Carnegie Observatories Astrophysics Series, Vol. 2:
Measuring and Modeling the Universe, 2004
ed. W. L. Freedman (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium2/proceedings.html)

Quasars as Cosmological Probes

C. D. IMPEY
Steward Observatory

Abstract

This review will cover the varied uses of quasars as cosmological probes. Unlike techniques that use galaxies as tracers, strong gravitational lensing and intervening absorption lines can be studied with nearly equal efficiency over the entire Hubble time. Strong lensing provides tests of the dark matter distribution from scales of galaxy nuclei to the scale of groups of galaxies. The lenses themselves give the unique opportunity to study the evolution of galaxies selected by mass. Well-constrained lens models offer direct tests of the parameters of the standard cosmological model, notably the Hubble constant. Quasar absorption lines can be used to trace the evolution of the IGM, using the Lyman-α forest, and the enrichment and clustering of galaxy halos, using metal lines. Paired and multiple quasar sightlines provide information on the topology of large scale structure and the spatial geometry of the world model.

1.1 Introduction

One of the most powerful ways to study the nature and evolution of the universe is to use quasars as flashlights at cosmological distances. On the rare occasions when a quasar lines up almost perfectly with a massive intervening galaxy, the deflection of light by gravity causes multiple image formation. Since the light deflection is sensitive to all forms of matter — luminous and dark — gravitational lensing is an effective way to measure the total mass of galaxies. Lens models are precise enough to constrain the structure and kinematics of the lenses over a wide range of redshifts. The incidence rate of gravitational lensing, and the redshift distribution of the lenses, are sensitive probes of the cosmological model. The second use of quasars as probes involves the study of narrow absorption features caused by hydrogen and heavier elements along the line of sight. The map of absorbers in wavelength converts via the cosmological redshift into a map of the absorbers in distance along the line of sight. When the spectra of two or more sightlines are combined, the coherence length and large scale clustering power of the absorbing gas can be measured. The evolution of the absorbers and their physical properties contain imprints of the geometry and curvature of space.

1.2 Gravitational Lensing

About one in 500 quasars has a sightline that intercepts an object with a high enough surface mass density to cause multiple image formation. There are currently about 80 gravitationally lensed quasars, and 6-8 more are discovered each year (see the list at http://cfa-www.harvard.edu/castles/, the CASTLES web site, maintained by the CfA-Arizona Space Telescope LEns Survey). The optical depth for lensing is given by

$$\tau \sim \int_0^{z_s} D(z_l)^2 \, (dD/dz_l) \, dz_l \int A(M) \, (dn/dM) \, dM$$

where the first integral is over the mass function of deflectors of mass M and cross sectional area A at redshift z_l, and the second is over the comoving distance out to the source redshift z_s. Early type galaxies provide 90% of the known lenses, in accord with their high central mass densities and an integral over the galaxy luminosity function (Kochanek 1993). As the number of lens systems has grown, lensing has moved from the category of esoterica to its current status as a mainstream and versatile cosmological tool (Blandford & Narayan 1992; Schneider, Ehlers & Falco 1992, Brainerd & Kochanek 2001). In addition to providing a fundamental test of weak field general relativity, we now have enough "experiments" in gravitational optics to look at ensemble properties and cosmic averages.

1.2.1 Probing Dark Matter

Despite the successes of CDM is explaining large scale structure and the large scale motions of galaxies, it is worth recalling that our knowledge of dark matter is entirely phenomenological. As a result, it is essential to have independent tests of the CDM paradigm in many different physical regimes. Lens models give mass directly. No assumptions are needed about stellar populations or evolution, or the degree to which visible baryons trace the underlying density field. Strong quasar lensing can probe dark matter on scales of 10 pc up to 1 Mpc, from the inner cores of galaxies to the scales of galaxy groups.

Lenses with smooth mass density profiles always generate an odd number of images (Schneider, Ehlers & Falco 1992). Optically selected systems project a degmagnified image onto the center of an elliptical galaxy, where it is difficult to detect. Radio surveys are therefore preferred because lenses are rarely radio-loud. In the CLASS survey, where the lenses are all doubles or quads, the upper limits on the flux of the odd central image are under 1% of flux of the brightest image (Norbury et al. 2004). Keeton (2002a) has shown that the absence of central images implies elliptical galaxies cores that are too cuspy on scales of $\sim$10 pc to be explained by CDM models (Munoz, Kochanek & Keeton 2001; Rusin & Ma 2001). Thus, mechanisms devised by simulators to remove cusps, and explain the unexpectedly flat cores of spiral galaxies (Weinberg & Katz 2002), cannot solve this problem.

