New Cosmological Data and the Values of the Fundamental Parameters
IAU Symposium, Vol. 201, 2005
Anthony Lasenby and Althea Wilkinson, eds.

Galaxy–Galaxy Lensing: Status & Applications

Tereasa G. Brainerd

Boston University, Department of Astronomy, 725 Commonwealth Avenue, Boston, MA 02215, USA

Abstract.
There are now 10 independent observational investigations which have detected systematic weak gravitational lensing of background field galaxies by foreground field galaxies. This effect, known as galaxy–galaxy lensing, results in a very slight (of order 1%) distortion to the intrinsic image shapes of the lensed galaxies. Although small, the galaxy–galaxy lensing signal is coherent about the lens centers and is, therefore, detectable in large data sets via an ensemble average over many candidate pairs of lenses and sources. Here I summarize the results of the recent detections of galaxy–galaxy lensing and discuss some applications that are likely to be implemented in the very near future.

1. Introduction

According to General Relativity, any massive object along the line sight to a distant luminous source will act as a gravitational lens and will, therefore, deflect light rays emanating from the source. The most visually striking instances of gravitational lensing are of course the giant arcs, rings, and multiple images which are produced by "strong" lensing. Strong lensing is a relatively rare phenomenon, however, because it occurs only when the source and the lens are almost exactly aligned along the observer's line of sight. By contrast, "weak" lensing is a relatively common phenomenon which has become routinely detectable in high–quality imaging data. Unlike strong lensing, which greatly distorts the images of extended sources, weak lensing induces a level of distortion in the images which is so small that it cannot be detected conclusively from the distorted shape of just one image. Instead, it is detected in a statistical sense from a local average over the images of many mildly–distorted sources. Weak lensing results in a net tangential alignment in the images of the lensed galaxies and, hence, it is detectable through the coherence of the distortion pattern about the center of the lens potential. The best–known and least controversial detections of weak lensing come from deep imaging of massive clusters (see, e.g., the review by Mellier 1999), which have allowed the distribution of the dark matter in lensing clusters to be mapped directly.

If, however, the dark matter halos of individual galaxies are as massive as suggested by standard dynamical or hydrodynamical arguments, they ought to act as extremely weak yet nevertheless *detectable* gravitational lenses. That is, systematically throughout the universe, individual foreground galaxies should act as weak lenses for individual background galaxies. If one could detect this effect it would be extremely useful because it would provide a probe of the

https://doi.org/10.1017/S0074180900216367 Published online by Cambridge University Press

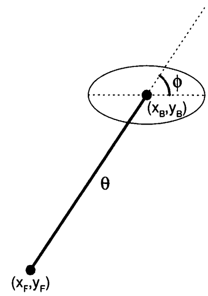

Figure 1. Orientation of a background "source" galaxy relative to a foreground "lens" galaxy.

gravitational potentials of the halos of the lens galaxies up to very large physical radii (on the order of $100h^{-1}$ kpc or so) where dynamical and hydrodynamical tracers of the potential are unlikely to be found. The advantage of using weak lensing to probe dark matter halos is, therefore, that the method can be applied to all galaxies without the need for a traditional tracer of the potential to be physically present at large galactic radius. The disadvantage, however, is that the weak lensing signal is so small that it cannot be detected convincingly for any one particular lens galaxy halo. That is, systematic galaxy–galaxy lensing only allows the study of the mean properties of the halo population *as a whole.*

Consider a large sample of galaxies which has been separated into a "foreground" and "background" population. For foreground–background pairs that are relatively nearby to each other on the sky ($\theta \lesssim 100''$), the presence or absence of systematic lensing of the background population by the foreground population can be tested with the following very simple–minded experiment. For each background galaxy, the orientation of its equivalent image ellipse can be computed relative to the direction vector that connects its centroid to that of a foreground, and possible lens, galaxy (see Fig. 1). Using all pairs of candidate lenses and sources, then, the probability distribution of the orientation of the background galaxies with respect to the foreground galaxies, $P(\phi)$, can be computed. In the absence of systematic lensing of the background population by the foreground population $P(\phi)$ will be consistent with a uniform distribution. However, if the background galaxies have been systematically lensed, there will be a very slight excess of pairs of galaxies in which the background galaxy is oriented tangentially and a correspondingly slight deficit of pairs of galaxies in which the background galaxy is oriented radially. Specifically, we expect

$$P(\phi) = \frac{2}{\pi}\left[1 - 2\langle\gamma\rangle\left\langle\epsilon^{-1}\right\rangle\cos 2\phi\right] \qquad (1)$$

where $\langle\gamma\rangle$ is the mean "shear" induced by gravitational lensing and $\langle\epsilon^{-1}\rangle$ is the harmonic mean of the (intrinsic) ellipticities of the lensed galaxies (see, e.g., Brainerd, Blandford & Smail 1996).

