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The WiggleZ project: AAOmega and Dark Energy

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Abstract. We describe the 'WiggleZ' spectroscopic survey of 400,000 star-forming galaxies selected from a combination of GALEX ultra-violet and SDSS + RCS2 optical imaging. The fundamental goal is a detection of the baryonic acoustic oscillations in galaxy clustering at high-redshift ($0.5 < z < 1$) and a precise measurement of the equation of state of dark energy from this purely geometric and robust method. The survey has already started on the 3.9m Anglo-Australian Telescope using the AAOmega spectrograph, and planned to complete during 2009. The WWW page for the survey can be found at `astronomy.swin.edu.au/wigglez`.

1. Introduction

One of the major triumphs of modern astrophysics over the last decade has been the extraordinary precision with which the cosmological parameters can now be

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measured from new experiments. The prime examples are measurements of temperature anisotropies in the Cosmic Microwave Background (CMB) radiation, the clustering of galaxies on large scales, the maximum brightness of distant Type Ia supernovae (SN), and the primordial abundances of the light elements. The age, expansion rate, geometry, matter and energy content of the Universe can now be determined to a precision of better than 10%. The remaining challenge to understanding the underlying physics is the profound discovery from distant SN studies that the expansion rate of the Universe is accelerating (Riess et al. 1998, Perlmutter et al. 1999). This result implies that the cosmic energy budget must be dominated by a new form of matter which has a negative pressure – 'dark energy' (Deffayet et al. 2002). The simplest explanation is an inherent energy density of the quantum vacuum (a 'cosmological constant' term) but is far short (by a factor of $c^5\,G^{-1}\hbar^{-1}H_0^{-2} \sim 10^{122}$) of the natural Planck energy density, thus motivating alternative models for the dark energy. Understanding the nature of this dark energy is one of the key 'Science Questions for the New Century' (Turner et al. 2003).

The most direct existing measurement of the cosmic acceleration comes from the observation of distant SN as 'standard candles'. After correction for the luminosity-light curve width correlation, these SN allow the measurement of distances to redshifts as high as $z = 1.7$ (Riess et al. 2004). However, there are concerns over potential systematic evolutionary effects masquerading as cosmological effects, suggesting that an independent cross-check of this result is crucial. A conceptually similar approach would be to use a 'standard ruler', or cosmic feature with a known absolute length-scale. The apparent size of this feature at a given redshift would yield the cosmic distance to that redshift. Since individual objects evolve, accurate cosmic measuring rods are rare. However, a newly-developed method is to use 'Baryonic Acoustic Oscillations' (BAO), which are features imprinted in the power spectrum of galaxy clustering. These features arise from acoustic oscillations in the dense early Universe that have a preferred scale, the 'sound horizon', and get frozen into the distribution of matter after recombination. After galaxy formation they are well-preserved on large scales despite the growth of non-linearities on smaller scales (Eisenstein, Seo & White 2007). Since the size of the sound horizon at recombination is accurately calibrated by CMB measurements, these 'baryon wiggles' act as a cosmic standard ruler and can in principle be used as a probe of dark energy (Blake & Glazebrook 2003, Seo & Eisenstein 2003). Currently the BAOs are only well-detected in the local Universe (Eisenstein et al. 2005 (E05), Cole et al. 2005), but in principle BAO galaxy redshift surveys can be performed at high redshift to measure precise distance scales. Spectroscopic surveys of $\gtrsim 10^3$ deg^2 and $\gtrsim 10^5$ galaxies are fundamentally required (Glazebrook & Blake 2005).

2. The WiggleZ survey

The goal of the 'WiggleZ' survey is to achieve the first detection of BAO features at *high-redshift* in a spectroscopic survey. A spectroscopic BAO survey has several requirements. A wide instrument field-of-view is desirable to cover large areas efficiently. A large-aperture telescope is required to reach high redshifts. A ready supply of deep well-calibrated imaging is necessary – which is one of the more difficult requirements to meet. One flexibility we can utilize is to sparsely-sample the large-scale structure with whichever class of galaxy allows the most rapid measurement of redshifts, given that all types of galaxies possess an approximately linear clustering bias on large scales. Also, the required redshift resolution is modest ($\Delta z \lesssim 0.001$), demanding only low-resolution spectroscopy. For the WiggleZ survey we found a good match to all these requirements from the combination of the wide-field ultra-violet GALEX satellite, the Sloan Digital Sky Survey (SDSS) and the AAOmega spectrograph on the 3.9m Anglo-Australian Telescope (AAT). This has allowed us to recently start a $0.5 < z < 1.0$ BAO survey of 400,000 emission-line galaxies over 1000 deg^2, which is planned to be completed during 2009.