Cuspy mass distributions on kiloparsec scales are a robust prediction of CDM and heirarchical structure formation (Navarro, Frenk, & White 1996; Moore et al. 1998), yielding density profiles of $\rho \propto r^{-\alpha}$, with α = 1-1.5 at small radii. This is in apparent conflict with the observation of shallow gradient cores in dwarf and low surface brightness galaxies, with α = 0-0.4 (van den Bosch & Swaters 2001; de Blok, McGaugh, & Rubin 2001). A well-constrained lens model gives the mass of the lens within the Einstein radius with 5% precision — the best measured parameter for any galaxy, high or low redshift. A statistical approach is to match the fraction of multiply imaged sources and the distribution of angular separations of the lensed images against realistic models where the baryons contract adiabatically within a dark halo (Keeton 2002). Dark matter can account for no more than 33% of the mass within one effective radius. This result is marginally inconsistent with the more centrally concentrated galaxies that build up in the "concordance" cosmology.

Density profiles of individual lens galaxies can be studied in cases where the quasar host galaxy is amplified enough to be easily detected. Spatially resolved light from the lensed quasar host breaks some of the degeneracies of lens models and allows a constraint on the radial profile of the lens (Munoz, Kochanek & Keeton 2001). This method is in its infancy, because deep observations with the Hubble Space Telescope are required to adequately detect the lensed host. Lensing studies have also shown that mass generally follows light. After correcting for tidal perturbations, the major axes of the mass and light distributions are aligned to better than 10 degrees (Kochanek 2001).

Continuing out to the scales of the extended halo, lensing can probe the smoothness of the lens galaxy mass distribution, leading to constraints on the properties of the dark matter particle. It has long been known that the flux ratios of multiply-imaged quasars are not always in accord with simple isothermal mass models (Mao & Schneider 1998). Flux ratio anomalies can be caused by micro-lenses (stars) or milli-lenses (sub-halos). The incidence of anomalies confirms the predominance of dark matter in the halos — a stellar component can only contribute 10-30% of the mass surface density along the sightlines (Schechter & Wambsganss 2002). Simulations with a few percent of the halo mass in the form of sub-structure successfully account for the flux ratios (Dalal & Kochanek 2002). Spectroscopy may provide an even cleaner signature of sub-structure lensing (Moustakas & Metcalf 2003). Already, lensing has given us the exciting confirmation of a fundamental prediction of heirarchical structure formation, the existence of dark halo satellites that have no visible baryonic counterpart (Moore et al. 1999; Kylpin et al. 1999).

Lensing also offers a way to detect and study galaxy groups at high redshift. Modest galaxy overdensities (which are the most typical cosmic environment for any galaxy) are extremely difficult to detect using optical or X-ray techniques. About 20% of lens galaxies are expected to be in groups, which is consistent with the fraction of lens systems where external shear of 10-20% is required for a successful lens model (Keeton, Christlein & Zabludoff 2000). Thus, lens models can be used to identify groups at high redshift, which must then be identified with spectroscopy. Tidal shear acts as a lever arm in a lens model, and the total mass can be measured once the group centroid has been located. Joint analysis of lensing and kinematics gives the best information on the dark matter distribution in groups.

1.2.2 Galaxy Evolution

Lensing effectively identifies early type galaxies over the redshift range $0.2 < z < 1$. No other method can select galaxies by mass; other optical techniques contain strong selection effects based on luminosity, surface brightness, or star formation rate. Lensing gives such an accurate measure of the mass within the Einstein radius that the mass-to-light uncertainty is usually dominated by the optical surface photometry. Since the radial mass distributions of lenses are self-similar, the equation above shows that lensing probability is nearly proportional to the mass of the lens galaxy. Therefore, the lens galaxy properties at any redshift are equivalent to the mass-weighted properties of all galaxies at that redshift, and the evolution of lens galaxies is equivalent to the mass-weighted evolution of all galaxies.

