The 2dF QSO Redshift Survey - II. Structure and evolution at high redshift

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ABSTRACT

In this paper we present a clustering analysis of QSOs over the redshift range \( z = 0.3 - 2.9 \). We use a sample of 10558 QSOs taken from preliminary data release catalogue of the 2dF QSO Redshift Survey (2QZ). The two-point redshift-space correlation function of QSOs, \( \xi_Q(s) \), is shown to follow a power law on scales \( s \approx 1 - 35 h^{-1} \) Mpc. Fitting a power law of the form \( \xi_Q(s) = (s/s_0)^{-\gamma} \) to the QSO clustering averaged over the redshift interval \( 0.3 < z \leq 2.9 \) we find \( s_0 = 3.99^{+0.34}_{-0.28} h^{-1} \) Mpc and \( \gamma = 1.58^{+0.16}_{-0.09} \) for an Einstein-de Sitter cosmology. The effect of a significant cosmological constant, \( \lambda_0 \), is to increase the separation of QSOs, so that with \( \Omega_0 = 0.3, \lambda_0 = 0.7 \) the power law extends to \( 60 h^{-1} \) Mpc and the best fit is \( s_0 = 5.69^{+0.42}_{-0.50} h^{-1} \) Mpc and \( \gamma = 1.56^{+0.10}_{-0.09} \). These values, measured at a mean redshift of \( \bar{z} = 1.49 \), are comparable to the clustering of local optically selected galaxies. We compare the clustering of 2QZ QSOs to generic CDM models with shape parameter \( \Gamma_{\text{eff}} \). Standard CDM with \( \Gamma_{\text{eff}} = 0.5 \) is ruled out in both Einstein-de Sitter and cosmological constant dominated cosmologies, where \( \Gamma_{\text{eff}} \approx 0.2 - 0.4 \) and \( \Gamma_{\text{eff}} \approx 0.1 - 0.2 \) respectively are the allowable ranges.

We measure the evolution of QSO clustering as a function of redshift. For \( \Omega_0 = 1 \) and \( \lambda_0 = 0 \) there is no significant evolution in comoving coordinates over the redshift range of the 2QZ. QSOs thus have similar clustering properties to local galaxies at all redshifts we sample. In the case of \( \Omega_0 = 0.3, \lambda_0 = 0.7 \) QSO clustering shows a marginal increase at high redshift, \( s_0 \) being a factor of \( \sim 1.4 \) higher at \( z \approx 2.4 \) than at \( z \approx 0.7 \). Although the clustering of QSOs is measured on large scales where linear theory should apply, the evolution of QSO clustering does not follow the linear theory predictions for growth via gravitational instability (rejected at the > 99 per cent confidence level). A redshift dependent bias is required to reconcile QSO clustering observations with theory. A simple biasing model, in which QSOs have cosmologically long lifetimes (or alternatively form peaks above a constant threshold in the density field) is acceptable in an \( \Omega_0 = 1 \) cosmology, but is only marginally acceptable if \( \Omega_0 = 0.3 \) and \( \lambda_0 = 0.7 \). Biasing models in which QSOs are assumed to form over a range in redshift, based on the Press-Schechter formalism, are consistent with QSO clustering evolution for a minimum halo mass of \( \sim 10^{12} M_\odot \) and \( \sim 10^{13} M_\odot \) in an Einstein-de Sitter and cosmological constant dominated universe, respectively. However, until an accurate, physically motivated, model of QSO formation and evolution is developed, we should be cautious in interpreting the fits to these biasing models.

Key words: galaxies: clustering – quasars: general – cosmology: observations – large-scale structure of Universe.

1 INTRODUCTION

The 2dF QSO Redshift Survey (2QZ) aims to compile a homogeneous catalogue of \( \sim 25000 \) QSOs using the Anglo-

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Australian Telescope (AAT) 2-degree Field facility (2dF; Taylor, Cannon & Watson 1997). This catalogue will constitute a factor of \(\geq 50\) increase in numbers to a equivalent flux limit over previous data sets (e.g. Boyle et al. 1990).

The main science goal of the 2QZ is to use QSOs to probe the large-scale structure of the Universe over a range of scales from 1 to 1000 h\(^{-1}\) Mpc, and in the redshift interval, \(0.3 \leq z \leq 2.9\).

Clustering of QSOs at small to intermediate scales (150–50 h\(^{-1}\) Mpc) supplies a wealth of information on large-scale structure. QSOs still give us the only method of directly determining the 3-dimensional clustering of redshift objects within a large enough volume for it to be truly representative. When complete, the 2QZ will sample a volume of \(1.5 \times 10^{8} h^{-3} Mpc^3\) (for \(\Omega_0 = 1\)), an order of magnitude larger than current galaxy redshift surveys (e.g. the 2dF Galaxy Redshift Survey; Colless 1999). This large volume also allows us to probe the scales where linear evolution occurs, simplifying comparisons with theory.

The shape and amplitude of the two-point autocorrelation function, \(\xi(r)\), is determined by two factors. The first is the distribution of matter fluctuations in the Universe. This depends on fundamental physics, such as the growth of structure via gravitational instability and the initial spectrum of fluctuations. The second factor concerns the complex and generally non-linear physics which occurs during galaxy and QSO formation. The difference between the matter and galaxy or QSO distributions is commonly called bias, \(b(r, z)\), such that

\[
\xi_Q(r, z) = b^2(r, z)\xi_g(r, z),
\]

where \(\xi_Q(r, z)\) and \(\xi_g(r, z)\) are the two-point correlation functions of QSOs and the density field respectively. Both are functions of scale, \(r\), and redshift, \(z\). Often, a linear bias is assumed, which has no scale dependence, and it appears likely that for any local process of galaxy formation \(b\) should tend to a constant value on scales where the density perturbations are linear (e.g. Mann, Peacock & Heavens 1998; Peacock 1997). We will assume a linear bias throughout this paper.

The first attempt to measure the clustering of QSOs was made by Osmer (1981). Shaver (1984) was the first to detect QSO clustering on small scales, although in an inhomogeneous sample. Shanks et al. (1987) made the first detection of clustering at \(\leq 10 h^{-1}\) Mpc in a complete and uniformly selected sample; part of the Durham/AAT UVX survey (Boyle et al. 1990). A number of authors have used this and other QSO samples to measure clustering. They all reach generally the same conclusions that clustering is detected at the \(\sim 3\sigma\) level and is approximately consistent with a clustering scale length \(r_0 \sim 6 h^{-1}\) Mpc, similar to local galaxy clustering, at a mean redshift of \(z \sim 1\) (Iovino & Shaver 1988; Andreon & Cristiani 1992; Mo & Fang 1999; Shanks & Boyle 1991; Croom & Shanks 1990). There has been significant disagreement over the redshift evolution of QSO clustering including claims for a decrease in the QSO correlation length (\(r_0\)) with redshift (Iovino & Shaver 1984, an increase in \(r_0\) with redshift (La Franca, Andreani & Cristiani 1998; hereforth LAC98) and no change with redshift (Croom & Shanks 1996; hereforth CS96).

