The zCOSMOS Redshift Survey

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The last ten years have seen the opening up of dramatic new vistas of the furthest reaches of space and time – an exploration in which the VLT has played a major role. However, the work so far has been exploratory, and sampled only small and possibly unrepresentative volumes of the distant Universe. The next step is to bring to bear on a single large area of sky the full range of techniques that have been developed, using almost all of the most powerful observing facilities in the world. This next step is called COSMOS and the ESO VLT will make a major enabling contribution to this programme through the zCOSMOS survey being carried out with the VIMOS spectrograph.

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It is well known that the finite speed of light enables us to observe very distant objects as they were when the Universe as a whole was much younger, and thereby to directly observe the evolving properties of the galaxy population over cosmic epoch. The most distant objects presently known lie at redshifts between six and seven ($6 < z < 7$) corresponding to a "look-back" time of about 95 % of the age of the Universe. Indeed, at the time that these objects emitted the light that we now detect, the Universe was less than one billion years old.

These observations have revealed a rich phenomenology in the early Universe. As we look back in time, we see that the global star-formation rate was about a factor of ten or more higher in the first third of the history of the Universe (at $z > 1$) than it is now. It is clear that the most violent star-bursting objects are enshrouded in dust and will make productive targets of study in the future with ALMA. Alongside these very active galaxies, there are also examples of more passive galaxies which must have completed their star formation quite early on. Consistent with our knowledge of the stellar content of galaxies today, we see in the high redshift Universe that high levels of star formation, and other signatures of youthfulness, appear in progressively more massive galaxies as we look back further in time, a phenomenon given the rather confusing name of "down-sizing".

In parallel, developments in cosmology and in particular the emergence of the "concordance cosmology" (from observations of the microwave background, large-scale structure in the present-day Universe and the Hubble diagram of distant Type 1a supernovae) have given us for the first time a theoretical paradigm for the formation of galaxies and other, larger scale, structures in the Universe – the Λ-CDM model: Structures in the Universe are the product of the gravitational growth of initially tiny density fluctuations in the distribution of dark matter in the Universe – fluctuations which likely arise from quantum processes in the earliest moments of the Big Bang, $\tau \sim 10^{-35}$ s. These density fluctuations eventually collapse to make gravitationally-bound dark matter structures within which the baryonic material cools, concentrating at the bottom of the gravitational potential wells where it forms the visible components of galaxies.

In many respects, the Λ-CDM paradigm is strikingly successful, especially in describing large-scale structure. On galactic scales, current implementations of it face some difficulties: for example, real galaxies appear to have more angular momentum than predicted in numerical Λ-CDM simulations and the down-sizing trend is in a sense opposite to that expected. There is also no clear understanding of the links between galaxies and their nuclear supermassive black holes. These various shortcomings almost certainly reflect our poor understanding of how dark matter and baryons interact, of the feed-back loops operating within the baryonic material due to energy injection from star formation and active galactic nuclei and of the relative importance in galaxies of internal dynamical evolution and externally driven events such as mergers, in redistributing material within them. Many of these current uncertainties are likely related to the environments that a forming and evolving galaxy finds itself in. Except for the very richest environments (i.e. the rich clusters of galaxies), knowledge of the environments of distant galaxies is rather poor. One of the aims of zCOSMOS is to characterise these environments over a wide range of redshifts and thus to lead to a much better physical understanding of the forces controlling the formation and evolution of galaxies through cosmic time.

Much of the progress in this field has been driven by "Legacy" style programmes, such as the Hubble Deep Fields (HDF), and the GOODS project, in which the data have been archived and released to the research community in a scientifically usable form. This allows a much larger community of astronomers, extending well beyond the original team who acquire and first analyse the data, to use the data to carry out their own research programmes. COSMOS and zCOSMOS are both undertaken in this spirit, and the purpose of this Messenger article is to bring to the attention of potential users across the ESO community the features of the zCOSMOS programme, which has just started on the VLT in P75.