If the halos of the lens galaxies may be reasonably approximated as singular isothermal spheres, the shear averaged over angular scales θ_1 to θ_2 is:

$$\langle\gamma\rangle = 4\pi\left(\frac{\sigma_v}{c}\right)^2\left[\frac{D_{ls}}{D_s}\right](\theta_1+\theta_2)^{-1} \qquad (2)$$

https://doi.org/10.1017/S0074180900216367 Published online by Cambridge University Press

where σ_v is the velocity dispersion of the halo, c is the velocity of light, D_{ls} is the angular diameter distance between the lens and the source, and D_s is the angular diameter distance between the observer and the source. If the lens galaxy is a typical spiral at redshift $z_l \sim 0.5$ with $\sigma_v = 155$ km/s, then for source redshifts $z_s \sim 1$ we expect $\langle\gamma\rangle \simeq 0.007$ for $10'' \lesssim \theta \lesssim 30''$. This is not a level of shear that can be convincingly detected for any one particular lens galaxy, but in the limit of high–quality imaging data, an ensemble average over many thousands of candidate lens–source pairs should yield a statistically–significant detection of systematic galaxy–galaxy lensing.

2. Detections of Galaxy–Galaxy Lensing

The first published attempt to detect systematic galaxy–galaxy lensing was that of Tyson et al. (1984). Despite a vast amount of data ($\sim 28,000$ foreground–background pairs), their result was consistent with a null detection on angular scales $\gtrsim 5''$. The first statistically–significant detection of galaxy–galaxy lensing to be published in the refereed literature was the work done by Brainerd, Blandford & Smail (1996), hereafter BBS, who used deep imaging data from a single CCD field (~ 72 sq. arcmin.) to investigate the orientation of 511 faint "background" galaxies relative to 439 brighter "foreground" galaxies. BBS claimed a formal 4-σ detection of galaxy–galaxy lensing on angular scales of $5'' \lesssim \theta \lesssim 35''$ and used their signal to place limits on the characteristic parameters of the dark matter halos of L^* field galaxies.

Since BBS, there have been 9 additional independent detections of galaxy–galaxy lensing by field galaxies (Dell'Antonio & Tyson 1996; Griffiths et al. 1996; Hudson et al. 1998; Ebbels 1998; Fischer et al. 2000; Hoekstra 2000; Jaunsen 2000; Smith et al. 2000; Wilson et al. 2000). The data and its analysis vary considerably amongst these investigations, but their results are all broadly consistent with one another and with BBS. So far, the most statistically significant measurement of galaxy–galaxy lensing is that of Fischer et al. (2000), who obtained a 6-σ detection of the mean tangential shear around candidate "lens" galaxies in the Sloan Digital Sky Survey (SDSS) commissioning data. It is this result in particular that has made the study of galaxy–galaxy lensing much less controversial than it was even a year ago since it has demonstrated conclusively that even in the limit of somewhat poor imaging quality (including the presence of a mildly anisotropic point spread function), galaxy–galaxy lensing can be detected with very high significance in deep, wide-field imaging surveys.

Given the diversity of the data used in the above investigations, it is difficult to compare all of the results directly. The imaging quality varies significantly and the categorization of the galaxies into "lenses" and "sources" is by no means consistent amongst the investigations. The latter is largely due to the fact that up until very recently, all of the galaxy–galaxy lensing detections were obtained with data that was *not* specifically acquired for the purposes of studying galaxy–galaxy lensing. Rather, the data are a broad heterogeneous mix of deep images that were oftentimes acquired for other purposes. Where possible, "lenses" were distinguished from "sources" on the basis of photometric redshifts, but many of the above investigations were limited to imaging in a single bandpass and, hence, only a very crude lens–source separation based upon apparent magnitude was performed. Only the Smith et al. (2000) result is truly "calibrated" in that all of the lens galaxies have spectroscopic redshifts. Despite the substantial variety in both the data and the analysis techniques, there is nevertheless remarkable agreement amongst these studies. All have inferred "reasonable" velocity dispersions for the halos of L^* galaxies (in the range of 140 km/s to 190 km/s) and all but one have been unable to place a direct constraint on the *maximum* radial extent of the halos of L^* field galaxies. The exception to this is Hoekstra's result which gives a 1-σ upper bound of order $600h^{-1}$ kpc and a 2-σ upper bound of order $1h^{-1}$ Mpc for the radius of the halos of L^* field galaxies.

