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Phil. Trans. R. Soc. Lond. A 1999 **357**, 185-198
doi: 10.1098/rsta.1999.0322

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QSO clustering and the AAT 2dF QSO Redshift Survey

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We review the latest results on large-scale structure based on observations of QSO clustering. We also present initial results from the 2dF QSO redshift survey. This survey currently contains over 1200 QSOs and, when complete, will comprise almost 30 000 QSOs. The 2dF QSO redshift survey will be used to provide new information on the nature and evolution of LSS over scales of 10–1000 Mpc.

Keywords: cosmology; large-scale structure of the universe;
galaxies, active; quasars, general

1. Introduction

The study of QSO clustering from large homogeneous surveys is likely to provide unique information on the nature of large-scale structure (LSS) in the universe. Even with relatively modest aperture telescopes, QSOs are readily detectable from the present cosmic epoch to a time when the universe was less than 25% of its present age. This approximately eight billion year time-interval provides a unique baseline over which to study the evolution of structure in the universe with cosmic time. QSO clustering also yields a direct measure of clustering on co-moving scales much greater than $100 h^{-1}$ Mpc \dagger , providing key information (see figure 1) on LSS at scales between those provided by the COBE results (greater than $1000 h^{-1}$ Mpc (Bennett *et al.* 1994)) and galaxy redshift surveys (less than $100 h^{-1}$ Mpc (Colless *et al.*, this issue)).

To date, QSO clustering has remained largely unexploited for LSS studies. This has largely been due to the lack of appropriate QSO catalogues. Although almost 10 000 QSOs with measured redshifts are now known (Véron & Véron-Cetty 1997, see figure 2) less than 20% of these QSOs form part of homogeneous catalogues suitable for detailed clustering analysis. The goal of the 2dF QSO redshift survey, currently underway at the Anglo-Australian Telescope (AAT), is to provide a new homogeneous catalogue of almost 30 000 QSOs with which to carry out such an analysis. The survey is almost two orders of magnitude larger than the previous largest homogeneous survey to this depth (Boyle *et al.* 1990).

In § 2 we review the existing results on QSO clustering and we describe the creation of the 2dF QSO redshift survey input catalogue in § 3. We report on the initial results

\dagger Throughout this paper, we use co-moving distances, $r_{\text{co-moving}} = (1+z)r_{\text{proper}}$, and define the Hubble constant as $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$.

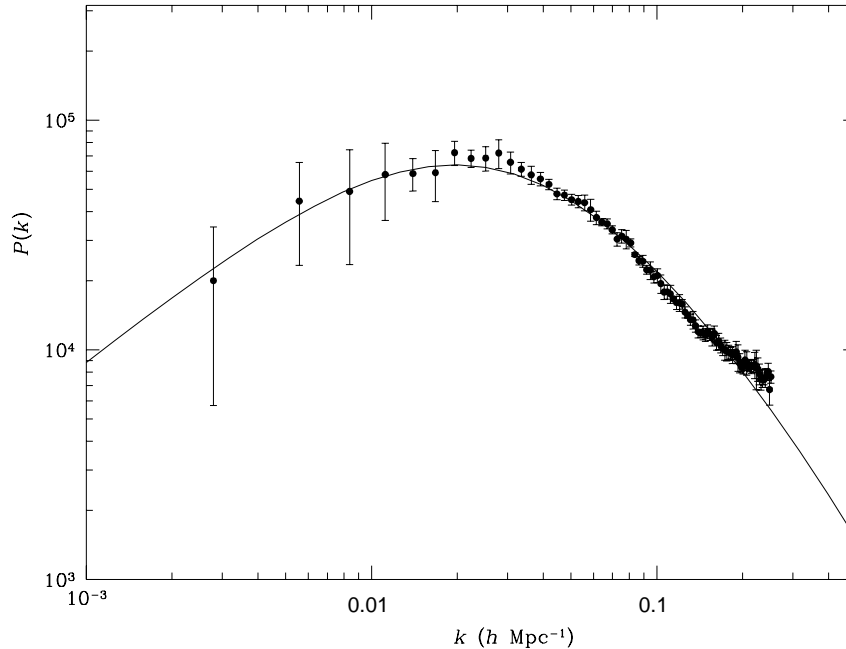


Figure 1. The QSO power spectrum, $P(k)$, based on a Zel'dovich approximation in a $(2250 h^{-1} \text{ Mpc})^3$ box containing 192^3 particles with $z_{\text{max}} = 2.2$. A τ CDM model with $\Omega_0 = 1$, $\Gamma = 0.2$, $\sigma_8 = 0.67$ and QSO bias $b_Q = 1.8$ at $z = 0$ is assumed. Errors on $P(k)$ are based on the RMS scatter from five simulations. Note the 2dF QSO redshift survey comprises two such slices, effectively reducing errors by 1.4. Simulation taken from Croom *et al.* (1998).

from the survey in § 4 and discuss the future prospects for this and other QSO surveys in § 5.

2. QSO clustering

(a) QSO–QSO clustering

First attempts to detect QSO clustering from samples of QSOs yielded no significant detections of QSO clustering on any scale up to $1500 h^{-1} \text{ Mpc}$ (see, for example, Osmer 1981). Nevertheless, a number of studies (Osmer 1981; Webster 1982) did comment on the possibly genuine nature of specific clusters of QSOs at intermediate scales of $50\text{--}100 h^{-1} \text{ Mpc}$. The first positive detection of clustering amongst QSOs at small scales (less than $10 h^{-1} \text{ Mpc}$) was made by Shaver (1984) using an earlier version of the heterogeneous Véron & Véron-Cetty (1997) catalogue, which then comprised 2000 QSOs. This was followed by similar results based on more homogeneous QSO catalogues, comprising a few hundred QSOs (Shanks *et al.* 1987; Iovino & Shaver 1988). The strength of QSO clustering in these studies was found to be similar to that of galaxies at the present day, with the two-point QSO autocorrelation function, $\xi_Q(r)$, fitted by a -1.8 power law $\xi_Q(r) = (r/r_0)^{-1.8}$ with a scale length $r_0 \sim 6 h^{-1} \text{ Mpc}$. None of these early QSO clustering studies found any significant QSO clustering on scales greater than $10 h^{-1} \text{ Mpc}$.

