QSO CLUSTERING

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ABSTRACT

We present results for QSO clustering from 4 surveys including the Durham/AAT UVX sample and the LBQS objective prism survey. From this sample of $\sim$1700 QSOs we have a detection of clustering at $\leq 10h^{-1}$Mpc (q_o=0.5) at the $>4\sigma$ level. A model where the QSO clustering evolution is fixed in comoving coordinates with $r_o \simeq 6h^{-1}$Mpc is suggested by the data when we take into consideration the low redshift Seyferts of Georgantopoulos & Shanks (1994)[1], possibly implying that QSOs randomly sample a comoving galaxy distribution. At larger scales we tentatively find anti-correlation between 40 and $100h^{-1}$Mpc at a 2σ level. We note that the position and amplitude of large-scale features in ξ are dependent on cosmology, this is particularly true in the case of a flat, $\Lambda \neq 0$ and $\Omega_o \leq 0.03$ universe. The QSO correlation function for this case is inconsistent with the known $\xi(r)$ of galaxies and Seyferts at low z at the 3σ level.

1. Introduction

The study of QSO clustering can reveal information about large-scale structure over a range of scales and redshifts that give them certain advantages over normal galaxies, their intrinsic luminosity means that large volumes and high redshifts can be sampled allowing evolution to be studied at both small ($\leq 10h^{-1}$Mpc) and large (10 to $1000h^{-1}$Mpc) scales. A problem is of course how the QSOs trace the underlying mass distribution, however the question of relating QSOs to galaxies, at least observationally, is starting to be answered by the auto-correlation of low z Seyferts[1] and from CCD imaging[2,3]. These CCD observations suggest the environment of radio-quiet QSOs is no more rich than that of normal optical galaxies out to z=1.5.

The first measurement of QSO clustering was made by Osmer[4] which placed upper limits on clustering over a range of scales. The first detection at small scales in a complete sample was in the first 170 QSOs of the Durham/AAT UVX survey[5]. At large scales ($\sim 50h^{-1}$Mpc) a "QSO supercluster" of 23 QSOs was found in the CFHT survey[6,7,8]. Considering evolution, initial results from the full Durham/AAT survey[9] suggested only small amounts of evolution at small scales.

Here we present clustering results from the complete, revised Durham/AAT sample together with three other surveys described in the next section. We will then look at the analysis used to obtain our results, paying particular attention to error analysis. Small and large-scale results are described in section 4. Concluding remarks are made in section 5.

2. The QSO Surveys

The Durham/AAT UVX survey[10] consists of 34 $40'$ diameter fields with $B<21^m$ within 8 UKST fields. Spectroscopy was carried out using FOCAP on the AAT, and 392 QSOs were detected with $0.3<z<2.2$.

The ESO/AAT survey[11,12] is a colour/UVX selected sample with $B<22.5^m$. The colours are taken from COSMOS scans of 1 ESO 3.6m and 3 AAT plates. The spectroscopy was again obtained from FOCAP, supplemented by ESO/EFOSC. 83 QSOs were detected with $0.3<z<2.2$.

The CFHT objective prism/colour survey[8] consists of 6 sub-fields based on 4 CFHT plate areas with $B<20.5^m$. 215 QSOs were detected in the same redshift range as the two surveys above. The 13^h38+27 sub-field was concentrated on a the "QSO supercluster" at z=1.1 and the results for this survey will be quoted with and without the QSOs in the $0.9<z<1.2$ range.

The LBQS objective prism survey (Morris et al 1991 and references therein)[13] is the largest of the four surveys with 18 APM scanned UKST plates with magnitude limits $18.41^m \leq B_{Jlim} \leq 18.85^m$. There are 1053 QSOs in the survey with $0.2<z<3.3$.

3. Data Analysis

We calculate the comoving separation ($\mathbf{X}'$) of two QSOs using the method of Osmer[4] which involves a coordinate transformation in the Robertson-Walker metric,

$$\mathbf{X}' = \mathbf{X} + \mathbf{a}(\sqrt{1-k\mathbf{X}^2} - (1-\sqrt{1-k\mathbf{a}^2})(\mathbf{X}.\mathbf{a}/\mathbf{a}^2)) \tag{1}$$

Where $\mathbf{a} = (0,0,s_1)$ and $\mathbf{X} = (s_2 sin\theta, 0, s_2 cos\theta)$, with s_1 and s_2 the dimensionless comoving distance to QSO 1 and 2 respectively, and θ their angular separation on the sky. s_1 and s_2 are generally dependent on cosmology, for a Λ=0 case s is given by[14]

$$s = \frac{zq_o + (q_o - 1)(\sqrt{2zq_o+1} - 1)}{(1+z)q_o^2} \tag{2}$$

and for an inflationary $\Lambda \neq 0$ model, Peebles (1984)[15] gives

$$s = z \text{ for } 1+z < (\Omega_o^{-1} - 1)^{1/3} \tag{3}$$

This last case is valid up to our redshift limit of 2.2 if $\Omega_0 \leq 0.03$ (consistent with baryon nucleosynthesis). We find that the same Δz corresponds to a different comoving separation, depending on cosmology and z. This is shown in Fig. 1.

