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VANDELS: Exploring the Physics of High-redshift Galaxy Evolution

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VANDELS is a new ESO spectroscopic Public Survey targeting the high-redshift Universe. Exploiting the red sensitivity of the refurbished VIMOS spectrograph, the survey is obtaining ultra-deep optical spectroscopy of around 2100 galaxies in the redshift interval $1.0 < z < 7.0$, with 85 % of its targets selected to be at $z \geq 3$. The fundamental aim of the survey is to provide the high signal-to-noise spectra necessary to measure key physical properties such as stellar population ages, metallicities and outflow velocities from detailed absorption-line studies. By targeting two extragalactic survey fields with superb multi-wavelength imaging data, VANDELS will produce a unique legacy dataset for exploring the physics underpinning high-redshift galaxy evolution.

Background

Understanding the formation and evolution of galaxies, from the collapse of the first gas clouds at early times to the assembly of the detailed structure we observe in the local Universe, remains the key goal of extragalactic astronomy. Despite the immense challenge, the last 15 years have been a period of unprecedented progress in our understanding of the basic demographics of high-redshift galaxies. Indeed, thanks largely to the profusion of deep, multi-wavelength survey fields, we now have a good working knowledge of how the galaxy luminosity function, stellar mass function and global star formation rate density evolve with redshift (see Madau & Dickinson, 2014 for a recent review).

As a consequence, we can now be confident that the star formation rate density we observe locally is approximately the same as it was less than a billion years after the Big Bang (i.e. $z \sim 7$), and that in the intervening period the Universe was forming stars about ten times more rapidly. However, despite this it is still perfectly plausible to argue that the peak in cosmic star formation history occurred anywhere in the redshift interval $1.5 < z < 3.5$, an uncertainty of two and a half billion years. Moreover, the results of the latest generation of semi-analytic and hydro-dynamical galaxy simulations (for example Somerville & Davé, 2015) demonstrate that, from a theoretical perspective, even reproducing the evolution of the cosmic star formation density can be problematic.

Over the last decade it has become clear that the majority of cosmic star formation is produced by galaxies lying on the so-called main sequence of star formation (Noeske et al., 2007). The main sequence is a roughly linear relationship between star formation rate (SFR) and stellar mass, the normalisation of which increases with lookback time. Galaxies lying well above the main sequence can be considered to be starbursts, while those falling well below the main sequence are passive, or quenched.

The evolution in the normalisation of the main sequence over the last 10 Gyr is now relatively well established, with the average SFR at a given stellar mass increasing by a factor of about 30 between the local Universe and redshift $z = 2$ (for example, Daddi et al., 2009). However, at higher redshifts the evolution of the main sequence is still uncertain, despite a clear theoretical prediction that it should mirror the increase in halo gas accretion rates (for example, Dekel et al., 2009). Depending on their assumptions regarding star formation histories, metallicity, dust and nebular emission, different studies find that at a given stellar mass the increase in average SFR between $z = 2$ and $z = 6$ is anything from a factor of about two (for example, González et al., 2014), to a factor of about 25 (for example, de Barros et al., 2014).

Moreover, although the decline in the global star formation rate density over the last 10 Gyr has been well characterised, the primary physical drivers responsible for this quenching remain uncertain. With varying degrees of hard evidence and speculation, active galactic nuclei (AGN) feedback, stellar winds, merging and environmental-/mass-driven quenching have all been widely discussed in the literature (see Fabian, 2012 and Conselice, 2014 for reviews). It seems clear that quenching must be connected to the interplay between gas outflow, the inflow of "pristine" gas, the build-up of the mass-metallicity relation and morphological transformation. However, to date, the relative importance of, and interconnections between, the different underlying physical mechanisms remain unclear.

Within this context, a series of spectroscopic campaigns with the Very Large Telescope (VLT) and the VIsible Multi-Object Spectrograph (VIMOS), such as the VIMOS Very Deep Survey (VVDS; Le Fèvre et al., 2005), the COSMOS spectroscopic survey (zCOSMOS; Lilly et al., 2007) and the VIMOS Ultra Deep Survey (VUDS; Le Fèvre et al., 2015), have played a key role in improving our understanding of galaxy evolution, primarily through providing large numbers of spectroscopic redshifts over wide fields. The VANDELS survey is designed to complement and extend the work of these previous campaigns by focusing on ultra-long exposures of a relatively small number of galaxies, pre-selected to lie at high redshift using the best available photometric redshift information.

