# Chapter 1

# Introduction

## 1.1 A Standard View of Cosmology

The field of cosmology addresses fundamental questions concerning our Universe. Observations made over the last 70 years have vastly increased our understanding of the physical processes involved, and this is particularly true of the last decade. Most cosmologists agree on a 'Standard Model' which provides the framework for further observational tests.

The standard cosmological model is founded on three key observational results. The first of these is the measured expansion of the Universe, determined from the recessional velocities of galaxies (Hubble, 1929). This expansion suggests that the Universe was previously more dense, and so at a higher temperature. The remnants of this hot, dense phase can be observed today and provide us with more evidence. At very early times, at temperatures of $\sim 10^9$K, nuclear reactions occurred producing the light elements (mainly hydrogen and helium). Measurements of the relative amounts of these light elements provide us with our second piece of evidence (Schramm, 1991). When the temperature falls below $\sim 4000$K protons and electrons combine to form hydrogen atoms and the radiation field decouples from the matter. This radiation field can then freely propagate through the Universe. The detection of this 'Cosmic Microwave Background Radiation' (Penzias & Wilson, 1965) is the last of the three key observations.

Underpinning these observations is the assumption of the 'Cosmological Principle'. This states that on large enough scales the Universe is both homogeneous and isotropic. The combination of this assumption and the observational evidence listed above gives us the standard picture of the 'Hot Big Bang'.

Assumption of the Cosmological Principle implies a specific type of metric to describe our Universe. This is the Friedmann-Robertson-Walker (FRW) metric,

$$d\tau^2 = c^2dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right] \tag{1.1}$$

where both $k$, which defines the curvature of the space, and $a(t)$, the expansion factor, depend on the matter content of the Universe. The parameters $r$, $\theta$ and $\phi$ define a *comoving* coordinate system. Applying this metric to the Einstein field equations we obtain the two Friedmann equations:

$$8\pi G\rho = \frac{3}{a^2}(kc^2 + \dot{a}^2) - \Lambda c^2, \tag{1.2}$$

$$\frac{8\pi Gp}{c^2} = -\frac{2\ddot{a}}{a} - \frac{\dot{a}^2}{a^2} - \frac{kc^2}{a^2} + \Lambda c^2 \tag{1.3}$$

$G$ is the gravitational constant, $\rho$ is the mean density, $p$ is the pressure and $\Lambda$ is the cosmological constant. We now introduce $H = \dot{a}/a$, the Hubble parameter; $q = -\ddot{a}/aH^2$, the deceleration parameter; $\Omega = 8\pi G\rho/3H^2$, the density parameter and $\lambda = \Lambda c^2/3H^2$, the normalized cosmological constant. Parameters with subscript zero e.g. $\Omega_0$, denote values at the present. With the assumption of zero pressure Equations 1.2 and 1.3 can then be reduced to

$$\lambda = \frac{\Omega}{2} - q \tag{1.4}$$

and

$$\frac{kc^2}{a^2H^2} = \Omega + \lambda - 1 \tag{1.5}$$

$k$ can take the values $1, 0, -1$, corresponding to closed, flat and open geometries respectively. It is therefore obvious that for a flat Universe, $\Omega_0 + \lambda_0 = 1$. Expansion causes the wavelength of light emitted from an object at time $t_e$ to be *redshifted* when observed at the present ($t_0$). The cosmological redshift, $z$, is defined as

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm e}} = \frac{a_0}{a(t_{\rm e})} \tag{1.6}$$

where $\lambda_{\rm obs}$ and $\lambda_{\rm e}$ denote the wavelength of the observed and emitted light.

## 1.2 Structure in the Universe

Our observations of the Universe locally show that the distribution of matter is not perfectly homogeneous. Structure is found over a huge range of scales. Galaxies are formed from an inhomogeneous mixture of stars, gas and 'dark matter', and galaxies themselves tend to clump together into groups, clusters, filaments and walls to scales $> 100\ h^{-1}$ Mpc (throughout this thesis we shall use a Hubble constant, $H_0 =$

$100h$ kms$^{-1}$Mpc$^{-1}$). How this structure was produced is a fundamental question in cosmology. The generally accepted picture is of a spectrum of primordial density perturbations which grow via gravitational instability. These tiny inhomogeneities could be produced from quantum fluctuations in the very early universe, during a period of *inflation* (Guth, 1981; Kolb & Turner, 1990). Measurements of the fluctuations in the Cosmic Microwave Background (CMB) tell us the amplitude of the perturbations at the time of matter-radiation decoupling. The CMB is observed to be smooth to better than one part in $10^4$ and only recently have experiments, such as the *COBE* satellite (Bennett et al, 1994), detected anisotropies at $\sim 10^{-5}$. These fluctuations continue to grow from the decoupling era, and at present the fluctuations are of order unity on scales of a few $h^{-1}$ Mpc.

