The WiggleZ Dark Energy Survey

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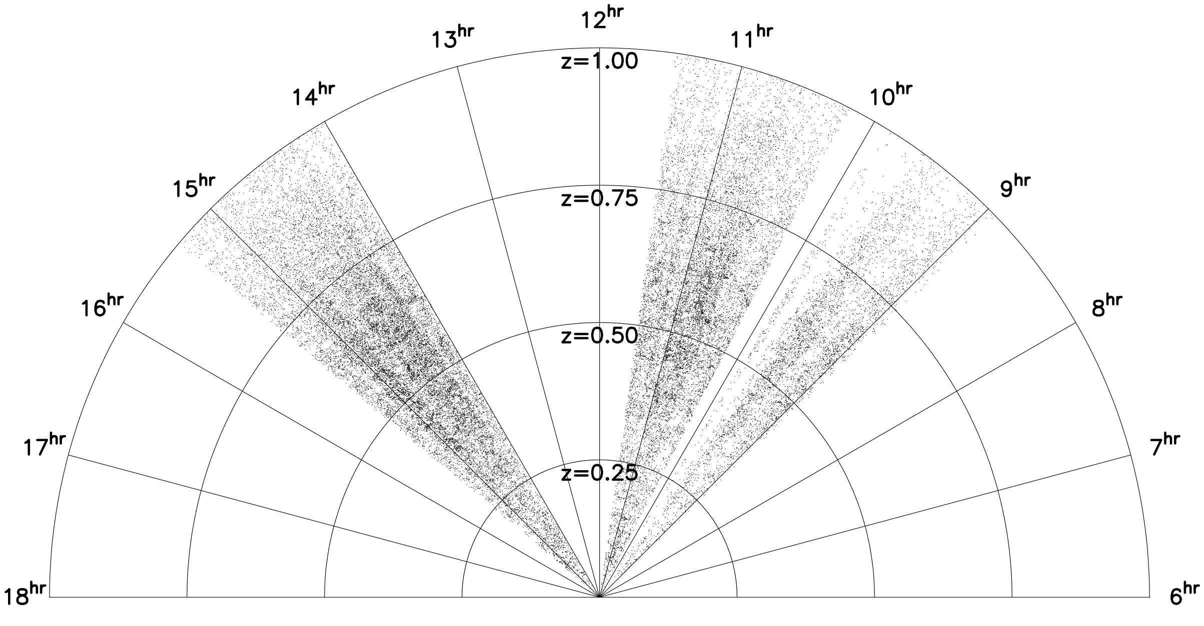
Abstract: The accelerating expansion rate of the Universe, attributed to "dark energy", has no accepted theoretical explanation. The origin of this phenomenon unambiguously implicates new physics via a novel form of matter exerting negative pressure or an alteration to Einstein's General Relativity. These profound consequences have inspired a new generation of cosmological surveys which will measure the influence of dark energy using various techniques. One of the forerunners is the WiggleZ Survey at the Anglo-Australian Telescope, a new large-scale high-redshift galaxy survey which is now 50% complete and scheduled to finish in 2010. The WiggleZ project is aiming to map the cosmic expansion history using delicate features in the galaxy clustering pattern imprinted 13.7 billion years ago. In this article we outline the survey design and context, and predict the likely science highlights.

Figure 1:



Caption: The distribution of galaxies currently observed in the three WiggleZ Survey fields located near the Northern Galactic Pole. The observer is situated at the origin of the co-ordinate system. The radial distance of each galaxy from the origin indicates the observed redshift, and the polar angle indicates the galaxy right ascension. The faint patterns of galaxy clustering are visible in each field.

Introduction: Dark Energy, a euphemism for new physics

A perplexing picture of cosmology has emerged over the last decade. Several different observations concur that the Universe has entered a startling phase of accelerating expansion propelled by a mysterious component of repulsive gravity known as "dark energy". This component apparently constitutes about 70% of the current energy density of the Universe. Intriguingly, the cosmic acceleration began at roughly the same time as the formation of life on our planet. The study of dark energy has a fascinating history as reviewed recently in these pages by Calder & Lahav [1].

There is currently no theoretical explanation for the existence or magnitude of dark energy. The accelerating cosmos therefore provides an outstanding opportunity for cosmologists to challenge fundamental physics, with two possible outcomes. Firstly, the Universe could be dominated by a new and unsuspected form of matter which exerts a negative pressure. The leading candidate here is the "cosmological constant", the energy of the quantum vacuum. However, it is extraordinarily difficult for fundamental quantum theory to reproduce the observed amplitude of dark energy; typical predictions are over-estimates by more than one hundred orders of magnitude. These problems have motivated a set of alternative suggestions in which dark energy is codified as a "scalar field" which fills all space. Examples of other hypothesized scalar fields in physics include the mechanism which propelled cosmic inflation, and the Higgs field which may endow particles with mass.