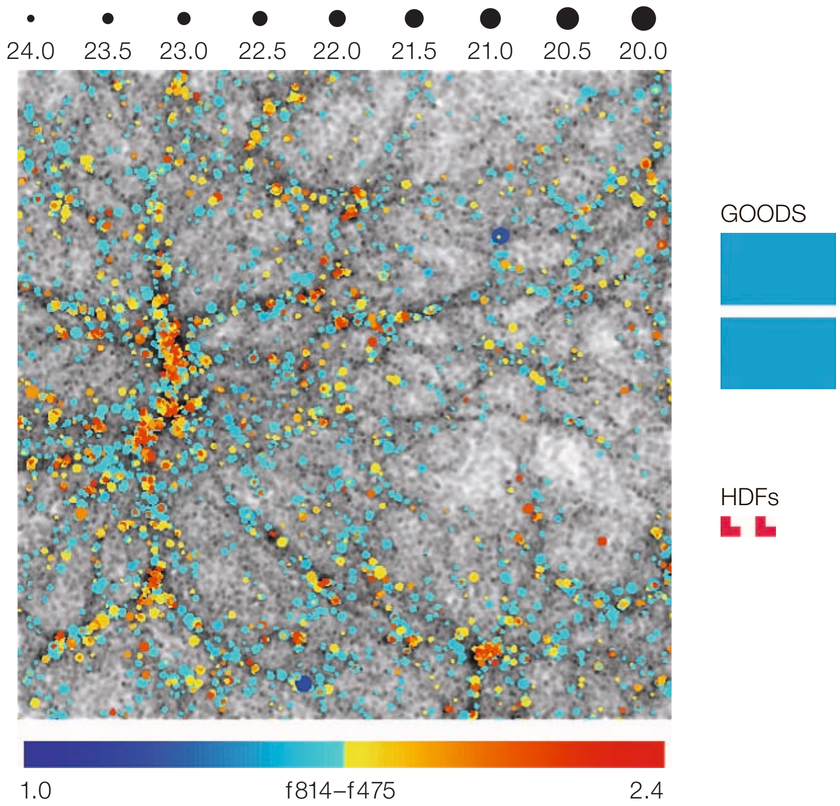

Figure 1: The 1.7 deg^2 COSMOS field compared with large-scale structure in a $\Delta z = 0.02$ slice of the Universe at $z \sim 1$ (courtesy Andrew Benson). Dots represent galaxies, colour-coded according to their observed colour (lower scale) and by size according to apparent magnitude (upper scale). The distribution of galaxies in the cosmic web of filaments and voids is clearly seen. By comparison the much smaller fields of view of the HDFs and the GOODS surveys (on the right) do not well sample the range of structures and environments that are present in the Universe at any epoch.

The global COSMOS project

The Cosmic Evolution Survey (COSMOS) was designed to bring to bear on a single very large field all of the tools and observational techniques that have been developed for the study of the distant Universe. The COSMOS field (centred on $10^h\,00^m\,29^s\ +02°\,12'\,21''$) was chosen to be near the Celestial Equator so that it can be accessed from observatories in both hemispheres, e.g. the ESO VLT and ALMA as well as the large optical/infrared telescopes in Hawaii and Chile and the VLA radio telescope in New Mexico, USA.

The COSMOS project is built around a mosaic of 600 images taken with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST). The mosaic covers a contiguous area of 1.7 deg^2 and represents the largest single programme undertaken with the HST to date. The field spans a transverse dimension of 80 comoving Mpc at $z \sim 1$ and 160 comoving Mpc at $z \sim 3$ and covers a volume to $z \sim 3$ (about 50 million Mpc^3) that is approaching that of the entire local Sloan Digital Sky Survey at redshifts $z < 0.1$. The HST observations were completed in June 2005. Despite being only single-orbit exposures, the broad F814W filter reaches to within 0.3 magnitudes of the well-known GOODS images even though the survey covers an area twenty times larger than the combined GOODS-N and GOODS-S fields (see Figure 1).