The field of density fluctuations in the Universe can be described as follows; we can define the density contrast such that

$$\delta(\mathbf{x}, t) = \frac{\rho(\mathbf{x}, t) - \bar{\rho}}{\bar{\rho}} \tag{1.7}$$

If the density perturbations are in the form of a Gaussian random field they can be completely defined by the two-point auto-correlation function, $\xi$, which is related to the density contrast via

$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x} + \mathbf{r}) \delta(\mathbf{x}) \rangle \tag{1.8}$$

or equivalently we can use the Fourier transform of the auto-correlation function, which defines the power spectrum of density fluctuations,

$$P(k) = |\delta_k|^2 = V \int \xi(\mathbf{r}) \exp(i\mathbf{k}.\mathbf{r}) d^3r \tag{1.9}$$

The exact form of the linear power spectrum is dependent on both cosmology and the type of matter which is dominant in the Universe. The simplest inflationary models predict a *scale invariant* primordial power spectrum, $P(k) \propto k$. This spectrum of fluctuations grows via gravitational instability and is also distorted from its original shape by several physical processes which occur in the early Universe. In the Cold Dark Matter (CDM) model, which fits a number, but not all, of current observations, growth is paused by acoustic oscillations on scales which become smaller than the Hubble length ($\sim c/H$) before the epoch of matter-radiation equality. After recombination the perturbations continue to grow with a power spectrum which now has the form $P(k) \sim k^{-3}$ at large $k$ (small scales) while keeping the scale invariant form on the largest scales. In all models the power spectrum is also distorted at late times by non-linear processes when the density contrast becomes large.

The measurement of the power spectrum of density fluctuations gives us an insight into the physical processes occurring in the early Universe. The measurement of the evolution of clustering is also of vital importance. The rate at which density perturbations grow depends on the cosmology of the Universe. In a high density Universe growth is faster than in a low density Universe. Linear perturbation theory

