

Large-Scale Structure Beyond the 2dF Galaxy Redshift Survey

Gavin Dalton^{a,b}

^aAstrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, UK,

^bRutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK

ABSTRACT

I present a summary of the main results so far obtained from the 2dF Galaxy Redshift Survey. These include its role in defining a detailed picture of contemporary cosmology, a description of the way in which different spectral types of galaxies trace the Large-Scale Structure of the present day Universe, and the way in which key results have been combined with recent observations of the Cosmic Microwave Background to produce the so-called Concordance Cosmology. I then discuss possibilities for a similar survey that could be constructed above $z = 1$ using FMOS and present a route for obtaining the requisite imaging data for such a survey in a timely manner, and conclude with a discussion of issues that may arise for a single FMOS survey programme which could be built from the merging of many disparate scientific themes.

1. INTRODUCTION: THE 2dF GALAXY REDSHIFT SURVEY

The 2dF Galaxy Redshift survey¹ was constructed from spectroscopic observations of 221,283 galaxies selected from the APM Galaxy Survey² to a magnitude limit of $b_J < 19.45$. The galaxies were selected regions either side of the Galactic plane to allow all-year-round observations which were carried out over some 250 nights at the AAT between October 1997 and April 2002. The survey selection function gives a median redshift of $\langle z \rangle = 0.11$ such that the majority of objects in the survey are found at $z < 0.3$. The selection function shows significant clustering at $z < 0.1$. The clustering pattern seen in the survey is illustrated in Figure 1.

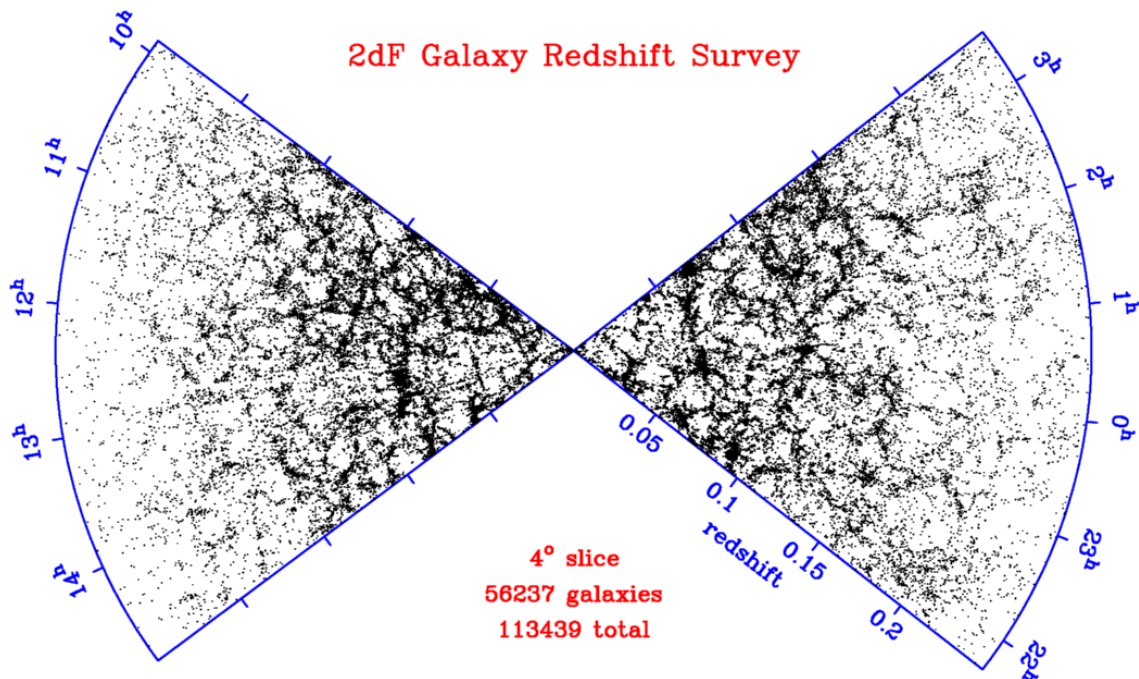


Figure 1: Cone diagram illustrating the clustering pattern seen in a 4° slice of the 2dFGRS in each hemisphere.