Elliptical galaxies in rich clusters have remarkably uniform colors out to $z \sim 1$ (Kelson et al. 2000; Pahre, Djorgovski & De Carvalho 2001), and tight fit to the fundamental plane argues for passive evolution and an early formation epoch. Far less is known about the homogeneity and evolution of ellipticals in less dense environments, even though the great majority of early-type galaxies are found in such environments. It turns out that lens galaxies are remarkably homogeneous; they fit the fundamental plane with no more scatter than local calibrators. Colors plus the fits to the fundamental plane are also useful in providing photometric redshifts with an accuracy of Δz = 0.04. Suprisingly, lens galaxies show an identical evolution rate to rich cluster galaxies, and a formation redshift $z_f > 2$ (Kochanek et al. 2000). This is contrary to theoretical expectation or the results of semi-analytic models (Kauffmann & Charlot 1998).

An entirely different regime of galaxy evolution is opened up by study of the lensed quasar hosts. Lensing provides the only effective way to image quasar hosts at $z \sim 2$ because it distorts the light away from the central point source and improves the contrast by factors of 10-100. The luminosities and colors of quasar hosts in the range $1 < z < 3$ are like those of moderate luminosity, mid-type spirals (Impey et al. 2001). High redshift quasar hosts are less luminous, smaller, and bluer that the hosts of either radio-loud or radio-quiet quasars at low redshift (McClure et al. 1999). Direct imaging studies at $z \sim 2$ tend to find high luminosities for hosts (Kukula et al. 2001), but they focus on highly luminous quasars and they cannot reach as far down the host luminosity function as the more sensitive lensing technique. Lensed hosts point to a higher ratio of black hole to bulge mass at high redshift than is observed locally (Magorrian et al. 1998; Tremaine et al. 2002). This implies that the supermassive black holes have grown faster than the surrounding stellar systems. The study of lensed quasars hosts has only just begun — deeper observations will allow use of the full information that is mapped into the Einstein ring (Kochanek, Keeton & McLeod 2001).

1.2.3 Cosmological Tests

The Hubble constant is required to infer the distance, age, luminosity, and physical size of almost every object at significant redshift. The HST Key Project team measured $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} (Freedman et al. 2001). However, if we are to enter an era of "precision cosmology," we need an independent measurement of comparable accuracy. In particular, the microwave background anisotropy experiments determine $\Omega_m h^2$ and $\Omega_b h^2$, but require an independent estimate of the Hubble constant to determine the matter density or the baryon density. Local methods may now be limited by effects like blending, metallicity variations, and the possibility that we live in a large local underdensity (Wu et al. 1995).

It has long been known that lensing offers a direct method of measuring the distance scale and bypassing the local distance ladder (Refsdal 1964). If a lensed quasar varies, the time delay in the arrival time of the signal at the observer depends on the geometric path difference between the different rays and the gravitational retardation as the light travels through the lens potential. The second factor is proportional to H_0^{-1} and depends only weakly on the cosmological model. The measurement of H_0 requires precise astrometry of the images, a measurement of Δt, and an accurate model of the galaxy potential. After intensive observational campaigns, time delays have been measured for 9 systems, with typical uncertainties of 10-20%. The current limitation on estimates of H_0 is the uncertainty in modelling the mass distribution of the lens.

The quasar image geometry determines the total mass enclosed by the images and the ellipticity of the gravitational field. The time delay measurements then constrain a combination of the Hubble constant and the surface mass density of the lens, $H_0 \propto (1 - \langle\kappa\rangle)/\Delta t$, where $\langle\kappa\rangle$ is the average surface density in the annulus between the images used to measure the delay in units of the critical density for gravitational lensing. The Hubble constant rises as the lens galaxy becomes more compact (smaller $\langle\kappa\rangle$), and it falls as it becomes more extended (larger $\langle\kappa\rangle$). Models of other lenses, weak lensing measurements, local stellar dynamical studies and X-ray observations all give $\langle\kappa\rangle \simeq 0.5$, compared to $\langle\kappa\rangle \simeq 0.1$ to 0.2 in the absence of dark matter (a constant M/L model). A joint analysis of the 4 (currently) best time delay lenses yields $H_0 \simeq 50$ km s^{-1} Mpc^{-1}, assuming a standard (singular isothermal sphere) dark matter model (Kochanek 2002).