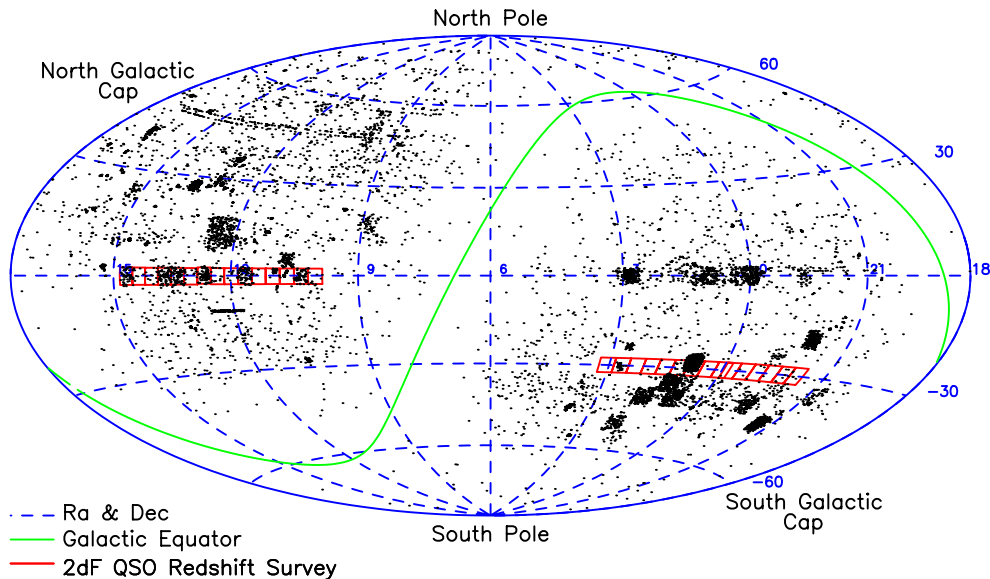


Figure 2. The all-sky distribution of the 8609 known QSOs from the catalogue of Véron & Véron-Cetty (1997). The 30 UKST fields of the 2dF QSO redshift survey are also shown in their two declination strips.

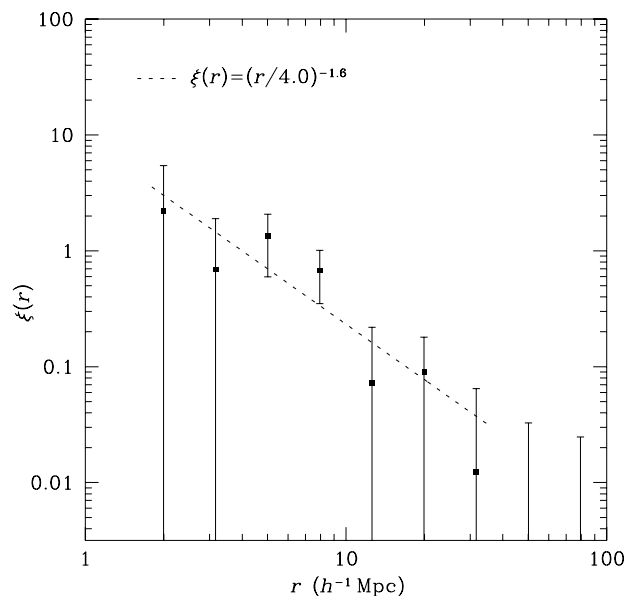


Figure 3. The QSO autocorrelation function $\xi_Q(r)$ for the redshift range $0.3 < z < 2.2$ derived by Croom & Shanks (1996) from the Durham/AAT (Boyle *et al.* 1990), CFHT (Crampton *et al.* 1989) and LBQS (Hewett *et al.* 1995) surveys. The total sample comprises 1743 QSOs.

Suitable QSO sample sizes have only increased slowly over the past 10 years, and latest analyses of QSO clustering (see, for example, Croom & Shanks 1996) still rely on a compilation of a few homogeneous catalogues (Durham/AAT, Boyle *et al.* 1990;

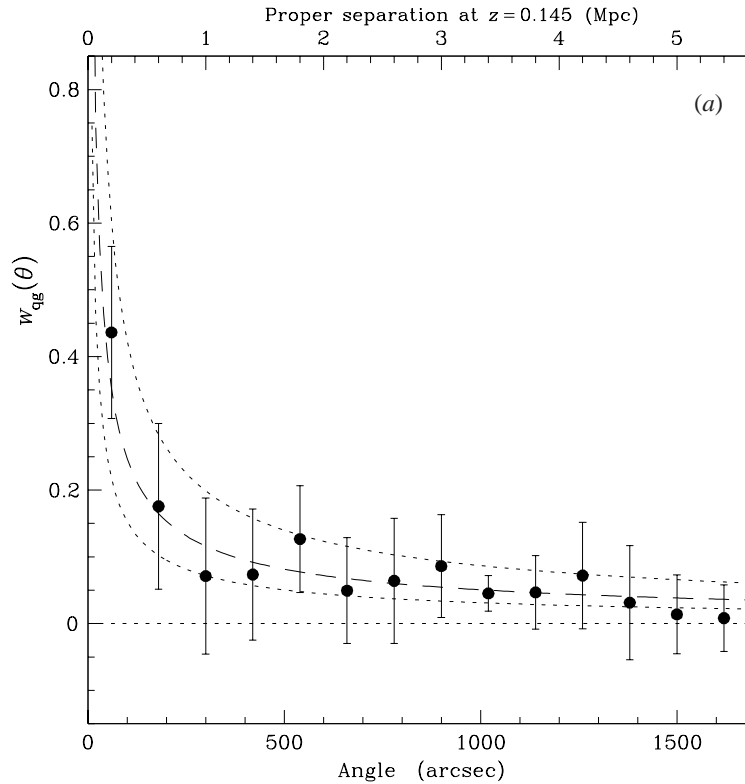


Figure 4. The QSO–galaxy cross-correlation functions, $w_{\text{QG}}(\theta)$, for samples of X-ray-selected QSOs: (a) all (north and south), $z < 0.3$, 169 QSOs.