The second possible outcome is that Einstein's vision of gravity, general relativity, is incorrect on large cosmological scales. In this case dark energy would encode the discrepancy between relativity and an unknown modified theory of gravity, for which a number of suggestions exist. Alternatively, perhaps our derivation of the equations of cosmology, in which we approximate the Universe as homogeneous despite its extreme clumpiness, can induce the illusion of apparent accelerating expansion [2].

In summary, dark energy is a precious clue in the quest to understand fundamental theory. Unravelling its origin is likely to entail a revolution in our understanding of physics, string theory or quantum gravity. A rich landscape of cosmological surveys has grown in recent years to meet this goal, measuring the influence of dark energy via a variety of observational techniques. A combination of observations is in fact required to identify unequivocally the nature of dark energy. In particular, we must seek out discrepancies between the expansion history of the Universe and the rate of growth of cosmic structure within that overall expansion. This comparison can distinguish between the different propositions of dark energy such as modified gravity and scalar fields.

WiggleZ in the landscape of galaxy redshift surveys

The WiggleZ Dark Energy Survey at the Anglo-Australian Telescope is one of the earliest of this new generation of dark energy-focussed surveys, commencing in August 2006 and scheduled to finish in July 2010. The observations are being performed by a small core team of 14 Australian-based astronomers. The goal of the project is to construct a new large-scale galaxy redshift survey spanning a deep and wide slab of the cosmos from moderate-redshift ($z \approx 0.25$) to high-redshift ($z \approx 1$) over a sky area of 1000 deg^2. Part of the current galaxy database is displayed in Figure 1.

This unprecedented combination of redshift depth and survey area will allow us to probe the nature of dark energy with multiple methods, covering the redshift range where the transformation from decelerating to acceleration expansion is thought to occur (see Figure 2). Our position in the parameter space of current and future galaxy redshift surveys is illustrated in Figure 3. WiggleZ is much deeper in redshift than previous wide-area spectroscopic surveys such as the 2-degree Field Galaxy Redshift Survey (2dFGRS) and the Sloan Digital Sky Survey (SDSS). It is orders of magnitude wider in areal coverage then previous high-redshift surveys such as the Deep Extragalactic Evolutionary Probe (DEEP2) [3].

The large-scale structure of the Universe is one of the most fertile sources of cosmological information and a long-standing pillar of cosmology's "standard model". The patterns of galaxy clustering, shaped by the competing forces of inward gravity and outward expansion, encode information about the constituents of the Universe and the physical processes by which cosmic structure condenses and amplifies from initial small fluctuations. In the early 1990s, combined analyses of galaxy clustering and the Cosmic Microwave Background (CMB) fluctuations provided the first strong evidence for the currently-accepted dark energy-dominated cosmological model [4]. This model received spectacular confirmation through later observations of faint supernovae as standard candles [5].