As an alternative to assuming standard mass models, Williams and Saha (2000) have modeled lenses pixel by pixel, with only broad and physically plausible constraints such as a monotonic light distribution. The method is checked by blind tests that explore parameter space, suggesting systematic errors $\leq 10\%$. A joint analysis of 6 time delays lenses gives $H_0 \simeq 50$ km^{-1} Mpc^{-1}. A better propsect would be to break the degeneracies in the mass models with information on the radial mass distribution. This has recently been done for one lens with a measured time delay by Treu & Koopmans (2002). They derive $H_0 = 59^{+12}_{-7}$ km s^{-1} Mpc^{-1}. It is intriguing that lensing join with the Sunyaev-Zeldovich effect in pointing to somewhat lower values of the Hubble constant than that derived by the HST Key Project. To accord with the Key Project, lens models would need constant M/L mass profiles, which would be in disagreement with the evidence of stellar kinematics in elliptical galaxies.

Lensing offers the opportunity to put a constraint on the most enigmatic and poorly defined parameter of the concordance model, the cosmological constant. This occurs because $\tau \propto D_{os}^3$, so the test is a volume test, and models with Λ have a larger volume (and larger dN/dz for the lensing population) out to a given redshift. The observational signatures of Λ reveal themselves as a large number of lenses in flux-limited surveys (Turner 1990) and in the relative distributions of lens and source redshifts (Kochanek 1992). It is important to have relatively complete lens redshift information, since selection effects can compromise the power of the test (Helbig & Kayser 1996). Early applications of the test showed its potential (Kochanek 1996; Quast & Helbig 1999; Chae et al. 2002).

Lens surveys do not yet have sufficient statistics and completeness on lens redshifts for a successful application of that aspect of the test. Meanwhile, Keeton (2002b) has pointed out that, in common with the classical galaxy count volume test, the lens count test is insensitive to Λ unless the density evolution of the lens population has been directly measured over the redshift range of interest. Upcoming redshift surveys will provide this critical information (Davis et al. 2002; Eisenstein et al. 2001). With more accurate models for an ensemble of lenses, additional cosmological tests are possible. All of the world model dependence is contained in the quantity $D_{ol}D_{os}/D_{ls}$, where D_{ol}, D_{os}, and D_{ls} are comoving distances between the observer, the lens, and the source. If measured with an accuracy of a few percent, these quantities are relatively insensitive to Ω_m, but they allow a direct measurement of q_0 (Lacroix & Schneider 1982) and in the case of an accelerating universe, they permit a measurement of w, the equation of state of the dark energy.

1.3 Absorption Lines

The narrow absorption lines in quasar spectra can be used to produce a map of intervening material along the line of sight. This field has benefited greatly from large new telescopes and efficient spectrographs, to the point where faint enough quasars (and therefore a high surface density) can be observed to set up a grid of absorption probes and attempt 3D "tomography" of the IGM. The opacity of the highly ionized hydrogen that give rise to the Lyman-α forest is given by

$$\tau \sim (1+z)^6 \, (\Omega_b h^2)^2 \, (T_{IGM})^{-0.7} \, (H(z)/H_0)^{-1} \, \Gamma_{HI}^{-1} \, \rho^{1.7}$$

where ρ is the mean gas density, Γ_{HI} is the photoionization rate, T_{IGM} is the temperature at the mean density, and the observable quantity is flux, given by $F = e^{-\tau}$. Over the past twenty-five years, the Lyman-α forest has grown steadily in importance as a cosmological tool (Sargent et al. 1980; Rauch 1998), providing a key test of the gravitational instability paradigm for the formation of large scale structure. In addition to the low column density (but highly ionized) HI that traces the IGM, quasar spectra also show high column density HI absorbers that trace cold gas inside galaxies, low ionization metal lines that trace the enriched halos of galaxies and high ionization metal lines that trace the warm-hot IGM (Blades, Turnshek & Norman 1987; Petitjean & Charlot 1997; Rosenberg & Putman 2002).

1.3.1 Probing Dark Matter

The column density distribution of HI follows a power law over nine decades (Tytler 1987). The low column density gas with $n_{HI} = 10^{12-16}$ cm^{-2} causes a "fluctuating Gunn-Peterson effect" due to the continuously varying opacity of the IGM (Gunn & Peterson 1965), while the higher column density Lyman limit (10^{17-19} cm^{-2}) and damped Lyman-α absorbers (10^{20-22} cm^{-2}) represent condensed cold gas in galaxies (Bahcall & Salpeter 1965). The Lyman-α absorbers arise from highly ionized gas that traces dark matter potentials of mildly non-linear structures. Even though the gas is out of thermal equilibrium, the basic physics is described fairly accurately the approximation in the equation above.