The measurement of galaxy clustering at high redshift has also taken dramatic steps forward in recent years. A number of surveys have made measurements of the clustering strength of galaxies up to \(z \sim 1\). These samples typically contain a few hundred to a thousand galaxies over relatively small areas. The Canada-France Redshift Survey (CFRS) shows a significant decrease in clustering amplitude on scales < 2 h\(^{-1}\) Mpc (Le Fevre et al. 1996). However, larger samples, such as the CNOC-2 survey (Carlberg et al. 1991) show much slower evolution, with a gradual decrease of clustering with redshift: \(r_0(z) \propto (1+z)^{-0.5\pm0.2}\). Deep wide-field (\(~\sim\) few degrees) imaging surveys used to measure the angular correlation function of galaxies also suggest higher clustering amplitudes than found in the CFRS (Postman et al. 1998). The differences found between these samples is partly due to the different selection methods (e.g. magnitude limits; photometric bands) used. It is likely that different galaxy types cluster differently, e.g. optically vs. infrared selected galaxies (Peacock 1997). Clustering is also likely to be a function of galaxy luminosity. It is possible that this is the case for QSOs, although we leave the discussion of luminosity dependent clustering of QSOs to a future paper. We note, however, that due to the stong luminosity evolution of QSOs (e.g. Boyle et al. 2000) an apparent magnitude limited survey of QSOs samples approximately the same part of the luminosity function at all redshifts up to \(z \sim 2\). A second affect responsible for the difference in galaxy clustering results is cosmic variance due to the small volumes and scales sampled, in particular by the CFRS. A key element of the 2QZ is that it is large enough to minimize any effects of cosmic variance on scales smaller than a few hundred h\(^{-1}\) Mpc. Although studies of galaxy clustering have been typically limited to \(z \leq 1\), Steidel et al. (1998) have used galaxies detected by their Lyman-break to derive the clustering properties of galaxies at \(z \sim 3\). These observations show that the clustering of \(L \sim L^*\) galaxies at \(z \sim 3\) is also similar to local galaxies on scales \(\lesssim 10 h^{-1}\) Mpc, with \(r_0 \approx 4 – 6 h^{-1}\) Mpc depending on the assumed cosmology (Adelberger et al. 1998).

In this paper we look at QSO clustering in the 2QZ on scales from \(\sim 1\) to 100 h\(^{-1}\) Mpc. We do not attempt to study larger scales because of the current non-uniformity of the data set. This will be reserved for future work, on completion of the survey. In Section 2 we describe the 2QZ data used and our methods of analysis. In Sections 3 and 4 we present our clustering results and compare them to physical models. Our conclusions are presented in Section 5.

## 2 DATA AND TECHNIQUES

### 2.1 The 2dF QSO Redshift Survey

For the analysis in this paper we have used the first public release catalogue of the 2QZ containing 10681 QSOs (the 10k catalogue). This 10k catalogue contains the most spectroscopically complete fields observed prior to November 2000 and will be released to the astronomical community in the first half of 2001. The sample contains 10558 QSOs in the redshift range \(0.3 \leq z \leq 2.9\) which will be included in our analysis below.

The identification of QSO candidates for the 2QZ was based on broad band \(ub\) colours from Automatic Plate Measuring (APM) facility measurements of UK Schmidt
Telescope (UKST) photographic plates. The survey comprises 30 UKST fields, arranged in two 75° × 5° declination strips centred in the South Galactic Cap (SGC) at δ = −30° and the North Galactic Cap (NGC) at δ = 0° with RA ranges α = 21h 40 to 3h 15 and α = 9h 50 to 14h 50 respectively. Each UKST field contains independent CCD calibration (Boyle et al. 1993, Croom et al. 1999). The completed survey will cover approximately 740 deg° (some areas having been removed due to bright stars, plate defects etc). Further details of the photometric catalogue can be found in Croom (1997), Smith (1998) and Smith et al. (2001).

Spectroscopic observations have been carried out using the 2dF instrument at the AAT in conjunction with the 2dF Galaxy Redshift Survey (Colless 1999), as the 2QZ and galaxy survey areas cover the same regions of sky. Typically, 225 fibres are devoted to galaxies, 125 to QSO candidates and 25-30 to sky in each 2dF observation. Spectroscopic data are reduced using the 2dF pipeline reduction system (Bailer & Glazebrook 1999). The identification of QSO spectra and redshift estimation was carried out using the AUTOZ code written specifically for this project (Miller et al. 2001 in preparation). This program compares template spectra of QSOs, stars and galaxies to the observed spectra. Identifications are then confirmed by eye for all spectra. Spectroscopic completeness is typically > 80 per cent when observations are made in reasonable or good conditions. In the analysis below we use all objects which have been classified as class 1 QSOs (class 1 being the highest quality identification; objects classified as class 2 IDs or “QSO?” were not included) and which were observed in fields within the 10k catalogue (which is limited to ≥ 85 per cent spectroscopic completeness).

2.2 Correlation function estimates

As the QSO correlation function, ξQ probes high redshifts and large scales, the measured values are highly dependent on the assumed cosmology. We employ the method of Osmer (1981), which uses the coordinate transform in the Robertson-Walker metric [Weinberg 1972] to determine the comoving separation of pairs of QSOs. We choose to calculate ξQ for two representative cosmological models; Ω0,λ0 = (1, 0) and (0.3, 0.7), where Ω0 and λ0 represent the conventional mass and vacuum energy (cosmological constant) density contribution respectively, to the total energy density of the Universe. We will call these cosmological models EdS (Einstein-de Sitter) and Λ respectively.

We have used the minimum variance estimator suggested by Landy & Szalay (1993) to calculate ξ(s), where s is the redshift-space separation of two QSOs. This estimator is

$$\xi_Q(s) = \frac{QQ(s) - 2QR(s) + RR(s)}{RR(s)},$$

where QQ, QR and RR are the number of QSO-QSO, QSO-random and random-random pairs counted at separation s ± Δs. We bin our pairs such that log(Δs) = 0.1 or 0.2. The density of random points used was 50 times the density of QSOs.

