The 2dF QSO Redshift Survey - XI. The QSO Power Spectrum

P. J. Outram, Fiona Hoyle, T. Shanks, S. M. Croom, B. J. Boyle, L. Miller, R. J. Smith & A. D. Myers

1 Department of Physics, Science Laboratories, South Road, Durham, DH1 3LE, U.K.
2 Department of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, U.S.A.
3 Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia
4 Department of Physics, Oxford University, Keble Road, Oxford, OX1 3RH, U.K.
5 Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead, CH41 1LD, U.K.

ABSTRACT

We present a power spectrum analysis of the final 2dF QSO Redshift Survey catalogue containing 22652 QSOs. Utilising the huge volume probed by the QSOs, we can accurately measure power out to scales of $\sim 500h^{-1}$Mpc and derive new constraints, at $z \sim 1.4$, on the matter and baryonic contents of the Universe. Importantly, these new cosmological constraints are derived at an intermediate epoch between the CMB observations at $z \sim 1000$, and local ($z \sim 0$) studies of large-scale structure; the average QSO redshift corresponds to a look-back time of approximately two-thirds of the age of the Universe. We find that the amplitude of clustering of the QSOs at $z \sim 1.4$ is similar to that of present day galaxies. The power spectra of the QSOs at high and low redshift are compared and we find little evidence for any evolution in the amplitude. Assuming a $\Lambda$ cosmology to derive the comoving distances, $r(z)$, to the QSOs, the power spectrum derived can be well described by a model with shape parameter $\Gamma = 0.13 \pm 0.02$. If an Einstein-de Sitter model $r(z)$ is instead assumed, a slightly higher value of $\Gamma = 0.16 \pm 0.03$ is obtained. A comparison with the Hubble Volume $\Lambda$CDM simulation shows very good agreement over the whole range of scales considered. A standard ($\Omega_m = 1$) CDM model, however, predicts a much higher value of $\Gamma$ than is observed, and it is difficult to reconcile such a model with these data. We fit CDM model power spectra (assuming scale-invariant initial fluctuations), convolved with the survey window function, and corrected for redshift space distortions, and find that models with baryon oscillations are slightly preferred, with the baryon fraction $\Omega_b/\Omega_m = 0.18 \pm 0.10$. The overall shape of the power spectrum provides a strong constraint on $\Omega_m h$ (where $h$ is the Hubble parameter), with $\Omega_m h = 0.19 \pm 0.05$.

Key words: cosmology: observations, large-scale structure of Universe, quasars: general, surveys - quasars

1 INTRODUCTION

The large-scale structure of the Universe represents one of the most powerful discriminants between cosmological models. QSOs are highly effective probes of the structure of the Universe over a wide range of scales and can trace clustering evolution over a look-back time which is 70-80 per cent of its present age. In the linear regime ($10 \leq r \leq 1000h^{-1}$Mpc), they are clearly superior to galaxies as probes of large scale structure by virtue of both the large volumes they sample and their flat $n(z)$ distribution. Accurately measuring the clustering over these scales bridges the gap between the clustering results on relatively small scales from galaxy redshift surveys out to scales previously only probed by microwave background anisotropy experiments.

The power spectrum perhaps provides the most natural description of the matter fluctuations that comprise large-scale structure; for a Gaussian field, the amplitude of the Fourier modes provide a statistically complete description of the density perturbations. One potential problem of using QSOs as probes of large scale structure is that they, like galaxies, are biased tracers of the mass density field. QSO
imaging experiments at redshifts out to \( z \sim 1 - 2 \) suggest that the QSOs reside in relatively modest (~ \( L_\ast \)) galaxy hosts (Rix et al. 2001; Ridgway et al. 2001) and that the clustering environment of UVX QSOs are similar to optically selected galaxies (Croom & Shanks 1999). This implies that at \( z \lesssim 1 - 2 \) QSOs and galaxies have a similar bias with respect to the underlying mass density field (Kauffmann & Haehnelt 2002). It is likely that the bias is scale-dependent, at least at small scales (Blanton et al. 1999). At larger scales \((r > 10 h^{-1} \text{Mpc})\), however, where QSO clustering statistics prevail, the shape (although not the amplitude) of the measured power spectrum can reasonably be assumed to apply to the mass and galaxies as well, since it is unlikely that the QSO bias will be scale dependent in this regime (Coles 1993; Mann, Peacock & Heavens 1998). For the purposes of modelling the QSO \( P(k) \) in this paper we assume that any bias is scale independent on the scales considered \((40 < r < 500h^{-1} \text{Mpc})\).

With the principal aim of determining the form of QSO clustering, and hence producing strong new constraints on cosmological models, we have used the 2dF multi-fibre spectrograph on the Anglo-Australian Telescope to make a large QSO redshift survey. The 2dF QSO Redshift Survey (2QZ) comprises two \( 5\deg \times 75\deg \) declination strips, one at the South Galactic Pole and one in an equatorial region in the North Galactic Cap. QSOs are selected by ultra-violet excess (UVX) in the \( u - b_1 : b_1 - r \) plane. The effectiveness of our QSO selection criteria has been demonstrated with an overall QSO sky density of \( 35 \text{deg}^{-2} \) to \( b_1 < 20.85 \) being achieved, at a completeness of 93 per cent. Spectroscopic observations are now complete, and we have been able to identify 86 per cent of the colour-selected candidates. Around half, 47 per cent, of the 47768 candidates are positively identified as QSOs, leading to a final catalogue containing 22652 QSOs. The QSOs typically have redshifts \( 0.3 < z < 3 \), and probe a volume of around \( 2 \times 10^9 h^{-3} \text{Mpc}^3 \) (assuming an Einstein-de Sitter cosmology).

The spectra of the first 10000 2QZ QSOs were released in April 2001 (Croom et al. 2001a) and can be obtained at http://www.2dfquasar.org. Hoyle et al. (2002) used these QSOs to measure the QSO power spectrum. They found that the QSO power spectrum has similar amplitude to that of local galaxies, and little evolution is seen with redshift. The main conclusion was that they detected large-scale power significantly in excess of the standard \((\Omega_m = 1)\) CDM prediction, strongly ruling out this model and more consistent with CDM models with lower mass content and a non-zero cosmological constant \((\Lambda CDM)\).

In this paper, we re-apply the power spectrum analysis described in Hoyle et al. (2002) to the final 2QZ catalogue containing 22652 QSOs. As well as having more than twice as many QSOs as available to Hoyle et al., this dataset has a much cleaner window function, significantly reducing the potential systematics on large scales. We briefly describe the 2QZ data set in Section 2, including the angular and radial selection functions which are required to estimate the survey window function. Section 3 discusses the power spectrum estimation method, and the resulting QSO power spectrum is presented in Section 4. In this section we compare the QSO power spectrum to that of present day galaxies and clusters, and investigate evolution in the clustering amplitude. Then, in Section 5, we compare the QSO power spectrum with models of large scale structure, deriving strong constraints on the baryon and matter content of the Universe, before drawing conclusions in Section 6.