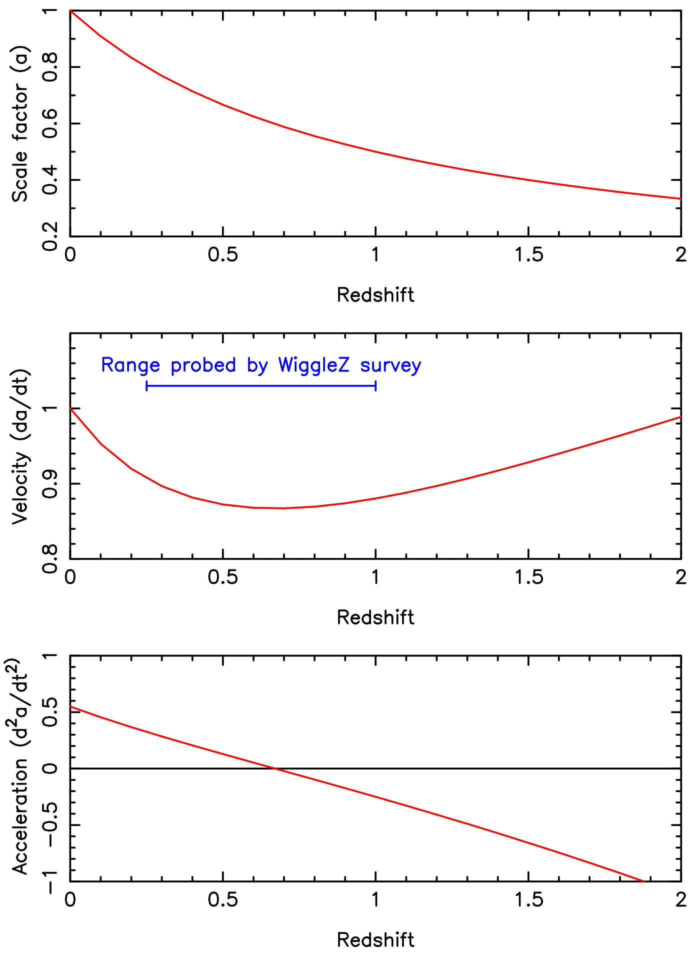
The cosmological power of galaxy redshift surveys was boosted further by the realization that the pattern of galaxy clustering encoded a robust "standard ruler" which could be used to map out the cosmic expansion history in a manner analogous to supernova standard candles [6]. The nature of this standard ruler is a small preference for pairs of galaxies to be separated by a co-moving distance of 150 Mpc. This favoured scale is an extraordinary echo of sound waves which propagated 13.7 billion years ago through the matter-radiation plasma before CMB last-scattering, less than 380,000 years after the Big Bang. These sound waves were sourced by primordial dark matter haloes, which launched spherical wave-crests driven by radiation pressure from the compressed baryon-photon plasma. These sound waves travelled rapidly in the early Universe, at 58% of the speed of light, covering a co-moving distance of 150 Mpc between the Big Bang and the last-scattering epoch. Both the initial dark matter halo and the spherical baryonic shell preferentially seed the later formation of galaxies, imprinting the standard ruler into the large-scale clustering pattern. Because the radiation is tightly coupled to the baryons, the signature of the acoustic waves is also imprinted in the microwave background photons (see Figure 4).

A powerful aspect of this cosmological distance probe that differentiates it from supernova observations is that the standard ruler can be applied in both the tangential and radial directions, i.e. perpendicular and parallel to our line-of-sight (see inset). Tangentially we measure a preferred angular clustering scale of about 3 degrees, which determines the cosmic distance in a similar manner to a supernova flux. Radially we extract a preferred redshift-space clustering scale, which specifies the cosmic expansion rate or Hubble parameter at high redshift. This expansion parameter depends directly on the underlying energy densities and is extremely difficult to measure with other methods.

The standard ruler scale of 150 Mpc can be predicted very accurately from the densities of dark matter and baryons inferred from observations of the CMB fluctuations. The Wilkinson Microwave Anisotropy Probe (WMAP) has already measured the scale with an error of 1.3% [7], and this will be improved even further by the European Space Agency's *Planck* satellite which will soon be launched [8]. The difficulty in applying the ruler lies in measuring the signal over vast cosmic distances. The accuracy with which a galaxy survey can measure the underlying spectrum of clustering fluctuations is limited ultimately by its volume, which determines the number of Fourier modes of a given scale that the survey can resolve. In Fourier space, the 150 Mpc preferred scale corresponds to a series of harmonics ("wiggles" or "baryon oscillations") in the galaxy power spectrum, by analogy with the set of frequency harmonics excited by an organ pipe of fixed length. It is interesting to note that current galaxy redshift surveys have mapped a vanishingly small fraction of less than 0.01% of the volume information (or Fourier amplitudes) contained in the observable Universe.

The baryon oscillation standard ruler has already been detected at low redshifts ($z = 0.2$ and $z = 0.35$) in the distribution of Luminous Red Galaxies in the SDSS [9, see Figure 4]. The aim of the WiggleZ Dark Energy Survey is to extend this delineation of the redshift-distance relation by adding further data points up to $z = 1$. After the addition of the WiggleZ results, which equate to a roughly 2% measure of the cosmic distance scale at $z = 0.7$, the accuracy with which baryon oscillation data can probe the properties of dark energy will be similar to supernova data (see Figure 5). This will provide a detailed cross-check of the two techniques, in which tensions could be indicative of systematic errors or new physics. Indeed, existing comparisons of the SDSS baryon oscillation measurements with supernova data are already showing hints of disagreements [10]. The WiggleZ Survey will also allow us to measure the growth of structure and test modified gravity theories.

Figure 2:



Caption: Behaviour of the scale factor of the Universe, a, for a cosmological constant model with matter density $\Omega_{\rm m} = 0.3$ and cosmological constant density $\Omega_\Lambda = 0.7$.