The survey

The VANDELS (Proposal ID 194.A-2003) survey is repeatedly targeting a total of eight overlapping VIMOS pointings (see Figure 1), four in the United Kingdom InfraRed Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) Ultra Deep Survey (UDS) and four in the Chandra Deep Field South (CDFS). VANDELS observations are exclusively performed using the medium resolution (MR) grism + GG475 order-sorting filter, which provides medium resolution ($R \sim 700$) spectra covering the wavelength range 4800–10 000 Å at a dispersion of 2.5 Å pixel^{-1}.

Each of the eight pointings is observed four times, each pass receiving 20 hours of on-source integration. Using a nested slit allocation strategy, targets are allocated either 20, 40 or 80 hours of integration, depending on their brightness. In total, VANDELS has been allocated 640 hours of on-source observing time, all of which is being obtained in Visitor Mode on the VLT between August 2015 and January 2018.

In order to justify such a large investment of observing time, VANDELS is deliberately focused on two of the best legacy fields for studying the high-redshift Universe. Crucially, both the UDS and CDFS are covered by deep optical–near-infrared Hubble Space Telescope (HST) imaging provided by the CANDELS survey (Grogin et al., 2011). In addition, both UDS and CDFS are covered by ultra-deep imaging with the Spitzer Space Telescope, HST near-infrared grism spectroscopy from the public 3D-HST survey (Brammer et al., 2012) and the deepest available *Y*+*K*-band imaging from the HAWK-I Ultra Deep Survey (HUGS; Fontana et al., 2014).

The fundamental science goal of VANDELS is to move beyond simple redshift acquisition and obtain a spectroscopic dataset deep enough to study the astrophysics of high-redshift galaxy evolution. The spectroscopic targets are all pre-selected using high-quality photometric redshifts, the vast majority being drawn from one of three main categories: bright star-forming galaxies, higher redshift star forming galaxies and passive galaxies.

Firstly, VANDELS is targeting a sample of more than 400 bright ($H_{AB} \leq 24$, $I_{AB} \leq$ 25 mag.) star-forming galaxies in the redshift range $2.4 < z < 5.5$. The spectra of these galaxies will cover the required rest-frame ultraviolet (UV) wavelength range with a signal-to-noise ratio (SNR) high enough to allow the stellar metallicity to be measured. Secondly, the VANDELS survey extends to higher redshifts and fainter magnitudes by targeting a large sample (around 1300) of star-forming galaxies at $3 < z < 7$ in the magnitude range ($25 < i_{AB} < 27$). Thirdly, to study the descendants of high-redshift star-forming galaxies, VANDELS also uses rest-frame *UVJ* selection (Williams et al., 2009) to target a complementary sample of around 300 massive ($H_{AB} \leq 22.5$), passive galaxies at $1.0 < z < 2.5$. Finally, thanks to the large number of targets that can be