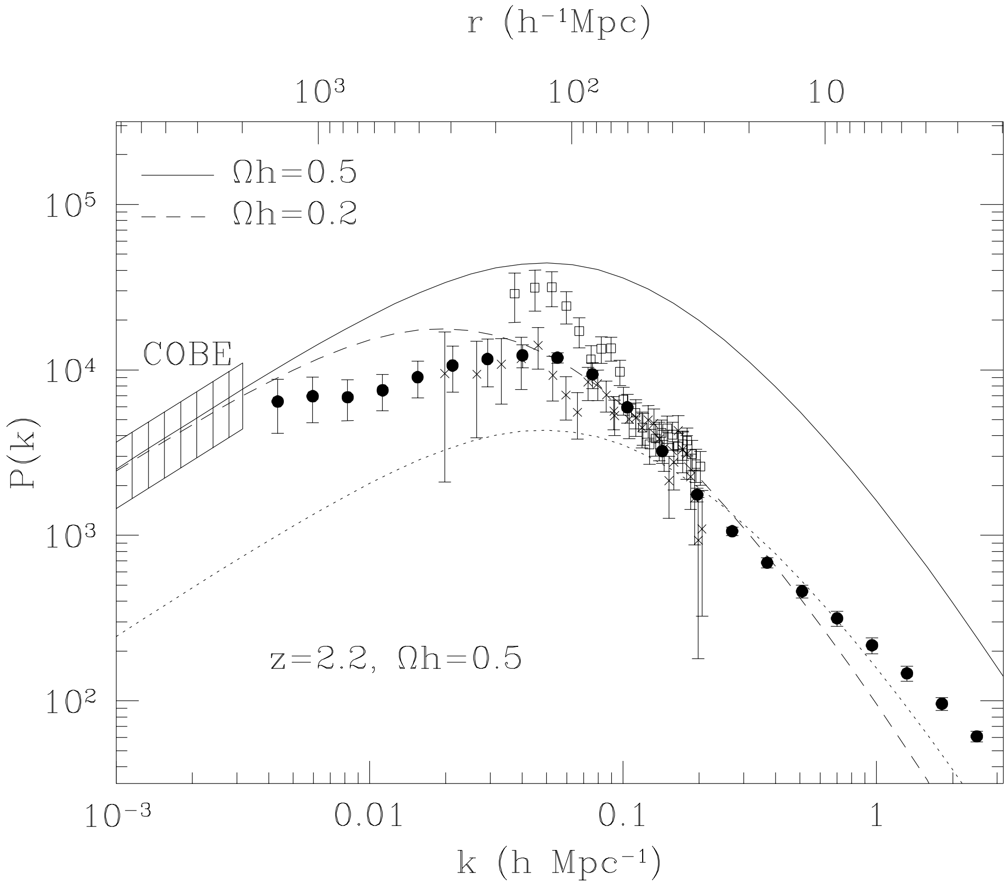


Figure 1.1: The power spectrum of density fluctuations. We plot Linear theory CDM power spectra (Efstathiou et al., 1992), which we normalize to the *COBE* CMB fluctuations and then multiply by a factor of 4 to match the galaxy clustering observations. Two models are shown, one with $\Omega h = 0.5$ at $z = 0$ (solid line) and $z = 2.2$ (dotted line), the other with $\Omega h = 0.2$ at $z = 0$ (dashed line). The data points show various estimates of $P(k)$. The filled circles show the power spectrum derived from the inversion of the angular two-point correlation function of the APM Galaxy Survey (Baugh & Efstathiou, 1993). The open squares are from the APM-Stromlo Redshift Survey (Tadros & Efstathiou, 1996), while the crosses are a combination of the QDOT and 1.2Jy IRAS redshift surveys (Tadros & Efstathiou, 1995).

can be used to find the rate of the growing mode of perturbations for different cosmologies. For $\lambda_0 = 0$ the change in density contrast is given by

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G \rho \delta \tag{1.10}$$

(Peebles, 1980). Solving this for a flat $\Omega_0 = 1$ Universe gives

$$\delta \propto \frac{1}{1+z} \tag{1.11}$$

For an open Universe with $\lambda_0 = 0$ the growth rate is slower than in the $\Omega_0 = 1$ case. Here the growth rate (normalized to the growth in the $\Omega_0 = 1$ case) is

$$D(z) = 1 + \frac{3}{x} + \frac{3(1+x)^{1/2}}{x^{3/2}} \ln\left[(1+x)^{1/2} - x^{1/2}\right] \tag{1.12}$$

where

$$x = |\Omega_0^{-1} - 1| \frac{1}{1+z} \tag{1.13}$$

The general solution for a flat Universe is given in Chapter 3 (Eq. 3.31) and other solutions for open and closed Universes are given by Peebles (1980). The major advantage of Quasi-Stellar Objects (QSOs or quasars) is that their high intrinsic luminosity means that they can be observed at very great distances, and so we have a long baseline in look-back time from which to measure evolution. In fact, QSOs allow us to study the 4-dimensional structure of the Universe. As the growth of perturbations is dependent on cosmology, we have a route to estimating $\Omega_0$ via the evolution of QSO clustering. Fig 1.1 shows a CDM power-spectrum at a redshift, $z = 2.2$, the effective limit of the 2dF QSO Survey, assuming linear evolution with $\Omega_0 = 1$ (Eq. 1.11). There is an order of magnitude growth in clustering amplitude from $z = 2.2$ to $z = 0$.

The measurement of the cosmological parameters ($\Omega_0$, $\lambda_0$, $H_0$) and the shape of the power spectrum of density fluctuations are the key aims for observational cosmology. The two are related, in so much as the shape of $P(k)$ for a given type of matter will depend on the cosmological parameters. The CDM model, which postulates that the majority of matter in the Universe consists of cold, non-baryonic particles which only interact via gravity, has been successful at fitting various observational data. However, the 'standard' CDM model, with $\Omega_0 = 1$ and $h = 0.5$, is inconsistent with the power spectrum measured on large scales by a number of surveys including the APM Survey (Baugh & Efstathiou, 1993), the IRAS QDOT and 1.2Jy Surveys (Tadros & Efstathiou, 1995) and the APM-Stromlo Survey (Tadros & Efstathiou, 1996). This can be seen in Fig. 1.1 where the shape of the observed power spectrum is clearly better fit by an $\Omega h = 0.2$ model. It should be noted that the amplitudes of neither model, when normalized to *COBE* measurements of the CMB fluctuations, fit the data, implying that the galaxy distribution may be *biased* with respect to the density field (see Section 1.4 below). The CMB measurements are vital, as they describe the density fluctuations in the early Universe. The galaxy observations, by comparison, describe the fluctuations in the galaxy distribution, which do not necessarily exactly follow those in the density distribution, in the local Universe. The large volume sampled by QSOs affords the possibility of measuring the power spectrum on the scales probed by *COBE*.