Impressive as the HST images are, the real power of COSMOS stems from the addition of a wealth of other observations that are being amassed on this field by the truly global COSMOS consortium. Most notably, the SuprimeCam on the Subaru 8-m has been used to obtain very deep BGVRIZ images of the whole field with a limiting magnitude (5σ) of about AB ~ 26–27. These have been supplemented by *U*-band and *K*-band images from the CFHT and NOAO 4-m telescopes. The combined photometric catalogue contains well over 1 million galaxies with photometrically estimated redshifts and approximate spectral types. The field has also been observed with the GALEX ultraviolet satellite to a depth of AB ~ 26 at 150 and 225 nm. Observing time on the Spitzer observatory has been awarded to extend this photometric coverage into the mid-infrared 3–8 μm which will substantially improve the photometric redshifts and the estimates of the stellar masses of the galaxies. Ultimately, we hope to have photometry and images from a suite of almost 30 intermediate- and broad-band filters spanning the full range of starlight in the ultraviolet, optical and near-infrared (150 nm – 8 μm) wavebands.

Deep imaging observations at other wavelengths, e.g. the X-ray and radio, reveal the signatures of accretion onto black holes in active galactic nuclei (AGN) and of energetic bursts of star formation that are obscured by dust. A mosaic of deep X-ray images obtained with the ESA XMM-Newton satellite have already yielded more than 1000 active galactic nuclei and about 100 X-ray selected groups and clusters of galaxies, while deep VLA images at 1.4 GHz reaching to about 50 μJy (5σ) will detect 4000 radio sources. Future observations planned at far-infrared and sub-millimetre wavelengths will complete the observational picture.

What distinguishes COSMOS from previous programmes such as the Hubble Deep Fields, GOODS and COMBO-17/GEMS, is its enormous area. This gives us:
- unprecedentedly large samples of objects in the distant Universe, thereby ensuring statistical weight even for rare classes of objects (see Table 1);
- confidence that we are sampling truly representative volumes of the Universe at high redshift (mitigating the so-called cosmic variance problem associated with smaller surveys that effectively probe a one-dimensional beam through the Universe);
- the ability to place all objects in their environment, from small scale groups of galaxies up to the largest structures in the Universe.

Table1: Numbers of representative objects in the COSMOS survey.

COSMOS Inventory Category	Selection	Number
Faint galaxies	$I_{AB} < 27$	1 million
X-ray selected AGN	$I_{AB} < 27$	3 400
X-ray selected clusters	$S_X > 5 \times 10^{-16}$ c.g.s.	100
Radio sources	$S_{1.4} > 50$ µJy	4 000
Bright quasars	$B < 21$	100
High z quarsars ($z > 4$)	$I_{AB} < 25$	50
ULIRGS	…	3 000
Lyman break galaxies	$I_{AB} < 25.5$	10 000
Passive galaxies ($z \sim 3$)	$K_{AB} < 24$	10 000
zCOSMOS $0.3 < z < 1.2$ galaxies with redshift	$I_{AB} < 22.5$	25 000
zCOSMOS $1.3 < z < 2.5$ galaxies with redshift	$B_{AB} < 25$	12 500

Such a unique data set of course opens other equally unique possibilities. For instance, the HST images will allow the distribution of dark matter to be mapped down to structures of order 3×10^{13} $M_\odot$, which may be compared with the distribution of luminous galaxies. In addition, the large number of quasars bright enough for absorption line spectroscopy (Table 1) will enable us to map the distribution of neutral gas in the intergalactic medium and again, compare that with the large-scale structure defined by the galaxies.