CFHT, Crampton *et al.* 1989; LBQS, Hewett *et al.* 1995) comprising less than 2000 QSOs in total.

Using the Durham/AAT, CFHT and LBQS catalogues, Croom & Shanks (1996) demonstrated that the QSO autocorrelation function at scales less than $30 h^{-1}$ Mpc was best-fit by $\xi_{\text{Q}}(r) = (r/r_0)^{-1.59 \pm 0.46}$, with $r_0 = 4.0 \pm 1.1 h^{-1}$ Mpc (figure 3). Croom & Shanks (1996) also found no evidence for any evolution in the strength of clustering with redshift. By investigating the predictions of a standard biasing model, they were able to demonstrate that the low values of r_0 obtained for $z < 0.2$ Seyfert galaxies (Boyle & Mo 1993) and IRAS-selected AGN (Georgantopoulos & Shanks 1994) favoured either a low Ω_0 universe, $\Omega_0 < 0.1$, with low values for the galaxy bias parameter ($b_{\text{g}} \sim 1$) or an $\Omega_0 = 1$ universe with a higher bias parameter ($b_{\text{g}} \sim 2$). On the basis of this model, Croom & Shanks (1996) were also able to rule out a universe with $\Omega_0 = 1$, $b_{\text{g}} = 1$ at the 3σ level.

These results on the evolution of the QSO correlation function are, however, contested by other authors. In their earlier analysis, Iovino & Shaver (1988) found that the correlation length decreased towards high redshift, while more recently La Franca *et al.* (1998) claimed to see an increase in the QSO correlation length with redshift, with $r_0 = 4.2 h^{-1}$ Mpc for $z < 1.4$ QSOs and $r_0 = 9.1 h^{-1}$ Mpc for $z > 1.4$ QSOs.

The lack of agreement between these results serves to underline the poor statistics on which the detection of QSO clustering at small scales is currently based. There are

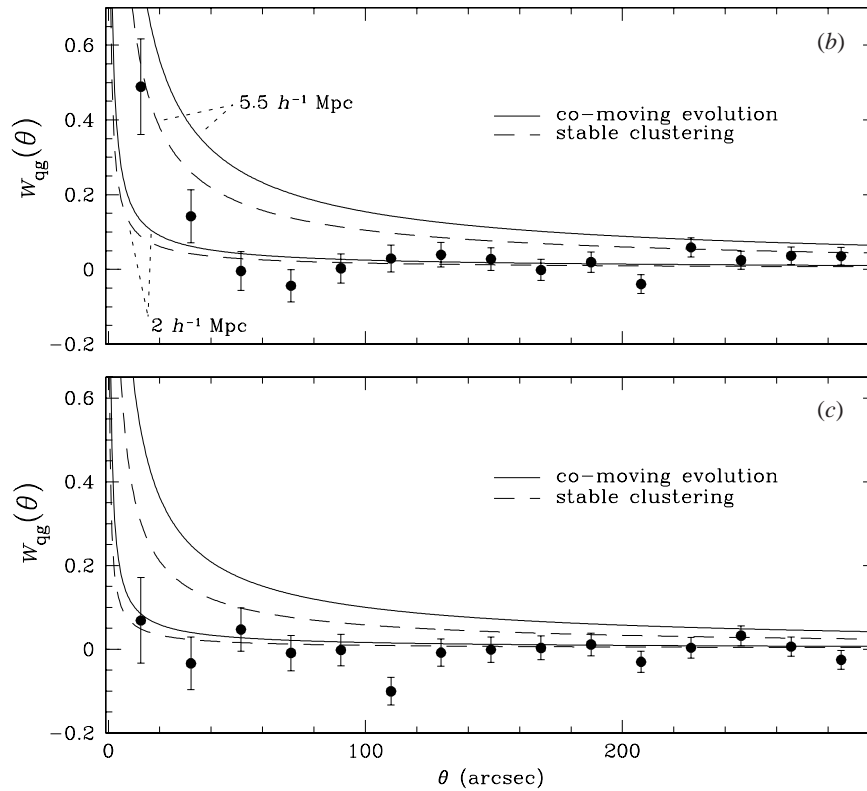


Figure 4. (*Cont.*) (b) $0.3 < z < 0.5$, $17 < m_v < 23$, 56 QSOs; (c) $0.5 < z < 0.7$, $18 < m_v < 24$, 26 QSOs. In (a) the $w_{QG}(\theta)$ is directly compared with the galaxy auto-correlation function (dashed line). In (b) and (c) predicted cross-correlations functions are shown for QSO–galaxy scale lengths of $r_0 = 2 h^{-1}$ Mpc and $r_0 = 5.5 h^{-1}$ Mpc under certain assumptions regarding the evolution of clustering (see Smith *et al.* 1995; Smith 1998).

less than 40 pairs of QSOs with co-moving separations $r < 10 h^{-1}$ Mpc identified in such clustering studies, even when averaged over the full range in redshift $0.3 < z < 3$.