We note that photometric-redshift surveys have already produced a tentative detection of BAOs at $z \approx 0.5$ (Padmanabhan et al. 2007, Blake et al. 2007). There are two main disadvantages of photo-z BAO surveys. Firstly, the radial smearing due to the photo-z error reduces the signal-to-noise of the power spectrum measurement. Secondly, spectroscopic surveys can resolve the oscillations in the *radial* and tangential directions, allowing direct determinations of the Hubble expansion rate $H(z)$ as well as the more conventional metric distance $D_A(z)$. Measurement of $H(z)$ at high-z is a unique feature of the BAO method.

2.1. Survey design: Imaging

When designing a BAO survey at high redshift we faced a key initial choice: *red galaxies or blue galaxies?* Red galaxies possess a higher clustering strength (galaxy bias), implying that a lower number density is required to minimize the shot noise of the large-scale structure measurement. Indeed, Luminous Red Galaxies in the SDSS produced the existing low-z BAO detection. On the other hand, it requires significantly more exposure time to obtain redshifts for red galaxies owing to their lack of emission lines and the consequent need to detect the galaxy continuum with a reasonable signal-to-noise ratio. Moreover, the higher clustering amplitude of red galaxies implies that the non-linear growth of structure (which erases the BAOs) influences the clustering pattern on larger scales. Our calculations of these factors showed that the blue galaxies were somewhat superior, with the emission-line redshifts promising greater robustness in poor observing conditions. Furthermore, we identified a clean way to select these blue galaxies as discussed below. We suggest that it will prove extremely valuable to pursue BAO detections using both blue and red galaxy populations, in order to understand the subtle systematic effects due to galaxy formation processes, and discover if these effects produce any significant distortion of the acoustic oscillation signature. We note that there are several proposed new surveys of red galaxies for BAO measurements in the $z < 1$ regime (Eisenstein et al., these proceedings), which the WiggleZ survey will complement.

A very elegant method of selecting emission-line galaxies with redshifts $z > 0.5$ is to use ultra-violet data from the GALEX satellite (Martin et al. 2005). Star-forming galaxies with $z > 0.5$ drop out of the far-UV (FUV) filter, due to the Lyman break, but have blue near-UV (NUV) to optical colours. We select galaxies with $20.5 < r < 22.5$, $NUV < 22.8$, $FUV - NUV > 1.5$ and $NUV - r < 2$, producing 400 galaxies deg^{-2} from the tip of the galaxy luminosity function at $z \sim 0.7$. These are luminous star-forming galaxies analogous to