The zCOSMOS redshift survey

The COSMOS data sets mentioned above consist of exquisite two-dimensional images of the sky at almost every imaginable wavelength. The crucial third dimension is added by knowledge of the redshifts of the sources. Some information on the redshifts may be derived from the broad-band colours of the objects, so-called "photometric redshifts", but the more secure and precise "spectroscopic redshifts" are required for many purposes: The increased precision relative to the best attainable photometric redshifts enables the delineation of the cosmic web of large-scale structure in the Universe, from small groups of galaxies up to the largest filaments and voids. The measurement of individual velocities of galaxies enables dynamical studies of these structures, yielding masses, dynamical states and cosmological information. The spectra themselves yield important diagnostics of the evolutionary state of individual galaxies, including measures of the star-formation rate, dust extinction, the gas and stellar metallicities, and stellar population parameters such as ages. The spectra can confirm the identifications of radio and X-ray sources through the characteristic signatures of AGN or starburst activity. Precise spectroscopic redshifts can of course also be used to improve and characterise the photometric redshift schemes which can then be applied to every galaxy in the field.

The VIMOS instrument on the VLT provides ESO with a unique capability for undertaking such a survey and in P75 a Large Programme was awarded 540 hours of observation time to carry out the zCOSMOS redshift survey. This programme is complementary to the other large VIMOS programme, the VVDS Survey carried out by the VIMOS Instrument Team.

The design of the zCOSMOS programme has been driven primarily by the desire to quantify the environments of galaxies and AGN over a broad range of epochs. This requires: A high sampling completeness (~ 70 % of objects observed from a given target sample); uniform sampling coverage across the whole field; a broadly contiguous redshift coverage from very low redshifts to redshifts $z > 2.5$ spanning 80 % of cosmic time; relatively high velocity accuracy (100 kms^{-1}). To achieve these requirements efficiently, the zCOSMOS programme is split into two components, each requiring different VIMOS configurations and exposure times.

The "bright" sample of 25 000 COSMOS galaxies is selected to have $I_{AB} < 22.5$. The straight *I*-band selection yields a sample of galaxies at $0.2 < z < 1.2$, reaching 1.5 mag below L* at $z \sim 0.7$ where it corresponds to selection in the rest-frame *V*-band. With a sampling rate of at least 70 % and a velocity accuracy of at least 100 kms^{-1}, enabling the isolation of groups down to $3 \times 10^{12.5}$ $M_\odot$, the "bright" sample is designed to be directly comparable to the very large zero-redshift samples (SDSS and 2dfGRS) but at a look-back time of half the age of the Universe. The input target list is generated from the HST/ACS images. The observations are made with the VIMOS MR grism in 1 hr exposures between $550 < \lambda < 960$ nm at resolution $R \sim 600$. About 160 galaxies can be observed simultaneously. Successive VIMOS pointings are stepped in Right Ascension and Declination so that every galaxy in the target sample has eight opportunities to be selected into a spectroscopic mask, ensuring a uniform statistical sampling across the field without significant biases against near neighbours, etc.

The extension to higher redshifts requires a different strategy. We know from the VVDS survey that simply selecting fainter galaxies results in a sample that is still dominated by relatively low redshift galaxies, with only a small "tail" at higher redshifts $1.5 < z < 4$ emerging faintwards of AB ~ 23.5. In order to isolate this tail, the zCOSMOS "faint" sample of 12 500 galaxies is selected using a combination of proven colour-colour selection criteria, specifically the (B-Z)/(Z-K) selection proven by the VLT K20 survey and a development of the (U-G)/(G-R) selection used by Charles Steidel and collaborators to isolate star-forming galaxies. These two selection criteria yield a sample of galaxies at $1.2 < z < 2.4$ and $B_{AB} < 25.0$. In order to keep the total programme size manageable, the higher redshift part of zCOSMOS is limited to the central 1 deg^2 area, which nevertheless still yields a comparable comoving transverse dimension to that of the lower redshift component. A four-pass strategy with VIMOS and the LR-Blue grism ($370 < \lambda < 670$ nm at R ~ 200) should yield redshifts in 4.5 hr exposures for 12 500 such galaxies, with a similar sampling rate as for the bright sample, and a velocity accuracy of 300 kms^{-1}.

