Abstract. Published galaxy power spectra from the 2dFGRS and SDSS are not in good agreement. We revisit this issue by analyzing both the 2dFGRS and SDSS DR5 catalogues using essentially identical techniques. We confirm that the 2dFGRS exhibits relatively more large scale power than the SDSS, or, equivalently, SDSS has more small scale power. We demonstrate that this difference is due the $r$-band selected SDSS catalogue being dominated by more strongly clustered red galaxies, due to these galaxies having a stronger scale dependent bias. The power spectra of galaxies of the same rest frame colours from the two surveys match well. It is therefore important to accurately model scale dependent bias to get accurate estimates of cosmological parameters from these power spectra.

1. Introduction

Measurements of large scale galaxy clustering place important constraints on cosmological parameters that complement those from the analysis of fluctuations in the cosmic microwave background (CMB). Measurements of the galaxy power spectrum from SDSS (Tegmark et al. 2004) and 2dFGRS (Cole et al. 2005) constrain the parameter combinations $\Omega_m h$ and $\Omega_b/\Omega_m$. The constraint on $\Omega_m h$ is particularly important as, for instance, it breaks a degeneracy in the CMB data and allows accurate determination of $\Omega_m$. Hence to be sure that systematic errors are not biasing the parameters it is very useful to have independent estimates from different surveys. However when one looks at the constraints coming from the published 2dFGRS and SDSS analysis one finds a tension. In figure 16a of Cole et al. (2005), which compares the published estimates of the galaxy power spectra, there is evidence of more large scale power in the 2dFGRS than in SDSS. This folds through and results in the headline value of $\Omega_m h = 0.168 \pm 0.016$ from 2dFGRS (Cole et al. 2005) being lower than that of Tegmark et al. (2004) SDSS, $\Omega_m h = 0.213 \pm 0.023$. Here one should be cautious as different priors have been assumed, but in the analysis of Sánchez et al. (2006), which treats each data set on an equal footing and separately combines each with CMB data, one sees in their figure 18 that the SDSS prefers a substantially higher value of $\Omega_m$ than does the 2dFGRS. In fact, while the 2dFGRS estimate is in good agreement with that from the CMB data alone (it significantly tightens the constraint without shifting the best fitting value) the SDSS data pull $\Omega_m$ to higher values than preferred by the CMB.

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Here we seek to investigate whether these differences are as a result of:
a) larger than expected cosmic variance, b) systematics due to differences in the
analysis technique (Cole et al. use simple Fourier methods in redshift space, while Tegmark et al. use the apparatus of KL decomposition and work in real
space), c) systematics due to problems with galaxy catalogues or d) intrinsic
differences in the underlying galaxy clustering. In order to directly compare the
2dFGRS and SDSS, we analyse each dataset using essentially identical methods
which we outline in Section 2. In Section 3 we briefly look at the region of
overlap between the surveys and then compare the resulting power spectra from
the full catalogues and interpret the differences. We conclude in Section 4.

2. Methods

2.1. 2dFGRS analysis

Our method of estimating the galaxy power spectrum, determining statistical
errors and fitting models is essentially identical to that set out in Cole et al.
(2005), but with three minor changes. In brief:

- We use masks, whose construction is described in Norberg et al. (2002),
to describe the angular variation of the survey magnitude limit, redshift
completeness and magnitude dependence of the redshift completeness.

- Random catalogues are generated by sampling from the luminosity func-
tion and viewing through the masks. To generate random catalogues corre-
spanding to red/blue subsets, the luminosity function of only the red/blue
galaxies is used.

- Close pair incompleteness due to “fibre collisions” is dealt with by redis-
tributing the weights of missed galaxies to their 10 nearest neighbours on
the sky.