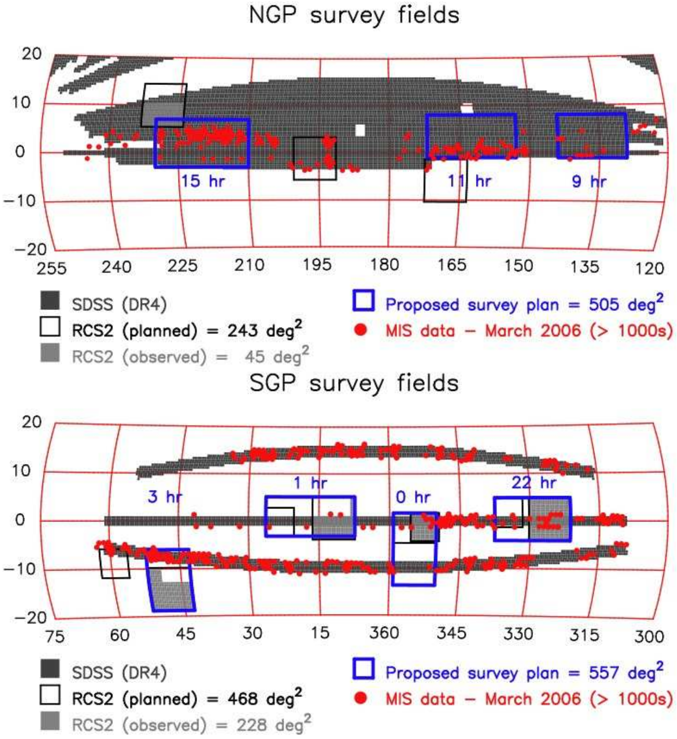

Figure 1. Layout of the WiggleZ fields in the NGP and SGP regions, illustrating the available SDSS, RCS2 and GALEX data.

(though somewhat redder than) the Lyman Break Galaxies at $z \sim 3$ (Steidel et al. 1996). The optical data is also required to produce an accurate fibre position for spectroscopy. The UV limit is the depth of the GALEX Medium Imaging Survey (MIS). The target density of 400 deg^{-2} is calculated as sufficient for suppressing galaxy shot noise assuming a reasonable clustering bias for high-redshift star-forming galaxies.

The choice of fields (Figure 1) is driven by the availability of existing optical data and the requirement that the sky patches be large and square enough (at least $\sim 9^\circ$ on each side) to probe structure on the scales relevant for BAOs (i.e., at least 2-3 times larger than the standard ruler size of $105\,h^{-1}$ Mpc). In the North Galactic Cap we are able to utilize the existing Sloan Digital Sky Survey (York et al. 2000). In the south, the SDSS stripes are too narrow (Figure 1). Accordingly, we supplement SDSS with data from the RCS2 survey (Yee et al., these proceedings) supplied to us via a collaborative arrangement. Additionally, we have chosen fields where large amounts of GALEX MIS data already exist. However, these data are patchy owing to GALEX bright-star avoidance constraints. This patchiness is on the scale of the GALEX field-of-view ($\approx 1^\circ$) and would produce unacceptable convolution of our measured power spectrum and damping of the measured BAOs. We are therefore using GALEX to tile these fields with a higher filling factor ($\gtrsim 70\%$, determined from

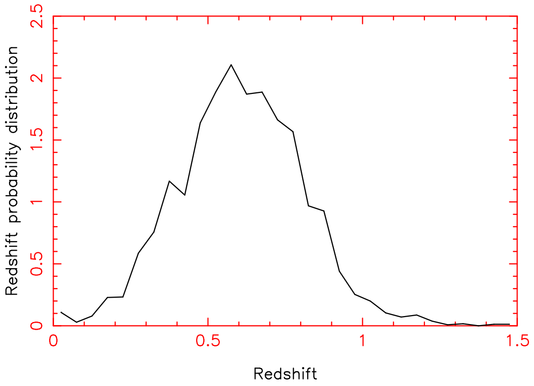

Figure 2. The galaxy redshift distribution resulting from the current WiggleZ survey target selection strategy.

simulations). This requires a modest additional amount of GALEX time at the rate of 400 orbits per year to extend MIS in order to feed the spectroscopic pipeline. Some care is needed with the GALEX observing plan: 'petal pattern' pointings must be used in some areas containing moderately bright stars.

2.2. Survey design: Spectroscopy

Sources are selected from matched UV and optical catalogues, and allocated to AAOmega pointing centres using a simulated annealing algorithm (Campbell, Saunders & Colless 2004). Fainter optical sources at preferentially higher redshift are assigned higher priority in the annealing scheme. On average, each part of the sky in our survey must be visited 4 times to achieve the required target density of 400 $\deg^{-2}$.

The WiggleZ survey is performed using the AAOmega spectrograph at the AAT. AAOmega is the upgraded Two Degree Field (2dF) system and is capable of taking spectra of 400 objects simultaneously across a 2° diameter field-of-view using optical fibres positioned by an XYZ robot. The fibres run down to a dual-beam spectrograph in the Coudé room which (for our setup) covers 3700–8750Å at a spectroscopic resolution of 5Å (FWHM). A full description of AAOmega and its various modes is given by Sharp et al. (2006).