2 THE 2QZ CATALOGUE

The 2QZ comprises two \( 5\deg \times 75\deg \) declination strips, one at the South Galactic Pole \((\text{centred at } \delta = -30^\circ, \text{with } 21^\text{h}40^\text{m} \leq \alpha \leq 03^\text{h}15^\text{m})\) and one in an equatorial region in the North Galactic Cap \((\text{centred at } \delta = 0^\circ, \text{with } 09^\text{h}50^\text{m} \leq \alpha \leq 14^\text{h}50^\text{m})\). We will refer to these regions as the SGC and NGC respectively. QSOs are selected to \( b_1 < 20.85 \) by ultra-violet excess (UVX) in the \( u - b_1 : b_1 - r \) plane, at a completeness of 93 per cent. The spectra of the objects are obtained using the 2dF instrument on the AAT and reduced using the 2dF pipeline reduction system (Bailey & Glazebrook 1999). Objects are identified as QSOs by an automated procedure known as AITSQZ (Miller et al., in prep.). AIT2QZ also determines the QSO redshifts; these have then been visually checked by two independent observers. The final 2QZ catalogue, containing 22652 QSOs \((\text{only those QSOs with quality } 1 \text{ are used in this analysis; see Croom et al. (2001a) for details)}\), covers an area of 740 deg\(^2\), and the data will be released to the community in the first half of 2003.

2.1 The QSO selection function

In order to estimate the QSO power spectrum, we need to take into account the various selection effects introduced when constructing the survey. This is achieved by generating a catalogue of random points that mimics the angular and radial selection functions of the QSOs but otherwise is unclustered.

The rapid luminosity evolution seen in QSOs (Boyle et al. 2000) means that at each redshift, over the redshift range we are considering, we are studying roughly the same part of the QSO luminosity function, relative to \( M^* \). In areas where the spectroscopic completeness is low, due for example to poor seeing conditions, we are sampling on average slightly brighter QSOs. This just has the effect of sampling QSOs further up the luminosity function at all redshifts, rather than sampling objects at lower redshift, as is typical with galaxy redshift surveys. Even if we cut back the magnitude limit of the survey by half a magnitude from \( b_1 = 20.85 \) to \( b_1 = 20.35 \), the mean redshift only drops slightly from \( \bar{z} = 1.48 \) to \( \bar{z} = 1.45 \). Therefore, for this work we have assumed that the radial and angular selection functions can be applied independently, and consider each in turn below.

2.1.1 The angular selection function

The QSOs were observed simultaneously with galaxies from the 2dF Galaxy Redshift Survey (2dFGRS), and an adaptive tiling algorithm was developed to allow as many galaxies and QSOs as possible to be observed in each pointing. The pointings overlap in high density regions to maximise the coverage in all areas of the survey, and with this algorithm, we have achieved a completeness of 93 per cent. In addition to the 7 per cent of objects on which we were unable to place fibres, regions around bright stars were omitted from

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the input catalogue, and hence the angular mask of the 2QZ is quite complicated.

The survey also suffers from spectroscopic incompleteness. We have failed to confirm the identity of approximately 14 per cent of the objects observed. The spectra of these objects are typically very noisy, with a lack of discernible spectral features. As some classes of objects are easier to identify in low S/N spectra than others, due to, for example, distinctive emission lines, the spectroscopic completeness of QSOs in the survey may differ from that of stars, or the input catalogue as a whole. To correct for spectroscopic incompleteness we therefore need to estimate the fraction of QSOs that remain in these unidentified spectra. By examining the results from objects that have been observed more than once, such an estimate can be obtained. For objects unidentified after their first observation, but identified in subsequent observations, the relative fractions of QSOs and stars are remarkably similar to those of the identified objects in the full survey. Hence we estimate that QSOs account for approximately the same proportion (\( \sim 59 \) per cent) of the identified and unidentified populations and so the spectroscopic incompleteness of QSOs is in fact the same as that of the input catalogue as a whole. However, the rate of identifications obtained through the re-observation of previously unidentified objects is significantly lower than the survey average, and hence it is still possible that the fraction of QSOs remaining in the unidentified population could be somewhat lower. Through consideration of the fraction of QSOs unidentified after their first observation that are subsequently identified, we can set a lower limit to the fraction of QSOs in the remaining unidentified population at about 40 per cent. We will consider the effect of different spectroscopic completeness corrections in Section 4.1.

To match the angular selection function of the QSOs, we construct a completeness map, estimating completeness both to observational and spectroscopic effects in regions defined by the intersection of 2dF pointings. In each such region we calculate the fraction of objects contained in the input catalogue that have been identified. As the spectroscopic incompleteness of QSOs is approximately the same as that of the full input catalogue, the proportion of QSOs in unobserved objects should be the same as the proportion of QSOs observed, but unidentified objects. Hence we can take this fraction to be the overall (observational and spectroscopic) completeness in that region. As we are applying a spectroscopic completeness correction, we have decided not to apply simultaneously a minimum spectroscopic completeness cut, as this would reduce the size of our sample.

We also account for the extinction due to Galactic dust, using the estimate of the dust reddening, \( E(B-V) \), as a function of position given by Schlegel, Finkbeiner & Davis (1998). As Galactic dust changes the effective magnitude limit, we weight the random distribution by

\[
W_{\text{ext}}(\alpha, \delta) = 10^{-3.4b_{\text{i}}}
\]

where \( b_{\text{i}} = 4.035E(B-V) \) and \( \beta = 0.3 \), the slope of the integral QSO number-magnitude relation at the magnitude limit of the survey, \( b_{\text{i}} = 20.85 \). As we apply a dust correction to the angular mask, we need to correct for dust extinction in the observed radial selection function (below) to avoid including the effect of dust twice.

![Figure 1. The radial number density of QSOs in bins of \( \Delta r = 50h^{-1}\)Mpc in the NGC (solid line) and SGC (dashed line), corrected for the average dust extinction in each region and calculated assuming an EdS \( r(z) \) (top) and the \( \Lambda r(z) \) (bottom). Overlaid are the 10th order polynomial fits used to create the random catalogues, plotted over the redshift range \( 0.3 < z < 2.2 \). The number density varies very slowly as a function of scale; almost constant, assuming the EdS \( r(z) \) and decreasing only by a factor of approximately three over the range \( 0.3 < z < 2.2 \), assuming the \( \Lambda r(z) \). At higher redshifts, the number density decreases rapidly.](image)

2.1.2 The radial selection function

We are measuring QSO clustering as a function of comoving distance, and so we need to adopt a cosmology to convert from redshift into comoving distance. In this paper we consider an Einstein-de Sitter (EdS hereafter) and an \( \Omega_m=0.3, \Omega_{\Lambda}=0.7 \) cosmology \( r(z) \) (EdS hereafter) and an \( \Omega_m=0.3, \Omega_{\Lambda}=0.7 \) cosmology \( r(z) \) (\( \Lambda \) hereafter).