Supercomputer simulations that incorporate gas dynamics can reproduce the basic features of the Lyman-α forest, which becomes important support for the standard picture of heirarchical structure formation (Cen et al. 1994; Hernquist et al. 1996). The diffuse Lyman-α gas contains 80-90% of all baryons at $z \geq 2$, in a "cosmic web" of relatively low overdensity gas, $\delta\rho/\rho \sim$ 10-30. By $z = 0$, much of that gas has fallen into galaxy potentials and filaments or has been shocked into the warm-hot medium (Davé et al. 1999). The equation of state yields a relationship between temperature and density, $T \propto \rho^{0.5}$. This characterization has allowed the Lyman-α forest to be used as a powerful cosmological tool, to measure Ω_b, the mass power spectrum on scales of 1-10 h^{-1} Mpc at $z = 3$, and the equation of state of the IGM (Rauch et al. 1997; Croft et al. 1998; Hui & Gnedin 1997).

The mass power spectrum is a particularly important quantity to derive from observations of the Lyman-α forest, because it accesses a regime of redshift and length scale not available by other means: redshifts $2 < z < 4$ and scales of 100 kpc (limited by the effect of thermal gas motion) to 20 Mpc (limited by cosmic and continuum variations). Combined 1D sightlines now yield accurate measures of the slope and amplitude of the power spectrum (Croft et al. 2002), and the precision will reach a ~ 1 percent when the full SDSS data on the Lyman-α forest has been analyzed (Hui et al. 2001). These techniques, which use continuous flux statistics rather than line-counting, can readily be extended to multiple sightlines and flux cross-correlations to recover the 3D dark matter power spectrum (Pichon et al. 2001; Viel et al. 2002).

1.3.2 Large-Scale Structure

The metal line doublets of C IV and Mg II commonly seen in the spectra of quasars are known to be tracers of the halos of massive galaxies (e.g. Blades, Turnshek, & Norman

1987). By extension, absorbers can potentially trace the large scale structure of the universe on scales up to 50-100 h_{100}^{-1} Mpc at high redshift, revealing superclusters and voids that would be hard to detect in any other way. Absorbers complement galaxy surveys in the following way: quasars provide continguous 1D sightlines $\sim$ 1 Gpc long and the absorption doublets are easy to identify, while galaxies provide 3D clustering information and the galaxies are challenging to locate at high redshift. The statistics of individual quasar/galaxy associations have already been used to address the important issue of the relative bias of absorbers and bright galaxies (Steidel, Dickinson & Persson 1994).

Superclustering of metal lines is routinely seen in absorber studies of many widely-separated sightlines (Quashnock & vanden Berk 1998) and in various individual studies. The great advantage of studying close groups of quasars is that the combination of absorber-absorber associations along the line of sight and across lines of sight greatly strengthens the clustering signal (Crotts, Burles & Tytler 1997; Loh, Quashnock & Stein 2001). With N_l lines of sight and an average of N_a absorbers per line of sight, the statistical power of the combination of widely separated sightlines, in terms of the sensitivity to correlation power, goes as $\sigma\{\xi(v)\} \propto N_a(N_a-1)N_l/2$. By contrast, with a dense grid of absorber probes, where the gain comes both from absorber and sightline multiplicity, the statistical power of such a 3D clustering measurement goes as $\sigma\{\xi(r)\} \propto N_l(N_l-1)N_a/2$. The large scales afforded by the absorber clustering measurements give sensitivity to a number of imprints of the early universe (Roukema, Mamon & Bajtlik 2002).

1.3.3 Cosmological Tests

Some prominent cosmologists have argued that cosmology is "solved." (e.g. Turner 2001). The Hubble constant has been reliably measured, there is rough concordance on $\Omega_{\rm m}$ from several techniques, and the acceleration inferred from observations of distant supernovae indicate that vacuum energy supplies the missing ingredient needed to explain the flat space observed using the microwave background (Peebles 1999). We should recall the phenomenal effort that it took to get the error on H_0 down to 10%, at which level there are still worrying systematic errors. None of the other cosmoligical parameters are yet determined with comparable precision.