Large-scale structure can also be used to make more direct measurements of cosmological parameters. For example, distortions between the measured clustering in real- and redshift-space can be used to estimate $\Omega_0$, from non-Hubble flow peculiar velocities (Kaiser, 1987). Distortions in clustering can also be caused by assuming the wrong cosmology when measuring large-scale structure, because the distances parallel and perpendicular to the line-of-sight have different dependences on cosmology. This effect can be used to determine cosmological parameters, and is particularly sensitive to the cosmological constant, $\lambda_0$ (Phillipps, 1994; Ballinger et al., 1996).

## 1.3 QSO Formation and the Relationship Between QSOs and Galaxies

It is evident that the QSO distribution contains a wealth of cosmological information. However, interpretation of this information is not necessarily a trivial problem. This is mainly due to the problem of relating the QSO distribution to the mass distribution, which drives cosmic evolution via gravitational instability. This is similarly a problem when using galaxies to study large-scale structure, although galaxies are far more numerous in the local Universe allowing us a clearer picture of the present day galaxy distribution. This is a vital starting point from which to look at the problem of cosmic evolution, and as such we are also required to understand the relation between QSOs and 'normal' galaxies. Possible answers to these problems may be found from a combination of theoretical and empirical investigation.

The discovery of the first QSO, 3C273 (Schmidt, 1963), initiated a considerable industry in the theoretical modelling of the QSO phenomenon. The substantial QSO flux (typically $\sim 10^{45}\mathrm{ergs}^{-1}$) is thought to be due to accretion of hot gas onto super-massive black holes of mass $\sim 10^6 - 10^{10} M_\odot$. Detailed reviews of the unified black hole model for QSOs and Active Galactic Nuclei (AGN) are given in Antonucci (1993) and Rees (1984) . These black holes form at high redshift with the most distant QSOs presently known having $z \sim 5$.

The mechanisms required to form these super-massive black holes are qualitatively similar to the processes which are likely to occur in the formation of galaxies at early epochs. In both cases clouds of gas cool and collapse in the peaks of the matter distribution. The eventual fate of the collapsing gas is largely dependent on the angular momentum of the system. Efstathiou & Rees (1988) investigate the formation of QSOs in the CDM cosmogony and find that luminous QSOs could only form within galaxy-sized dark matter halos because of the small fraction of baryonic matter in the halo and the fact that only a fraction of baryons will collapse to the centre of the halo, while some will be expelled via a supernova driven wind. Loeb (1993) discusses the angular momentum considerations in the collapse of quasi-spherical gas clouds. Tidal torques from neighbouring density perturbations provide angular momentum to collapsing clouds, which then become rotationally supported and fragment into stars. In order to collapse to the Schwarzschild radius of the system, the specific angular momentum must be reduced by several orders of magnitude. One possibility is that QSOs are associated with rare peaks which obtain low angular momentum from tidal torques. Alternatively at very high redshifts, $z > 100$, Compton interactions between free electrons and the CMB can effectively extract angular momentum from a system.

The physical processes which occur once the black hole has formed are understood far better than the formation process. A large amount of gas needs to continue to fall into the system to fuel the QSO luminosity and will usually form a stable disk. The centre of the gaseous disk will be stable for black hole masses $\sim 10^6 M_\odot$ or greater (Loeb & Rasio, 1994). The black hole then continues to grow at the Eddington rate (the rate at which radiation pressure balances the inflow of gas) assuming a sufficient supply of gas, so that the luminosity approaches the Eddington limit

$$L_{\mathrm{E}} = \frac{Mc^2}{t_{\mathrm{E}}} \tag{1.14}$$

where $t_{\mathrm{E}}$ is the Eddington time, the time needed for an object to radiate away its total rest mass at $L_{\mathrm{E}}$. The Eddington time is

$$t_{\mathrm{E}} = \frac{\sigma_{\mathrm{T}} c}{4\pi G m_{\mathrm{p}}} \tag{1.15}$$

where $\sigma_{\mathrm{T}}$ is the Thompson cross-section and $m_{\mathrm{p}}$ is the proton mass. This occurs while the QSOs inhabit gas rich environments. However, a QSO will cease to radiate at this high luminosity when the rate of gas fuelling the central black hole slows down or stops. Small & Blandford (1992) and others use this mechanism to produce a strong density evolution in the QSO luminosity function with relatively short-lived QSOs.