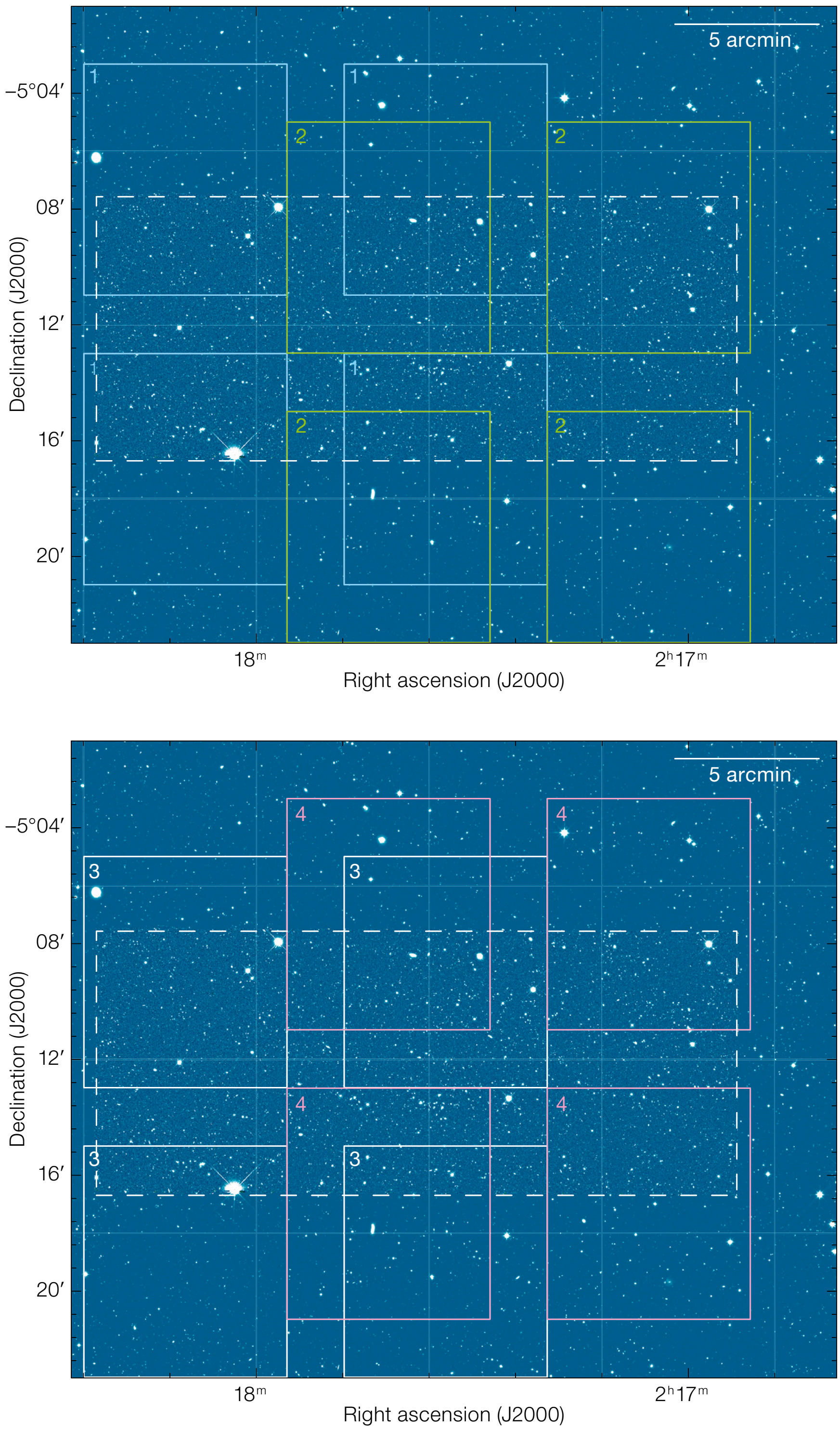

Figure 1. Illustration of how the four VANDELS VIMOS pointings are organised within the UDS survey field. The rectangle indicated by the dashed white line shows the region covered by deep *H*-band HST imaging from the CANDELS survey. The four VIMOS pointings (labelled 1–4), each with four quadrants, are located to ensure that 100 % of the HST imaging area is covered. Outside the central region, the background image shows the deep *H*-band imaging from the UKIDSS UDS survey. To maximise the slit allocation efficiency, targets can be allocated to slits on quadrants in different overlapping pointings. The four pointings within the CDFS survey fields are organised in a similar fashion.

allocated on each VIMOS mask, VANDELS is also targeting small samples of rarer bright systems such as AGN and galaxies detected by the Herschel satellite.

The VANDELS observing strategy is designed to provide consistently high SNR continuum detections for the bright star-forming and passive galaxy sub-samples (see Figure 2 for example spectra). For those objects with $i_{AB} \leq 24.5$, the final 1D spectra will typically provide SNR of 15–20 per resolution element, based on total exposure times of 20, 40 or 80 hours. For the faintest objects in these sub-samples ($I_{AB} \sim 25$), the final spectra typically have a SNR ~ 10 per resolution element, based on 80 hours of integration. For the faintest ($25 < i_{AB} < 27$) targets at $z \geq 3$, the VANDELS observing strategy is designed to provide a consistent Ly-α emission-line detection limit (5σ) of ~ 2×10^{-18} erg s^{-1} cm^{-2} and a continuum SNR of about 3 per resolution element. The data reduction and survey management of VANDELS are performed within the *Easylife* system (Garilli et al., 2012). *Easylife* is an updated version of the original VIMOS Interactive Pipeline and Graphical Interface (VIPGI) system and was originally developed to process the data from the VIMOS Public Extragalactic Redshift Survey (VIPERS; Guzzo et al., 2014).