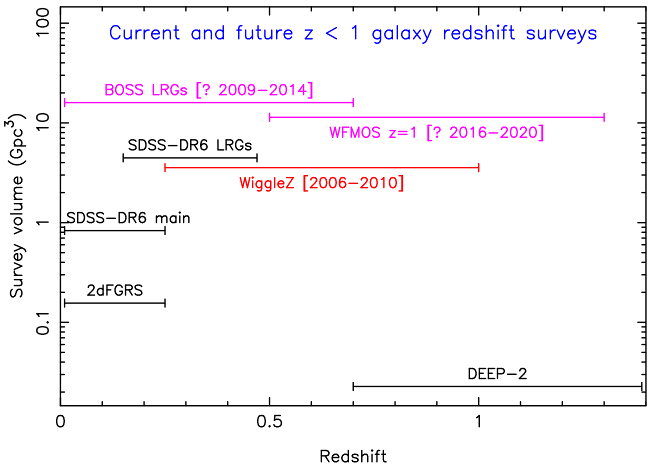
Top: Variation with redshift of the scale factor.

Middle: Variation with redshift of the time derivative of the scale factor, $\dot{a}$, which represents the "velocity" of the cosmic expansion. The y-axis is in units of H_0, the Hubble constant at $z = 0$.

Bottom: Variation with redshift of the second time derivative of the scale factor, $\ddot{a}$, which represents the "acceleration" of the cosmic expansion. The y-axis is in units of H_0^2.

Notice that the transition from decelerating to accelerating expansion occurs at redshift $z \approx 0.7$, which lies near the centre of the target redshift range of the WiggleZ Survey, as illustrated in the middle plot.

Figure 3:



Caption: The redshift range and cosmic volume mapped by the WiggleZ Survey (red line) compared to various current (black) and future (pink) galaxy redshift surveys [11] –

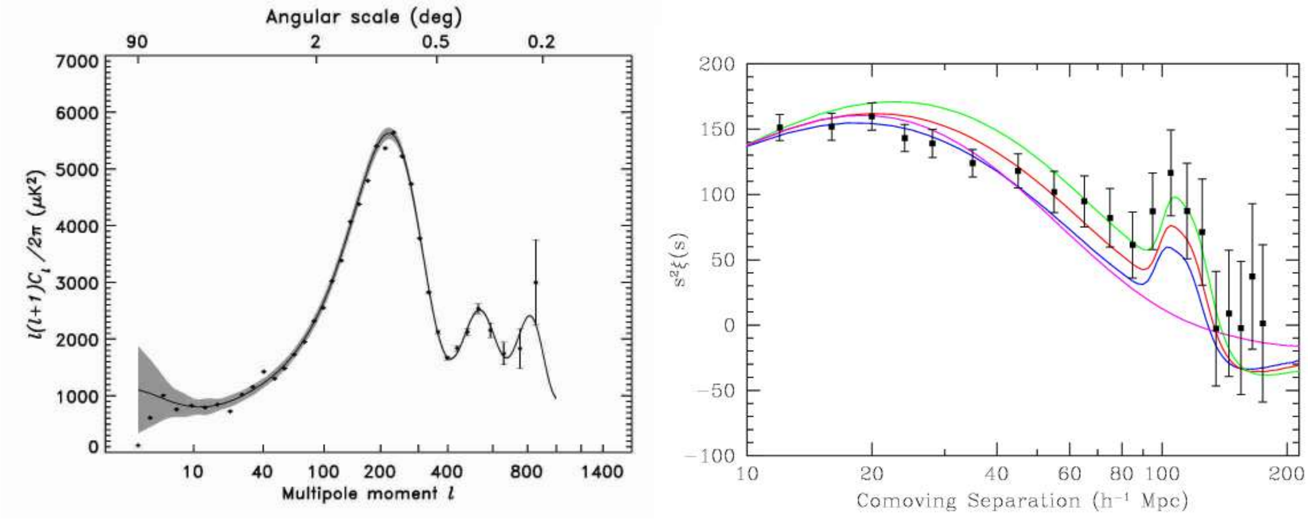
2dFGRS: 2-deg Field Galaxy Redshift Survey

SDSS-DR6: Sloan Digital Sky Survey

BOSS: Baryon Oscillation Spectroscopic Survey to be undertaken by the Sloan Consortium

WFMOS: survey performed by the proposed Wide-Field Multi-Object Spectrograph

Figure 4:



Caption: Baryon acoustic oscillations measured in the CMB radiation and galaxy distribution.