The life-time of QSO activity is crucial to understanding their role in tracing large-scale structure. A model of short lived QSOs implies many generations, with QSO activity in a substantial fraction of all galaxies, while a life-time similar to the Hubble time ($\sim H_0^{-1}$) would imply that QSOs are intrinsically rare. A possible explanation of this rarity would be that QSOs only trace the very highest peaks in the density field. Observational evidence from a number of areas does now appear to point to QSOs being short-lived. While pure luminosity evolution was originally found to fit the evolution of the QSO luminosity function, recent evidence shows that this is not exactly the case (Goldschmidt & Miller, 1991). Obviously pure luminosity evolution would be strong circumstantial evidence for a long QSO lifetime, although with QSOs becoming brighter in the past this requires the evolution to be due to a change in fuelling rate rather than the continual growth of a black hole accreting at the Eddington limit. Observations of the cores of a number of nearby galaxies (Kormendy & Richstone, 1995) suggest that some contain black holes in the mass range $\sim 10^6 - 10^9 M_\odot$ and rule out substantially larger masses. A black hole which accreted at the Eddington limit for a Hubble time would have a mass considerably larger than these observed limits.

The observed comoving QSO number density evolves strongly with redshift, increasing rapidly to $z \sim 2$. Above this redshift, QSO detection is more difficult, particularly using optical techniques in which QSO colours become more similar to stars. However, several high redshift data sets show a likely decline in the space density of QSOs at $z \sim 3 - 5$ using optical and variability selection methods (Hawkins & Veron, 1996) and radio selected samples (Shaver et al., 1996). This evolution is comparable to estimates of star formation in high redshift galaxies found from ultra-deep imaging experiments. Madau et al., (1996) use data from the *Hubble Deep Field* (HDF) (Williams et al, 1996) recently observed using the *Hubble Space Telescope* (HST) to constrain star formation history up to $z \sim 4$. Combining the HDF data with data from the Canada-France Redshift Survey (Lilly et al., 1995) Madau et al., find that star formation increases dramatically from the present to at least $z \simeq 1$ and appears to decrease from $z \sim 3$ to $z \sim 4$. Metcalfe et al., (1996) use data from both the HDF and the Herschel Deep Field imaged with the *William Herschel Telescope* (WHT) to show that the large population of 'faint blue galaxies' is most likely to lie at $z \sim 2$. It therefore appears that the 'Epoch of Galaxy Formation', the period in cosmic history when the bulk of stars were formed, occurred at $z \sim 2$, which coincides with the period at which the QSO space density reached a maximum. This is not altogether surprising when we consider that both star formation and QSO activity are heavily reliant on the supply of gas. Indeed the sharp fall off in both the QSO density and star formation rate to low redshift does imply that the amount of gas available in galaxies declines dramatically from $z \sim 2$ to the present. This picture suggests that QSOs and galaxy evolution are closely related.

## 1.4 Aims: QSOs as Cosmological Probes

The main aim of this thesis is to investigate the clustering of QSOs via objectively selected, complete, QSO catalogues. We wish to use clustering properties of QSOs to infer the form and evolution of the spectrum of density fluctuations in the Universe. This will allow us to make estimates of cosmological parameters, and give us a new insight into the underlying cosmological model.

The first question we should ask when using QSOs as tracers of large-scale structure is: how do we relate QSOs to the underlying mass distribution? and second, how do we relate QSOs to galaxies, the other main tracers of large-scale structure? Direct evidence for the manner in which QSOs trace the galaxy distribution can be found from deep imaging of QSO environments. There is much evidence that radio-loud QSOs appear to exist in rich environments (Ellingson et al., 1991; Hintzen et al., 1991), in some cases with similar richness to Abell class 1 galaxy clusters. Observations of radio-quiet QSOs find them in generally poorer surroundings at low ($z < 0.3$) (Smith et al., 1995) and intermediate ($z \sim 1$) (Boyle & Couch, 1993) redshift. The majority of optically selected QSOs ($\sim 90\%$) are found to be radio-quiet, and so are expected to exist in poor environments. In Chapter 2 we investigate the environment of a large sample of optically and X-ray selected QSOs in an attempt to confirm that such objects do not live in rich cluster-like environments.