A comparison with the SDSS data (spectroscopic limit $r' < 17.8$) over the overlap region of the two surveys shows that the 2dFGRS samples fainter galaxies than SDSS, and hence provides a better sampling of the mass distribution in the local Universe.

2. CONTEMPORARY COSMOLOGY FROM 2dFGRS

The measured galaxy power spectrum³ of the 2dFGRS can be directly compared to model power spectra with varying values of the matter density, Hubble parameter, and baryonic fraction. A visual comparison gives good agreement with the BBNS value of the baryon fraction for $\Omega_m h \approx 0.25$. An unconstrained fit gives $\Omega_m h = 0.20 \pm 0.03$ with a baryon fraction of 0.15 ± 0.07 . A fit constrained to have spectral index $n=1$ gives $\Omega_m h = 0.18 \pm 0.02$ with a baryon fraction of 0.17 ± 0.06 (Figure 2). These values are in good agreement with determinations from Boomerang⁴ observations of the CMB, BBNS, and the abundance of galaxy clusters as a function of redshift. The lack of baryonic oscillations seen in the raw $P(k)$ spectrum can be taken as a direct indication of the presence of a collisionless component of the matter distribution. Taken together with the HST Key Program measurements of the Hubble constant⁵, these results imply a low matter density for scale-invariant fluctuations.

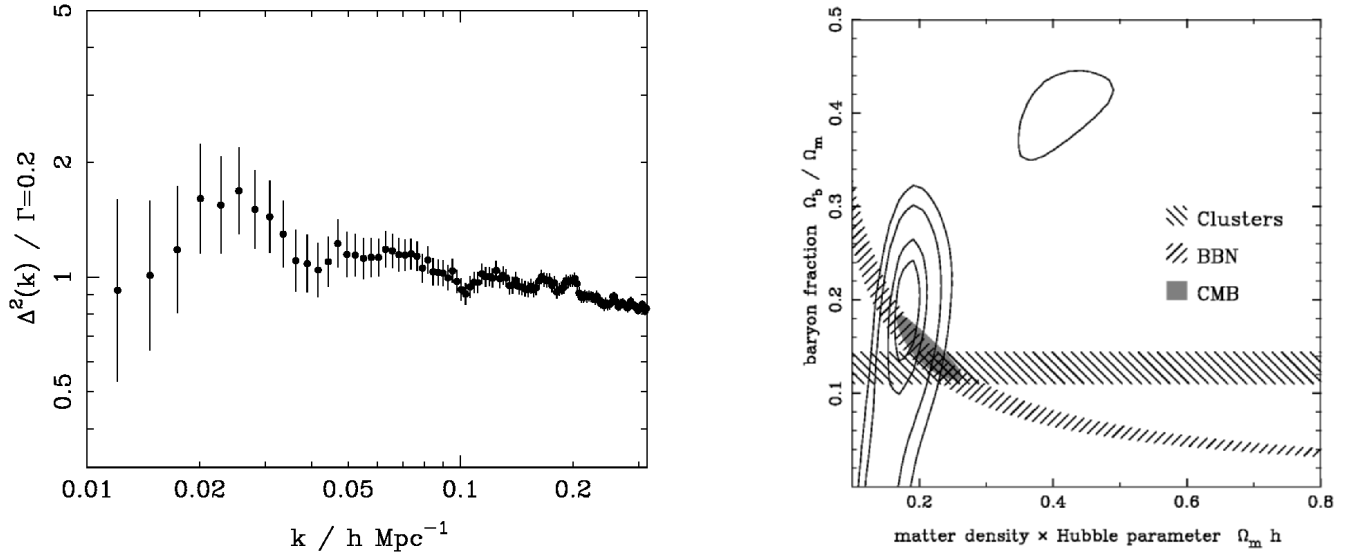


Figure 2: (Left) The power spectrum divided by a fiducial model in which $\Omega_m h=0.2$, illustrating the turn-over seen at large scales. Constraints (Right) on the cosmological matter density as a function of the baryon fraction from the 2dFGRS are shown as contours, and compared with constraints from cluster abundance measurements, the cosmic microwave background measurements from Boomerang, and observations of primordial element abundances.

It should be noted that these results may be subject to additional uncertainties if, for example, the biasing of the galaxy population varies as a function of scale in the local Universe.