Left: The spectrum of temperature fluctuations in the CMB, as determined by the Wilkinson Microwave Anisotropy Probe [12]. The "wiggles" are produced by acoustic waves in the baryon-photon plasma before recombination. The peak in the power spectrum at an angular scale of ≈ 1 deg corresponds to the angular size of the 150-Mpc sound horizon projected at the distance of the CMB.

Right: The spectrum of density fluctuations in the distribution of Luminous Red Galaxies in the Sloan Digital Sky Survey [9]. The bump at separation $105h^{-1}$ Mpc $= 150$ Mpc corresponds to a preferred clustering scale and is the corresponding imprint of the acoustic waves in the galaxy distribution. The amplitude of this signal is much lower than that seen in the CMB radiation because the baryons, which carry the imprint of acoustic oscillations, are sub-dominant to cold dark matter.

Inset: the use of baryon oscillations as a standard ruler

Galaxies cluster with a known preferred separation, $\Delta S_{\rm BAO}$, which is determined from the physics of the CMB. In our observations of the galaxy distribution this preferred length imprints itself as a preferred angular separation on the sky, $\Delta\theta_{\rm BAO}$, and a preferred redshift separation, $\Delta Z_{\rm BAO}$. Measurements of $\Delta\theta_{\rm BAO}$ and $\Delta Z_{\rm BAO}$ at different redshifts can be used to deduce the cosmic distance-redshift relation, $D_A(z)$, and Hubble-parameter-redshift relations, $H(z)$:

$$D_A(z) = \Delta S_{\rm BAO}/\Delta\theta_{\rm BAO} \quad (1)$$

$$H(z) = c\,\Delta Z_{\rm BAO}/\Delta S_{\rm BAO} \quad (2)$$

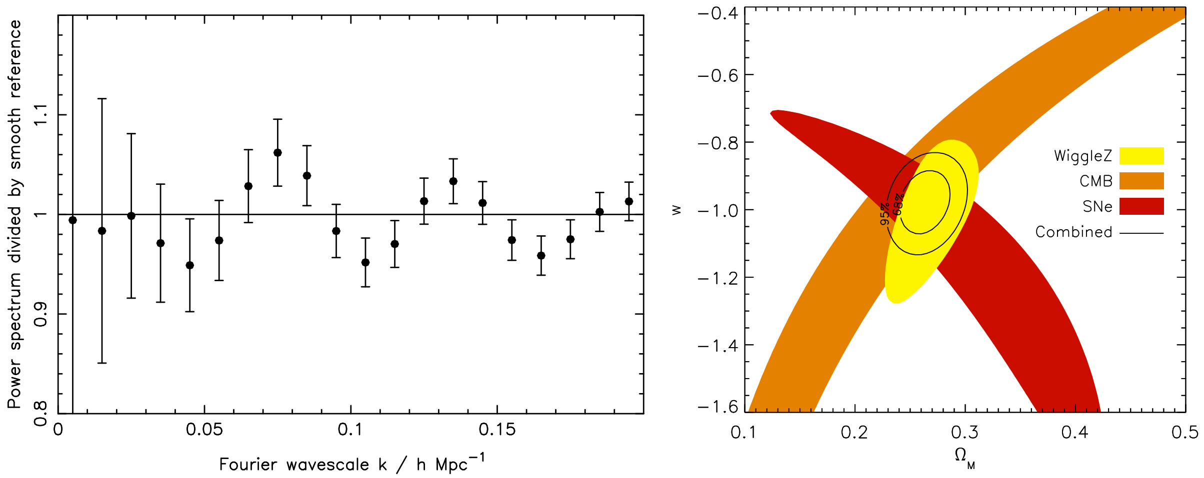
The measurements of D_A and H may be linked to the underlying contents of the Universe that determine the expansion history. For a geometrically flat Universe containing dark energy with an equation of state w:

$$H(z) = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + (1-\Omega_{\rm m})(1+z)^{3(1+w)}} \quad (3)$$

$$D_A(z) = \int_0^z [c/H(z')]\,dz' \quad (4)$$

where $\Omega_{\rm m}$ is the current matter density, H_0 is Hubble's constant, and c is the speed of light. Thus measurements of $H(z)$ and $D_A(z)$ may be used to deduce the properties of dark energy.

Figure 5:



Caption:

Left: A simulation of the power spectrum of galaxy clustering which will be measured from the final WiggleZ Dark Energy Survey. The power spectrum has been divided by a smooth "reference" spectrum fit in order to illustrate the detection of the baryon oscillations in the clustering pattern.