The area of the survey is covered by a mosaic of 2dF pointings. These pointings overlap in order to obtain complete coverage in all areas, including regions of high galaxy and QSO density. As the survey is not yet complete this means that certain areas within 2dF fields will not have had all candidates observed, and therefore the observational completeness of the sample varies strongly with angular position on the sky. This variation in observational completeness can clearly be seen in Fig. 1. Where a large number of 2dF pointing overlap the coverage is ∼ 100 per cent, while in overlap regions which have yet to be observed a second or third time the completeness is significantly lower. Particular care has been taken to construct the random point distribution so as to take into account this angular selection function. In each region defined by the intersection of 2dF fields we have counted the number of QSO candidates observed and compared this to the total number to calculate the fractional observational completeness. We then weight the probability of a random being placed in that region by this fractional completeness. This corrects for the angular incompleteness due to overlapping 2dF fields.

Our candidate density is not completely uniform over the length of the strips, due to an increase in stellar contamination in areas closer to the galactic plane. Secondly, small residual calibration errors in the relative magnitude zero points of the UKST plates could add spurious structure on large scales. Any possible offsets are being corrected by calibration from further CCD photometry, however in this paper we will correct for this effect by normalizing the
number of random points to the number of QSOs with
spectroscopically determined redshifts in each UKST field. This
correction will clearly remove power on large scales, which
is why we do not discuss structure on scales larger than
~ 100 h⁻¹ Mpc in this paper. After constructing the angular
mask, we then assign the random points a random redshift,
taken from a spline fit to the binned (Δz = 0.2) redshift
distribution of the full 2QZ sample (changing Δz by a fac-
tor of 2 makes no observable difference to ξQ). The redshift
distributions for the NGC and SGC data sets are shown in
Fig. 2. The fit used to generate the redshift distribution for
the random points is also shown (the smooth curves in Fig.
2), in each case normalized to the number of QSOs in each
2QZ strip. The above process for correcting observational
completeness and calculating ξQ we call method 1.

We have tested the effectiveness of this process by mak-
ing comparisons to correlation functions derived using two
other methods. The first (method 2) is to calculate the cor-
relation function from regions of the survey that have no
overlapping fields still to be observed, that is, they have
~ 100 per cent observational coverage. The number of QSOs
in these regions is significantly less that in the total sam-
ples, ∼ 100 per cent observational coverage. The number of QSOs
in these regions is significantly less that in the total sample,
reducing the signal-to-noise in ξQ. The second comparison
method (method 3) is to allocate each random point an (α,δ)
taken from the QSO catalogue, so that the random distribution
has exactly the same angular distribution as the QSOs.
The redshifts of the random points are then allocated using
the spline fit discussed above.

Two other observational biases could, in principle, af-
fact our measurements of ξQ. The first is due to the fact
that the 2dF instrument cannot position two fibres closer
than ~ 30″. We are therefore currently biased against small
angular separation QSO pairs (this problem is being re-
edied by independent follow-up of close QSO pairs). We have
measured the angular correlation function of observed can-
idates, which shows this bias (see Fig. 3). Measuring the
extent of the anti-correlation in Fig. 3 allows us the correct
for the close pairs bias. The dotted line, which traces the
anti-correlation is ω(θ) = 4.0 × 10⁻⁵ θ⁻², and this can be
used to construct a function
\[
W_{cp}(θ) = \frac{1}{1 - 4.0 \times 10^{-5} \theta^{-2}},
\]
which is the weight function for close pairs separated by θ
degrees. In practice this correction makes no difference to
the measured correlation function as almost all of the QSO
pairs with small angular separations have widely differing
redshifts, and the weighting of a small number of pairs has a
negligible effect on large scales.

Extinction by galactic dust will also imprint a signal on
the angular distribution of the QSOs. Primarily this changes
the effective magnitude limit in b_2 by \( A_{b_2} = 4.035 \times E(B-V) \)
where we use the dust reddening \( E(B-V) \) as a function of
position calculated by Schlegel, Finkbeiner & Davis (1998).
We then weight the random distribution according to the
reduction in number density caused by the extinction such that
\[
W_{ext}(α, δ) = 10^{-5} A_{b_2}(α, δ),
\]
where \( β \) is the slope of the QSO number counts at the mag-
nitude limit of the survey. At \( b_2 = 20.85 \), the magnitude
limit of the 2QZ, the QSO number counts are flat, with
\( β \sim 0.3 \). Again we find that applying this correction makes
no significant difference to the measured ξQ.

It can be useful to present clustering results in a non-parame-
tric form, specified by the clustering amplitude
within a given comoving radius, rather than as a scale length.
which depends on a power law fit to $\xi_Q$. This is generally represented by the integrated correlation function, $\bar{\xi}$, within a given radius in redshift-space, $s_{\text{max}}$.

$$\bar{\xi}(s_{\text{max}}) = \frac{3}{s_{\text{max}}} \int_0^{s_{\text{max}}} \xi(x)x^2dx.$$  

(5)

Authors tend to choose a variety of values for $s_{\text{max}}$, e.g. $s_{\text{max}} = 10 h^{-1} \text{Mpc}$ (Shanks & Boyle 1994; Croom & Shanks 1996) or $s_{\text{max}} = 15 h^{-1} \text{Mpc}$ (La Franca et al. 1998). The choice is a compromise, selecting the scale for which a significant signal is seen. It is easiest to relate these measurements to theory for large scales, where linear evolution occurs. Below we will quote clustering amplitudes with $s_{\text{max}} = 20 h^{-1} \text{Mpc}$ as this is a scale at which evolution should be linear to better than a few per cent. We note that choosing a large radius also reduces the effects of small scale peculiar velocities and redshift measurement errors, which may well be a function of redshift.

We calculate the errors on $\xi_Q$ using the Poisson estimate of

$$\Delta \xi(s) = \frac{1 + \xi(s)}{\sqrt{QQ(s)}}.$$  

(6)

At small scales, $\lesssim 50 h^{-1} \text{Mpc}$, this estimate is accurate because each QSO pair is independent (i.e. the QSOs are not generally part of another pair at scales smaller than this). On larger scales the QSOs pairs become more correlated and we use the approximation that $\Delta \xi(s) = (1 + \xi(s))/\sqrt{N_Q}$, where $N_Q$ is the total number of QSOs used in the analysis (Shanks & Boyle 1994; CS96). In this paper, we will generally be concerned with analysis on small scales ($\leq 50 h^{-1} \text{Mpc}$), where the Poisson error estimates are applicable. As a confirmation of our Poisson error estimates we have also derived field-to-field errors, by splitting the NGC and SGC strips into two, and determining the scatter between the resulting four independent regions. The errors determined in this fashion are approximately equal to or less than the Poisson errors. We also test bootstrap errors which are found to be $\sim \sqrt{3}$ times greater than Poisson on all scales of interest, in agreement with expected theory (Mo, Jing & Borner 1992) and previous measurements (e.g. Boyle & Shanks 1994; CS96). On small scales, $\lesssim 2 h^{-1} \text{Mpc}$, the number of QSO-QSO pairs can be $\lesssim 10$. In this case simple root-$n$ errors (Eq. 6) do not give the correct upper and lower confidence limits for a Poisson distribution. We use the formulae of Gehrels (1986) to estimate the Poisson confidence intervals for one-sided 84% upper and lower bounds (corresponding to 1$\sigma$ for Gaussian statistics). These errors are applied to our data for $QQ(s) < 20$. By this point root-$n$ errors adequately describe the Poisson distribution.