Figure 1 shows the radial selection function of QSOs in the NGC (solid line) and SGC (dashed line), corrected for the average dust extinction in each region and calculated assuming the EdS \( r(z) \) or the \( \Lambda r(z) \). Due to the contribution from the host galaxy, QSOs at low redshift are lost from our input catalogue because they do not appear stellar. The host galaxy also reddens faint QSOs causing them to be preferentially lost from the sample. To limit this incompleteness, we restrict our analysis to \( z > 0.3 \) (\( r > 740h^{-1}\)Mpc, assuming EdS, or \( r > 835h^{-1}\)Mpc, assuming \( \Lambda \)). At high redshifts the UVX colour selection technique breaks down as the Lyman-alpha forest enters the \( U \) band, and the completeness of the survey rapidly drops. Therefore, we also limit our analysis to \( z < 2.2 \) (\( r < 2645h^{-1}\)Mpc, assuming EdS, or \( r < 3820h^{-1}\)Mpc, assuming \( \Lambda \)). Over the redshift range \( 0.3 < z < 2.2 \) the completeness of the 2QZ colour
Table 1. The radial selection function is fitted separately in NGC and SGC, assuming either the EdS \( r(z) \) or the \( \Lambda \) \( r(z) \) to derive comoving distances from the QSO redshifts. This table shows the values of the 10 coefficients obtained from a 9th order polynomial fit, \( N(r) = \sum_{i=0}^{9} c_i (\frac{r}{50})^i \), to the number of QSOs in each strip, in the range \( 500 < r < 4200 \, h^{-1} \text{Mpc} \) (EdS), or \( 500 < r < 2800 \, h^{-1} \text{Mpc} \) (EdS), in bins of \( \Delta r = 50h^{-1} \text{Mpc} \). The QSO number density, \( n(r) \), is then obtained via \( n(r) = \frac{1}{\Delta r} N(r) \), where \( a_{NGC} = 0.2456 \) and \( a_{SGC} = 0.2281 \) are constants that take into account the average completeness and extinction in each strip.

|        | NGC, EdS | NGC, \( \Lambda \) | SGC, EdS | SGC, \( \Lambda \) |
|--------|----------|------------------|----------|------------------|
| \( c_0 \) | 104.623  | 47.1019          | 295.615  | 124.692          |
| \( c_1 \) | -448.886 | -216.212         | -987.737 | -90.183          |
| \( c_2 \) | 576.207  | 339.671          | 615.208  | 463.583          |
| \( c_3 \) | -35.6319 | -154.792         | 883.628  | -44.2143         |
| \( c_4 \) | -176.484 | 18.5957          | -858.731 | -92.7632         |
| \( c_5 \) | 17.0201  | 0.628647         | -20.3508 | 20.7977          |
| \( c_6 \) | -6.8416  | 1.38275          | -188.357 | 8.12686          |
| \( c_7 \) | -13.6702 | -0.301663        | -13.6225 | -2.35053         |
| \( c_8 \) | -0.636965| -0.126688        | -21.3586 | -0.123221        |
| \( c_9 \) | 0.269846 | 0.022045         | 4.13687  | 0.049514         |

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2.2 Mock 2QZ catalogues

To test our method of power spectrum estimation described below, as well as our error estimates, we have used the huge Hubble Volume \( \Lambda \) CDM simulation (Frenk et al. 2000, Evrard et al. 2002), where the particles have been output along an observer’s past light cone to simulate the 2QZ. The cosmological parameters of the simulation are \( \Omega_M = 0.26 \), \( \Omega_{\Lambda} = 0.7 \), \( H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} \) and \( \sigma_8 = 0.9 \). One billion mass particles are contained within a cube that is \( 3,000h^{-1} \text{Mpc} \) on a side. To create realistic QSO mock catalogues to match the final 2QZ sample, we bias the mass particles to give a similar clustering pattern, and introduce the same angular and radial selection function as seen in the final 2QZ sample, described in the previous section. For further details see Hoyle (2000), where the Hubble Volume simulation was compared to the 10k QSO catalogue.

3 POWER SPECTRUM ESTIMATION

The power spectrum estimation is carried out as described in Hoyle et al. (2002), using the method outlined in Tadros & Efstathiou (1996). The two declination strips are treated separately. They are embedded into a larger cubical volume, and the density field is binned onto a \( 256^3 \) mesh, using nearest grid-point assignment. The power spectrum of each region is estimated using a Fast Fourier Transform (FFT), and the average of the resulting power spectra is taken. The Fourier modes are binned up logarithmically to reduce the covariance between each bin. The FFT is unreliable at small scales; for a \( 256^3 \) FFT and a box of size \( 400h^{-1} \text{Mpc} \), the Nyquist frequency of the transform is \( k_{\text{Nyq}} = 0.2 \, h \, \text{Mpc}^{-1} \). The limit out to which the power spectrum measurement is reliable depends on the grid assignment scheme, and is a fraction of \( k_{\text{Nyq}} \). Using the nearest grid point assignment scheme, \( k_{\text{lim}} \approx 0.5 \, k_{\text{Nyq}} \) (Hatton 1999), which, for the above box size, corresponds to a value of \( \log(k_{\text{lim}}/h \, \text{Mpc}^{-1}) \approx -1 \) or a scale of \( 60h^{-1} \text{Mpc} \).

The measured power spectrum is convolved with the power spectrum of the window function. As the QSO comoving number density is almost constant out to very large scales, we are effectively considering a volume limited sample. Hence each QSO carries equal weight, and the survey window function, \( W(x) \), simply takes a value of unity in the volume of the universe included in the survey, and zero elsewhere. This is approximated using a catalogue containing a large number of unclustered points with the same radial and angular distribution as the survey, and its power spectrum is calculated in a similar manner to that of the data.

To enable measurements of the power spectrum on the result using a 10 coefficient polynomial fit, we find that the power is significantly enhanced on scales \( > 200h^{-1} \text{Mpc} \) (\( \log(k/h \, \text{Mpc}^{-1}) < -1.5 \)). Slightly increasing the order of the polynomial fit, however, has little effect our power spectrum estimate. Remeasuring the \( \Lambda \) power spectrum using a 15 coefficient polynomial fit, and comparing to the result using a 10 coefficient polynomial fit, we find that out to scales of \( 400h^{-1} \text{Mpc} \) (\( \log(k/h \, \text{Mpc}^{-1}) > -1.8 \)), the power spectra agree in amplitude to within 4 per cent, considerably smaller than the fractional error at this scale.
smaller scales, we use a direct method of computing the Fourier transform. This method is time intensive and can only be applied to a small number of particles (so cannot be applied to the random catalogue). Therefore, we make the assumption that the window function has a small amplitude, and so negligible effect on the power spectrum estimate. Using mock catalogues drawn from the Hubble Volume simulation, Hoyle (2000) demonstrated that on scales smaller than ≈ 100h⁻¹ Mpc (log(k/h Mpc⁻¹) ≈ −1.2) this approximation is accurate.

Finally, to obtain a single 2QZ power spectrum for each assumed cosmology, we average the power spectrum of the QSOs in the NGC and SGC strips together, weighting by the inverse of the variance on each scale.