The only direct evidence for acceleration (and the implied vacuum energy that presumably causes it) is an uncorroborated technique using supernovae as standard candles. In addition, most of the baryons predicted by the hot big bang have not been observed (Cen & Ostiker 1999), and CDM models cannot explain the flat cores or angular momentum of galaxies (Navarro & Steinmetz 2000). Moreover, we have no physical theory that predicts the microscopic basis of the two dominant components of the universe: dark matter and dark energy. Perhaps there is still something useful to do in cosmology after all.

A fundamental method to measure the cosmological metric is to observe the angular size and extent in redshift of any set of objects which are spherically symmetric on average. The function $f(z) = c^{-1}H(z)D_A(z)$ brings in the world model through its dependence on the Hubble parameter and the angular diameter distance. Alcock & Paczynski (1979) showed that this measurement at high redshift is sensitive to the cosmological constant. In key distinction with the supernova method, the test makes no assumption of standard candles or rods and it is therefore independent of evolutionary effects. The major contaminating signal is due to peculiar velocity distortion of the redshift correlation function in redshift space. Nevertheless, simulations show that with several dozen quasar pairs at separations of a couple of arcminutes, it should be possible to make this critical cross-check for Λ (McDonald & Miralda-Escude 1999; Lin & Norman 2004).

Acknowledgements. It is pleasure to acknowledge many insightful conversations with Chris Kochanek and Chick Keeton on the subject of gavitational lensing, and my other colleagues on the CASTLES project. I also gratefuly recognize my long-time collaborators on the subject of quasar absorption lines, Craig Foltz and Cathy Petry.

References

Alcock, C., & Paczynski, B. 1979, Nature, 281, 358
Bahcall, J. N., & Salpeter, E. E. 1965, ApJ, 142, 1677
Blades, J. C., Turnshek, D., & Norman, C. A. 1987, ed., QSO Absorption Lines, STScI Symposium Series No. 2 (Cambridge: Cambridge Univ. Press)
Blandford, R. D., & Narayan, R. 1992, ARA&A, 30, 311
Brainerd, T. G., & Kochanek, C. S. 2001, ed., Gravitational Lensing: Recent Progress and Future Goals (San Francisco: ASP)
Cen, R., Miralda-Escude, J, Ostriker, J. P., & Rauch, M. 1994, ApJ, 437, L59
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Chae, K.-H., et al. 2002, Phys. Rev. Lett., 89, 1301
Croft, R. A. C., et al. 2002, ApJ, 581, 20
Croft, R. A. C., Weinberg, D. H., Katz, N., & Hernquist, L. 1998, ApJ, 495, 44
Crotts, A. C. S., Burles, S., & Tytler, D. 1997, ApJ, 489, L7
Dalal, N., & Kochanek, C. S. 2002, ApJ, 572, 25
Davé, R., Hernquist, L., Katz, N., & Weinberg, D. H. 1999, ApJ, 511, 521
Davis, M., Newman, J. A., Faber, S. M., & Phillips, A. C. 2001, in Deep Fields, ed. S. Cristiani et al. (Berlin: Springer), 241
de Blok, W. J. G., McGaugh, S. S., & Rubin, V. C. 2001, AJ, 122, 2396
Eisenstein, D. L., et al. 2001, AJ, 122, 2267
Freedman, W. L., et al. 2001, ApJ, 553, 47
Gunn, J. E., & Peterson, B. A. 1965, ApJ, 142, 1633
Helbig, P., & Kayser, R. 1996, A&A, 308, 359
Hernquist, Katz, N., Weinberg, D. H., & Miralda-Escude, J. 1996, ApJ, 457, L5
Hui, L., Burles, S., Seljak, U., Rutledge, R. E., Magnier, E., & Tytler, D. 2001, ApJ, 552, 15
Hui, L., & Gnedin, N. 1997, MNRAS, 292, 27
Impey, C. D., et al. 2001, in QSO Hosts and Their Environments, ed. I. Marquez et al. (Dordrecht: Kluwer), 313
Kauffmann, G., & Charlot, S. 1998, MNRAS, 294, 705
Keeton, C. R. 2002a, ApJ, 561, 46
——. 2002b, ApJ, 575, L1
Keeton, C. R., Christlein, D., & Zabludoff, A. I. 2000, ApJ, 545, 129
Kelson, D. D., Illingworth, G. .D., van Dokkum, P. G., & Franx, M. 2000, ApJ, 531, 184
Klypin, A., Kravtsov, A. V., Venezuela, O., & Prada, F. 1999, ApJ, 522, 82
Kochanek, C. S. 1992, ApJ, 384, 1
——. 1993, ApJ, 417, 438
——. 1996, ApJ, 466, 638
——. 2001, in The Shapes of Galaxies and Their Dark Matter Halos, ed. P. Natarajan (Singapore: World Scientific), 62
——. 2002, ApJ, 578, 25
Kochanek, C. S., et al. 2000, ApJ, 543, 131
Kochanek, C. S., Keeton, C. R., & McLeod, B. A. 2001, ApJ, 547, 50
Kukula, M. J., et al. 2001, MNRAS, 326, 1533
Lacroix, G., Schneider, J. 1982, A&A, 115, 54
Lin, W.-C., & Norman, M. L. 2004, ApJ, in press
Loh, J.-M., Quashnock, J. M., & Stein, M. L. 2001, ApJ, 560, 606
Magorrian, J., et al. 1998, AJ, 115, 2285
Mao, S., & Schneider, P. 1998, MNRAS, 295, 587

