UltraVISTA: A VISTA Public Survey of the Distant Universe

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Large samples of distant galaxies covering degree-scale areas are an unparalleled source of information concerning the first sources that ionised the Universe and the origin of cosmic structures. The UltraVISTA public survey, using the unique capabilities of the VISTA telescope, aims to assemble a unique sample of remote, very high-redshift galaxies. The characteristics of the first UltraVISTA data release (DR1) and the upcoming DR2 data products are described. The DR1 data, comprising just a few months of observing time, already equals or exceeds in depth all previous wide-field near-infrared images taken on the COSMOS field in the last decade. The first scientific results from UltraVISTA are presented, including new measurements of the high redshift (z ~ 7) galaxy luminosity function and an accurate determination of the type-dependent galaxy stellar mass function from z ~ 0 to z ~ 4. DR2 will reach one to two magnitudes deeper in all bands and provide our clearest picture of the structure and composition of the Universe at high redshifts.

Introducing UltraVISTA

In the last two decades, the utility of deep-field observations for extragalactic astrophysics has been conclusively demonstrated. These surveys, typically comprising effective exposure times totalling tens or hundreds of hours per pixel, have revolutionised our knowledge of the high-redshift Universe, leading to the detection and subsequent spectroscopic confirmation of significant numbers of high-redshift (z ~ 3) and very high-redshift (z > 4) objects. However, the largest ultra-deep fields probed by space-based observatories, whilst reaching very faint magnitude limits (typically AB ~ 27) using the Wide-Field Camera 3 on the Hubble Space Telescope typically have contiguous areas of only a few tens of arcminutes, leaving the region of parameter space comprising square degree angular coverage and moderate depth in near-infrared (NIR) wavelengths unexplored.

This combination of depth, wavelength and areal coverage is crucial for a number of reasons. Firstly, as the first structures in the Universe form at the peaks of the underlying dark matter density field, the numbers of objects at megaparsec scales will fluctuate significantly. Secondly, because the number densities of galaxies fall off exponentially at the bright end of the galaxy luminosity function, a wide-area survey is essential to yield a useful sample of high-redshift galaxies of sufficient brightness for spectroscopic follow-up with the current generation of large telescopes. Finally, this combination of depth and areal coverage will find large numbers of objects suitable for spectroscopic follow-up with the James Webb Space Telescope and the next generation of ground-based extremely large telescopes. The characterisation of these high-redshift, moderately bright objects is essential to understand the nature of the sources that re-ionised the Universe and which are the origin of the seeds of present-day large-scale structures.

The arrival of the VISTA telescope, and the prospect of a substantial time allocation for public surveys, prompted four independent responses to the initial call for VISTA surveys of the very distant Universe, each capitalising on the strengths of VISTA and the excellent observing conditions at Paranal. Given the factor of three or four speed improvement with VIRCAM, compared to existing cameras such as WIRCAM (Canada France Hawaii Telescope [CFHT]) or WFCAM (United Kingdom Infra-Red Telescope), it became possible, for the first time, to think of a ground-based survey reaching to AB limiting magnitudes of 25–26 over ~ 0.9 square degrees in the time envelope allocated to VISTA surveys. These independent proposals were merged to form the UltraVISTA survey[1], which was subsequently allocated 1800 hours of telescope time. Survey operations started in December 2009. UltraVISTA lies in the COSMOS field (Scoville et al., 2007), where a rich data heritage means that a wealth of secondary science has been enabled by UltraVISTA observations.

The UltraVISTA project comprises two components: a deep survey covering the central 1.6 square degrees of COSMOS, and an ultra-deep part covering 0.9 square degrees in four parallel stripes, each of which is separated by one VIRCAM detector width. Observations are made in four broadband filters, Y, J, H, and Ks, as well as a narrowband filter. By blocking bright OH sky-lines, this narrowband (NB) filter enables the most extensive search to date for Lyman-α emitters at z ~ 8.8 (Milvang-Jensen et al. [2013] describe this filter in detail). In addition to Lyman-α emitters at very high redshift, the NB survey will detect hundreds of [O II]-emitters at z = 2.2 and thousands of Hα emitters at z ~ 0.8. A dedicated survey using this filter only on the ultra-deep stripes has been incorporated into the UltraVISTA survey plan.