3.1 The window function

In Fig. 2 we show the window function, |Wₖ|², of the 2QZ, measured assuming either EdS or Λ. The window function is anisotropic, due to the shape of the survey and variations in completeness, described by the selection function. In order to compare model power spectra with that determined here for the 2QZ, we need to convolve the model power spectra with the window function. In the case where the power is isotropic, the same result would be obtained by convolving with the spherically averaged window function. In reality, whilst we expect the real-space power spectrum to be isotropic, redshift-space distortions introduce small anisotropies into the shape of the redshift-space 2QZ power spectrum (see Outram et al. 2001). However, the Hubble Volume simulations suggest that these anisotropies have little effect on the spherically averaged power spectrum estimation, and so we only consider the spherically averaged window function from here on. We also show an analytic fit to the spherically averaged window function in Fig. 2:

\[
<|Wₖ|^2>_{EdS} = [1 + (k/0.00204)^2 + (k/0.00362)^2]^{-1} \quad (2)
\]

\[
<|Wₖ|^2>_{Λ} = [1 + (k/0.00132)^2 + (k/0.00258)^2]^{-1} \quad (3)
\]

Due to the huge volume probed by 2QZ, the window function is much more compact than that of galaxy surveys, and it takes the form of a steep power law, proportional to \(k^{-4}\) out to scales of \(\approx 600h^{-1}\) Mpc (log(k/h Mpc⁻¹) ≈ −2) for Λ. For comparison we also show an analytic fit to the 2dFGRS window function (Percival et al. 2001) in Fig. 2. The 2QZ window function has a very similar shape to that of the 2dFGRS, but shifted to larger scales; a factor of 2.5 × larger for the 2QZ EdS window function, or a factor of 3.5 × for Λ.

Fig. 3 demonstrates the effect that the 2QZ window function has on power spectra. On scales \(< 200h^{-1}\) Mpc (log(k/h Mpc⁻¹) > −1.5), the window function has very little effect on the true power spectrum, whilst on scales larger than this the true power is slightly suppressed. Even out to scales of \(\approx 600h^{-1}\) Mpc (log(k/h Mpc⁻¹) ≈ −2), the effect of the window function is considerably smaller than the statistical errors on the power spectrum estimate. The broader 2dFGRS window function has a much larger effect, not only suppressing power on scales \(> 100h^{-1}\) Mpc, but also smoothing out any baryonic ‘wiggles’ at smaller scales (Miller, Nichol & Chen 2002), and introducing covariance between the P(k) data points.

3.2 Error determination

The errors on the power spectrum determination are estimated using the method of Feldman, Kaiser & Peacock (1994; FKP), equation 2.3.2. The error is given by

\[
\frac{σ²(k)}{P²(k)} = \frac{(2π)^3}{V_k V_s} \cdot \frac{1}{n_{(n+k)}} \approx \frac{(2π)^3}{V_k V_s} \cdot \frac{1}{n_{(n+k)}}^2
\]

where \(V_k\) is the volume of each bin in k-space, estimated by \(V_k = N_k(Δk)^3\) with \(N_k\) the number of independent modes in the k-shell and \(Δk\) the volume of one k-mode. \(V_s\) is
Figure 3. The effect of convolving a model power spectrum with the 2QZ Λ window function. The solid line shows a linear ΛCDM power spectrum, with Ω_0 = 0.3, H_0 = 70km s^{-1}Mpc^{-1}, and Ω_b = 0.04. The dotted line shows the same power spectrum convolved with the 2QZ Λ window function, and the dashed line shows the power spectrum convolved with the 2dFGRS window function.

the volume of the survey. (We have assumed that the QSOs carry equal weight when estimating the power spectrum and associated errors). Hoyle (2000) demonstrated that over a wide range of scales these errors were found to be in reasonable agreement with errors estimated from the dispersion over power spectrum estimates from the Hubble Volume mock catalogues. On the smallest scales, non-linearities may lead to a larger error than the FKP error estimate (Meiksin & White 1999).

4 THE QSO POWER SPECTRUM

In Figure 4 we show the power spectrum estimate obtained, using the method outlined above, for the 2QZ dataset restricted to QSOs with redshift in the range 0.3 < z < 2.2. We compare the NGC and SGC power spectra measured assuming the EdS (a) or Λ (b). The combined power spectra are also shown, assuming EdS (c) or Λ (d). The power spectra measured from the two strips agree well over a wide range of scales, with a dispersion that is consistent with our error estimate. The errors shown here and throughout the paper are 1σ errors estimated using the FKP method. The power spectrum estimates obtained are also given in Table 2 (assuming EdS) and Table 3 (assuming Λ).

We compare this power spectrum estimate (assuming Λ) to that obtained by Hoyle et al. (2002) using the 10k 2QZ catalogue in Fig. 5. On scales smaller than log(k/h Mpc^{-1}) ∼ −1.6, the spectra are very similar, with the main difference being the reduced errors for the new estimate due to the increased sample size. On large scales, however, the 10k power spectrum estimate is slightly higher than the latest determination. This over-estimate was largely due to problems accounting for the complicated window of the incomplete 10k survey. However, with this difference in mind we now examine some of the other potential contributions to systematic errors in the power spectrum determination on large scales.

Table 2. Values of the QSO power spectrum P(k) estimated from QSOs with redshift in the range 0.3 < z < 2.2 contained in the 2dF QSO Redshift Survey Catalogue, assuming an EdS cosmology r(z). The errors are estimated using the method of Feldman, Kaiser & Peacock (1994).

| log(k/h Mpc^{-1}) | P(k)/h^{-3}Mpc^3 | ΔP(k)/h^{-3}Mpc^3 |
|------------------|------------------|------------------|
| -1.91250         | 7947.36          | 15528.9          |
| -1.83750         | 9975.61          | 14241.7          |
| -1.76250         | 11055.6          | 9826.21          |
| -1.68750         | 14009.9          | 8392.96          |
| -1.61250         | 17765.4          | 6605.29          |
| -1.53750         | 14482.3          | 4921.19          |
| -1.46250         | 7753.39          | 3518.10          |
| -1.38750         | 10000.78         | 2758.25          |
| -1.31250         | 7918.47          | 2079.62          |
| -1.23750         | 10850.0          | 1668.21          |
| -1.16250         | 8722.57          | 1252.32          |
| -1.08750         | 6644.70          | 940.720          |
| -1.01250         | 4991.80          | 710.215          |
| -0.93750         | 3716.06          | 538.652          |
| -0.86250         | 2851.89          | 411.061          |
| -0.78750         | 1703.66          | 312.109          |
| -0.71250         | 1924.72          | 241.619          |
| -0.63750         | 1194.02          | 184.568          |
| -0.56250         | 900.635          | 141.926          |

Table 3. Values of the QSO power spectrum P(k) estimated from QSOs with redshift in the range 0.3 < z < 2.2 contained in the 2dF QSO Redshift Survey Catalogue, assuming a Λ cosmology r(z). The errors are estimated using the method of Feldman, Kaiser & Peacock (1994).

| log(k/h Mpc^{-1}) | P(k)/h^{-3}Mpc^3 | ΔP(k)/h^{-3}Mpc^3 |
|------------------|------------------|------------------|
| -1.98750         | 34280.1          | 40765.3          |
| -1.91250         | 31228.7          | 30009.9          |
| -1.83750         | 30285.0          | 22002.5          |
| -1.76250         | 66904.5          | 20668.8          |
| -1.68750         | 42073.0          | 14148.3          |
| -1.61250         | 27967.6          | 10203.46         |
| -1.53750         | 36571.7          | 8169.82          |
| -1.46250         | 19371.4          | 5884.91          |
| -1.38750         | 22035.7          | 4602.21          |
| -1.31250         | 20998.8          | 3522.13          |
| -1.23750         | 16388.0          | 2646.94          |
| -1.16250         | 16152.2          | 2040.24          |
| -1.08750         | 10279.27         | 1531.78          |
| -1.01250         | 8100.51          | 1171.00          |
| -0.93750         | 5322.25          | 891.509          |
| -0.86250         | 5013.59          | 687.006          |
| -0.78750         | 3816.35          | 527.254          |
| -0.71250         | 2233.81          | 403.834          |
| -0.63750         | 841.637          | 309.547          |
| -0.56250         | 800.378          | 238.849          |
4.1 Large-scale systematic errors