2.3 Fitting models to $\xi(s)$

Below we make comparisons of the data to a number of models, both simple functional forms (power laws) and more complex, physically motivated, models (e.g. CDM). We use the maximum likelihood method to determine the best fit

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Figure 4. The distribution of 2QZ QSOs in the 10k catalogue. Note that only objects at $0.3 < z \leq 2.9$ are used in our analysis. The SGC strip is on the left, the NGC on the right. The rectangular regions show the distribution projected onto the sky in each strip.
Figure 5. The two-point correlation function for 2QZ QSOs in the redshift interval $0.3 < z \leq 2.9$ for an EdS cosmology, using the different estimators discussed in the text. a) method 1, b) method 2, c) method 3 and d) all three methods. In plots a), b) and c) we show $\xi_Q$ from the combined NGC and SGC strips with the best fit power law at $s \leq 35 \, h^{-1} \, \text{Mpc}$ in each case. In d) we compare the three methods, the two points for each method being separate estimates in the NGC (filled symbols) and SGC (open symbols) strips. The lines are identical to those in a), b) and c) denoting the best fit power law in each method.

parameters. The likelihood estimator is based on the Poisson probability distribution function, so that

$$L = \prod_{i=1}^{N} \frac{e^{-\mu} \mu^\nu}{\nu!}$$

(7)

is the likelihood, where $\nu$ is the observed number of QSO-QSO pairs, $\mu$ is the expectation value for a given model and $N$ is the number of bins fitted. We fit the data with bins $\Delta \log(r) = 0.1$, although we note that varying the bin size by a factor of two makes no noticeable difference to the resultant fit. In practice we minimize the function $S = -2\ln(L)$, and determine the errors from the distribution of $\Delta S$, where $\Delta S$ is assumed to be distributed as $\chi^2$. This procedure does not give us an absolute measurement of the goodness-of-fit for a particular model. We therefore also derive a value of $\chi^2$ for each model fit in order to confirm that it is a reasonable description of the data. In particular this is appropriate when fitting on moderate to large scales ($\gtrsim 5 \, h^{-1} \, \text{Mpc}$), where the pair counts are large enough that the Poisson errors are well described by Gaussian statistics.
3 THE CORRELATION FUNCTION OF 2QZ QSOs

Here we present the results of our clustering analysis on an initial sample of 2QZ QSOs. This sample contains 10558 QSOs taken from the 2QZ 10k catalogue. Fig. 1 shows the distribution of QSOs projected onto a plane of constant declination. We note that the current distribution is highly non-uniform, as the survey is only partially complete.

3.1 The redshift averaged QSO correlation function

We first measure the QSO two-point correlation function averaged over the entire redshift interval $0.3 < z < 2.9$. For an EdS cosmology we estimate $\xi_Q$ using the three different processes discussed in Section 2.3: 1) full accounting for non-uniform coverage, 2) taking only completely observed regions, and 3) using the QSO $(\alpha, \delta)$ for the random point positions. These are presented in Fig. 5a, b and c respectively. The results demonstrate that QSO clustering follows a power law on small to intermediate scales. There is some evidence of a break in the power law at $\sim 35 \ Mpc^{-1}$. We fit a power law of the conventional form,

$$\xi(s) = \left(\frac{s}{s_0}\right)^{-\gamma}.$$  

The best fits using the maximum likelihood technique are $(s_0, \gamma) = (3.99^{+0.28}_{-0.34}, 1.58^{+0.16}_{-0.09})$, $(4.59^{+0.37}_{-0.39}, 1.64^{+0.12}_{-0.11})$ and $(3.87^{+0.29}_{-0.32}, 1.63^{+0.11}_{-0.31})$ for methods 1, 2 and 3 respectively, where $s_0$ is in units of $h^{-1} \ Mpc$. We fit the power law on scales $0.7 - 35 h^{-1} \ Mpc$. The minimum scale is set by the smallest scale at which we find QSO pairs and the maximum scale is set by scale of the observed break in $\xi(s)$. A comparison of all three methods is shown in Fig. 5d. Here we also plot separately the clustering of the NGC and SGC strips.

First, we note that the signals from the NGC and SGC strips are consistent. The NGC has no pairs at very small scales ($< 1.5 h^{-1} \ Mpc$), however the SGC strip only contains 3 pairs at these scales, and fewer are expected in the NGC due to the smaller number of objects in this strip (4005 in the NGC vs. 6553 in the SGC). Second, there appears to be no significant difference between our different estimations of $\xi_Q$. Method 2 shows a slightly higher signal while method 3 is marginally lower than the other two methods. We estimate how much of the difference between methods 1 and 3 could be due to the removal of real signal by taking the measured correlation function from method 1 and integrating it over our redshift range, weighted by the QSO redshift distribution. This then gives us an angular correlation function with which we weight the random distribution when deriving the 3-D correlation so suppressing the angular component. The results of this analysis are shown in Fig. 5e. On small scales there is very little effect on the 3-D clustering, however on scales $\gtrsim 20 h^{-1} \ Mpc$ the clustering signal becomes suppressed by larger amounts (dotted line). The correlation functions measured from the data using the two methods are also plotted in Fig. 5f. The difference in the measured values at $\gtrsim 20 h^{-1} \ Mpc$ is similar to that predicted by the model, suggesting that some large-scale power is removed by method 3. We therefore choose to use method 1 throughout the remainder of our analysis (method 2 contains half as many QSOs as method 1, only 5348 and they are generally distributed in many small overlap regions; the dark shaded regions in fig. 4). Any residual systematic errors caused by the variable observational completeness are not significant enough to affect any of the conclusions of this paper.
Table 1. 2QZ clustering results for various cosmologies and redshift intervals. The $s_0$ and $\gamma$ are best fit values. The results for the 2 parameter fit are allowing both $s_0$ and $\gamma$ to vary freely. For the 1 parameter fit we constrain $\gamma$ to be the best fit value for each cosmology over the full redshift interval ($0.30 < z < 2.90$) and allow only $s_0$ to vary. The reduced $\chi^2$ for each fit are also listed.