In both parts of the survey, radio source and X-ray source candidate identifications are added to the masks either as random targets (which will be observed with a roughly 70 % sampling rate) or, for high priority and urgently needed sources, as compulsory targets which are observed with close to 100 % efficiency early in the programme.

zCOSMOS schedule and data release plans

Execution of a programme of the size of zCOSMOS on a single field places unique demands on ESO in the scheduling of the VLT: to be completed in a timely manner, the UT3 must be used for this programme for essentially all the time that the field is observable. Periodic data releases will be made with a final comprehensive data set placed in the ESO Archive shortly following completion of the programme, thereby providing the general research community with a detailed census and sample of the distant Universe.

URL references

http://www.astro.caltech.edu/~cosmos
http://www.exp-astro.phys.ethz.ch/zCOSMOS

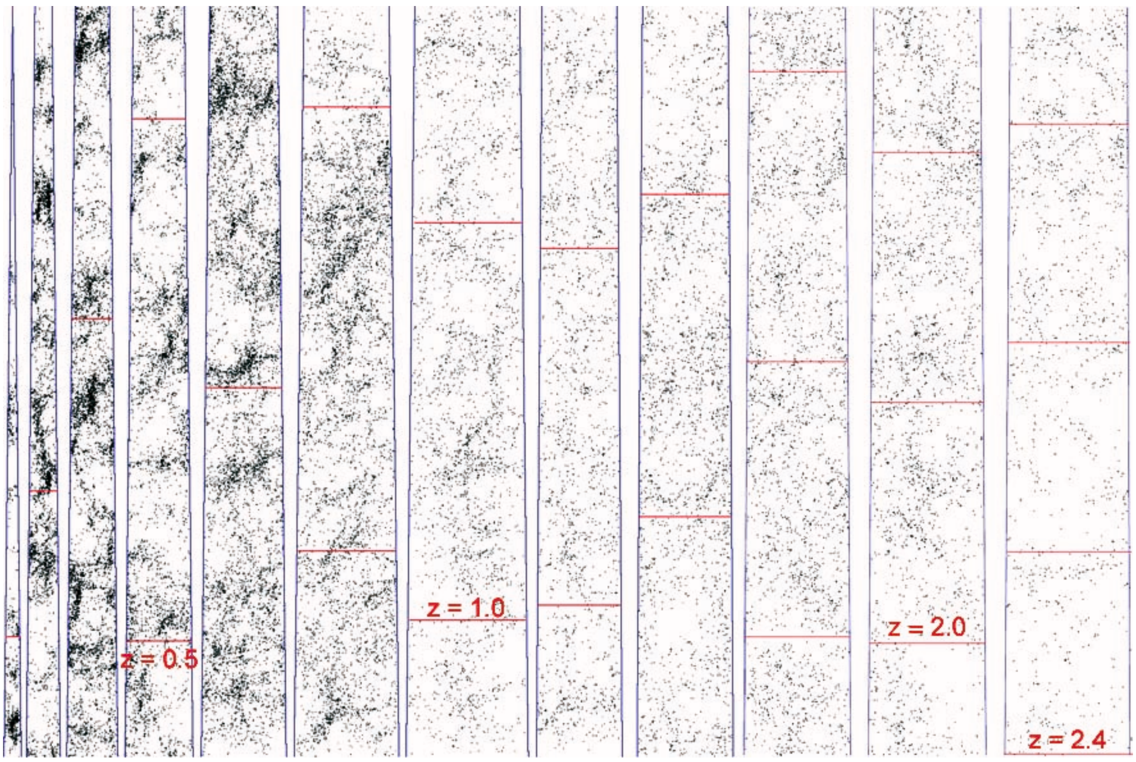

Figure 2: Simulation of the final zCOSMOS redshift survey showing the spatial distribution (in comoving space) of objects in the survey over the redshift interval $0 < z < 2.4$, in which every dot represents a zCOSMOS galaxy with spectroscopically determined redshift. The red bars mark increments of 0.1 in redshift z. The figure has been generated from the COSMOS mock catalogues produced from the Millennium Run cosmological simulation (courtesy of Manfred Kitzbichler).