At intermediate scales, $30 h^{-1}$ Mpc $< r < 100 h^{-1}$ Mpc, there have been a number of claims for marginal (2σ) detections of features in the QSO autocorrelation function. However, none of these has stood up to critical examination with larger data-sets (see Croom & Shanks 1996). At these scales, the growth of LSS largely follows linear theory and thus features in $\xi_Q(r)$ at these co-moving separations should not change co-moving scale as a function of redshift. If detected, such features would therefore provide a useful cosmological ‘standard rod’ with which to measure the deceleration parameter q_0 or the cosmological constant λ_0 .

Croom & Shanks (1996) also compared $\xi_Q(r)$ in the $8\text{--}50 h^{-1}$ Mpc region with an extrapolation of the CDM power spectrum normalized by the COBE data. This directly compares the fluctuations in the QSO distribution with those in the mass distribution and is thus a potentially powerful way to measure directly the QSO bias parameter. For a standard CDM model with $\Omega_0 = 1$, they obtained a QSO bias of $b_Q(z=0) = 1.40^{+0.28}_{-0.43}$. For a CDM model with a cosmological constant ($\Omega_0 = 0.2$, $\lambda_0 = 0.8$, $\Gamma = 0.2 \sim \Omega_0 h$), they obtained $b_Q(z=0) = 1.20^{+0.13}_{-0.18}$.

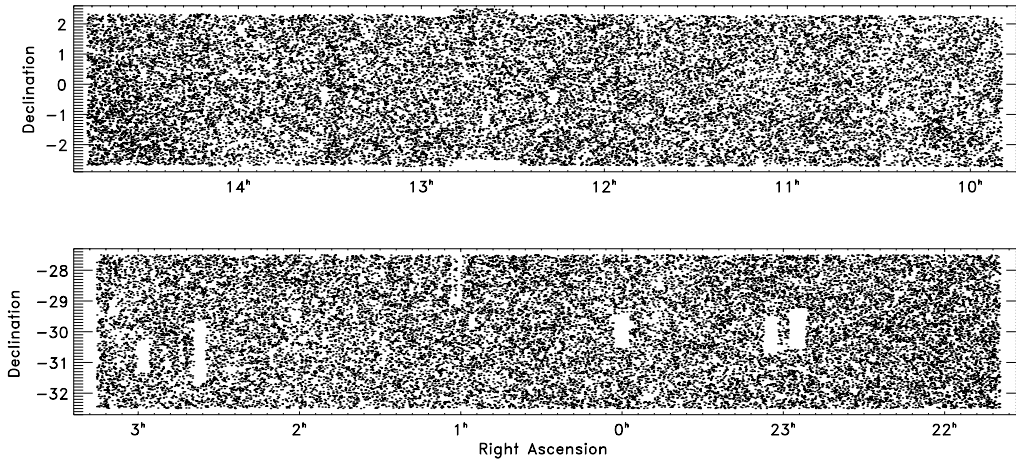


Figure 5. The 2dF QSO survey input catalogue based on the selection of stellar objects from UB_JR UK Schmidt photographic material. Holes in the data-set represent areas excised due to bright stars. Total area of survey, 740 deg^2 ; number of candidates, 47 845; magnitude limits, $18.25 \leq b_J \leq 20.85$; expected completeness, $> 90\%$; colour selection, $(u' - b_J) \leq -0.36$, $(u' - b_J) < 0.12 - 0.8(b_J - r)$, $(b_J - r) < 0.05$; number of expected QSOs, 30 000.

The inconsistency between the small-scale results, which favour a high bias for $\Omega_0 = 1$, and the COBE comparison, which favours a low bias for $\Omega_0 = 1$, could be taken to mean that a low value for Ω_0 may be more appropriate. However, the errors are still large, and it will take surveys such as the 2dF QSO survey to reduce them to the point where more effective discrimination between these models is possible.

Phillipps (1996) and Ballinger *et al.* (1996) also developed a potentially useful geometric test that may be employed at these scales to place limits on the value of λ_0 . The test relies on the fact that, on average, QSO clusters should be spherically symmetric, i.e. with as large an extent along the line of sight as transverse to it. Since λ_0 has a different effect on these two distances, clusters will appear to be spherically symmetric only when the correct value of λ_0 is used. Ballinger *et al.* (1996) demonstrated that the 2dF QSO redshift survey would indeed be able to measure this effect, although effects such as redshift space distortions serve to weaken the signal and complicate the analysis.

At the largest scales, all measures of the correlation function give a signal consistent with zero clustering. At co-moving separations greater than $100 h^{-1} \text{ Mpc}$, Croom & Shanks (1996) find $\xi_Q(r) = 0 \pm 0.025$. Isolated examples of QSO ‘superclusters’ with dimensions $100\text{--}200 h^{-1} \text{ Mpc}$ have previously been identified (Crampton *et al.* 1989; Clowes & Campusano 1994), but it is unclear how representative they are of the QSO population as a whole.

(b) QSO–galaxy clustering

A limiting factor in the study of LSS with QSOs is the unknown bias factor that exists between the QSO population and the underlying mass distribution. Studies of the galaxy clustering around QSOs provide a useful constraint on the relationship between the QSO and galaxy bias.