| ($\Omega_0, \lambda_0$) | redshift range | $\bar{z}$ | $N_Q$ | 2 parameter fit | 1 parameter fit | $\xi(20)$ |
|--------------------------|----------------|----------|-------|-----------------|-----------------|-----------|
|                          |                |          |       | $s_0$           | $\gamma$       | $\chi^2$  |
| (1.0,0.0)                | $0.30 < z < 2.90$ | 1.49     | 10558 | $3.99^{+0.28}_{-0.34}$ | $1.58^{+0.10}_{-0.09}$ | 1.42      |
| (0.3,0.7)                | $0.30 < z < 0.95$ | 1.49     | 10558 | $5.69^{+0.42}_{-0.50}$ | $1.56^{+0.10}_{-0.09}$ | 1.33      |
|                          |                |          |       | $s_0$           | $\gamma$       | $\chi^2$  |
| (1.0,0.0)                | $0.30 < z < 0.95$ | 0.69     | 2299  | $3.84^{+0.56}_{-0.69}$ | $1.76^{+0.27}_{-0.26}$ | 1.14      |
| (1.0,0.0)                | $0.95 < z < 1.35$ | 1.16     | 2116  | $2.72^{+1.18}_{-0.94}$ | $1.25^{+0.27}_{-0.25}$ | 1.37      |
| (1.0,1.0)                | $1.35 < z < 1.70$ | 1.53     | 2177  | $3.49^{+0.61}_{-0.70}$ | $1.63^{+0.22}_{-0.21}$ | 1.51      |
| (1.0,1.0)                | $1.70 < z < 2.10$ | 1.89     | 2186  | $3.31^{+0.55}_{-0.61}$ | $1.83^{+0.21}_{-0.20}$ | 0.64      |
| (1.0,1.0)                | $2.10 < z < 2.90$ | 2.36     | 1780  | $4.43^{+0.77}_{-0.94}$ | $1.84^{+0.39}_{-0.36}$ | 1.14      |
| (0.3,0.7)                | $0.30 < z < 0.95$ | 0.69     | 2299  | $5.28^{+0.72}_{-0.46}$ | $1.72^{+0.23}_{-0.22}$ | 1.21      |
| (0.3,0.7)                | $0.95 < z < 1.35$ | 1.16     | 2116  | $4.05^{+1.21}_{-1.52}$ | $1.38^{+0.27}_{-0.24}$ | 0.69      |
| (0.3,0.7)                | $1.35 < z < 1.70$ | 1.53     | 2177  | $5.23^{+0.92}_{-0.94}$ | $1.55^{+0.21}_{-0.20}$ | 1.92      |
| (0.3,0.7)                | $1.70 < z < 2.10$ | 1.89     | 2186  | $6.24^{+0.86}_{-0.99}$ | $1.80^{+0.21}_{-0.19}$ | 0.83      |
| (0.3,0.7)                | $2.10 < z < 2.90$ | 2.36     | 1780  | $6.93^{+1.64}_{-1.65}$ | $1.64^{+0.29}_{-0.27}$ | 1.26      |

We also calculate $\xi_Q$ for the $\Lambda$ cosmology, with $\Omega_0 = 0.3$ and $\lambda_0 = 0.7$. This is compared to the method 1 estimate for the EdS case in Fig 3. The effect of introducing a significant cosmological constant term is to increase the relative separation of QSOs, and hence increase the clustering scale length. The break in the power law is now seen at $\approx 60 h^{-1}$ Mpc, we therefore make our power law fits out to this scale. The best fit power law for the $\Lambda$ cosmology is $(s_0, \gamma) = (5.69^{+0.42}_{-0.50}, 1.56^{+0.10}_{-0.09})$. All results are listed in Table 4.

3.2 QSO clustering compared to local galaxies

In Fig 3 we compare our QSO clustering results at $\bar{z} = 1.49$ to galaxy clustering at low redshift ($z \sim 0.05$). In particular the Las Campanas (Tucker et al. 1997) and Durham/UKST (Ratcliffe et al. 1998) galaxy surveys (open squares and triangles respectively). We see that there is good general agreement between the galaxy and QSO clustering, although the samples have differing redshift ranges. The EdS $\xi_Q$ is slightly lower than the $\Lambda$ case, while $\xi_Q$ in the $\Lambda$ cosmology is closer in amplitude to the galaxies. Both QSOs and galaxies
show a break in $\xi(r)$ at $\sim 40$ h$^{-1}$ Mpc. We note that the errors on $\xi_Q$ are smaller than those on $\xi_{\text{gal}}$ at $> 20$ h$^{-1}$ Mpc.

### 3.3 QSO Clustering compared to CDM

In order to compare directly to theory, and include all non-linear effects and redshift-space distortions, we have used the Hubble Volume simulations of the Virgo Consortium (Colberg et al. 1998). We have produced mock 2QZ QSO catalogues with the same survey geometry and explicitly included evolution of the density field by outputting the simulation at different times along the light cone. A detailed discussion of the simulations, including a number of biasing models will be given in Hoyle et al. (2001 in preparation). Here we simply compare the dark matter correlation function averaged over the light cone to the 2QZ data. In particular we compare the redshift-space mass correlation function of a ΛCDM model to $\xi_Q$. This model has $\Omega_0 = 0.3$, $\Omega_{\text{baryon}} = 0.04$, $\lambda_0 = 0.7$, $\sigma_8 = 0.9$, $h = 0.7$ and an effective shape parameter, taking into account the baryon component (Sugiyama 1995), of $\Gamma_{\text{eff}} = 0.17$. The model and data are shown in Fig. 9. The amplitude of $\xi_Q$ is $\sim 4$ times larger than the ΛCDM mass correlation function, $\xi$. When scaled by this factor, the model and data appear to be well matched with a best fit bias value of 2.1.

Increasing the value of $\Gamma_{\text{eff}}$ will move the models away from the data by steepening $\xi$. At large scales, we do not have a large suite of simulations with which to compare the effect of changing $\Gamma_{\text{eff}}$ and cosmology. However, on the scales which we are fitting, linear theory is a reasonable approximation. Therefore the effect of redshift space distortions will be simply to scale $\xi$ by $(1 + 2\beta/3 + \beta^2/5)$ where $\beta = \Omega_b^{0.6}/b$ (Kaiser 1987). We can then simply absorb this factor into an effective linear bias factor. We then fit model real space non-linear correlation functions at $z = 1.49$ to the data (again at scales 5 to 100 h$^{-1}$ Mpc) using the ansatz of Peacock & Dodds (1996) to determine the non-linear correction to the model $\xi$. The deviation from non-linearity is small (typically $\lesssim 5\%$) on the scales of interest. We do not take into account small-scale non-linear velocity dispersions in our model, however these should be small at the scales and redshifts considered. We also do not consider the effects of redshift measurement errors on $\xi(r)$, these again should only be a factor on small, $\lesssim 5$ h$^{-1}$ Mpc, scales. We use five
different models with $\Gamma_{\text{eff}} = 0.1, 0.2, 0.3, 0.4, 0.5$ and fit for
the effective linear bias value. The results of this procedure
are shown in Fig. [10]. In the EdS cosmology, models with
$\Gamma_{\text{eff}} = 0.2, 0.3$ and 0.4 are acceptable at the 10% level, while
$\Gamma_{\text{eff}} = 0.1$ and 0.5 are ruled out at greater than 90% confi-
dence. The main reason that a broad range of models are
acceptable is the relatively low point at $\sim 20 \ h^{-1} \ Mpc$ in
$\xi_Q$. In the $\Lambda$ cosmology the $\Gamma_{\text{eff}} = 0.1$ and 0.2 models are
the only ones to agree with the data, the others being ruled
out at greater than 99.9% confidence. Thus the QSO corre-
lation function detects excess large-scale power over what is
expected in the $\Gamma_{\text{eff}} = 0.5$ standard CDM model. Confirming
the results from the APM galaxy survey [Maddox et al.
1998].