One possible source of systematic errors is the uncertainty in the zero-point calibration of the UKST field plates that were used to define the input catalogue for the 2QZ survey. The fields are 5 deg × 5 deg, and so any differences in the plate calibration could introduce power on the largest scales probed. The recent release of the SDSS EDR data (Stoughton et al. 2002) has given us the opportunity to apply a new calibration to our data in the NGP to test this effect, after converting the Sloan colours to our bands (Blanton et al. 2001; Fukugita, Shimasaku, & Ichikawa 1995). A comparison of the two calibrations suggests that our calibration introduces plate-to-plate uncertainty in the QSO number density of the order of 4 per cent. In Fig. 6 we show the effect of using the SDSS calibration in the NGP on our power spectrum estimate. The difference in log $P(k)$ determined using the two calibrations is shown by the solid line. On scales log($k$/h Mpc$^{-1}$) > −1.8 there is virtually no difference. On large scales, using the SDSS calibration would lead to a small decrease in the measured power spectrum. Unfortunately we have no similar data to re-calibrate the SGP strip, and so, because this effect is very small, we have continued to use our original calibration.

A second potential source of systematic error is Galactic dust. We account for dust extinction using the estimates given by Schlegel, Finkbeiner & Davis (1998). If dust extinction is not correctly accounted for then this could introduce large scale variations in the observed QSO number density, and hence power. The short-dashed line in Fig. 6 shows a comparison between the power spectrum estimates with and without a dust correction. Applying the correction significantly reduces power on scales log($k$/h Mpc$^{-1}$) < −1.8. Whilst this gives us confidence in the dust maps, their resolution is fairly low, and so dust could still affect our estimate on smaller scales.

Finally we consider the effect of different choices of spectroscopic incompleteness corrections. In the 10k power spectrum analysis, only regions with spectroscopic completeness in excess of 85 per cent were considered, and no further correction was applied to account for any QSOs still missing in the unidentified spectra. As identification is dependent on the quality of the spectra, which varies with each pointing due to observing conditions, the fraction of missing QSOs could vary slightly from region to region even in this 85...
per cent complete sample, introducing large scale power. To investigate this we compare the power spectra determined using an 85 per cent spectroscopic completeness cut, then a further correction for observational completeness (as carried out in the 10k analysis) to one with the same 85 per cent cut, but also correcting for spectroscopic completeness, using the same form of correction as in this paper; assuming that fraction of QSOs in unidentified objects is the same as the fraction in the identified spectra. The result is shown by the dotted line in Fig. 6. The lack of a spectroscopic completeness correction introduces a slight over-estimate in the power, especially at large scales. This may also partly explain the difference between the 10k and final power spectrum estimates.

The spectroscopic completeness correction we apply simply assumes that the spectroscopic incompleteness of the QSOs is the same as that of the full input catalogue, and hence that \( \sim 59 \) per cent of unidentified objects are QSOs. Whilst this is favoured by evidence from re-observations, there is still uncertainty in the proportion of QSOs remaining in the unidentified spectra, and a slightly lower fraction of unidentified QSOs is still compatible with the observations. To test the effect of this uncertainty in the spectroscopic completeness correction we can construct a new completeness map where we instead assume that a lower fraction of approximately 40 per cent of objects that remain unidentified after observation are QSOs. A comparison between the power estimated using the two completeness corrections is shown by the long-dashed line in Fig. 6. The difference in power is very small on all scales, indicating that the uncertainty in the unidentified QSO fraction has a negligible effect on the power spectrum estimate.

It is also possible that there are spectroscopic completeness variations across individual 2dF fields, which could in principle introduce power on smaller scales. By artificially introducing completeness gradients across the 2dF fields in the random catalogue, we can investigate the likely size of any systematic uncertainty due to this effect. Even with a completeness gradient of 20 per cent from the centre to the edge of each field, the change in the measured power spectrum is no larger than that observed for any of the other potential systematics discussed above. As this artificially introduced gradient is much larger than the expected size of completeness variations across 2dF fields, given that the overall spectroscopic completeness for the survey is 86 per cent (and this is largely due to other effects such as weather conditions and seeing), we conclude that the power added by such an effect would be small, and we do not attempt to correct for this.

All of the potential systematics discussed above are much smaller than the statistical errors on all scales. With the exception of the dust correction, they are of the order of \( \Delta \log P(k) \sim 0.05 \) even on scales of \( \log(k/h\,\text{Mpc}^{-1}) \sim -2 \). Therefore we have confidence that our estimate is robust out to these scales.

### 4.2 The shape of the QSO power spectrum

In CDM models, the power spectrum should turn over at a scale which depends on the shape parameter, \( \Gamma \), of the power spectrum. The shape of the power spectrum and the position of the turnover contains information on cosmological parameters that can lead to strong constraints. In pure CDM models (i.e. without baryons) with a scale-invariant spectrum of initial fluctuations \( \Gamma = \Omega_m h \). However, the inclusion of baryons, or a tilted spectrum of initial fluctuations complicates the picture, so a measurement of \( \Gamma \) alone cannot be inverted reliably to give \( \Omega_m h \) (Sugiyama 1995,

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**Figure 5.** A comparison between the 2QZ power spectrum (assuming \( \Lambda \)) from the final sample (filled circles) with that derived from the initial 10k catalogue (open circles; Hoyle et al. 2002). Both sets of points have been offset by 0.01 in \( \log(k/h\,\text{Mpc}^{-1}) \) for clarity. There is very good agreement, except on the largest scales where the excess power was introduced by the complicated incomplete window function in the 10k sample.

**Figure 6.** The effect of making several changes to the observation mask are demonstrated. The solid line shows the change in the estimated power spectrum when SDSS photometry is used to calibrate the UKST plates in the NGP, rather than our own calibration. The short dashed line shows the effect of not correcting for dust. The long dashed line shows the difference between the power spectrum determinations using two different spectroscopic completeness estimates. The dotted line shows the effect of including a spectroscopic completeness estimate when considering only a sample with spectroscopic completeness \( > 85 \) per cent. For comparison, the double lines show the \( 1\sigma \) errors for the power spectrum estimation.
To parametrize the QSO power spectra we have measured, we fit model CDM power spectra with different values of the shape parameter $\Gamma$. We assume the fit to the CDM transfer function given by Bardeen et al. (1986). For each value of $\Gamma$, we allow the amplitude to vary freely, and minimize the $\chi^2$ of the fit. The best fit models are shown in Fig. 7. For an EdS $r(z)$, we find that models with $\Gamma = 0.16 \pm 0.03$ (1$\sigma$ errors) provide the best fit to the power spectrum, whereas assuming a $\Lambda$ $r(z)$, the power spectrum is slightly steeper, with $\Gamma = 0.13 \pm 0.02$. These low measurements of $\Gamma$ indicate significant large-scale power, considerably in excess of Standard ($\Omega_m = 1$) CDM model predictions, and consistent with the $\Lambda$ model prediction discussed above. In the case of the $\Lambda$ $r(z)$, whilst the power spectrum flattens at the largest scales probed, we see no evidence of the expected turnover below scales of $\sim 400 h^{-1}$Mpc ($\log k \sim -1.8$). However, in the slightly flatter EdS $r(z)$ power spectrum there is a hint of a possible turnover by scales of $\sim 400 h^{-1}$Mpc. In either case we can strongly rule out a turnover in the power spectrum at scales below $\sim 300 h^{-1}$Mpc ($\log k \sim -1.7$). We will consider the effect of baryons, the window function, and redshift-space distortions in Section 5 in order to derive constraints on $\Omega_m h$ from the shape of the power spectrum.