The relationship between the mass, galaxy and QSO distributions can be understood in terms of *biasing*. Our lack of knowledge concerning the complex physical processes which occur during galaxy and QSO formation can be parameterized by a bias parameter, the simplest version of this being a linear bias such that

$$\xi_{\rm q}(r) = b^2 \xi_\rho(r) \tag{1.16}$$

where the bias parameter $b$ relates the QSO correlation function ($\xi_{\rm q}$) and the mass correlation function ($\xi_\rho$). Bardeen et al., (1986) use the peaks-bias formalism to determine the number density of peaks at a given threshold in a Gaussian random field. This shows that rare high peaks will be more strongly clustered than peaks at lower thresholds. The physical motivation for biasing is that primordial density peaks might be more likely to collapse if they already exist in an overdense region (Kaiser, 1984). Other effects such as the re-ionization of the inter-galactic medium by the first generation of stars or QSOs might well prevent the collapse of perturbations which have not already collapsed. Biasing is an observed fact; we see that the clustering of galaxy clusters with scale length $r_0 \sim 15\ h^{-1}$ Mpc (e.g. Dalton et al., 1994) is stronger than the clustering of galaxies with $r_0 \sim 6\ h^{-1}$ Mpc (e.g. Loveday et al., 1995; Ratcliffe et al., 1996). Different populations of galaxies have also been shown to have significantly different clustering properties; for example, the results from the APM-Stromlo Redshift Survey show that late and early type galaxies have significantly different correlation-functions (Loveday et al., 1995), while Park et al. (1994) have found that the amplitude of the power spectrum in the Extended CfA Galaxy Redshift Survey is dependent on luminosity. It is therefore obvious that at least a large sub-sample of galaxies cannot exactly trace the mass distribution. Bias, and particularly the possible evolution of bias with redshift, is then an important parameter to include when studying large-scale structure in QSO samples. In Chapter 3 we use a number of previous QSO catalogues to study the evolution of QSO clustering as a function of redshift, using the evolution to try and constrain the density parameter $\Omega_0$. We include a model for the evolution of bias with redshift in order to relate the QSO evolution to the mass evolution which is dependent on $\Omega_0$.

We will see in Chapter 3 that to make accurate measurements of QSOs clustering and clustering evolution a large, deep, QSO survey is required. For example, the present catalogues are not able to constrain the shape of the QSO clustering power spectrum. To improve the statistics of the measured QSO clustering we start the process of producing a large homogeneous QSO catalogue. The 2-degree Field (2dF) instrument at the Anglo-Australian Telescope (AAT) allows spectra for up to $\sim 400$ objects to be obtained at one time. This huge multiplex gain enables surveys to be constructed with many times more QSOs than previously possible. The 2dF QSO Redshift Survey will obtain redshifts for $\sim 25000$ QSOs, an order of magnitude more redshifts than the present largest QSO sample. The construction of the ultra-violet excess (UVX) catalogue used for candidate selection in the Southern half of this survey is discussed in Chapter 4. We take particular care to quantify the source and amount of incompleteness expected in the sample. Chapter 6 contains the results of preliminary spectroscopic data from the 2dF QSO Redshift Survey. In this chapter we compare the measured QSO densities to the expected values and suggest some possible improvements that could be made to the input QSO candidate catalogue.

Another use of QSO catalogues is to use the two-dimensional UVX catalogue to place constraints on gravitational lensing from foreground galaxy clusters by carrying out a cross-correlation with the clusters. Boyle et al., (1988) found a significant anti-correlation between UVX objects and galaxy clusters. In Chapter 5 we interpret this result in terms of gravitational lensing and then extend our investigation to the 2dF UVX catalogue. We also consider the effect of lensing on the measured cross-correlation between QSOs and faint galaxies in Chapter 2.

Chapter 7 contains a discussion of the general conclusions of this thesis and includes a look at the future prospects of using QSOs to increase our understanding of the Universe with particular reference to the 2dF QSO Redshift Survey.