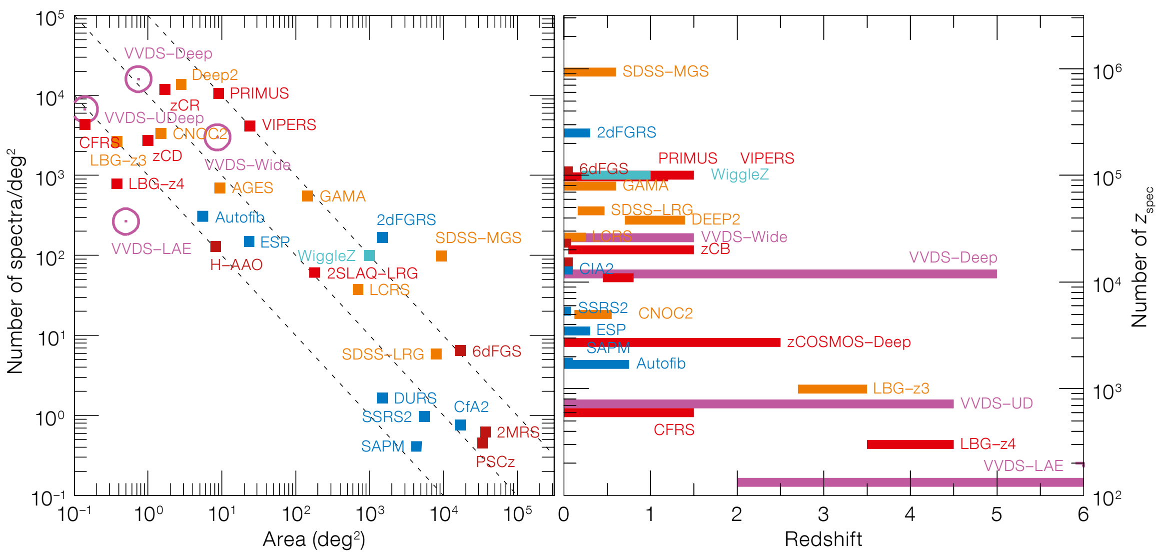

Figure 2. Comparison of VVDS surveys to other spectroscopic redshift surveys. Left: The density of spectra by number per square degree (inspired by Baldry et al., 2010). Right: The number of spectroscopic redshifts measured as a function of redshift (see Le Fèvre et al. 2013a). The important contribution of VVDS among these surveys both in terms of number of spectra and redshift coverage is evident.

important physical process driving galaxy evolution, perhaps not too surprisingly if the picture of hierarchical structure assembly is valid.

It is important to recognise the role of spectroscopic surveys, like the VVDS, in the emergence of the widely used photometric redshift technique. Photometric redshift methods need to be calibrated on reliable spectroscopic redshifts, so that they can then be applied in computing photometric redshifts for hundreds of thousands of sources. This was done for the CFHT Legacy Survey, which was calibrated using the VVDS (Ilbert et al., 2006). Photometric redshifts can in turn provide pre-selected targets for the new generation of spectroscopic surveys (e.g., the VIMOS Ultra Deep Survey [VUDS], Le Fèvre et al., p. 37). Photometric and spectroscopic redshift surveys are therefore highly complementary.

VVDS legacy

More than 50 refereed papers were published from the VVDS collaboration, the latest in 2013, and more than 50 other papers published by other teams making use of previous VVDS data releases. The possibility for young scientists to be involved in a large international project is an important aspect of the VVDS, which has been an excellent training ground for young scientists. More than 15 PhD theses have been defended based on the VVDS and an equivalent number of postdocs have made the VVDS their main project. In all, the VVDS has helped to develop key expertise on deep spectroscopic surveys in Europe, which have motivated and supported other VIMOS surveys at the VLT (e.g., zCOSMOS, Lilly et al., 2007; VIMOS Public Extragalactic Redshift Survey [VIPERS], Guzzo et al., 2013a,b; VUDS, Le Fèvre et al., p. 37), or enabled a large target base for specific and unbiased follow-up surveys, like 3D spectroscopy (e.g., Mass Assembly Survey with SINFONI in VVDS [MASSIV], Contini et al., 2012a,b).

The VVDS contributes to maintaining a strong European presence in the rich field of deep galaxy redshift surveys, as identified in Figure 2, where the return of the VVDS is compared to other surveys in this field. The legacy of this survey rests on the publicly available data[1] and on the invaluable expertise developed all along, with a broad base of scientists now planning for the next generation surveys with the VLT and the European Extremely Large Telescope.

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Links

[1] Access to all VVDS data: http://cesam.lam.fr/vvds