A more direct determination of the matter density can be obtained by consideration of the velocity field at large separations from galaxy clusters. This can be analysed statistically by considering the decomposition of the redshift-space correlation function into the contributions from pairs separated in the redshift (velocity) direction and pairs separated in the angular direction. By fitting contours to this decomposition we can solve for the matter density and the mean cluster velocity dispersion. The best fit⁴ for $r > 8 h^{-1}$ Mpc (allowing for correlated errors) gives: $\beta = \Omega^{0.6}/b = 0.43 \pm 0.07$ and $\sigma_p = 385 \pm 50 \text{ km s}^{-1}$, where this applies at $z=0.17$, for a mean luminosity of $L = 1.9 L^*$ (significant corrections).

3. SPECTRAL CLASSIFICATION AND GALAXY TYPES AS TRACERS OF LSS

It is important to emphasise that the 2dFGRS not only gives the three-dimensional positions of the galaxies in the survey, but also provides a wealth of spectral information which has been used to provide automatic, internally consistent classifications by means of a principle component analysis⁶. Comparison of the individual components with the recovered spectra reveals that most of the information content is contained within the first three components, such

that PC1 reflects the emission lines, and correlates well with the blue continuum shape of star-forming galaxies; PC2 also reflects emission line components, but with no sensitivity to the continuum shape; PC3 is dominated by the contribution to the spectra from the Balmer lines and their strength relative to emission components. A dimensionless parameter, η , can be constructed from these three components, such that increasing values of η trace the increasing strengths of emission lines as we move from early-type to late-type galaxies. The spectral equivalent of the Hubble sequence thus emerges naturally from the data. Unsurprisingly, η is also strongly correlated with the (B-R) colours obtained when data from the red survey plates is incorporated into the galaxy catalogue.

Once the spectral types have been derived, we can determine the clustering signal as a function of galaxy type, with the result (from a further analysis of redshift-space distortions in the correlation function) that passive galaxies are found to have $b=1.2$, whilst active galaxies are more weakly clustered, with $b=0.9$. This behaviour can be seen directly in cone diagrams, similar to Figure 1, but divided by spectral type. The active galaxies exhibit a lower average velocity dispersion (418km s^{-1} , compared to 618km s^{-1} for the elliptical population). One can also consider the clustering behaviour of the galaxy population(s) as a function of luminosity: A clear trend is shown to exist, such that the brightest galaxies are strongly biased, whilst low-luminosity dwarfs are found to exhibit a slight anti-bias. This luminosity dependence is observed to exist for both early and late-type galaxies. Detailed consideration of the shapes of the power spectra obtained from the different populations show variations in amplitude, but not in the details of the shape (Figure 3).