- The power spectrum is estimated using a simple cubic FFT method with
the optimal weighting scheme of Percival, Verde & Peacock (2004, PVP)
and then spherically averaged in redshift space. The assumed linear em-
pirical bias factors that are used in this weighting scheme are

\[
\begin{align*}
    b_{\text{blue}} &= 0.9 (0.85 + 0.15 \frac{L}{L_*}) \quad \text{for rest frame } b_{\text{J}} - r_F < 1.07 \\
    b_{\text{red}} &= 1.3 (0.85 + 0.15 \frac{L}{L_*}) \quad \text{for rest frame } b_{\text{J}} - r_F > 1.07.
\end{align*}
\]

- The covariance matrix describing the errors on the power spectrum mea-
surements and their correlations is estimated using mock catalogues which
are constructed from the random catalogues by generating a log-normal
density field with a specified power spectrum and using it to modulate the
selection of galaxies from the random catalogue. Thus, by construction,
these catalogues have a power spectrum very close to the best fitting model
and have luminosity and colour dependent clustering consistent with the
bias factors of equation (1).

- The survey window function is determined directly from the random cat-
ologue. When fitting models the theoretical model power spectra are con-
volved with the survey window function.
The three minor changes we have made are:

- We have changed the binning scheme so that now $P(k)$ is estimated in bins uniformly spaced in $\log_{10} k$, rather than the linearly spaced bins with different bin widths in different ranges of $k$ that were used in Cole et al. (2005).

- We used new sets of log-normal catalogues in which the modulation of the density field used for galaxies with different bias factors is linear rather than the slightly more complicated scheme that was employed by Cole et al. (2005).

- Power spectra fits are done using Cosmo-MC (Lewis & Bridle 2002) as in Sánchez et al. (2006) which uses CAMB to estimate of $P(k)$ rather than the Eisenstein & Hu (1998) fitting formula. (We have found the use of the approximate Eisenstein & Hu (1998) fitting formula causes a small shift in $\Omega_m h$.)
2.2. SDSS analysis

In most respects our analysis of the SDSS is identical to that of the 2dFGRS. The only differences are a simpler way of generating the survey masks and of populating the corresponding random catalogue.

The sky coverage mask we have adopted for the SDSS-DR5 data is shown in Fig. 1 and compared with corresponding 2dFGRS mask. We constructed this mask by simply noting the angular coverage of each of the stripes from which the SDSS survey is built and by removing a few small regions with poor coverage. Most of the SDSS survey goes to a uniform magnitude limit of $r = 17.77$, but a sub-area, which is easily identified using the target selection date, has a variety of different magnitude limits. In this sub-area we simply imposed a fixed magnitude limit of $r = 17.5$ and discarded all galaxies fainter than this limit. The number of galaxies with redshifts that are retained by the mask and magnitude limits and used in our analysis is 443,424. The mask is cruder than the more sophisticated ones employed by Tegmark et al. (2004) and for the 2dFGRS as it ignores the smaller scale variation in the redshift completeness. However in the case of the 2dFGRS, where the incompleteness variation is much larger, we showed that provided this incompleteness is accounted for using our method of redistributing the weights of galaxies without redshifts to neighbours with redshifts the resulting power spectrum estimates are very accurate (see figure 17g of Cole et al. 2005).

![Figure 2.](image)

Figure 2. The redshift distribution of the SDSS $r < 17.77$ sample. The solid line shows the analytic fit used to generate the corresponding random catalogue. The dashed line is this same fit scaled down in amplitude to be always below the redshift histogram.

As most of the catalogue goes uniformly to the deeper magnitude limit a simple method can be used to construct the random catalogue. Fig. 2 shows the
The Galaxy Power Spectrum

redshift distribution of this sample together with an analytic fit that smooths away the effect of large scale clustering. Our procedure is:

1. Select a random direction on the sky.

2. Choose at random a genuine galaxy from the region of the survey that goes to \( r = 17.77 \).

3. Keep the galaxy with a probability proportional to the ratio of the height of redshift histogram to that of the scaled fit shown as the dashed line in Fig. 2 at the redshift of the selected galaxy.