One hour exposures with AAOmega yield redshifts for 80% of our galaxies in average usable conditions, for our optimized target selection. 1 hr is well-matched to the fibre reconfiguration time of the positioner system. Redshifts are usually identified from the [OII] and Hβ/[OIII] emission lines. For $z > 0.8$ only [OII] is visible, but at our spectroscopic resolution it is usually marginally resolved: we either see two peaks from the doublet or a 'fat' line. The only possible sources of contamination of emission lines with similar equivalent widths are Hα at $z \sim 0.1$ (removed by our FUV$-$NUV selection), or Lyα at $z \sim 5$ (which would have no UV flux). Additionally Hα would have to be very low metallicity to avoid [NII] being picked up. Thus we believe that our single-line redshift identifications are robust.

The resulting galaxy redshift distribution is shown in Figure 2 and covers the range $z < 1.3$. For the baryon oscillations analysis we plan to focus on redshift bins in the range $z > 0.5$. The entire redshift range will be used for galaxy evolution studies. Currently, about 70% of redshifts satisfy $z > 0.5$; we are still considering colour cuts to exclude $z < 0.5$ galaxies more efficiently. The

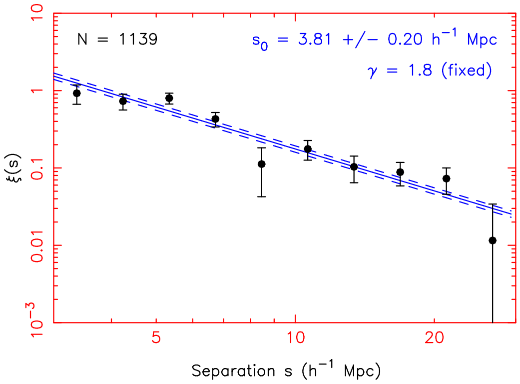

Figure 3. The projected redshift-space correlation function of the first $N = 1139$ WiggleZ survey galaxies. A spatial correlation function $\xi(r) = (s/s_0)^{-\gamma}$ was assumed in the fit.

ability to reach up to $z \sim 1$ in the same exposure time as the previous 2dF Galaxy Redshift Survey at $z \sim 0.1$ (Colless et al. 2001) is due to a combination of increased spectrograph sensitivity and the judicious target selection.

3. Current Status and Predicted Survey Performance

There have been two WiggleZ survey observing runs in August and November 2006, during which we accumulated a combined total of 15,000 redshifts. GALEX data acquisition is on-going. The full 220 nights of AAT time has been awarded, subject to a mid-term review in 2008. The WiggleZ team is planning mid-term and final public data releases in 2008 and 2009 respectively, in a VO-compliant format together with an SQL database.

We have measured the clustering properties of our sample using the first ≈ 1000 redshifts. Analysis of the full set of 15,000 redshifts is currently ongoing (Jurek et al. 2007, in prep.). The preliminary measurement of the two-point correlation function (Figure 3) is consistent with other measurements of luminous blue galaxies at these redshifts (Coil et al. 2006, Meneux et al. 2006).

Based on the clustering strength analysis, we can predict the signal-to-noise ratio of the final power spectrum measurement for a 1000 deg^2 survey. A simulation of this is shown in Figure 4. It can be seen that the sinusoidal BAO features are well detected; a Monte-Carlo analysis (Blake & Glazebrook 2003) finds that the BAO scale (and consequently the standard ruler at $\overline{z} \sim 0.7$) can be measured with an accuracy of about 2%. A full analysis of radial and tangential Fourier modes predicts that we can measure the expansion rate of the Universe at high redshift, $H(z = 0.7)$, with 4% accuracy. Implementing the improved method of 'reconstructing' the density field (Eisenstein et al. 2007), the predicted measurements of D_A and H are 1.8% and 2.7%, respectively.