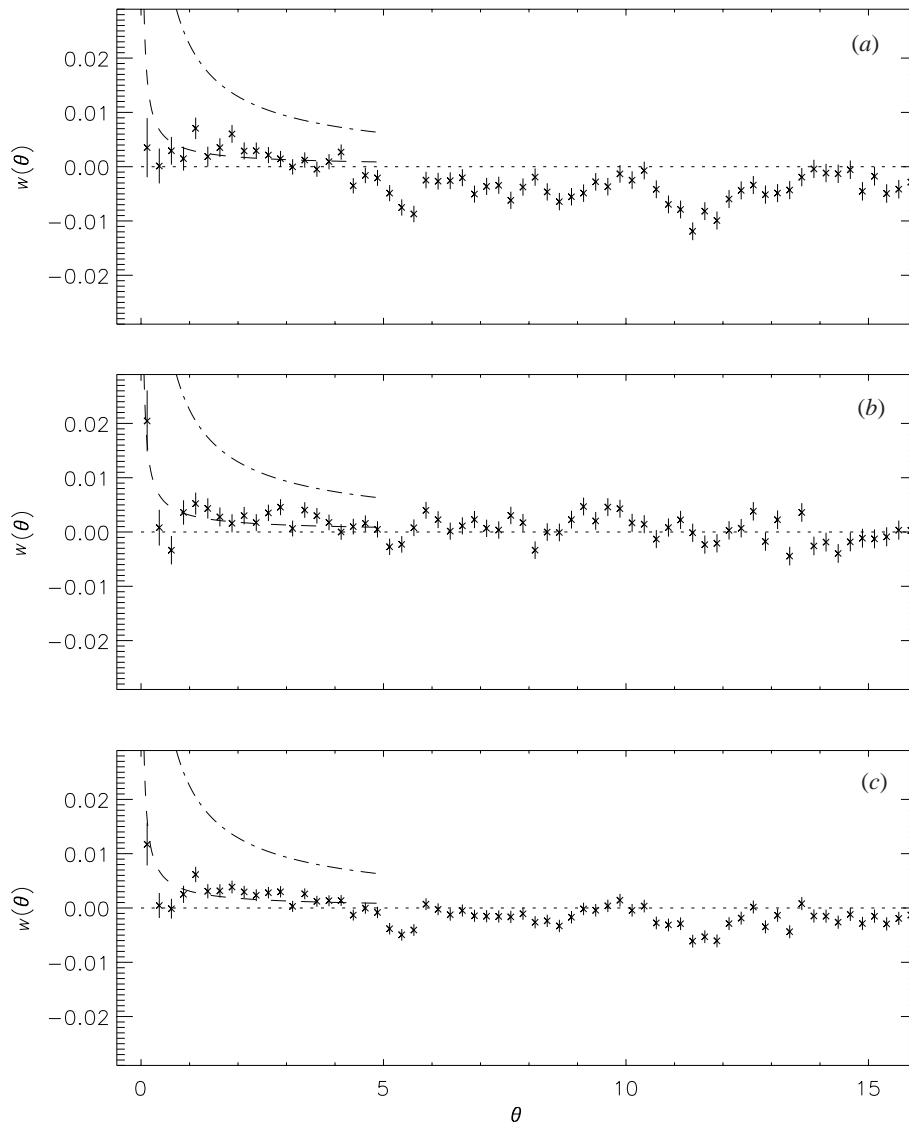


Figure 6. The auto-correlation function for the 2dF QSO survey input catalogue. The curves denote the expected angular correlation function assuming $r_0 = 6 h^{-1}$ Mpc (dashed line) or $r_0 = 18 h^{-1}$ Mpc (dot-dashed line) for a -1.8 power-law spatial correlation function and stable clustering in co-moving space.

The study of the galaxy environment around QSOs was first put on a sound statistical footing by Stockton (1982) and later developed by Yee and his co-workers in a series of papers (see Ellingson *et al.* 1991, and references therein).

The work of Ellingson *et al.* (1991) largely focused on radio-loud QSOs, and demonstrated that their galaxy environment undergoes a dramatic increase in richness from low redshifts to intermediate redshifts, corresponding to an evolution in the galaxy clustering scale length around QSOs from $r_0 \sim 5 h^{-1}$ Mpc (consistent with field galaxies) at $z \sim 0.3$ to $r_0 \sim 15 h^{-1}$ Mpc (similar to Abell richness class 1) at $z \sim 0.6$.

Evidence for similar levels of strong galaxy clustering around radio-loud QSOs at yet higher redshifts ($z \sim 1$) have been found by Tyson (1986) and Hintzen *et al.* (1991).

In contrast, the environments of the vast majority of QSOs which are radio-quiet appear to be significantly poorer. Smith *et al.* (1995) demonstrated that the QSO–galaxy cross-correlation function for a sample of over 100 X-ray-selected radio-quiet AGN at $z < 0.3$ from the Einstein medium sensitivity survey was identical to the galaxy auto-correlation function over a similar range in redshift.

Smith (1998) has now extended this analysis to higher redshift QSOs in the same X-ray-selected sample, finding evidence for the evolution in the QSO–galaxy cross-correlation function in the opposite sense to that witnessed for radio-loud QSOs. The QSO–galaxy scale length decreases from $r_0 = 5 h^{-1}$ Mpc at $z < 0.3$ to $r_0 \sim 2 h^{-1}$ Mpc in the redshift range $0.5 < z < 0.7$ (figure 4). The inferred evolution of the QSO–galaxy cross-correlation function may be expressed in the form $\xi_{\text{QG}}(r) \propto r^{-1.8}(1+z)^{-3+\epsilon}$, with $\epsilon \sim 0.8$, equivalent to the growth of structure predicted by linear theory in an $\Omega_0 = 1$ universe (Peacock 1997).

This evolution is also similar to the evolution of the galaxy scale length as inferred indirectly from the galaxy angular auto-correlation function derived from deep imaging surveys (see Efstathiou 1995) and measured directly from deep redshift surveys (Le Fèvre *et al.* 1996).

Based on these results we can infer that radio-loud and radio-quiet QSOs inhabit different galaxy environments, probably indicative of different levels of bias between the two populations. This is further borne out by the QSO correlation length ($r_0 \sim 18 h^{-1}$ Mpc) inferred from two-dimensional radio-source catalogues (Loan *et al.* 1997). This level of clustering is more consistent with recent estimates of the galaxy cluster correlation length ($r_0 \sim 14 h^{-1}$ Mpc (Dalton *et al.* 1994)). However, the extent to which the radio-quiet QSO population is representative of the galaxy population will probably only be answered by detailed redshift-dependent QSO clustering studies in the 2dF QSO redshift survey.