4.3 Comparison with $P(k)$ from galaxy and cluster surveys

We compare the QSO power spectrum with the power spectra of local galaxies, determined from the 2dFGRS (Percival et al. 2001), PSCz (Sutherland et al. 1999), APM (Gaztanaga & Baugh 1998), and DUKST (Hoyle et al. 1999) galaxy surveys and the power spectra of local Abell/ACO clusters (Miller & Batuski 2001) and APM clusters (Tadros, Efstathiou & Dalton 1998) in Fig. 8. Assuming a $\Lambda$ $r(z)$, the amplitude of QSO clustering at $\bar{z} \sim 1.4$ is similar to that of local galaxies, and almost an order of magnitude below that of galaxy clusters. Assuming an EdS $r(z)$, the amplitude of QSO clustering is slightly lower than the local galaxy clustering amplitude. The $\Lambda$ $r(z)$ QSO power spectrum appears steeper than that of the 2dFGRS, with more power on large scales. This is largely due, however, to the effects of the window function on the 2dFGRS power spectrum, as demonstrated in Fig. 3. For a true comparison of the relative shapes of the galaxy and QSO power spectra, we will fit models convolved with their respective window functions in Section 5.

4.4 The evolution of QSO clustering

To investigate the effects of evolution on the amplitude of QSO clustering we split the QSO sample into two, a high redshift sample with $z > 1.4$, and a low redshift sample with $z < 1.4$, and compare their respective power spectra. The results are shown in Fig. 9. Assuming either EdS or $\Lambda$, we see virtually no evolution in the amplitude of clustering between the two samples, at $0.3 < z < 1.4$ and $1.4 < z < 2.2$. To quantify this, we fit the amplitude of the best fitting model power spectra for each cosmology found in section 4.2 ($\Gamma = 0.16$ for EdS and $\Gamma = 0.13$ for $\Lambda$) separately for each redshift bin. The results are shown in Table 4. We find that the amplitude of QSO clustering is almost identical in the
two redshift bins. Assuming EdS, the difference in amplitude between the two redshifts is insignificant. Assuming Λ, we marginally detect a slight fall in amplitude of ∆ log P = 0.05 from high redshift to low redshift, at about 1σ significance. This is in very good agreement with the results of the 2QZ correlation function analysis of Croom et al. (2001b).

We fixed the value of Γ for the above analysis, as the shape parameter is assumed not to evolve with redshift (in the linear regime), in order to investigate the evolution of the amplitude of QSO clustering. We can test this assumption by comparing the value of Γ in the low and high redshift bins. For the Λ r(z), we find that this is indeed the case, with best fit values of Γ = 0.14 ± 0.03 at 0.3 < z < 1.4 and Γ = 0.13 ± 0.03 at 1.4 < z < 2.2. For the EdS r(z), however, there is marginal evidence for a slight flattening of the power spectrum at higher redshift, with best fit values of Γ = 0.15 ± 0.05 at 0.3 < z < 1.4 and Γ = 0.20 ± 0.05 at 1.4 < z < 2.2. One possible, though unlikely explanation for this observed flattening could be evolution of a scale-dependent QSO bias on ≥ 100 h⁻¹Mpc scales. If this were the case it could be a major problem for the cosmological parameter analysis in the next section, and other similar analyses that use galaxies or QSOs as tracers of large-scale structure. Alternatively, the flattening could be due to the different shape of the window function in the two redshift bins. However, the two window functions are very similar, and if anything, the high redshift window function is slightly more compact, so we would expect less suppression of large-scale power, not more, at high redshift.

If our assumption of an EdS cosmology r(z) were incorrect, as suggested by the low measured values of Γ and hence Ω₉₃h (see Section 5) then we would have a simple explanation for the observed flattening. If, for example, the Λ cosmology were the true cosmology, then our assumption of an EdS r(z) would lead to an underestimate of the comoving distance scale, by about 25 per cent in the low redshift bin, and 50 per cent in the high redshift bin. If we apply this correction to distance scale of the power spectrum determined assuming EdS, we then obtain consistent values of Γ = 0.12 ± 0.03 at 0.3 < z < 1.4 and Γ = 0.13 ± 0.03 at 1.4 < z < 2.2. The observed evolution in shape assuming an EdS r(z) could therefore be taken as further marginal evidence against an EdS cosmology.

Table 4. The amplitude of model power spectra fitted to QSO power spectra in redshift bins, assuming either EdS or Λ. In both cases, the shape parameter, Γ, was fixed at the best fitting value for that cosmology.

| Cosmology | Redshift bin | Γ   | log(P(k=0.1)) |
|-----------|-------------|-----|--------------|
| EdS       | 0.3 < z < 2.2 | 0.16 | 3.66 ± 0.03 |
| EdS       | 0.3 < z < 1.4 | 0.16 | 3.65 ± 0.05 |
| EdS       | 1.4 < z < 2.2 | 0.16 | 3.67 ± 0.05 |
| Λ         | 0.3 < z < 2.2 | 0.13 | 3.90 ± 0.03 |
| Λ         | 0.3 < z < 1.4 | 0.13 | 3.88 ± 0.04 |
| Λ         | 1.4 < z < 2.2 | 0.13 | 3.93 ± 0.04 |

5 COMPARISON WITH MODELS OF LARGE SCALE STRUCTURE

5.1 The Hubble Volume simulation

The Hubble Volume simulation was introduced in section 2.2. The power spectrum determined from biased mock QSO catalogues, created using the final 2QZ selection function imprinted on the Hubble Volume simulation, is shown in Fig. 10, where it is compared to the real space input mass power spectrum for the simulation, together with the 2QZ power spectrum with Λ assumed. The simulation was designed to mimic the 2QZ as closely as possible, and so any differences in shape should give a good test of the cosmological assumptions.

The first thing to note is that over a wide range of scales, the output redshift-space mock catalogue power spectrum follows very closely the real space input mass power spectrum for the simulation. On the largest scales (log(k/h Mpc⁻¹) ≲ −1.5), this demonstrates that the effects
The QSO Power Spectrum

Figure 9. The power spectrum of QSOs measured at different redshifts. The EdS $r(z)$ is assumed in the upper plot and $\Lambda$ is assumed in the lower plot. The open circles show the power spectrum of QSOs with redshifts in the range $0.3 < z < 1.4$ and the filled circles show the power spectrum of QSOs with redshifts in the range $1.4 < z < 2.2$. The errors are $1\sigma$ FKP errors. The points are slightly offset for clarity.