Right: Simulated cosmological parameter measurements using baryon oscillations in the final WiggleZ Dark Energy Survey. This figure focuses on measurements of the matter density, $\Omega_{\rm m}$, and the equation of state of dark energy, w. We assume a fiducial cosmological constant model with $\Omega_{\rm m} = 0.27$ and $w = -1$. The yellow ellipse indicates the 68% confidence region for measurement of these parameters using the WiggleZ Survey baryon oscillations combined with the CMB "acoustic scale parameter" ℓ_A, which calibrates the baryon oscillation preferred scale. The orange band indicates the confidence region obtained from WMAP measurements of the CMB "shift parameter". The red region displays the confidence region for latest supernova measurements. When the WiggleZ Survey is complete, the baryon oscillation data will measure the properties of dark energy with a similar precision to the supernova data, providing a detailed cross-check of the two techniques. The central confidence circles illustrate the dark energy measurements obtained by combining all the datasets.

Designing the WiggleZ Survey

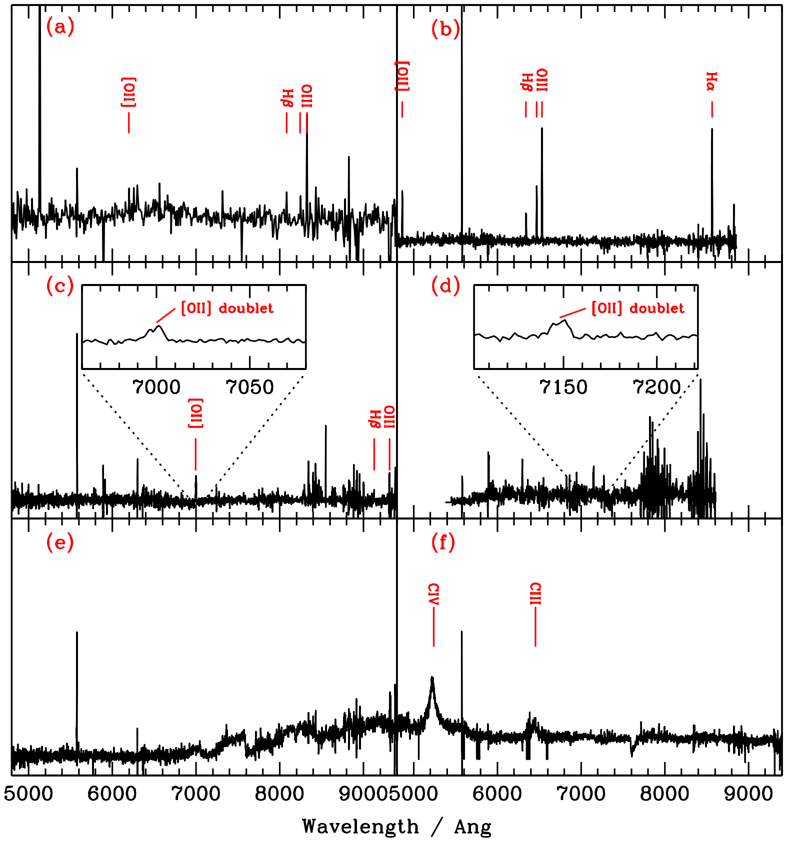
The key design decision for a galaxy redshift survey is how to select the spectroscopic targets. From a cosmological viewpoint, galaxies are simply tracer particles of the underlying spectrum of density fluctuations which encodes the baryon oscillation and growth information. Different classes of galaxy vary in the details of how they trace the density fluctuations. For example, red quiescent elliptical galaxies inhabit dense cluster environments more often than blue star-forming spiral galaxies. However, on large cosmological scales these details of galaxy formation are unimportant and can be essentially reduced to a single number, a "galaxy bias factor" specific to each galaxy class. The decision of galaxy target can then be simplified to observational considerations such as exposure time required to obtain a successful redshift.

The WiggleZ Survey is obtaining redshifts for over 200,000 luminous blue star-forming galaxies. The spectra of these galaxies, illustrated in Figure 6, are dominated by patterns of strong atomic emission lines originating in the ionized nebular gas in star-forming regions (in particular the rest-frame lines [OII] 3727Å, Hβ 4861Å and [OIII] 4959Å, 5007Å). These emission lines provide the galaxy redshift in a relatively short exposure of 1 hour on the 3.9-m Anglo-Australian Telescope, avoiding the need to detect the galaxy "continuum" light, which is about 4 magnitudes fainter than the spectroscopic targets observed by 2dFGRS or SDSS. The primary target database for the WiggleZ Survey is provided by the orbiting Galaxy Evolution Explorer (GALEX) satellite, a NASA Small Explorer Class mission, which is mapping the sky in ultraviolet (UV) light between 1400Å and 2800Å usually blocked by the Earth's atmosphere. Star-forming galaxies produce prodigious amounts of UV emission from their population of hot, young stars. The WiggleZ and GALEX collaboration is delivering about 1000 orbits of new UV imaging data across our target fields. In order to produce a sharp angular position for follow-up spectroscopy, we match the UV catalogues with optical imaging from the SDSS and the Red Cluster Sequence (RCS2) database obtained at the Canada-France-Hawaii Telescope [13].