The required $\Gamma_{\text{eff}}$ is larger in the $\Lambda$ cosmology, as struc-
ture is moved to larger scales. This suggests a test with the
full 2QZ which will be devoid of observational incomplete-
ess as well as having increased statistical accuracy. The break of the correlation function in a CDM type cosmology
can be used as a standard rod to determine cosmological
parameters, in particular $\lambda$, if it is at linear scales. For ex-
ample, if at low redshift the shape is well defined, then if the
break is in the linear theory regime it should remain at
the same scale at high redshift. Measuring the break at a
different scale at high redshift would imply the wrong cos-
lomical parameters were being used in the determination
of the high redshift correlation function. This is similar to
the geometric tests discussed by several authors [Alcock &
Paczynski 1976; Phillips 1994; Ballinger et al. 1998] but has the
advantage of not being affected by redshift-space distor-
tions if clustering can be measured on a sufficiently large
scale. This is because linear redshift space distortions only
affect the amplitude and not the shape of $\xi$. Shanks & Boyle
(1994) proposed a similar method, using linear features in
the correlation function on $\gtrsim 100 \ h^{-1} \ Mpc$ scales.

4 EVOLUTION OF QSO CLUSTERING

4.1 Measurements of QSO clustering evolution

In the previous section we calculated $\xi_Q$ averaged over a
large redshift interval. We now split the 2QZ QSO sample
up into five redshift intervals containing approximately equal
numbers of QSOs. The exact limits and numbers of QSOs are
given in Table [1]. The measured $\xi_Q$ are shown in Fig.
[4] for the EdS cosmology. QSO clustering appears to vary
little over the entire redshift range we consider. The data
points are consistent with the redshift averaged $\xi_Q$ (dotted
line in Fig. [3]). For each redshift interval we fit a power
law, the results of which are shown by the solid lines in Fig.
[3] and in Table [2]. As for the redshift averaged analysis we
fit the power law within $35 \ h^{-1} \ Mpc$. We similarly fit $\xi_Q$
in redshift intervals for the $\Lambda$ cosmology (Fig. [12]) using
the $60 \ h^{-1} \ Mpc$ maximum as above. Again there is very little
evidence of evolution. We note that there is some variation
in the slope and amplitude of these power laws, but this
appears to be mainly driven by the relatively low signal-to-
noise in each redshift bin. Great care should be taken when
trying to interpret these power law fit results, as amplitude
and slope are correlated.

An alternative method to derive a measurement of evo-
lution is to constrain the power law slope and fit only for
the scale length, $s_0$. This should be valid as we don’t see any
evidence for significant evolution in the slope of $\xi_Q$. We con-
strain the slope to be that found over the full redshift range
(Section 3), $\gamma = 1.58$ for the EdS cosmology and $\gamma = 1.56$
for the $\Lambda$ cosmology. The results of this fitting process are
seen in Table [1] and plotted in Fig. [3].

In Table [1] we also list the reduced $\chi^2$ values for these fits. Limiting the fit
to one parameter does not significantly alter the $\chi^2$ values, demonstrating that the redshift averaged power law slope is
a reasonable description of the data at all redshifts. Fig. [13]
shows that in the EdS cosmology clustering is constant as
a function of redshift. The $\Lambda$ cosmology result is shown in
Fig. [3b]. In this case there appears to be a marginal increase by a factor of $\sim 1.4$ from $z = 0.7$ to 2.4. We compare our
results in the EdS cosmology to previous QSO clustering re-

dults from CS96 and LAC98, using their measurements of $\xi$
from 10 and 15 $h^{-1} \ Mpc$ to obtain a value of $s_0$ assuming a
$\gamma = 1.58$ power law (the best fit power law slope). Our
results are in disagreement with those of LAC98 who find a
$\sim 2\sigma$ increase in clustering between $z = 0.95$ and $z = 1.8$.
A possible cause of this is cosmic variance as LAC98 carry
out their analysis in a single 24.6 deg$^2$ area of sky. However,
given the large errors on the LAC98 data points, they only
disagree with the 2QZ results at $\sim 2\sigma$ at $z = 1.8$.

A non-evolving clustering distribution has strong impli-
cations for models of structure and QSO formation. We first
compare the 2QZ data to the simplest possible model, that
of linear theory gravitational evolution in an $\Omega = 1$ uni-
verse. This model is applicable when QSOs either directly
trace the mass distribution, or have a bias which is constant
as a function of redshift. When fitting linear theory to the
evolution in $s_0$ for the EdS cosmology we find that the model
is rejected by the 2QZ data at 99.8 per cent confidence.
In the $\Lambda$ cosmology the linear theory evolution rate is reduced.
However in Fig. [13b] we see that $s_0$ increases with redshift,
although the significance of the increase is marginal: a con-
stant $s_0$ as a function of redshift is not rejected by the data.
When we try to fit linear evolution in this case it is rejected
at $> 99.9$ per cent significance. If we require that the nor-
malization of the mass clustering be fixed by either the local
abundance of massive clusters [Eke et al. 1996] or the 4-yr
COBE results [Bennett et al. 1996] then the mass clustering
scale length is forced to be less than $s_0(z = 0) \sim 5 \ h^{-1} \ Mpc$.
In this case linear theory evolution is even more clearly re-
jected by the 2QZ data. It therefore appears that QSO clus-
tering cannot follow the linear evolution of the density field,
and QSO bias must be a function of redshift.

We should also make comparisons to galaxy clustering
measurements. The typical scale length found in local galaxy
surveys is $s_0 \sim 5 - 6 \ h^{-1} \ Mpc$, only marginally higher than
the 2QZ results for the EdS cosmology, and identical to the
values found in the $\Lambda$ cosmology. At $z \sim 3$ Adelberger et al.
(1998) find a scale length of $r_0 \sim 4 - 6 \ h^{-1} \ Mpc$ for Lyman-
break galaxies, depending on the assumed cosmology. This
again is very similar to the results derived from the 2QZ.