Figure 10. The points show the 2QZ power spectrum with $\Lambda$ assumed. The dashed line shows the real space input power spectrum for the Hubble Volume simulation. The solid line shows the Hubble Volume $\Lambda$CDM mock QSO catalogue redshift space power spectrum (see Hoyle et al. 2002), updated to match the final 2QZ selection function, with $1\sigma$ errors indicated by the dotted lines.

it is also very time consuming. We need to compare many different CDM models to derive constraints on cosmological parameters. Therefore in the next section we instead compare the QSO power spectrum to model CDM power spectra with a variety of different cosmologies.

5.2 Fitting model power spectra

Assuming that QSO bias is not scale-dependent on the scales we are probing, the shape of the QSO power spectrum provides new constraints on the matter and baryonic contents of the Universe at a different (much higher) redshift than that of the 2dFGRS, or other galaxy / cluster power spectrum determinations. Therefore, the QSO power spectrum measurement at $z \sim 1.4$ can provide a powerful new test for cosmological models that have previously only been constrained locally ($z \sim 0$) and at recombination ($z \sim 1000$). Model power spectra with a variety of CDM cosmologies have been created using transfer function formulae from Eisenstein & Hu (1998) to compare with the 2QZ data. We have chosen to vary $\Omega_b/\Omega_m$ (where $\Omega_m = \Omega_{cdm} + \Omega_b$), and $\Omega_m h$, considering the range $0 < \Omega_b/\Omega_m < 0.5$ and $0 < \Omega_m h < 1.0$ in order to determine constraints on these important parameters. We have assumed a scale invariant spectrum of initial fluctuations.

The models generated have been numerically convolved with the 2QZ window function. We noted in the comparison with the Hubble Volume simulation that small-scale power is slightly suppressed in the redshift-space power spectrum by small-scale peculiar velocities of the mock QSOs. A comparison between the Hubble Volume and 2QZ power spectra shows that the simulation provides a very good fit to the observed data over virtually the whole range observed. The 2QZ power spectrum is therefore entirely consistent with the $\Lambda$CDM cosmological model assumed to create the Hubble Volume. Whilst performing detailed analyses of N-body simulations such as the Hubble Volume is very useful, providing a good test of the power spectrum estimator and a way of examining possible systematic effects,
to the true QSO small-scale velocity dispersion. We can apply a simple model to correct the power spectrum for these redshift-space distortions (Ballinger et al. 1996). Following Outram et al. (2001) we assume an apparent QSO line of sight pairwise velocity dispersion, due to both redshift determination errors and peculiar velocities, of 700 km s$^{-1}$, and a value of $\beta = \Omega_m^0 / b = 0.39$ to describe the coherent peculiar velocities on large, linear scales due to the infall of galaxies into overdense regions. We do not attempt a correction for geometric distortions introduced by incorrect cosmological model assumptions when measuring the power spectrum.

For this analysis, we have assumed that the data points are independent. Due to the compactness of our window function, this should be a good approximation. We have also had to assume a cosmology to derive the QSO $r(z)$ prior to measuring the QSO power spectrum. Ideally one would like to fit each power spectrum model to the power spectrum measured assuming the appropriate cosmology. However, this would be very time consuming, and beyond the scope of this paper. Therefore we limit our analysis to power spectra measured assuming either an EdS or $\Lambda$ $r(z)$. Despite assuming a particular cosmology to derive the $r(z)$, we do not initially restrict the fitted parameters to match these cosmologies. We determine the likelihood of each model by calculating the $\chi^2$ value of each fit, per-

Figure 11. The plots show the best fit CDM models (solid lines) to the 2QZ power spectra (points). In the upper plot, the EdS $r(z)$ is assumed. The solid line shows the best fit CDM model with $\Omega_b/\Omega_m = 0.18$ and $\Omega_m h = 0.24$. The dotted line shows a CDM model from the second branch of solutions ($\Omega_b/\Omega_m = 0.42$ and $\Omega_m h = 0.70$) that fit the 2dFGRS power spectrum. The lower plot shows the best fit CDM model to the 2QZ power spectra assuming the $\Lambda r(z)$, with $\Omega_b/\Omega_m = 0.18$ and $\Omega_m h = 0.19$ (solid line). The dotted line shows, for comparison, the same model prior to correction for window function and redshift-space distortion effects.

Figure 12. Filled contours of decreasing likelihood in the $\Omega_m h - \Omega_b/\Omega_m$ plane, marginalizing over $h$ and the power spectrum amplitude, for fits to the 2QZ power spectra, assuming EdS for the upper plot, and $\Lambda$ for the lower plot. Contours are plotted for a one-parameter confidence of 68 per cent (dashed contour), and two-parameter confidence of 68, 95 and 99 per cent (solid contours). + marks the best fit models to the 2QZ data ($\Omega_b/\Omega_m = 0.18$, $\Omega_m h = 0.24$, or with lower likelihood, $\Omega_b/\Omega_m = 0.42$, $\Omega_m h = 0.70$ assuming EdS, and $\Omega_b/\Omega_m = 0.18$, $\Omega_m h = 0.19$ assuming $\Lambda$), and x marks the best fit models ($\Omega_b/\Omega_m = 0.18$, $\Omega_m h = 0.23$ assuming EdS, and $\Omega_b/\Omega_m = 0.15$, $\Omega_m h = 0.2$ assuming $\Lambda$) determined in a similar analysis on the 2dFGRS data (Percival et al. 2001).
The QSO Power Spectrum

As the shape of the power spectrum is primarily dependent on $\Omega_m h$, and relatively invariant to changes in $h$ for a given $\Omega_m h$, the value of $h$ has relatively little effect on the results. Repeating the fit, with $h$ fixed at $h = 0.7$, following, for example, the results of Tanvir et al. (1995) and the HST Key Project (Mould et al. 2000) only marginally improved the constraints on the parameters of interest.

The best fit models, shown in Fig. 11, fit the data well over the full range of scales considered. The effect of the window function and redshift-space corrections can be seen in the $\Lambda$ plot. The solid line in the plot shows the best fit model to the $\Lambda$ 2QZ power spectrum, with $\Omega_b/\Omega_m = 0.18$ and $\Omega_m h = 0.19$. The dotted line shows the same model prior to correction for window function and redshift-space distortion effects. The effect of the window function can be seen on large scales, slightly supressing the power, and on small scales the effect of redshift-space distortions can be seen. This lack of small scale power steepens the power spectrum, leading to a lower value of $\chi^2$. If not corrected for, therefore, it would lead to an under-estimate of $\Omega_m h$. The effect of the window function is slightly larger when an EdS $r(z)$ is assumed.

Likelihood contours in the $\Omega_m h - \Omega_b/\Omega_m$ plane for fits to the 2QZ power spectra are shown in Fig. 12 (allowing $h$ to vary), and Fig. 13 (with fixed $h = 0.7$). Assuming an EdS QSO $r(z)$, we find a degeneracy between the two parameters. The best fit model has $\Omega_b/\Omega_m = 0.18 \pm 0.09$ and $\Omega_m h = 0.24 \pm 0.04$, however a second solution with $\Omega_b/\Omega_m = 0.42$ and $\Omega_m h = 0.70$ cannot be rejected at 95 per cent confidence from this analysis alone. For comparison, we show the best fit derived from the 2dFGRS data (Percival et al. 2001), which is in good agreement with the result derived here. The degeneracy we see is also very much like that found in the 2dFGRS data. We note that the best fit value of $\Omega_m h$ obtained is totally inconsistent with the assumed EdS cosmology. Whilst the second solution is consistent with EdS, it is strongly rejected by other analyses such as estimates of the baryon content from big-bang nucleosynthesis (O'Meara et al. 2001) and recent Cosmic Microwave Background (CMB) results (e.g. Sievers et al. 2002).