The projected AB depths at survey completion are ~ 25 (5σ for 2 arcseconds) for the deep part and ~ 26 for the ultra-deep part. As of the time of writing (October 2013), the deep survey has been largely completed, and around 40 % of the ultra-deep survey has been finished. At this rate of progress, we expect the survey to be completed by around 2017.

UltraVISTA DR1: The first VISTA survey of the high-redshift Universe

The first UltraVISTA data release, DR1[2], which took place in February 2012, contains stacks created from data taken during approximately the first five months of survey operations (around 8000 images) and contains only deep survey data. As the survey's primary scientific objective relies on detecting objects several orders of magnitude fainter than the bright NIR sky, the principal processing challenge

Figure 1. UltraVISTA DR2 ultra-deep image. This colour image comprises *Ks*, *J*, *Y* (RGB) stacks with an effective exposure time per pixel in each band of 82, 35 and 53 hours respectively.

involves an accurate and uniform sky-subtraction. To do this, we used the normal two-pass sky background subtraction method, starting from individual images pre-processed by the Cambridge Astronomy Survey Unit (CASU), adding back the already-subtracted sky, and using an object mask computed from the stacked image in each band to compute and subtract an individual sky frame for each of the 8000 images.

The same techniques have been applied to the upcoming DR2 release, containing almost 20 000 images. Such a computationally intensive technique was possible thanks to the use of the TERAPIX facility at the Institut Astrophysique de Paris. The advantage of this method is that the stacked images are extremely flat and uniform. They also bear testament to the excellent optical design of the VIRCAM camera and the high quality of the detector and amplifier chain (almost all remaining instrumental effects can be removed in software either at TERAPIX or CASU). Figure 1 shows a tiny area of one of the "deep stripes" observations from the upcoming DR2 release, where objects as faint as *Ks* ~ 23 AB mag are easily visible. This image is a colour composite of separate *Y*, *J* and *Ks* stacks.

DR1 images have appeared in an ESO press release[3] and also featured prominently on Phil Plait's well-known *Bad astronomy* blog[4], attracting hundreds of comments. Catalogues extracted from these images were released by ESO as part of the DR1 Phase 3 catalogue release in September 2012[2]. The processing steps used to create and validate these images and catalogues are described fully in McCracken et al. (2012).

The UltraVISTA DR1 represents a significant advance over previous NIR data in the COSMOS field. In only five months of operations, the depths in each of the broadband images meets or exceeds all previous near-infrared images taken in COSMOS over the past ten years. In bluer wavebands (*Y* and *J*) it is more than two magnitudes deeper. This enhanced sensitivity in bluer wavelengths (and overall better NIR wavelength coverage) is one of the defining features of UltraVISTA compared to previous NIR surveys at this depth and areal coverage. It ensures that lower-redshift (z ~ 2) interlopers for high-redshift galaxies can be reliably rejected and that secure photometric redshifts at z ~ 1–1.5, free from systematic errors, can be computed. At the time of writing, it remains the deepest NIR survey of the sky on square-degree areas, and is likely to remain so for the foreseeable future. Thanks to queue-scheduled observations and stringent seeing control, all final stacked images have seeing better than 1 arcsecond full width at half maximum, with variation in seeing between the bands less than 20 %, further limiting the impact of systematic photometric errors.

Mass assembly and the high-redshift galaxy luminosity function

Scientific exploitation of this first release has proceeded rapidly. Bowler et al. (2012), by combining DR1 UltraVISTA images with multi-band data from the Subaru Observatory, the CFHT and the Spitzer Space Telescope, searched for UltraVISTA objects undetected in optical wavelengths and derived a new list of ten candidate high-redshift ($z > 6.5$) galaxies. Stacking the four most robust of these candidates, they derived a photometric redshift of z ~ 7 and (thanks to UltraVISTA *Y* and *J* data) show that low-redshift galaxy contaminants and T-dwarf star solutions are convincingly rejected. These are the first robust, bright very high-redshift galaxies discovered in COSMOS. This demonstrates also how future UltraVISTA data releases will place stringent limits on the bright-end slope of the high-redshift luminosity function (Figure 2).