We obtain WiggleZ redshifts using a multi-object fibre spectrograph at the Anglo-Australian Telescope called *AAOmega*, which is one of the world's most complex and successful pieces of astronomical instrumentation [14, see Figure 7]. AAOmega provides the capacity to obtain up to 392 galaxy spectra simultaneously using optical fibres placed on the focal plane by a robot positioner. The large field-of-view of the instrument, a 2-degree diameter circle on the sky, provides an unrivalled mapping speed. The new dual-beam spectrographs were commissioned in Febuary 2006 to replace the original spectrographs which had been used for the 2dFGRS. Mounted in the stable West Coude room at the AAT, the new spectrographs feature a wider simultaneous wavelength coverage, higher spectral resolution and improved sensitivity. The WiggleZ collaboration has also provided a new dichroic to extend the wavelength coverage of the low-resolution mode redwards to 9500Å in order to detect the highly-redshifted emission lines of our targets.

Completing the full WiggleZ Survey will require 160 clear nights of telescope time which have been spread over 4 years, mapping a total area of 1000 deg^2 split into several fields. At the time of writing (July 2008) the WiggleZ Survey is roughly 50% complete, having expended 112 nights to gather 110,000 galaxy redshifts. The first major scientific results will be announced during the next few months. The survey is also committed to public data releases of spectra and redshifts, the first being scheduled for about October 2008.

Figure 6:



Caption:

Example spectra from the survey:

(a) Galaxy with a high-quality redshift ($z = 0.6628$) determined by multiple emission lines.

(b) Galaxy with a high-quality redshift ($z = 0.3048$) determined by multiple lines, at a lower redshift than (a).

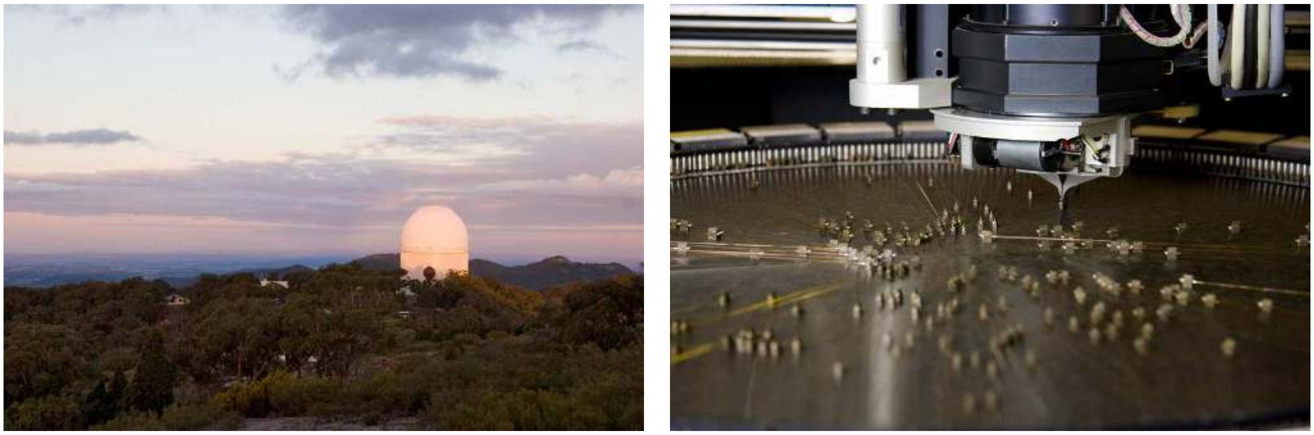
(c) Galaxy with fewer confirming emission lines but a confident redshift($z = 0.8775$) based on the [OII] doublet feature.

(d) Galaxy with a redshift ($z = 0.9173$) based solely on the [OII] doublet.

(e) Galactic star at $z = 0$.

(f) Quasar with a high-quality redshift ($z = 0.3048$).

Figure 7:



Caption:

Left: The Anglo-Australian Telescope, situated near the Warrumbungle National Park, New South Wales, Australia.