4. Keep or discard the galaxy based on the sky coverage and magnitude limit of the mask. (Note, for galaxies that fall where the magnitude limit is only 17.5, the fainter galaxies will be discarded and the redshift distribution of the retained galaxies will be appropriately shallower than that of Fig. 2.)

These steps are done repeatedly until a random catalogue containing 100 times more galaxies than the genuine catalogue is built up. Selecting from the genuine catalogue in this way means we automatically have apparent magnitudes and colours for all the galaxies in the random catalogue and so can select sub-samples from it and weight its galaxies in just the same way as the genuine catalogue.

To utilize the Percival, Verde & Peacock (2004) optimum weighting we need to determine bias factors for the galaxies in the genuine, random and mock catalogues. We do this by first converting the SDSS magnitudes to the 2dFGRS \( b_J \) and \( r_F \) bands using

\[
\begin{align*}
b_J &= g + 0.15 + 0.13 (g - r) \\
r_F &= r - 0.13
\end{align*}
\]

and the simple colour dependent \( k \)-corrections that were used for the 2dFGRS data (see section 3 of Cole et al. 2005). Then we are able to define the bias factors using equation (1) just as for the 2dFGRS data.

3. Results

Our main focus is the comparison of the power spectra of the two surveys, but we first directly compare the two surveys in the region of their overlap to get a feel for the different selections used and the level of incompleteness.

3.1. Survey overlap

In the northern galactic hemisphere there is a contiguous area of overlap between the two surveys, which runs for 74 degrees of RA and is for the most part 5.2 degrees wide in declination. If we select from the SDSS photometric catalogue all galaxies brighter than \( b_J = 20 \) (we do not apply the \( r \approx 17.77 \) magnitude limit of the SDSS main galaxy survey, but we do apply all the other star-galaxy classification criteria used in that sample (see Strauss et al. 2002)), then in this area there are 53382 galaxies that are in both catalogues. We find the fraction of SDSS galaxies which are also in the 2dFGRS to be constant at 89% as faint as \( b_J \approx 18.9 \). Fainter than this, SDSS galaxies are missing from the
Cole, Sánchez and Wilkins

Figure 3. Cone plots showing RA and redshift for galaxies in the region of sky where the 2dFGRS and SDSS surveys overlap. There are 53,382 within this area that are in both surveys and in the upper panel we plot the sub-sample of 27,004 that (estimated from SDSS photometry) have $b_J < 19$ and redshift $z > 0.01$. The lower panel shows the 2754 galaxies that are in SDSS and pass the same magnitude and redshift cuts, but are missing in the 2dFGRS catalogue.

2dFGRS sample simply due to the (variable) magnitude limit of the 2dFGRS survey and its 0.15 magnitude random photometric errors. This finding is in perfect accord with the estimates made with the SDSS EDR (Stoughton et al. 2002) in Norberg et al. (2002). This 11% incompleteness has been investigated by (Cross et al. 2004) as well as Norberg et al. (2002) and has been shown to be predominately due to incorrect star-galaxy classification. The star-galaxy classification parameters based on the APM photometry are noisy and this level of incompleteness is in line with what was expected (Maddox et al. 1990).

The issue here is whether this incompleteness has any influence on estimates of galaxy clustering. We can look at this directly by plotting cone plots (Fig. 3) of the galaxies the two catalogues have in common and those missed by the 2dFGRS. Here we plot only galaxies with $b_J < 19$ to avoid issues with the 2dFGRS magnitude limit. Here we see that 91% of the SDSS galaxies are in the 2dFGRS. Comparing the two cone plots in Fig. 3 it appears that the galaxies
Figure 4. Comparison of the power spectra estimated from the full 2dFGRS and SDSS DR5 samples - corrected for the effect of the window function as described in the text. Inset: The contours show 68% and 95% joint confidence intervals for the baryon fraction $\Omega_b/\Omega_m$ and $\Omega_m h$ for fits to this SDSS and 2dFGRS data in the range $0.02 < k < 0.15 \, h\, \text{Mpc}^{-1}$. The parameter $Q$ modelling the distortion of power spectrum due to nonlinearity, redshift space distortions and scale dependent bias was kept fixed at $Q = 5$ in these fits.

missed by 2dFGRS are just a random sparse sampling of the structure seen in the matching sample and so there is no evidence that the incompleteness has a spatial imprint.