We use the form for the 2-point auto-correlation function, $\xi(r)$ with

$$\xi(r) = \frac{N_{qq}}{N_{qr}} - 1 \tag{4}$$

with N_{qq} the number of QSO-QSO pairs and N_{qr} the number of QSO-random pairs. The randoms are normalised to the number density in each field and have the same redshift distributions as the QSOs.

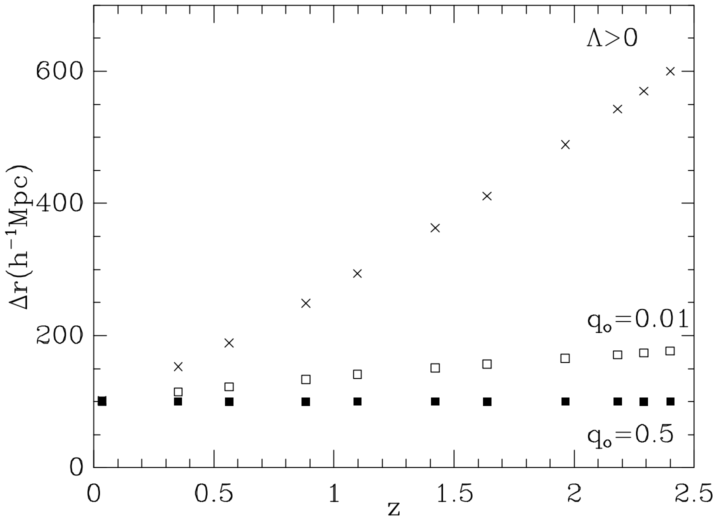

Fig. 1. The comoving separation corresponding a Δz equivalent to $100h^{-1}$Mpc for q_o=0.5, as a function of z for q_o=0.5, 0.01 and inflationary $\Lambda \neq 0$ models.

The error analysis is carried out using a variety of different methods. Firstly the integral constraint should be small because of the small number of correlated pairs, an approximation of the error on $\xi(r)$ from the integral constraint is $\Delta\xi \simeq (1+n_c)/N_{QSO}$, where n_c is the average number of correlated pairs per QSO and N_{QSO} is the total number of QSOs. For the Durham/AAT sample $\Delta\xi = 1.5 \times 10^{-2}$ compared with what might be considered a fundemental lower limit at large scales, $1/\sqrt{392} \simeq 0.05$. We also look at field-to-field errors, 30 random simulations and bootstrap resampling. This analysis suggests that both field-to-field and simulated errors are consistent with $\sqrt{N_{qq}}$ errors until $N_{qq} \simeq N_{QSO}$ (at a scale of $\sim 100h^{-1}$Mpc), both tend to $\sqrt{N_{QSO}}$ errors at larger scales with the field-to-field errors slightly lower than the simulations. The bootstrap errors are consistent with the other estimations at scales $\sim 1000h^{-1}$Mpc but over estimate them by ~ 1.7 between 10 and $100h^{-1}$Mpc. This is expected at small scales where bootstrapping reduces the number of independent points, increasing the error by a factor of $\sqrt{3}$ above the true ensemble error[16]. In this paper we will use $\sqrt{N_{qq}}$ until $N_{qq} = N_{QSO}$ and then $\sqrt{N_{QSO}}$ errors, to display our results.

4. Results

4.1. Small Scales

The combined surveys have a 4.3σ detection of clustering at scales $\leq 10h^{-1}$Mpc for q_o=0.5 and a 3.3σ detection for q_o=0.01. The QSOs were split into low ($0.3 < z < 1.4$) and high ($1.4 < z < 2.2$) redshift bins in an attempt to look at the evolution of clustering.