McClure, R. J., et al. 1999, MNRAS, 308, 377
McDonald, P., & Miralda-Escude, J. 1999, ApJ, 518, 24
Moore, B., Governato, F., Quinn, T., Stadel, J., & Lake, G. 1998, ApJ, 499, L5
Moore, B., Quinn, T., Governato, F., Stadel, J., & Lake, G. 1999, MNRAS, 310, 1147
Moustakas, L. A., & Metcalf, R. B. 2003, MNRAS, 339, 607
Munoz, J. A., Kochanek, C. S., & Keeton, C. R. 2001, ApJ, 558, 657
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Navarro, J. & Steinmetz, M. 2000, ApJ, 528, 607
Norbury, M. A., Rusin, D., Jackson, N. J., & Browne, I. W. A. 2004, MNRAS, in press
Pahre, M. A., Djorgovski, S. G., & De Carvalho, G. G. 2001, A&AS, 276, 983
Peebles, P. J. E. 1999, PASP, 111, 274
Petitjean, P., & Charlot, S. 1997, ed., Structure and Evolution of the Intergalactic Medium from QSO Absorption Line Systems (Paris: Editions Frontiéres)
Pichon, C., Vergely, J. L., Rollinde, E., Colombi, S., & Petitjean, P. 2001, MNRAS, 326, 597
Quashnock, J. M., & vanden Berk, D. E. 1998, ApJ, 500, 28
Quast, R., & Helbig, P. 1999, A&A, 344, 721
Rauch, M., et al. 1997, ApJ, 489, 7
Rauch, M. 1998, ARA&A, 36, 267
Refsdal, S. 1964, MNRAS, 128, 307
Rosenberg, J., & Putman, M. 2002, ed., The IGM-Galaxy Connection: The Distribution of Baryons at $z = 0$ (Dordrecht: Kluwer)
Roukema, B. F., Mamon, G. A., & Bajtlik, S. 2002, A&A, 382, 397
Rusin, D., & Ma, C.-P. 2001, ApJ, 549, L33
Sargent, W. L. L., Young, P. J., Boksenberg, A., & Tytler, D. 1980, ApJS, 42, 41
Schechter, P. L., & Wambsganss, J. 2002, ApJ, 580, 685
Schneider, P., Ehlers, J., & Falco, E. E. 1992, ed., Gravitational Lenses (Berlin: Springer-Verlag)
Steidel, C. C., Dickinson, M., & Persson, S. E. 1994, AJ, 108, 2046
Tremaine, S., et al. 2002, ApJ, 574, 740
Treu, T., & Koopmans, L. .V. E. 2002, MNRAS, 337, L6
Turner, E. L. 1990, ApJ, 365, L43
Turner, M. L. 2001, Physica Scripta, T85, 210
Tytler, D. 1987, ApJ, 321, 49
van den Bosch, F. C., & Swaters, R. A. 2001, MNRAS, 325, 1017
Viel, M., Matarrese, S., Mo, H. J., Haehnelt, M. G., & Theuns, T. 2002, MNRAS, 329, 848
Weinberg, M. D., & Katz, N. 2002, ApJ, 580, 627
Williams, L. L. R., & Saha, P. 2000, AJ, 119, 439
Wu, X.-P., Deng, Z., Zou, Z., Fang, L.-Z., & Qin, B. 1995, ApJ, 448, L65