The overall depths of the initial DR1 release precluded the discovery of significant numbers of high-redshift objects (although nevertheless demonstrating that our filter selection could reliably find such objects). However, for the redshift z ~ 2 population it represents a considerable advance over the existing COSMOS datasets, making possible the most precise assessment to date of the build-up in stellar mass in the Universe from $0 < z < 4$, and providing new constraints on the evolution

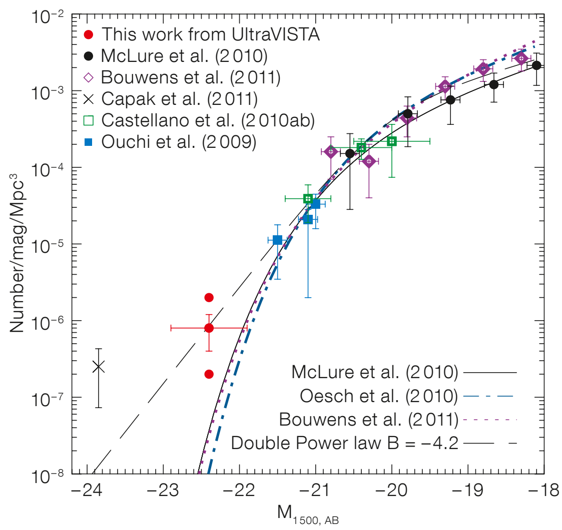

Figure 2. Ultraviolet z ~ 7 galaxy luminosity function (from Bowler et al., 2012). The red point shows UltraVISTA measurements if ten, four or one of the candidate objects are at z ~ 7. A literature compilation of similar measurements and Schechter function fits to fainter data is also shown.

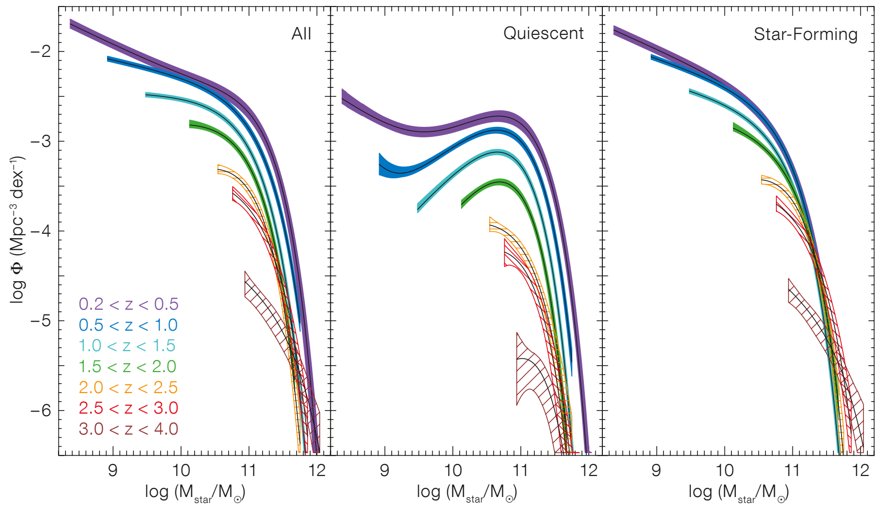

Figure 3. UltraVISTA galaxy stellar mass functions separated by star formation activity and redshift (colour-coded) are shown (from Muzzin et al., 2013).

of the faint-end slope of the mass function several magnitudes below M*. In addition, the galaxy population can be separated into star-forming and non-star-forming (quiescent) objects, the first time that this has been possible over such a large redshift range. The uniquely rich spectral coverage of the COSMOS field (more than 25 bands) and large numbers of extremely difficult-to-acquire spectroscopic redshifts in the $1 < z < 2$ redshift range, means that we can compute the most accurate photometric redshifts to date over a wide redshift baseline with low numbers of catastrophic failures.