Science goals

As outlined briefly above, current studies of high-redshift galaxies are limited by interrelated and insidious uncertainties in the measurements of key physical parameters such as stellar mass, metallicity, star formation rate and dust attenuation. The VANDELS survey is specifically designed to provide the high-SNR spectra necessary to derive accurate physical parameters via absorption line studies,

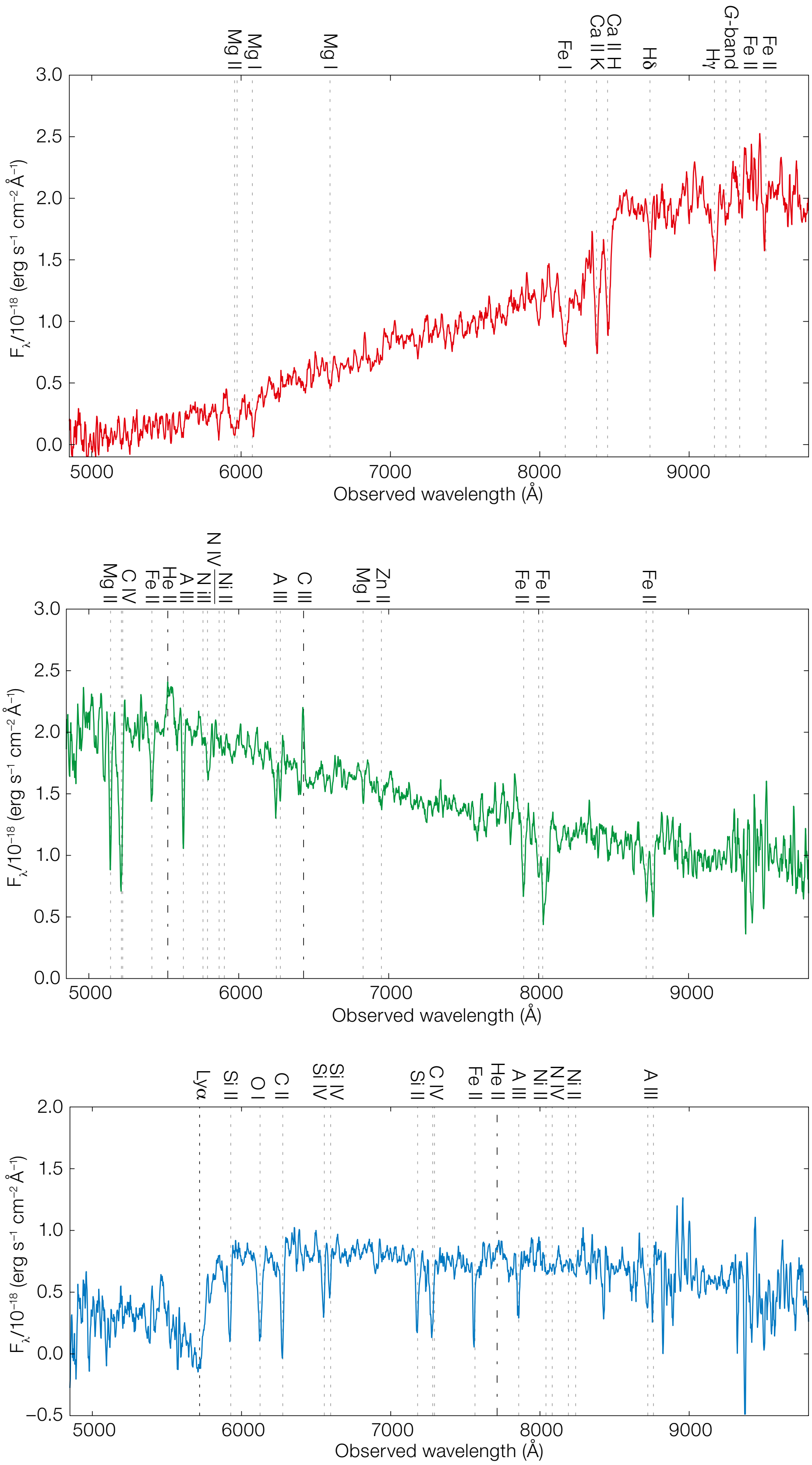

Figure 2. Example spectra from the VANDELS survey. The top panel shows a redshift z = 1.1303 passive/quiescent galaxy. The middle panel shows a bright star-forming galaxy at z = 2.372 and the bottom panel shows a bright star-forming galaxy at z = 3.703. Common absorption (dotted lines) and emission (dot-dashed lines) features are highlighted. For the type of objects shown, the VANDELS observations are designed to provide spectra with sufficiently high SNRs to allow key physical properties (for example, metallicity and outflow velocities) to be measured on an individual, object-by-object, basis.