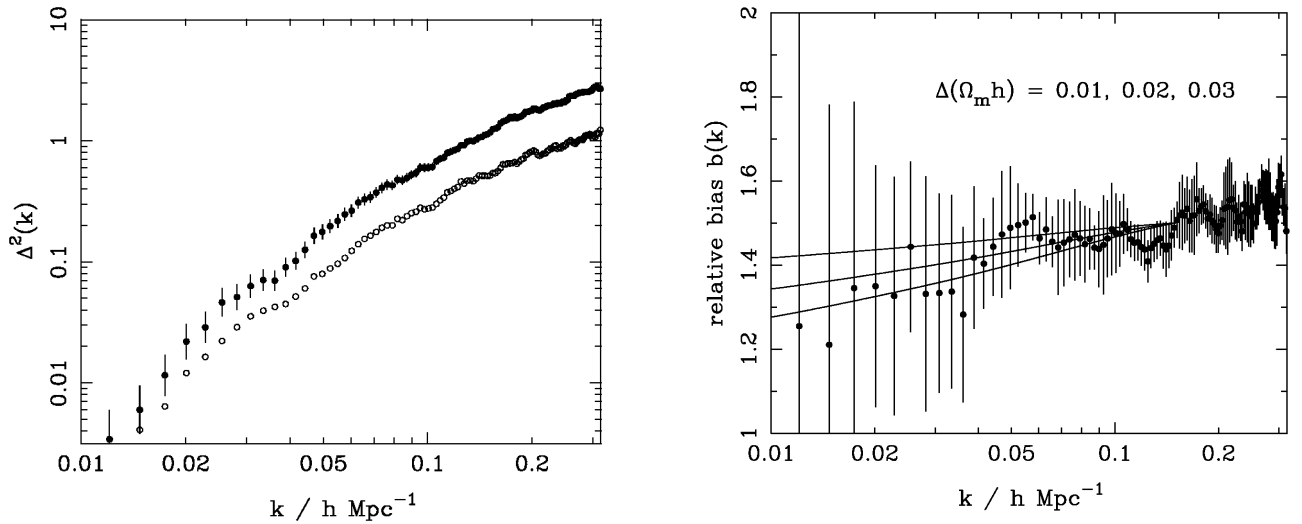


Figure 3: The power spectra (left) for early (filled circles) and late-type (open circles), and the relative bias exhibited by the ratio of the two (right). Solid diagonal lines show the predictions for different values of $\Delta(\Omega_m h)$.

4. COMBINING 2dF WITH CMB MEASUREMENTS

The completion of the 2dFGRS was extremely timely, in that the above results currently provide the best description of the matter power spectrum to combine with recent measurements of the CMB⁷. CMB measurements are sensitive to the total matter-energy density of the Universe, since the value of this quantity at the epoch of recombination determines the amplitude of the primary ‘Doppler’ peak in the angular CMB per spectrum. The combination of the CMB and Large-Scale Structure measurements provides constraints for the whole range of cosmological parameters (Figure 4). In particular, since the combination implies a flat Universe, this in turn gives $\Omega h^{3.4} = 0.0078$, which then leads to $\Omega_m = 0.26 \pm 0.04$.

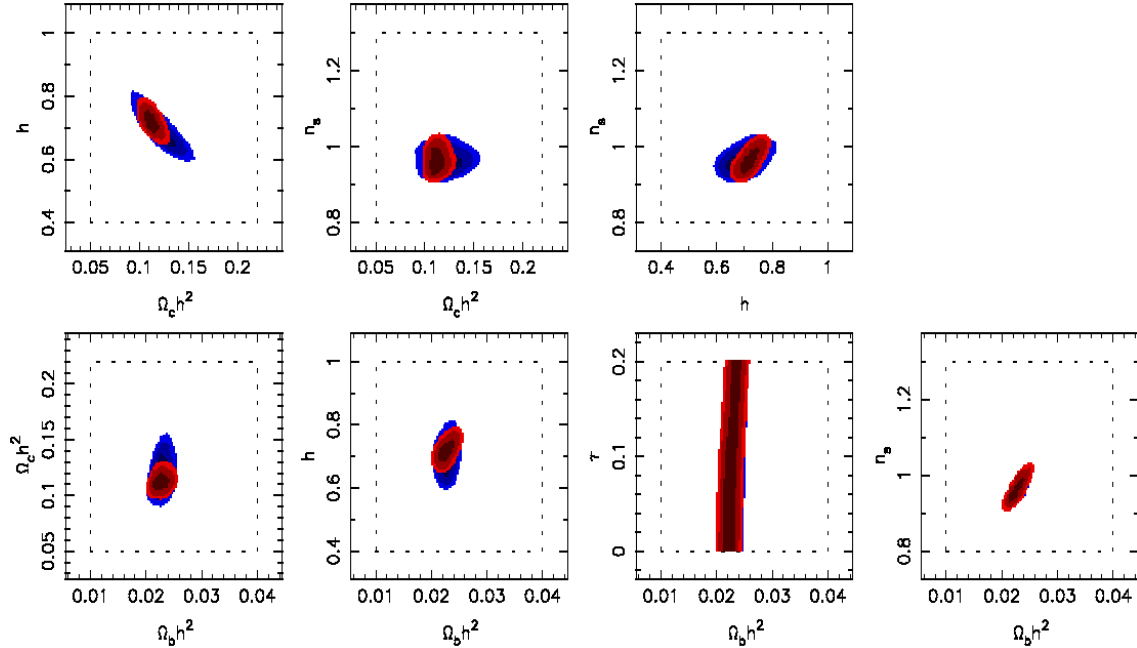


Figure 4: Likelihood contours for a variety of cosmological parameters showing the 1-3 σ limits for the combination of 2dF and WMAP data with no constraints (blue contours) and when the cosmology is constrained by the HST Key Program value of the Hubble constant. In both cases, the value of τ has been constrained to the flat cosmology implied by the position of the CMB Doppler peak.