3.2. Comparison of power spectra

In Fig. 4 we compare the ‘deconvolved’ power spectra estimated from the full 2dFGRS catalogue and full SDSS-DR5 sample using the methods we outlined in Section 2. The power spectra we estimate are the underlying galaxy power spectra convolved with the window function of either the SDSS or 2dFGRS as appropriate

$$\hat{P}(k) = P(k) \otimes W^2(k).$$  \hspace{1cm} (3)
Figure 5. A sample of the window functions for our individual band power estimates for both SDSS (red dashed) and 2dFGRS (black solid).

Our random catalogues allow us to accurately estimate $W^2(k)$ and from it determine the matrix of window functions that describe how our spherically averaged band power estimates are related to unconvolved power spectrum

$$\hat{P}(k) = \sum_i P(k_i)W_m(k_i, k_j).$$  \hspace{1cm} (4)

Examples of these window functions for the SDSS and 2dFGRS are shown in Fig. 5. For all our quantitative analysis we use these window functions to convolve the model power spectra before comparing with the data. However for the purposes of visually comparing the 2dFGRS and SDSS power spectra we have corrected the convolved estimates by multiplying them through by the ratio a similar model power spectrum to its convolved counterpart. This 'deconvolution' is accurate provided the power spectra are smooth.

In Fig. 4 we note that the SDSS and 2dFGRS galaxy power spectra agree well for $k > 0.07$ h Mpc$^{-1}$. The good agreement in amplitude at this wavenumber is due to the bias dependent weights used in the PVP estimator which have sucessfully modelled the difference in the clustering strength of the red selected SDSS galaxies and blue selected 2dFGRS galaxies. This is by design as the bias factors were normalized empirically by the 2dFGRS red and blue samples at this scale (see figure 15 of Cole et al. 2005). In contrast, on larger scales we see evidence for significantly more large scale power in the 2dFGRS than in SDSS. Fitting power spectra of the form

$$P(k) = P_{\text{linear}}(k, \Omega_m, h, \Omega_b) \frac{1 + Qk^2}{1 + Ak},$$  \hspace{1cm} (5)
to these data yields the parameter constraints on $\Omega_m h$ and $\Omega_b/\Omega_m$ shown in inset panel of Fig. 4. Here we have kept the parameters $A$ and $Q$, which model non-linear distortions of the power spectrum, fixed at fiducial values of $A = 1.4$ and $Q = 5$ such that the difference in shape of the fitted power spectra are completely characterized by the parameter combinations $\Omega_m h$ and $\Omega_b/\Omega_m$. We note that the 2dFGRS and SDSS best fit values lie outside each others 95% confidence contours and that the SDSS parameter estimates are completely in accord with those from Tegmark et al. (2004), but with much tighter bounds due to the larger SDSS dataset used here. Thus the first thing to note is that the difference between the SDSS and 2dFGRS results that was noted in the introduction and which motivated this analysis is certainly significant and not an artifact of differing analysis techniques.

We now investigate if the discrepant shapes of the galaxy power spectra are due to the difference in the clustering properties of red and blue galaxies. Fig. 6 shows histograms of rest frame $b_J - r_F$ colours for both the 2dFGRS and SDSS catalogues. The SDSS magnitudes have been converted to these bands assuming the relations given in equation 2. The colour distributions are clearly bimodal with a natural dividing point at $b_J - r_F = 1.07$. The 2dFGRS has roughly equal numbers of red and blue galaxies while the SDSS, being red selected, is naturally dominated by red galaxies.