3. The 2dF input catalogue

(a) Creation

The identification of the QSO candidates for the 2dF redshift survey was based on broadband UB_JR colour selection from APM measurements of UK Schmidt (UKST) photographic plates. The survey area comprises 30 UKST fields, arranged in two $75^\circ \times 5^\circ$ declination strips centred on $\delta = -30^\circ$ and $\delta = 0^\circ$ (see figure 5). The $\delta = -30^\circ$ strip extends from $\alpha = 21^{\text{h}}40^{\text{m}}$ to $\alpha = 3^{\text{h}}15^{\text{m}}$ and the equatorial strip from $\alpha = 9^{\text{h}}50^{\text{m}}$ to $\alpha = 14^{\text{h}}50^{\text{m}}$. The total survey area is 740 deg^2 , when allowance is made for regions of sky excised around bright stars, and is a subset of the survey area for the 2dF galaxy redshift survey.

In each UKST field, APM measurements of one J plate, one R plate and up to four U plates/films were used to generate a catalogue of stellar objects with $B_J < 20.85$. A sophisticated procedure was devised to ensure catalogue homogeneity across plate boundaries (Smith 1998). The criteria for inclusion in the catalogue were

$$(U - B_J) \leq -0.36; \quad (U - B_J) < 0.12 - 0.8(B_J - R); \quad (B_J - R) < 0.05.$$

The full UB_JR -selected catalogue is shown in figure 5. Based on the colours of QSOs that have previously been identified in the survey region, we estimate the catalogue

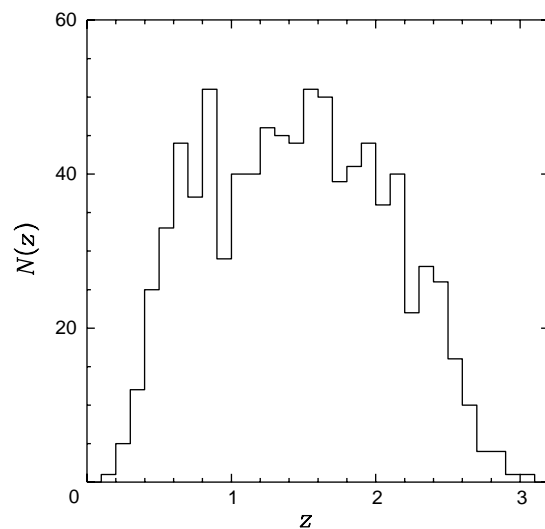


Figure 7. The number–redshift relation for the QSOs identified to date (March 1998) in the 2dF QSO redshift survey.

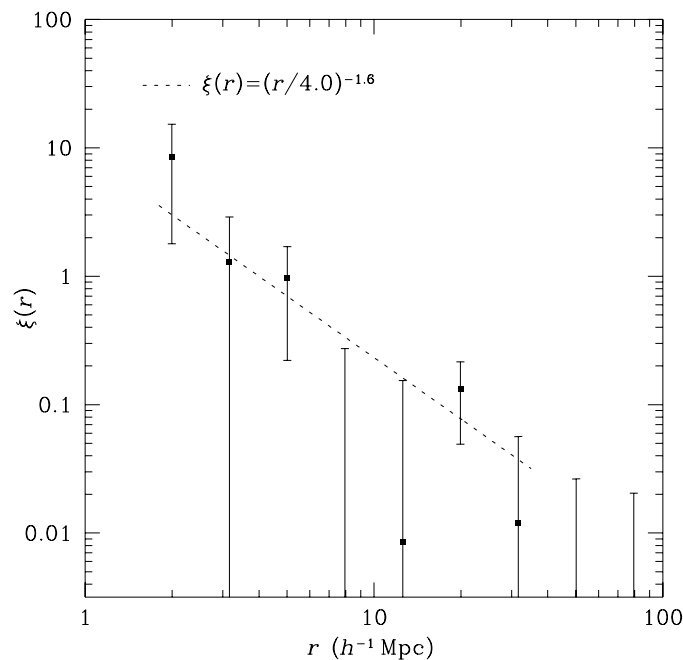


Figure 8. The spatial auto-correlation function for QSOs identified to date in the 2dF QSO redshift survey. The dotted line denotes $\xi_Q(r) = (r/4 h^{-1} \text{ Mpc})^{-1.6}$.

is 93% complete for $z < 2.2$ QSOs. QSOs comprise 55% of all candidates (see Croom 1997). Preliminary indications from the 2dF survey confirm this QSO fraction, with the principal contamination arising from galactic subdwarfs and compact blue galaxies.

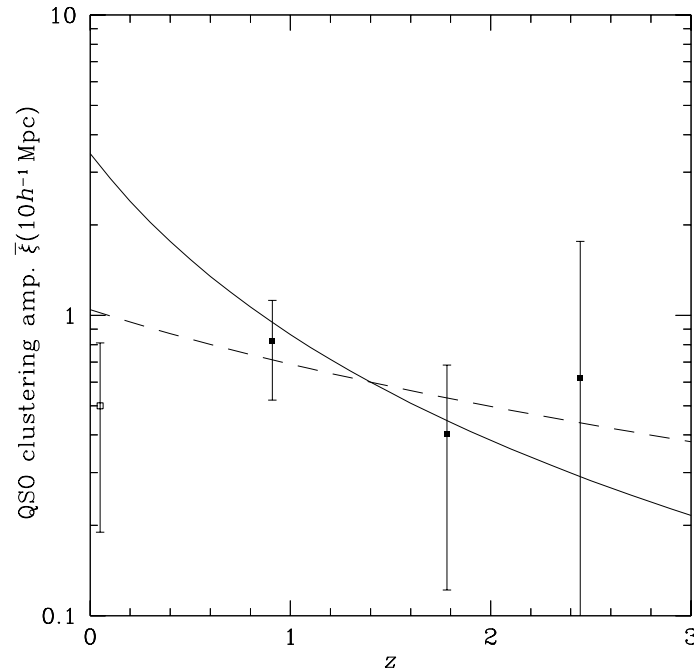


Figure 9. $\bar{\xi}_Q(10)$, the mean amplitude of the QSO correlation function below $10 h^{-1}$ Mpc, plotted as a function of redshift (filled squares). Estimates are based on the combined Durham/AAT, CFHT, LBQS and the 2dF survey data currently available. The point at $z \sim 0$ (open square) is derived from the AGN correlation functions of Boyle & Mo (1993) and Georgantopoulos & Shanks (1994). Model predictions for the growth of structure based on linear theory in an $\Omega_0 = 1$ (solid line) and $\Omega_0 = 0.1$ universe (dashed line) are shown.