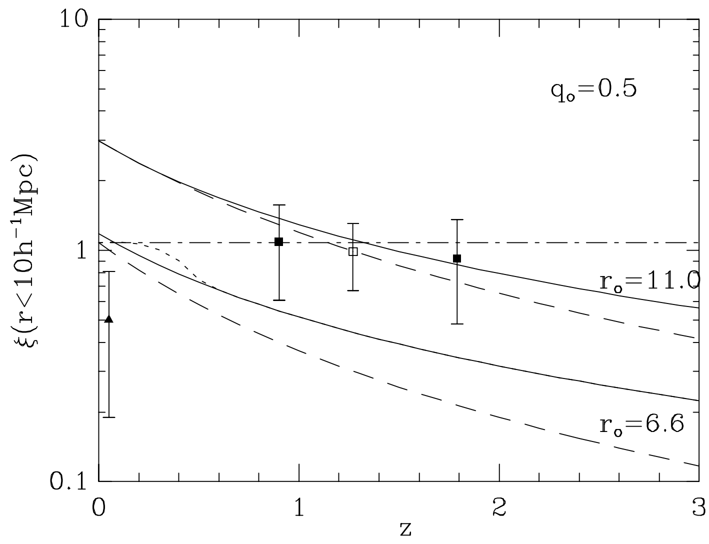

Fig. 2. The evolution of mean $\xi(r<10h^{-1}\mathrm{Mpc})$ for q_o=0.5. The filled squares are for all the QSO surveys in z bins $0.3<z<1.4$ and $1.4<z<2.2$. The open square is for these two bins combined, these points are excluding the CFHT "Supercluster". The filled triangle is the result for the low z Seyferts[1]. The solid, dotted, dashed and the dot-dashed lines are models 1, 2, 3 and 4 respectively. All models are plotted for $r_o(z=0)=6.6h^{-1}$Mpc models 1 and 3 are also plotted for $11.0h^{-1}$Mpc.

The mean $\xi(r<10h^{-1}\mathrm{Mpc})$ is compared to evolutionary models for clustering, we use both stable and comoving models in this comparison. The models and data points are shown in Fig. 2. Model 1 is a stable model with a -1.8 power law for $r<r_o$ and a -3 power law for $r>r_o$ where $r_o\propto(1+z)^{-2/3}$, model 2 is similar to 1 but with $r_o\propto(1+z)$, model 3 is again similar to 1 but with a -1.8 power law for all r. Lastly model 4 is a comoving model, similar to 1 but with no evolution of r_o in comoving coordinates, for a more detailed description of these models see Shanks & Boyle (1994)[17]. Thus if the low z Seyferts are assumed to have the same clustering properties as QSOs then the high amplitude stable model can be ruled out and the most likely evolutionary model is a comoving one with $r_o\sim 6h^{-1}$Mpc.

4.2. Large Scales

To first order $\xi(r)$ is consistent with Poisson statistics above $20h^{-1}$Mpc (for q_o=0.5). At a lower level there may be small amplitude deviations from Poisson, we find limited evidence for an anti-correlation between 40 and $100h^{-1}$Mpc. From the Durham/AAT, ESO and CFHT surveys $\xi(40<r<100h^{-1}\mathrm{Mpc})=-0.089\pm0.038$ (with the CFHT "supercluster" included as at these scales it has little effect on the correlation function), however this result is not reproduced in the LBQS survey where ξ in the same region is -0.006 ± 0.035 (see Figs. 3a & b), the errors on each of these values are large, making them only marginally inconsistent. If these features do exist we can use them to discriminate between cosmologies. The evolution of large scale features can be used as a test for q_o. In the linear regime only the amplitude of features should evolve, with an evolution that is dependent on q_o, for example in a

q_o=0.5 model $\xi \propto (1+z)^{-2}$ (in an unbiased case), but in a low q_o universe ξ is constant in our redshift range.

Large scale features can also be used as standard rods. Measurements of the scale of features at both high and low z would be a powerful test for the inflationary $\Lambda \neq 0$ model as in the linear regime the scale of features should not evolve.