4.2 Comparison to biased models of clustering evolution

In the previous section we showed that for viable cosmologi-
cal models, with evolution based on the gravitational growth
of structure, QSOs do not simply trace the density fluctu-
Figure 11. The two-point correlation function for 2QZ QSOs as a function of redshift for the EdS cosmology. Redshift increases, left to right and top to bottom. In each plot the solid line is the best fit power law on scales $\leq 35 \ h^{-1} \text{Mpc}$. The dotted line is the best fit to all the QSOs in the redshift range $0.3 < z \leq 2.9$ and is shown to aid comparison between redshift intervals. The points without error bars at $\xi(s) = 0.001$ are where there are zero QSO pair counts in a bin. These points are fully taken into account in the fitting process.
Figure 12. The two-point correlation function for 2QZ QSOs as a function of redshift for the $\Lambda$ cosmology. Redshift increases, left to right and top to bottom. In each plot the solid line is the best fit power law on scales $\leq 60\,h^{-1}\text{Mpc}$. The dotted line is the best fit to all the QSOs in the redshift range $0.3 < z \leq 2.9$ and is shown to aid comparison between redshift intervals.
4.2.1 A long-lived QSO model

The next simplest assumption, after assuming that bias does not evolve with redshift, is that QSOs are long lived (with ages of order a Hubble time). We assume that after formation at some arbitrarily high redshift the subsequent evolution of QSO clustering is governed purely by their motion within the gravitational potential produced by the density fluctuations in the Universe [Turner (1992), which is good to a few per cent (note that our $G(\Omega_0, \lambda_0, z)$ is the full evolution term, and shouldn’t be confused with the function of Carroll et al. which only contains the cosmological dependence). The biasing model of Eq. (8) is also equivalent to QSOs forming in peaks of the density field above a constant threshold (CS96). This model places certain limitations on the form of evolution. First, bias will tend to unity as time increases. Secondly, positive evolution (an increase in clustering) as redshift increases is not possible. This is because at most the bias only evolves as fast as $G(\Omega_0, \lambda_0, z)$, cancelling out the growth in the density field.

For comparison to the observed clustering we have normalized the mass evolution in two ways; using both local cluster abundances [Eke et al. 1996] and the 4-yr COBE results [Bennett et al. 1996]. We calculate $s_0(z)$ for the mass assuming a CDM power spectrum with a shape parameter of $\Gamma_{\text{eff}} = 0.25$ (varying the shape parameter $\Gamma_{\text{eff}}$ only has an impact on the normalization when using the COBE data). In the EdS cosmology the $s_0$ gives $b(0) = 1.82^{+0.07}_{-0.07}$ ($1.62^{+0.06}_{-0.06}$) for cluster (COBE) normalization. These correspond to $\sigma_8 \simeq 1$ for QSOs at $z = 0$ ($\sigma_8$ for mass fluctuations is 0.52 and 0.65 for cluster and COBE normalization respectively).

Figure 13. The best fit values for $s_0$ with fixed $\gamma$ as a function of redshift in the a) EdS and b) $\Lambda$ cosmologies. The solid lines show the best fit linear theory evolution model in each case. The dotted lines show the best fit long-lived QSO biasing model (bias model 1) from Section 4.2.1. The dashed lines show the the models of Matarrese et al. (1997) (bias model 2) for different values of the minimum halo mass. The dot-dashed lines show the best fit empirical bias model (bias model 3). In a) the two dotted and dot-dashed lines are for COBE (top at $z = 0$) and cluster (bottom at $z = 0$) normalization.
or around the break in the luminosity function) have host galaxies that are remarkably similar to normal galaxies, except for a bias towards spheroid dominated galaxies. Approximately 55 per cent of their sample had hosts which were best fit by a bulge-only model. Elliptical galaxies are well known to be more strongly clustered than spirals (Loveday et al. 1995) with a relative bias factor of \( b_{\text{E}} \approx 1.9 \). Correcting for this morphological segregation gives an expected \( \sigma_8 = 1.2 - 1.3 \) for QSOs at low redshift, approximately in line with the above value.

For the \( \Lambda \) cosmology a biased model of the form in Eq. 8 provides only a marginally adequate fit to the data (rejected at 88%) with a best fit bias of \( b(0) = 1.84_{-0.08}^{+0.06} \). This is because the model cannot reproduce the increase in clustering strength at high redshift visible in this cosmology. The hypothesis that QSOs have cosmologically long (\( \sim \) Hubble time) lifetimes therefore appears unlikely in the \( \Lambda \) cosmology.

### 4.2.2 More general models of biasing

The above simple model of biasing can be extended in a number of ways. The most obvious is to remove the constraint that objects formed at an arbitrarily high redshift, and allow objects to continue to form at lower redshift. The problem then becomes one of deciding how and when objects do form. A natural method for deciding when dark matter haloes form is based on an application of the Press-Schechter (1974) formalism which describes the evolution of the number density of dark matter haloes. Working within this formalism Mo & White (1996) have obtained an approximation for the linear bias of dark matter haloes as a function of mass. Matarrese et al. (1997) have used these ideas to provide biasing models in a COBE normalized \( \Omega_0 = 1 \) universe assuming a CDM power spectrum with a shape parameter of \( \Gamma_{\text{cdm}} = 0.25 \). These were extended to a number of different cosmological models by Moscardini et al. (1998). In particular we are interested in the transient model of Matarrese et al., so called because the model does not require a normalization at \( z = 0 \). In this model, one assumes that all objects exceeding a given mass cut off can be observed at any given redshift. The bias (which we call model 2) then has the form

\[
b(z) = 1 - 1/b_\delta + [b(0) - (1 - 1/b_\delta)]G(\Omega_0, \lambda_0, z)\beta
\]

where \( b_\delta \) is the critical linear overdensity for spherical collapse. For an EdS cosmology \( b_\delta = 1.686 \) for all redshifts, however it only varies away from this value by a few per cent for the other cosmologies considered here (Lilje 1992).

Matarrese et al. find the values of \( b(0) \) and \( \beta \) by fitting to their Press-Schechter based models. These parameters depend on the minimum halo mass \( M_{\text{min}} \) considered. We compare this model of biasing to QSO clustering is an EdS universe in Fig. 13, for minimum halo masses of \( M_{\text{min}} = 10^{11}, 10^{12} \) and \( 10^{13} M_\odot \). In this cosmology the data are approximately consistent with a minimum halo mass of \( 10^{12} M_\odot \) (although the model is still too steep), while the normalization is too low (COBE normalization) for lower mass haloes, and the evolution is too steep for higher mass haloes. In the \( \Lambda \) cosmology, we compare the COBE normalized CDM model of Moscardini et al. to our data. We note that this model is, in fact, for \( \Omega_0 = 0.4, \lambda_0 = 0.6 \). However, given the model and data uncertainties these are adequate to make a general comparison to the 2QZ clustering evolution in the \( \Lambda \) cosmology. In this case we find that the data are more consistent with (although slightly above) a model with \( M_{\text{min}} \approx 10^{13} M_\odot \).