Right: The robot positioner placing optical fibres on the field plate of the AAOmega spectrograph.

WiggleZ Science – expected highlights

The WiggleZ Survey will have substantial impact beyond the measurement of baryon oscillations. Firstly, the survey will yield an accurate measurement of the shape of the galaxy clustering power spectrum on large scales. This shape depends on the relative abundance of baryons and dark matter in the early Universe, and can be used in conjunction with the CMB to provide more accurate estimates of the composition of the Universe. Of particular interest is that massive neutrinos act as hot dark matter in the early Universe, free-streaming to smooth out patterns of structure. Whilst particle physics neutrino oscillation experiments accurately determine the mass difference between neutrino species, cosmological observations can yield the absolute mass.

Secondly, the survey will test theories of gravity by mapping the growth of structure with redshift. This is achieved by extracting the coherent patterns of galaxy velocities that result from the bulk flow of matter into clusters and superclusters. These velocities cause small distortions in the measured galaxy redshifts, which collectively imprint a characteristic signature in the derived clustering spectrum. The strength of this signature, in comparison to the overall clustering amplitude of the galaxies, allows us to track the growth rate of structure.

Thirdly, detailed analysis of the star-formation rates, environments, morphologies and luminosity functions of the WiggleZ dataset will provide information on galaxy evolution. These objects are typically forming stars at a rate of tens of solar masses per year, significantly exceeding our own Milky Way. The highest-redshift galaxies in the sample have prodigious star formation rates exceeding 100 $M_\odot$ yr^{-1}. Do these massive starbursts result from major galaxy mergers? Does this process get suppressed or enhanced in dense cluster environments? Finally, the provision of hundreds of thousands of high-redshift galaxy spectra results in statistically-significant samples of rare and interesting classes of object such as Active Galactic Nuclei.

In parallel with our program of observations, we are generating large-scale cosmological N-body simulations using the supercomputer at Swinburne University of Technology. These simulations, populated with star-forming galaxies, will be a crucial ingredient in our interpretation of the survey data.

Conclusion: future prospects

The next decade is expected to be a golden age of cosmology as a series of impressive new surveys are executed. In the landscape of galaxy redshift surveys, WiggleZ will be succeeded by the Baryon Oscillation Spectroscopic Survey (BOSS) which should be executed by the upgraded SDSS telescope between 2009 and 2014. BOSS will target a vast volume of Luminous Red Galaxies over 10,000 deg^2 out to redshift $z = 0.7$ and also plans to map higher-redshift structure along the lines-of-sight to high-redshift quasars. In the medium-term, there is a currently-unfunded proposal to build a powerful 5000-fibre Wide-Field Multi-Object Spectrograph (WFMOS) for an 8-m telescope. At higher redshifts the Hobbly-Eberly Telescope Dark Energy Experiment (HETDEX) is planning to harvest spectra of Lyman-α emitting galaxies. Future radio telescopes will begin to detect the faint glow of neutral hydrogen emission from high-redshift galaxies, enabling transformational radio redshift surveys [15].

In parallel, a new suite of deep and wide optical imaging surveys will emerge. The first PanStarrs telescope on Mauna Kea is already operating and another three are planned. The Dark Energy Survey project will be mapping 5000 deg^2 of southern sky from the 4-m Blanco telescope in

Chile. A dedicated 8-m wide-field Large Synoptic Survey Telescope (LSST) is on the horizon. These deep images will allow cosmologists to detect millions of new supernovae and perform precise measurements of the faint signature of gravitational lensing. New space missions have also been proposed, including the Joint Dark Energy Mission (JDEM) in the United States and the Euclid mission in Europe [16].

This wealth of new data will pose an unprecedented challenge to the existing standard cosmological model. If the unexpected need for dark energy is interpreted as a serious failure of the model, then we could be on the brink of a paradigm shift which introduces a new cosmological framework.

References

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[3] Websites of the projects mentioned in this paragraph are as follows –
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BOSS: `http://www.sdss3.org/cosmology.php`
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BOSS: `http://www.sdss3.org/cosmology.php`

HETDEX: `http://www.as.utexas.edu/hetdex`
Square Kilometre Array: `http://www.skatelescope.org/pages/page_astronom.htm`

[16] Websites of the projects mentioned in this paragraph are as follows –
PanStarrs: `http://pan-starrs.ifa.hawaii.edu/public/`
DES: `http://www.darkenergysurvey.org/`
LSST: `http://www.lsst.org/lsst_home.shtml`
JDEM: `http://universe.nasa.gov/program/probes/jdem.html`