Two independent papers (Ilbert et al., 2013; Muzzin et al., 2013) derived UltraVISTA–COSMOS photometric redshifts and used them to compute how the amount of mass in stars per cubic megaparsec (the stellar mass function) evolves as a function of cosmic time and star formation activity (Figure 3). Both confirm that most of the evolution in the stellar mass function is driven by a rapidly changing population of quiescent galaxies and that this evolution is mass-dependent. Massive galaxies are already in place at early times and the amount of stellar mass in these systems evolves only slowly. In contrast, the rapid build-up of mass in quiescent galaxies in the lower redshift Universe seems to be the result of different physical processes, which stop star formation in more massive galaxies at higher redshifts and less massive galaxies at lower redshifts. Furthermore, the cosmic evolution of the stellar mass density inferred from these measurements has now been shown to be consistent with the latest measurements of the evolution of the star formation rate (green shaded area in Figure 4). These photometric redshift catalogues and stellar mass measurements have been made publicly available[5].

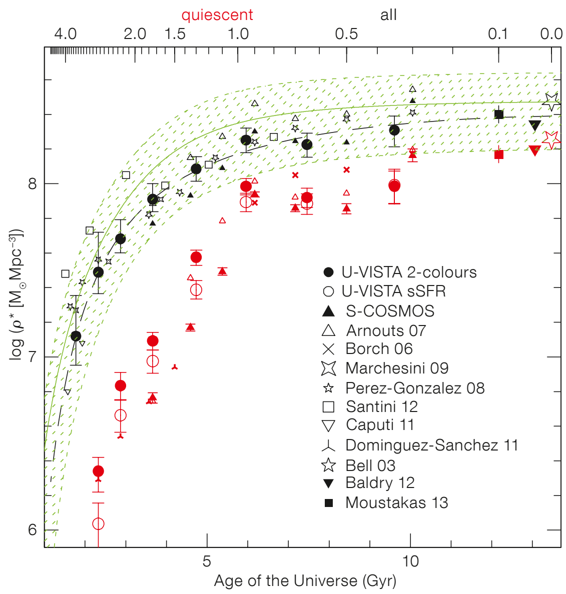

Figure 4. The total stellar mass density as a function of cosmic time as measured in UltraVISTA is shown (filled circles; from Ilbert et al., 2013) for all galaxies (in black) and for quiescent galaxies (in red). Other measurements from the literature are also shown.

Further and deeper: UltraVISTA DR2

Today, DR2 data processing has been completed, and the forthcoming release will contain all data taken during the first three years of operations. The deep survey component remains approximately the same depth as DR1. The ultra-deep stripes, however, have much longer integration times (30–50 hrs per pixel) and now reach *Ks* ~ 25 AB mag (5σ, 2 arcsecond).

The UltraVISTA–COSMOS field remains unparalleled in wavelength coverage and in the next four years several supplementary datasets will enhance the unique legacy value of the UltraVISTA dataset. Ultra-deep Spitzer observations will extend current CH1 and CH2 observations by the Infrared Array Camera (IRAC) to AB ~ 25.5 mag (the SPLASH programme), enabling reliable stellar mass measurements at z ~ 4. In addition, in 2014 the COSMOS-UltraVISTA field will be observed by the Hyper-Suprime-Cam on Subaru, increasing depths in optical bands by one to two magnitudes. Coupled with the complete UltraVISTA dataset, this will provide an unparalleled picture of representative volumes of the high-redshift Universe until the advent of Euclid in 2020.

References

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Muzzin, A. et al. 2013, ApJ, in press, arXiv:1303.4409
Scoville, N. et al. 2007, ApJS, 172, 1

Links

[1] UltraVISTA web page: http://home.strw.leidenuniv.nl/~ultravista/
[2] UltraVISTA DR1 public release: http://www.eso.org/sci/observing/phase3/data_releases/ultravista_dr1.html
[3] ESO Release 1213: http://www.eso.org/public/news/eso1213/
[4] Phil Plait's Bad astronomy blog: http://www.slate.com/blogs/bad_astronomy.html
[5] UltraVISTA catalogue availability: http://terapix.iap.fr/article.php?id_article=844