Although these models appear to adequately describe the clustering evolution of QSOs, it is not at all clear what the physical justification for this is. The models of Matarrese et al. assume that at each redshift QSOs inhabit the same mass haloes; this need not necessarily be the case. For example, Percival & Miller (1999) compare the evolution of bright QSOs, \( -25.4 < M_B > -27.9 \), to the dark matter halo formation rate in a number of cosmologies. They find that for an EdS universe, with a CDM-type power spectrum of shape parameter \( \Gamma_{\text{cdm}} = 0.25 \) which is cluster abundance normalized, the evolution of bright QSOs is best fit by haloes of mass \( \sim 10^{10.6} M_\odot \). Our \( \Lambda \) cosmology increases the mass to \( \sim 10^{11.8} M_\odot \). These masses are \( \sim 10 \times \) smaller than those required to fit the 2QZ QSO clustering according to the models of Matarrese et al. This serves to demonstrate that we should be wary of over interpreting fits to models which do not contain a physical description of QSO formation. For example, it is possible that QSO clustering is a function of luminosity, a point which has not been discussed in this paper, but will be investigated in future work.

### 4.2.3 An empirical biasing description

Lastly we fit a purely empirical biasing model to the data. For this model we use a generalization of Eqs. 8 and 10 which is

\[
b(z) = 1 + (b(0) - 1)G(\Omega_0, \lambda_0, z)\beta
\]

where \( b(0) \) and \( \beta \) are left free to be determined by fitting to the data. We call this form of bias evolution model 3. The normalization of the mass density field is set by either cluster (COBE) normalization. As we might expect the \( \Lambda \) cosmology has a larger cluster (COBE) normalization. In particular we are interested in the transient model of Matarrese et al. to our data. We note that this model is, in fact, for \( \Omega_0 = 0.4, \lambda_0 = 0.6 \). However, given the model and data uncertainties these are adequate to make a general comparison to the 2QZ clustering evolution in the \( \Lambda \) cosmology. In this case we find that the data are more consistent with (although slightly above) a model with \( M_{\text{min}} \approx 10^{13} M_\odot \).

5 CONCLUSIONS

The preliminary release dataset of the 2QZ contains 10681 QSOs. It is already a factor of \( \sim 25 \) larger than previous QSO surveys to this depth (\( b(0) \approx 20.85 \)). When completed the full sample will contain \( \sim 25000 \) QSOs. The current data set already allows us to measure the clustering of QSOs to un-precedented accuracy. In particular we find:

1) QSO clustering integrated over the redshift interval \( 0.3 < z \leq 2.9 \) is well fit by a power law on scales \( \sim 1 - 35 h^{-1} \) Mpc. In an Einstein-de Sitter universe the best
fit power law has $s_0 = 3.99^{+0.22}_{-0.33} h^{-1}$ Mpc and $\gamma = 1.58^{+0.10}_{-0.09}$. Introducing a cosmological constant increases the distances between QSOs, so that the scale length of clustering increases also. The power law then extends to $\sim 60 h^{-1}$ Mpc and is best fit by $s_0 = 5.69^{+0.52}_{-0.56} h^{-1}$ Mpc and $\gamma = 1.56^{+0.10}_{-0.09}$. These results are remarkably similar to the clustering of normal galaxies locally ($z \simeq 0.05$).

2) We compare the clustering of 2QZ QSOs to the $\Lambda$CDM model and find that the shapes of model and data are consistent. A comparison to a family of CDM models with different shape parameters, $\Gamma_{\text{d}}$, finds that $\Gamma_{\text{d}} = 0.2$ to 0.4 provides an acceptable fit in the EdS cosmology. In the $\Lambda$ cosmology only $\Gamma_{\text{d}} = 0.1$ or 0.2 provide an acceptable fits due to the movement of structure to larger scales. This suggests a test for cosmological parameters using the linear break in the correlation function which will be possible using the completed 2QZ data set.

3) We measure the clustering amplitude of QSOs as a function of redshift, parameterized by $s_0$ assuming a fixed power law slope. In an Einstein-de Sitter universe we find that QSO clustering is constant in comoving coordinates over the entire redshift range we probe. In a $\Lambda$ dominated universe we find that clustering appears to increase (although constant clustering is not excluded) with increasing redshift. For both EdS and $\Lambda$ cosmologies a model in which QSOs follow the same evolution as linear theory gravitational clustering (or have a bias which is constant as a function of redshift) is rejected at the $> 99$ per cent level. If the constant clustering is extrapolated to $z \geq 3$ it comfortably overlaps the clustering amplitude found for Lyman-break galaxies [Adelberger et al. 1998].

4) We compare simple redshift dependent bias models to the measured clustering evolution. We first use a model in which QSOs are long lived (on cosmological time scales), so that their clustering simply evolves according to their motion in the gravitational potential. This is consistent with 2QZ clustering evolution in an EdS case, and predicts $\sigma_8(z = 0) \simeq 1$ for QSOs, which is consistent with galaxy clustering. The long lived model is not able to reproduce the increase in clustering seen in the $\Lambda$ cosmology and is marginally rejected at 88 per cent confidence. More complex models of QSO bias based on the Press-Schechter formalism, have been developed by a number of authors. We use the models of Matarrese et al. (1997) and Moscardini et al. (1998) to make comparisons to the evolution of the 2QZ data set. These models adequately describe the 2QZ clustering evolution when the minimum halo mass considered is $M_{\text{min}} \sim 10^{12} M_\odot$ (EdS) or $M_{\text{min}} \sim 10^{13} M_\odot$ ($\Lambda$). However, without a convincing model of QSO formation, the interpretation of the comparison to these models of clustering evolution is questionable. We lastly derive a fit to an empirical biasing model based on power law evolution of bias.

The large volumes sampled by QSO surveys allow structure to be investigated on the scales where growth is governed by linear theory. Thus, meaningful measurements of large-scale structure, that are easily related to the underlying cosmology, can be made irrespective of the relative bias of QSOs. QSOs therefore play an crucial role in linking low-redshift/small-scale galaxy clustering measurements to the fluctuations in the density field at high redshift seen in the cosmic microwave background. The completed 2QZ survey, without the current varying observational coverage, will allow detailed measurements of structure on a range of scales from $\sim 1$ to $1000 h^{-1}$ Mpc.

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