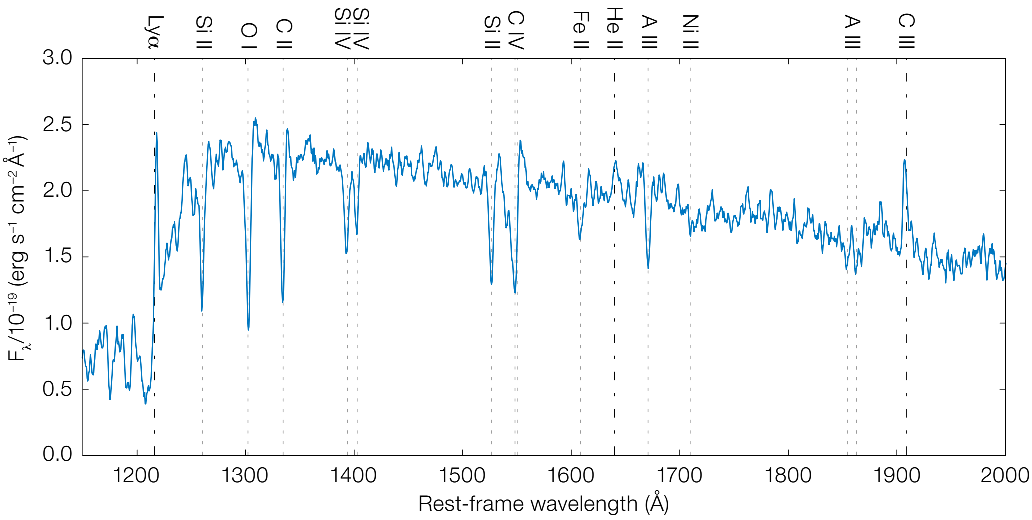

Figure 3. An illustration of the potential within the VANDELS dataset for producing high-SNR stacked spectra. This example shows the stacked spectrum of 100 fainter star-forming galaxies in the redshift interval $3.0 < z < 4.0$. Common absorption (dotted lines) and emission (dot-dashed lines) features are highlighted. The stacked spectra from VANDELS will allow key physical properties to be investigated over a wide dynamic range in redshift, stellar mass and star formation rate.

and will therefore have an impact on many areas of high-redshift galaxy evolution science. However, the original VANDELS survey proposal was motivated by a small number of key science goals, three of which we briefly discuss below.

1. Stellar metallicity and dust attenuation
   Tracing the evolution of metallicity is a powerful method of constraining high-redshift galaxy evolution via its direct link to past star formation and sensitivity to interaction (inflow/outflow) with the intergalactic medium. Moreover, accurate knowledge of metallicity is essential for deriving accurate star formation rates and breaking the degeneracy between age and dust extinction (for example, Rogers et al., 2014).

   Recent studies using stacked spectra of relatively small samples (for example, Steidel et al., 2016) have shown that it is possible to derive accurate stellar metallicities from the rest-frame UV spectra of galaxies at $z \geq 2$, provided the spectra have a high enough SNR. The VANDELS data will allow metallicities to be measured for hundreds of galaxies at $2.4 < z < 5.5$, both individually and via stacking (see Figures 2 and 3) and therefore offers the prospect of transforming our understanding of metallicity at high redshift.

   It is worth noting that the ability to independently constrain the stellar metallicity and dust attenuation (from the ratio of observed to intrinsic UV spectral slopes) will also lead to significantly improved estimates of stellar masses and SFRs. Importantly, this means that the VANDELS dataset will allow the stellar mass – stellar metallicity relation to be studied out to $z \sim 5$ for the first time. Moreover, the improved stellar mass and SFR estimates for about 1800 spectroscopically confirmed star-forming galaxies at $2.4 < z < 7.0$ will also allow accurate calibration of photometric determinations of the evolving stellar mass and SFR functions.

2. Outflows
   Along with stellar metallicity measurements, a key science goal for VANDELS is the study of outflowing interstellar gas. It is now becoming increasingly clear that high-velocity outflows may be ubiquitous amongst star forming galaxies at $z > 1$, with mass outflow rates comparable to the rates of star formation (for example, Bradshaw et al., 2013). Such outflows may be playing a major role in the termination of star formation at high redshift and the build-up of the mass–metallicity relation.