5. POSSIBILITIES FOR A SURVEY AT $z > 1$ USING FMOS

The 2dFGRS illustrates not only the tremendous power of a dedicated Large-Scale Structure survey, but also the diverse range of scientific problems that can be addressed using such a dataset. It is important to realise that although the survey was effectively designed with a single primary goal in mind, the existence of such a broad and yet homogeneous sample of galaxy spectra is an invaluable asset for many further studies.

FMOS will provide a wide grasp of the high-redshift Universe, with the H-alpha line visible for $0.4 < z < 1.74$ and OII visible for $1.4 < z < 3.8$. In particular, for a survey of the Universe at $1 < z < 2$, the FMOS spectra will provide a wavelength coverage and sampling that will be extremely well-matched to the 2dFGRS ‘consensus sample’ of the local Universe. Moreover, the sensitivity implied by the instrument signal-noise ratio calculations suggests that for a sample selected to a magnitude limit of $H < 20$ the requisite exposure times that will produce spectra of similar quality to the 2dFGRS dataset are comfortably short at 20 minutes for a late-type galaxy and up to 1 hour for an early type spectrum. When combined with the fast setup time allowed by ECHIDNA, these numbers allow for a survey which could measure as many as 7000 galaxy spectra per night.

The lessons learned from the execution of the 2dFGRS suggest that a large number of scientific programmes can therefore be combined into a single overarching FMOS survey project. Furthermore, the experience of exploiting the 2dFGRS suggests that the combined impact of such a survey will be much greater than the sum of the individual programmes.

6. INPUT DATASETS

There is an obvious synergy between the combined power of Suprime-Cam, FMOS, and the UKIDSS survey datasets. In this context, the natural starting point for the survey described above would be the UKIDSS DXS, which aims to

cover 35 square degrees to $K=21.5$, $J=22.5$ (5σ limits). For the $H=20$ limit suggested above, this would generate roughly 60,000 targets with $z>1$, and so could be expected to provide sufficient targets for the first 20 nights of an extended survey to this limit. Beyond this number of targets, UKIDSS is unlikely to be able to deliver a significant improvement on this number, given the likely timescale of the UKIDSS survey programme, and the relatively short interval that is expected to elapse between the WFCam and FMOS commissioning dates. Further targets would therefore have to be drawn from larger-scale IR imaging surveys, such as those planned for the VISTA telescope which will be commissioned at the Paranal observatory mid-2006. VISTA will provide an IR imaging camera with a 1.67° FOV on a single-instrument telescope, which would be capable of extending the UKIDSS DXS to 500 square degrees of coverage in only a single year of operation –Much faster than would be necessary to feed an FMOS survey, given realistic constraints on the number of Subaru nights that could be dedicated to such a project in any one year. Furthermore, the extension to VISTA data is naturally facilitated by the fact that UKIDSS and VISTA share a common data-reduction pipeline and archiving system, and so the transition from WFCam data to VISTA data should be seamless as far as input catalogues for an FMOS survey are concerned. ESO is effectively committed to supporting VISTA operations with complementary optical band imaging from the VST, and so it should be reasonable to assume that photometric redshifts can be obtained for these samples on the timescale required for FMOS selection.

7. CONCLUSIONS

The 2dFGRS provides both a reassuringly complete picture of the local Universe and a remarkable example of the way in which multiple scientific goals can be addressed by a single wide-reaching survey programme. The prospects for conducting a similar scale of survey programme with the FMOS instrument, such as that proposed by Glazebrook et al⁸, are good, and the requisite imaging datasets are becoming available on timescales which are consistent with these goals. The last point to consider is that of possible competition. The present author is not aware of any IR spectroscopy facility which will be able to compete with FMOS for large-area surveys until Gemini's WFMOS instrument is commissioned. This is unlikely to occur before 2012. Other programmes with comparable cosmological goals include SNAP (now apparently unlikely to fly before 2019) and LSST (still not approved, and unlikely to be built any earlier than WFMOS). One can therefore conclude that time would be on the side of a large-scale survey programme with FMOS, and that it would be reasonable to think of a fairly long duration project requiring not more than 10 nights/semester which would still be able to reach its scientific objectives without becoming endangered by competition.

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