(b) Results

Smith (1998) measured the angular auto-correlation function, $w_{QQ}(\theta)$, from the 2dF QSO input catalogue. To minimize the contamination from sources other than QSOs, Smith (1998) restricted the auto-correlation analysis to objects in the input catalogue with $U - B_J < -0.5$. Based on the derived contamination rates, this restricted sample comprises almost 80% of QSOs.

The angular auto-correlation function derived by Smith (1998) is plotted in figure 6. Smith (1998) reports a 3σ detection of clustering consistent with a scale length of $r_0 = 4.9 \pm 1.0 h^{-1}$ Mpc, assuming the scale length of the QSO correlation remains constant in co-moving space as a function of redshift. This is the first detection of QSO clustering on the plane of the sky from an optically selected catalogue, and the amplitude is consistent with the scale length of QSO clustering previously derived from spatial clustering studies. It is inconsistent with the much greater scale length of $r_0 \sim 18 h^{-1}$ Mpc inferred for radio-loud QSOs by Yee & Green (1987).

At angular scales that are multiples of the mean field-to-field separation, 5.5° and 11° , $w_{QQ}(\theta)$ does show systematic deviations from zero amplitude. Although these deviations are small (less than 0.005), they may represent the fundamental limit of the accuracy to which large-scale structure can be measured at scales $r \sim 400 h^{-1}$ Mpc (the co-moving separation corresponding to 5° at $z = 1.5$).

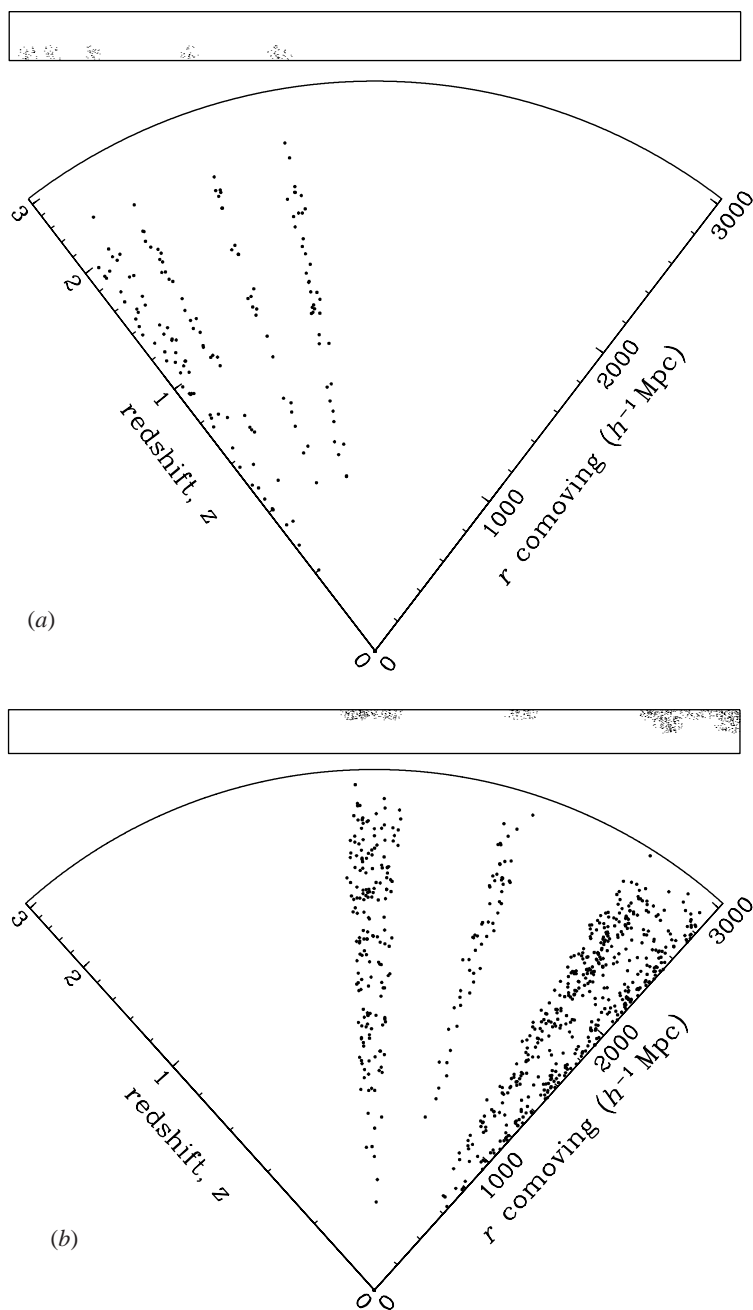


Figure 10. Cone plots for QSOs identified in the 0° and -30° declination strips from 2dF observations to date: (a) north; (b) south.