The best fit model to the $\Lambda$ $r(z)$ 2QZ data has $\Omega_b/\Omega_m = 0.18 \pm 0.10$ and $\Omega_m h = 0.19 \pm 0.05$. Although the contours are again elongated in the direction of the degeneracy seen in the EdS plot, the second peak seen in the greyscale is ruled out at over 95 per cent confidence. Due to the huge volume of the 2QZ, particularly in a $\Lambda$ cosmology, we are able probe larger scales than with the 2dFGRS. Whilst the second solution is not a bad fit on scales $\log(k/h\mathrm{Mpc}^{-1}) > -1.5$, we can discriminate between the two models on the largest scales probed by the 2QZ. When repeating the fits, considering only models with $h = 0.7$, we see a marginal tightening of the contours, shown in Fig. 13, with best fit models of $\Omega_b/\Omega_m = 0.17 \pm 0.09$ and $\Omega_m h = 0.19 \pm 0.04$. This is totally consistent with the $\Lambda$ cosmology assumed to calculate $r(z)$.

These results agree well with those obtained by Yamamoto (2002) who produced a similar analysis of the cosmological parameter constraints that could be derived from the 2QZ 10k catalogue. The values of $\Omega_m h$ and $\Omega_b/\Omega_m$ obtained assuming either $r(z)$ are very similar, indicating that these results are largely independent of our $r(z)$ assumption. When fitting models in the $\Omega_m h - \Omega_b/\Omega_m$ plane we have considered only a family of CDM models with a scale invariance.

**Figure 13.** Filled contours of decreasing likelihood in the $\Omega_m h - \Omega_b/\Omega_m$ plane, marginalizing the power spectrum amplitude but fixing $h$, for fits to the 2QZ power spectra, assuming EdS for the upper plot, and $\Lambda$ for the lower plot. Contours are plotted for a one-parameter confidence of 68 per cent (dashed contour), and two-parameter confidence of 68, 95 and 99 per cent (solid contours). + marks the best fit model to the 2QZ data ($\Omega_b/\Omega_m = 0.12$, $\Omega_m h = 0.21$, or with lower likelihood, $\Omega_b/\Omega_m = 0.43$, $\Omega_m h = 0.82$ assuming EdS, and $\Omega_b/\Omega_m = 0.17$, $\Omega_m h = 0.19$ assuming $\Lambda$), and × marks the best fit models ($\Omega_b/\Omega_m = 0.18$, $\Omega_m h = 0.23$ assuming EdS, and $\Omega_b/\Omega_m = 0.15$, $\Omega_m h = 0.2$ assuming $\Lambda$) determined in a similar analysis on the 2dFGRS data (Percival et al. 2001). In each case, the dotted vertical line shows the value of $\Omega_m h$ assumed to calculate $r(z)$.

formed over the range $-1.9 < \log(k/h\mathrm{Mpc}^{-1}) < -0.75$, and assuming that $\mathcal{L} \propto \exp(-\chi^2/2)$. For each model, we allowed the amplitude to vary (to account for linear QSO bias; we assumed that QSO bias is scale independent on scales $\log(k/h\mathrm{Mpc}^{-1}) < -0.75$), choosing the value that maximised the likelihood of the fit.

We also allowed $h$ to vary, within the range $0.4 < h < 0.9$, choosing the value that maximised the likelihood of the fit.
ant spectrum of initial fluctuations \((n = 1)\). If we relaxed these assumptions we would introduce new degeneracies (Efstathiou et al. 2002), and significantly reduce the constraints on the above parameters. However, the degeneracies between cosmological parameters derived from power spectral analyses of large-scale structure (e.g. probed by the 2QZ or the 2dFGRS) alone are different from those from other datasets, such as the CMB, and Efstathiou et al. demonstrated that by combining such datasets, these degeneracies can be broken, leading to strong cosmological constraints.

6 CONCLUSIONS

We have presented a power spectrum analysis of the final 2dF QSO Redshift Survey catalogue containing 22652 QSOs. Utilising the huge volume probed by the QSOs, we have accurately measured the power over the range \(-2 < \log(k/h \text{Mpc}^{-1}) < -0.7\), thus covering over a decade in scale, and reaching scales of \(\sim 500 h^{-1}\text{Mpc}\). The \(\Lambda\) \(\tau\) (QSO) power spectrum can be well described by a model with shape parameter \(\Gamma = 0.13 \pm 0.02\). If an Einstein-de Sitter model is instead assumed, a slightly higher value of \(\Gamma = 0.16 \pm 0.03\) is obtained. These low measurements of \(\Gamma\) indicate significant large-scale power and assuming either cosmology we can strongly rule out a turnover in the power spectrum at significant large-scale power and assuming either cosmology we is obtained. These low measurements of \(\Gamma\) indicate significant large-scale power and assuming either cosmology we can strongly rule out a turnover in the power spectrum at scales below \(\sim 300h^{-1}\text{Mpc}\) \((\log(k/h \text{Mpc}^{-1}) \sim -1.7)\). The amplitude of clustering of the QSOs at \(z \sim 1.4\) is similar to that of present day galaxies, and an order of magnitude lower than present day clusters. A comparison of the power spectra of QSOs at high and low redshift shows little evidence for any evolution in the amplitude of clustering.

A comparison with the Hubble Volume ACDM simulation shows very good agreement over the whole range of scales considered. To derive constraints on the matter and baryonic contents of the Universe, we fit CDM model power spectra (assuming scale-independent bias and scale-invariant initial fluctuations), convolved with the survey window function, and corrected for redshift space distortions. Assuming a \(\Lambda\) cosmology \(\tau(z)\), we find that models with baryon oscillations are slightly preferred, with the baryon fraction \(\Omega_b/\Omega_m = 0.18 \pm 0.10\). The overall shape of the power spectrum provides a strong constraint on \(\Omega_m h\) (where \(h\) is the Hubble parameter), with \(\Omega_m h = 0.19 \pm 0.05\). These new constraints are derived at \(z \sim 1.4\), which corresponds to a look-back time of approximately two-thirds of the age of the Universe. Cosmological constraints at this intermediate epoch provide a strong test for models previously constrained to match CMB observations at \(z \sim 1000\) and the local Universe at \(z \sim 0\).

ACKNOWLEDGEMENTS

The 2dF QSO Redshift Survey was based on observations made with the Anglo-Australian Telescope and the UK Schmidt Telescope, and we would like to thank our colleagues on the 2dF Galaxy Redshift Survey team and all the staff at the AAT that have helped to make this survey possible. We would like to thank Adrian Jenkins, Gus Evrard, and the Virgo Consortium for kindly providing the Hubble Volume simulations. PJO would like to acknowledge the support of a PPARC Fellowship.

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