These distance measurements can be propagated to constraints on the cosmological parameters, including the properties of dark energy, characterizing it by an equation of state $w = P/\rho$ (where $w = -1$ for a pure cosmological constant). Essentially we measure the cosmic distance and expansion rate at $z \approx 0.7$ in units of the sound horizon at recombination. In addition to w, these quantities depend on the matter density $\Omega_{\rm m}$, the zero redshift Hubble parameter h, and potentially a non-zero curvature $\Omega_{\rm k}$. Independent measures of these additional parameters are possible using the CMB or overall shape of the galaxy power

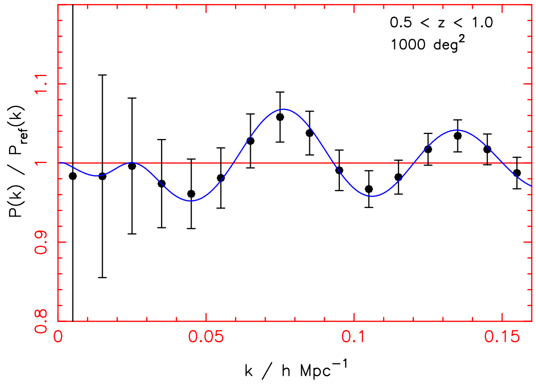

Figure 4. Simulated final survey power spectrum $P(k)$ of the WiggleZ survey. The overall shape of the power spectrum has been divided out to highlight the BAO features.

spectrum. As an example, Figure 5 shows simulated parameter measurements in the (Ω_m, w) space, assuming $\Omega_\mathrm{k} = 0$ and an external prior $\sigma(\Omega_\mathrm{m}) = 0.03$. Confidence contours for the WiggleZ survey (assuming the conservative case of no 'density reconstruction') are compared to those from the Supernova Legacy Survey current data (Astier et al. 2006) in order to illustrate the superb complementarity and systematic cross-checking possible with these two probes of dark energy. The equation of state can be measured with accuracy $\Delta w \approx 0.1$ in both cases. Introducing a curvature degree of freedom does not degrade these contours significantly, because curvature is tightly constrained by these distance measurements in conjunction with the CMB. In this context the BAO and SN methods are also complementary, because the BAOs measure distances relative to the last-scattering surface at $z \approx 1100$, whilst SN measure distances relative to a local calibration at $z \approx 0$.

In addition to the dark energy measurements, such a large galaxy spectroscopic survey will deliver much more science. A partial list includes: tests of neutrino masses and the physics of inflation using the shape of the large-scale power spectrum; testing galaxy formation models via small-scale clustering measurements and the dependence of luminosity functions, star-formation rates, metallicity and colour on environment.

4. Summary

The WiggleZ survey is on schedule to deliver the first precision high-redshift BAO dark energy constraints. It will be an independent, complementary and constraining test of the accelerating Universe paradigm: measuring cosmological acceleration completely independently of any SN systematic effects; complementary to SN observations via orthogonal confidence regions; and highly constraining by virtue of per-cent level distance and expansion rate measurements. Given the current progress of the WiggleZ survey we are expecting our first BAO detection and dark energy results to appear in 2008. The results from WiggleZ will have a major impact on the design of future BAO experiments using new instruments and larger 8m-class telescopes, such as WFMOS (Glazebrook et al. 2005) and HETDEX (Hill et al. 2004).

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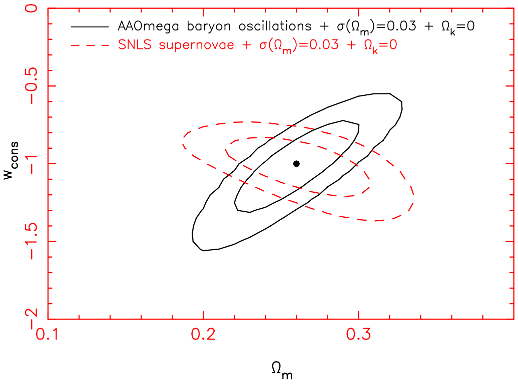
Figure 5. Simulated cosmological parameter measurements in the space of $(\Omega_{\rm m}, w)$ comparing those from the future WiggleZ survey (+ the E05 $z \simeq 0.35$ BAO constraint from SDSS) with the current Supernova Legacy Survey data.



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