   Crucially, the high-SNR, medium-resolution, VANDELS spectra will allow accurate measurements of outflowing interstellar medium velocities from high- and low-ionisation UV interstellar absorption features (for example, Shapley et al., 2003). The fundamental goal is to measure the outflow rate as a function of stellar mass, SFR, and galaxy morphology, in order to understand the impact of galactic outflows on star formation at $z \geq 2$. Measuring the balance of inflow, outflow and star formation will enable models of the evolving gas reservoir to be tested and address the origins of the Fundamental Metallicity Relation (Mannucci et al., 2010). Finally, comparing the outflow velocities of star-forming galaxies with and without hidden AGN (as identified from X-ray emission) will allow the role of AGN feedback in quenching star formation and the build-up of the red sequence to be investigated.

3. Massive galaxy assembly and quenching
   A key sub-component of VANDELS is obtaining deep spectroscopy of ~300 massive, passive galaxies at $1.0 < z < 2.5$. This population holds the key to understanding the quenching mechanisms responsible for producing the strong colour bi-modality observed at $z < 1$, together with the significant evolution in the number density, morphology and size of passive galaxies observed between $z = 2$ and the present day. For the majority of the passive sub-sample, the VANDELS spectra will provide a combination of crucial rest-frame UV absorption-line information and Balmer break measurements. Combined with the unrivalled photometric data available in the UDS and CDFS fields, it will be possible to break age/dust/metallicity degeneracies and deliver accurate stellar mass, dynamical mass, star formation rate, metallicity and age measurements via full

spectrophotometric spectral energy distribution (SED) fitting.

Legacy science

Finally, given that VANDELS is fundamentally a public spectroscopic survey, it is worth briefly considering the question of legacy science. The immense legacy value of the VANDELS survey is compelling: simply by providing spectra of relatively faint targets with unprecedentedly high signal-to-noise, VANDELS is guaranteed to open up new parameter space for investigating the physical properties of high-redshift galaxies. For example, VANDELS will fundamentally improve our knowledge of the statistics of Ly-α emission in star-forming galaxies approaching the reionisation epoch (see Pentericci et al., 2014) and expedite the identification of the progenitors of compact galaxies amongst star-forming galaxies at $z \geq 2.5$. Moreover, additional science will be facilitated by the samples of rarer bright systems, such as the Herschel detected galaxies and AGN, targeted by VANDELS. For these systems, the deep VANDELS spectroscopy will make it possible to assess their physical conditions (for example, metallicities, ionising fluxes and outflow signatures) and compare them with those of less active systems at the same redshifts.

In terms of future follow-up observations, there is an excellent synergy between VANDELS and the expected launch date of the James Webb Space Telescope (JWST) in late 2018. The opportunity to combine ultra-deep optical spectroscopy with the unparalleled near-infrared spectroscopic capabilities of the JWST near-infrared spectrograph NIRSpec will make VANDELS sources an obvious choice for follow-up spectroscopy with JWST. As a specific example, high-SNR spectra of the Balmer break region of typical $z \sim 5$ galaxies targeted by VANDELS could be obtained with NIRSpec in less than one hour.

Finally, it is also worth noting that the southern position of both the UDS and CDFS make them ideal survey fields for sub-millimetre and millimetre wavelength follow-up observations with the Atacama Large Millimeter/submillimeter Array (ALMA). One of the key scientific questions that VANDELS will help to address is the evolution of star formation and metallicity in galaxies at $z \geq 2$. However, in order to derive a complete picture it will be necessary to obtain dust mass and star formation rate measurements at long wavelengths, which can now be provided by short, targeted, continuum observations with ALMA.

Timeline

The VANDELS survey has just finished its second of three observing seasons and, weather depending, is scheduled to be completed in January 2018. All of the raw data are immediately available for download via the ESO Science Archive Facility (SAF). In addition, the VANDELS team are committed to a regular schedule of data releases (starting with data release 1 in June 2017), through which fully reduced 1D and 2D spectra, plus redshifts and basic target parameters, will be provided to the astronomy community via the SAF. More information about the VANDELS survey, including a full list of Co-Is, can be found at the team website[1].

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Links

[1] VANDELS team website: http://vandels.inaf.it

Part of the Chandra Deep Field South (10.1 × 10.5 arcminutes) imaged by the Wide Field Imager on the MPG/ESO 2.2-metre telescope shown in a *B*-, *V*- and *R*-band composite. See Release eso0302 for further details.