4. The 2dF QSO redshift survey

2dF spectroscopic observations for the QSO redshift survey began in January 1997, although the bulk of the redshifts were obtained in October 1997 and January 1998

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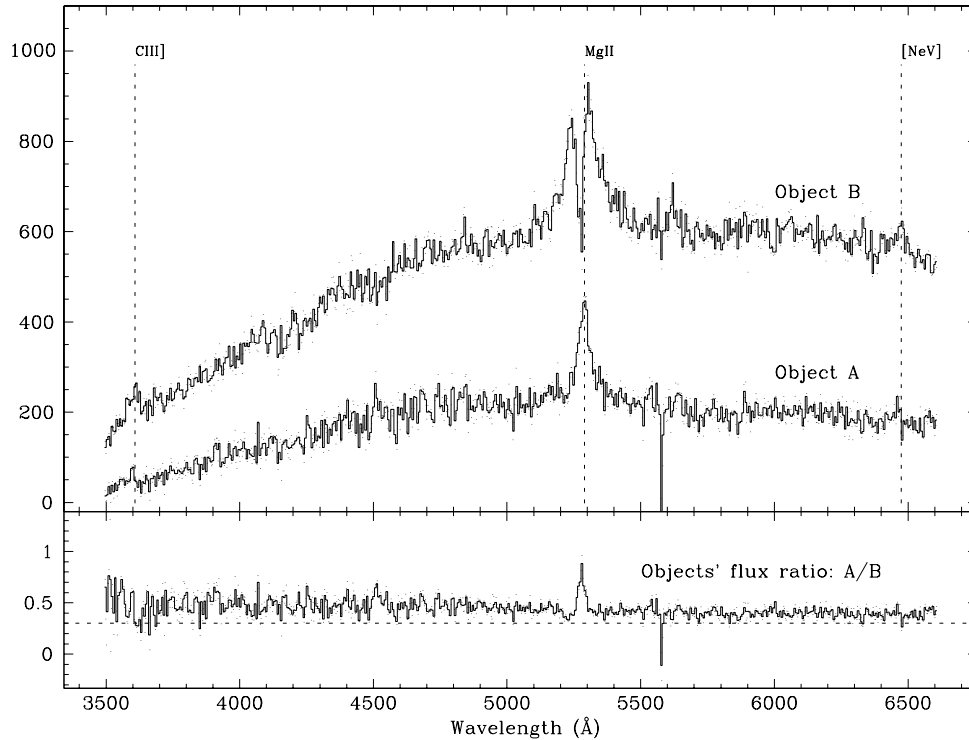


Figure 11. Spectra for the QSO pair Q0101.8–3012A,B, with the ratio spectrum plotted at the bottom.

observing runs as the 2dF system gained functionality (increased number of fibres and faster field reconfiguration times). Over 1000 QSO redshifts have been obtained with the 2dF system, and the 2dF QSO redshift survey is already the largest single homogeneous QSO catalogue in existence. Initial results from this survey are shown in figures 7–10.

Figure 7 shows the number–redshift, $n(z)$, relation for the sample. The $n(z)$ shows a broad flat distribution, with no obvious redshift peaks or troughs due to selection biases. The auto-correlation function plotted in figure 8 is consistent with the form previously derived by Croom & Shanks (1996); $\xi(r) = (r/4 h^{-1})^{-1.6}$. Although the error bars are still large, there is still no strong evidence for evolution of the correlation length with redshift (figure 9). The predictions for two linear theory models of structure growth confirm the result of Croom & Shanks (1996) that the lack of evolution favours a low- Ω_0 universe in such models.

With 97% of the 2dF QSO redshift survey remaining to be completed, the survey cone diagram plotted in figure 10 is currently rather empty, but it does serve to illustrate the eventual scale of the 2dF QSO redshift survey.

The input catalogue is also useful as a resource for other QSO studies. In a separate project, we have cross-correlated the input catalogue with the NRAO/VLA sky survey (NVSS, Condon *et al.* 1998), yielding over 600 detections (corresponding to 5% of the QSOs in the input catalogue). Keck spectra have been obtained for almost 100 of these sources, the vast majority of which (greater than 95%) are QSOs.

We have also begun a more conventional long-slit spectroscopic programme to

obtain redshifts for all input catalogue pairs with angular separations less than 20 arcsec. Such objects are candidate wide-separation gravitational lenses or binary QSOs. The incidence of wide-separation gravitational lenses can be used to place constraints on the value of the cosmological constant. Following Maoz *et al.* (1997), Croom (1997) calculated that lensing by ‘typical’ cluster masses ($2 \times 10^{14} M_{\odot}$) would result in between 4 ($\Omega_0 = 1$, $\lambda_0 = 0$) and 14 ($\Omega_0 = 0.4$, $\lambda_0 = 0.6$) 5–20 arcsec QSO lenses being seen in the survey. To date, we have surveyed approximately 25% of the catalogue pairs at these separations, and found only one possible lens candidate (figure 11). The two components of the possible lens (Q0101.8–3012A,B) have a separation of 17 arcsec on the sky. At the redshift of the system ($z = 0.89$), this corresponds to a projected proper spatial separation of $71 h^{-1}$ kpc.

5. Future prospects

Currently the 2dF QSO redshift survey is only 3% complete. Yet it is already the single largest homogeneous QSO redshift survey yet compiled. Many of the cosmological tests proposed above will become possible when the survey is completed, providing measures of Ω_0 , b_Q and λ_0 , as well as new information on the redshift evolution of structure in the universe and on LSS at scales of many hundreds to thousands of Mpc. In addition the catalogue will provide a unique resource for damped Ly α systems and common absorption-line systems. It may also prove possible to derive information on the power spectrum of mass fluctuations at $z > 2$ through the Ly α forest absorption via the method of Croft *et al.* (1998).

The next decade will see the completion of the 2dF QSO survey together with the Sloan Digital Sky Survey (10^5 QSOs; see Margon, this issue). The LAMOST survey (10^6 QSOs, see Chu & Zhao 1997) is also planned to be well into its operational phase. When QSOs were first discovered, the hope was that they could be used to carry out standard cosmological tests. Now, almost 40 years on, with the advent of these new surveys, this goal may finally be realized.

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