In Fig. 7 we compare the galaxy spectra estimated from just the galaxies redder than $b_J - r_F > 1.07$ in both samples. Comparing the SDSS $P(k)$ from just the red galaxies with the previous estimate from the full SDSS catalogue reveals them to be in very close agreement. This is to be expected as the SDSS sample is both dominated by red galaxies and the PVP power spectrum estimator that we employ gives them more weight than their less clustered blue counterparts.
Figure 7. Comparison of the 2dFGRS and SDSS-DR5 power spectra from red subsamples that satisfy the rest frame colour $b_J - r_F > 1.07$. Inset: The contours show 68% and 95% joint confidence intervals for the baryon fraction $\Omega_b/\Omega_m$ and $\Omega_m h$ for fits to this SDSS and 2dFGRS data in the range $0.02 < k < 0.15 h \text{Mpc}^{-1}$. Again the parameter $Q$ was kept fixed at $Q = 5$.

In contrast the estimate for just the red 2dFGRS galaxies differs from that from all the 2dFGRS catalogue. In fact it is a much closer match to the result from the SDSS data. The only places where the two estimates are not in excellent agreement is on the very largest scales $k < 0.025 h \text{Mpc}^{-1}$, where the estimates are both noisy and highly correlated, and also around $k \approx 0.05 h \text{Mpc}^{-1}$. In fact this difference is also due to sample variance. Cole et al. (2005) investigated the effect of removing from the 2dFGRS catalogue the two largest super clusters. Their figure 17 (panels o and p) shows that this in general has a small effect, but does perturb the power just around $k \approx 0.05 h \text{Mpc}^{-1}$.

Agreement, within the expected statistical uncertainty, is confirmed in the inset panel of Fig. 7, where we see the best fitting parameters for 2dFGRS lie within the SDSS 67% confidence contour and vice versa. Note that again we have kept the parameters describing the nonlinear distortion fixed.
4. Conclusions

The conclusion of this investigation is that a significant difference exists between the shape of the galaxy power spectra measured in the 2dFGRS and SDSS surveys and that this difference is due to scale dependent bias. If a homogenous sample of red galaxies is selected from each survey then the resulting power spectra agree to within the expected statistical errors. In contrast, when the full 2dFGRS and SDSS catalogues are analyzed the resulting 2dFGRS power spectrum differs in shape to that of SDSS. If normalized on scales around \( k \approx 0.1 \, h \, \text{Mpc}^{-1} \), as is done automatically by the scale independent bias factors assumed in the PVP estimator, then the 2dFGRS \( P(k) \) exhibits more large scale power than SDSS. However, if one instead normalizes on large scales one finds the equivalent result that SDSS exhibits more small scale power than 2dFGRS. This behaviour is exactly what one expects if the more strongly clustered red galaxies live in denser environments where the effects of nonlinearity are greater.

This comparison has revealed that to get unbiased estimates of the cosmological parameters it is necessary to better understand and constrain the distortion in the shape of the power spectrum caused by nonlinearity and scale dependent bias. In Cole et al. (2005) a first attempt at modelling this distortion was introduced using the \( Q \) and \( A \) parameters of equation (5). For the mix of red and blue galaxies present in the 2dFGRS survey, the necessary value of \( Q \) was reasonably small and the hence the scale dependent correction quite modest. However for samples of redder or more luminous and hence more clustered galaxies one expects greater nonlinearity and either greater values of \( Q \) or the possible breakdown of this simple model. Thus to get robust constraints from the main SDSS survey and in particular the SDSS luminous red galaxy survey will require more detailed modelling of nonlinearity and scale dependent bias.

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\(^1\)Subsequent to the presentation of this talk on the 1st August 2007, three preprints analyzing the SDSS-DR5 (Tegmark et al. 2007; Percival et al. 2007a,b) appeared on astro-ph. As anticipated here, strong scale dependent bias was found necessary to reconcile the measured power spectrum with linear theory (e.g. \( Q = 26 \) in Percival et al. 2007b)