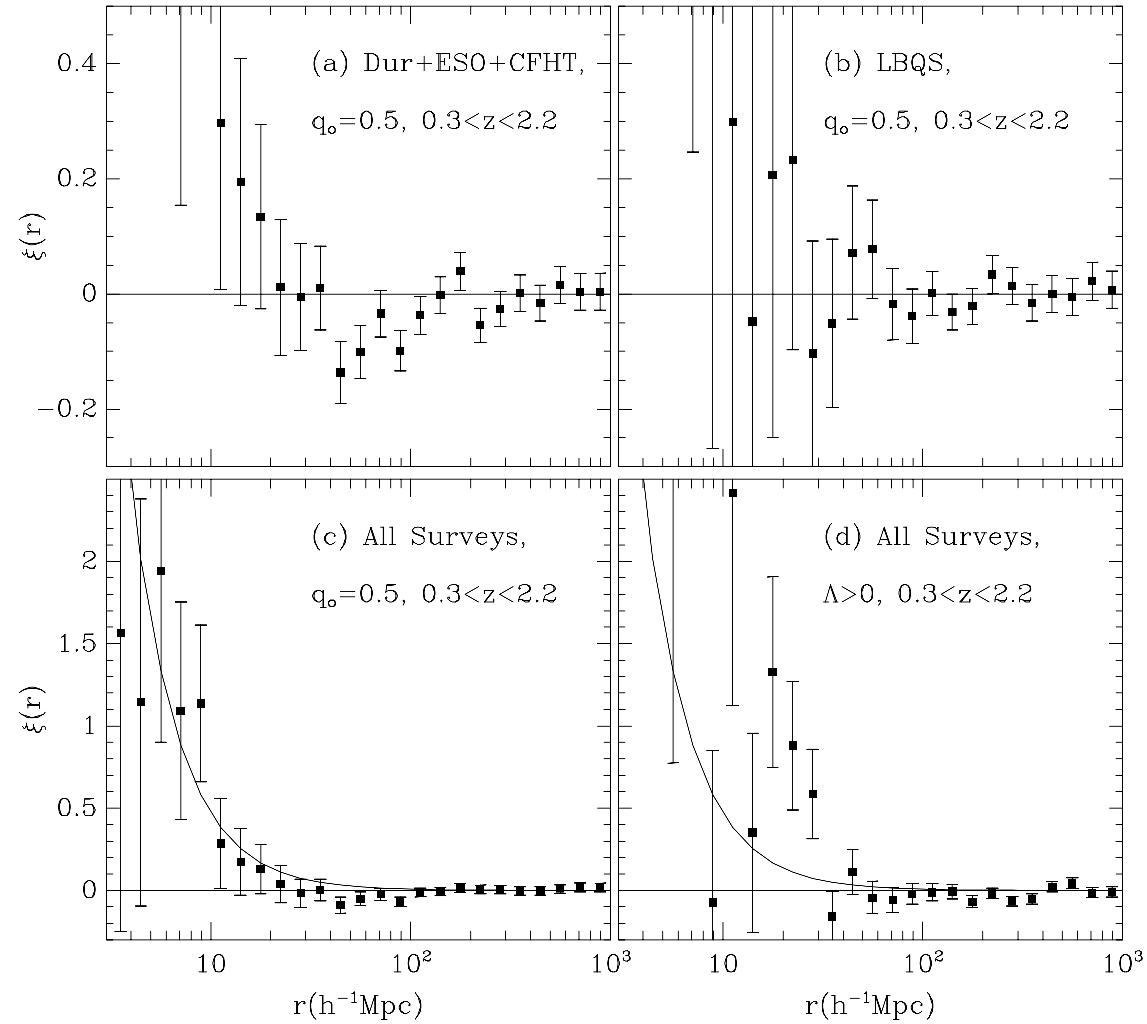

Fig. 3. Correlation functions for (a) Durham/AAT, ESO and CFHT for q_o=0.5, (b) LBQS, (c) all surveys, (d) all surveys with $\Lambda \neq 0$. All the curves are the comoving model with r_o=6.6h^{-1}Mpc.

We calculate the correlation function for our inflationary $\Lambda \neq 0$ and $\Omega_o \leq 0.03$ model (Fig. 3d), the effect of Λ is to stretch the clustering out to larger scales. We compare this result to the r_o=6.6h^{-1}Mpc comoving model described above, within 30h^{-1}Mpc the level of rejection is 3.4σ.

5. Conclusions

We have looked at the clustering properties of a large ($\sim$1700) sample of QSOs, in the total sample we have 4σ detection of clustering at r<10h^{-1}Mpc (q_o=0.5). Our results together with the low z Seyferts and the CCD imaging of QSO environments suggest that QSOs may randomly sample a comoving galaxy distribution.

We have a tentative detection of anti-correlation at 40 to $100h^{-1}$Mpc at the 2σ level. If these large scale features are real then we may use amplitude evolution as a test for q_o, we can also use the features as standard rods to test for Λ.

In spatially flat inflationary cosmologies with $\Lambda\neq0$ and $\Omega_o\leq0.03$, $\xi(r)$ extends strongly to $\sim30h^{-1}$Mpc. Comparisons of this to an $r_o=6.6h^{-1}$Mpc comoving model give a rejection at the 3.4σ level.

In the future we would like to confirm the results presented here via a QSO and galaxy redshift survey using AAT 2dF, in collaboration with L. Miller, M.A. Read (ROE) and F. La Franca (ESO) in a survey area of two SGP declination strips that have already been surveyed by FLAIR in the Durham/UKST galaxy survey, each strip $75\times2\text{deg}^2$. We would expect to observe 150 UVX QSO candidates ($B\leq21^m$) and 200 galaxies ($B\leq20^m$) per 2dF field. This should give a total of $\simeq12000$ $z<2.2$ QSOs. An order of magnitude improvement on existing surveys.

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