In combination, these studies have helped to make the study of galaxy–galaxy lensing a respectable endeavour, which was certainly not the case five years ago! They have established that even in the presence of a realistic level of noise, systematic errors can be overcome and not only can galaxy–galaxy lensing be detected, it can be used as a direct probe of the halos of the lens galaxies. This is a field that is sure to see a tremendous amount of growth in the future and its success will depend critically on the acquisition of very large data sets (i.e., in order to reduce the "noise" due to the intrinsic shapes of the background galaxies), the quality of the imaging data (i.e., in order to obtain accurate image shapes), and the ability to discriminate background galaxies from foreground galaxies (i.e., separating candidate lenses and sources).

3. Applications of Galaxy–Galaxy Lensing

Galaxy–galaxy lensing is expected to become a particularly useful method by which particular aspects of the history of galaxy formation can be studied directly, and it should be able to address some fundamental questions about galaxy formation which, for the most part, cannot be addressed particularly well with other techniques. Some of the major issues for which galaxy–galaxy lensing promises to provide especially useful statistical constraints are: [1] the degree to which dark matter halos are truncated during the infall of galaxies into clusters, [2] the typical parameters associated with the dark matter halos of field galaxies, including any systematic deviations from spherical symmetry (i.e., flattened halos), [3] the evolution of the total mass–to–light ratio of galaxies, both in the field and in clusters, [4] the morphological dependence of the halo potential (i.e., early– versus late–type galaxies), [5] the scaling of mass with luminosity (i.e., $M \propto L^\alpha$) and any strong evolution of the Tully–Fisher and Faber–Jackson relations with redshift, [6] the "bias" of light versus mass in the universe via the galaxy–mass correlation function, and [7] the shape of the redshift distribution of distant faint galaxies whose redshifts fall between $z \sim 1$ and $z \sim 3$. Observational and theoretical investigations into the use of galaxy–galaxy lensing to address all of these issues have already begun and, although some constraints have been obtained in the above investigations, the constraints are not especially strong at present. However, the preliminary results are more than sufficiently interesting to justify significantly more work and below I briefly summarize a few of the current investigations.

3.1. Galaxy–Galaxy Lensing through Clusters

Natarajan et al. (1998) and Geiger & Schneider (1999) have studied the systematic weak lensing of background galaxies by the individual galaxies within lensing clusters. That is, they have searched for instances of galaxy–galaxy lensing in which the lens galaxies are embedded within a larger cluster potential. Although it may seem extremely challenging to detect the galaxy–galaxy lensing signal due to the apparently "complicating" presence of the larger cluster potential, it is in fact not considerably more difficult than detecting galaxy–galaxy lensing in the field. This is in part due to the fact that on the angular scales over which galaxy–galaxy lensing is detected (a few arcseconds or so), the cluster potential changes very slowly and, so, weak lensing by the cluster does not swamp the galaxy–galaxy lensing signal. In addition, since lensing conserves surface brightness and since cluster lenses magnify the images of distant galaxies somewhat, it is possible to use sources that are more distant than one would otherwise be able to use in the statistical analysis. The primary motivation for this work is, of course, to determine whether or not the dark matter halos of cluster galaxies have been truncated significantly compared to those of field galaxies, and the preliminary results from some of the current investigations seem very promising. In particular, Natarajan et al. have extended their initial work to include a set of clusters that span a wide range of redshifts and they find that not only are the dark matter halos of cluster galaxies truncated compared to those of field galaxies, the proper length of the truncation radius increases with the redshift of the cluster and the total mass–to–light ratio of the cluster galaxies also increases with the redshift of the cluster.

3.2. Flattened Dark Matter Halos

One of the especially interesting future prospects for galaxy–galaxy lensing is a measurement of the projected shapes of dark matter halos. Popular models of structure formation that are based on collisionless dark matter generically give rise to galaxy halos which are not spherically symmetric but are, instead, triaxial with a mean projected ellipticity of order 0.3 (e.g., Dubinski & Carlberg, 1991; Warren et al. 1992). Additionally, there is diverse observational evidence which suggests that halos may be substantially flattened (see, e.g., the comprehensive review by Sackett 1999 and references therein); however, there are only relatively few galaxies for which the shape of the halo can be determined via traditional dynamical or hydrodynamical techniques and it is likely that galaxy–galaxy lensing will be the only method which will be able to provide strong constraints on the mean flattening of the halo population *as a whole*.

Consider a polar coordinate system which is centered on the center of mass of a foreground lens galaxy and which is specified by a radial distance, r, and a polar angle, φ. If the dark matter halo of the lens galaxy is elliptical, the galaxy–galaxy lensing signal will be anisotropic about the lens center in the sense that at a fixed radial distance, r, from the lens, sources whose polar angles, φ, place them closest to the major axis of the mass distribution of the halo will experience *greater* shear than those sources whose polar angles place them closest to the minor axis of the mass distribution of the halo. Recently, both Natarajan & Refregier (2000) and Brainerd & Wright (2000) have concluded that such "anisotropic" galaxy–galaxy lensing should be detectable in deep, wide–field

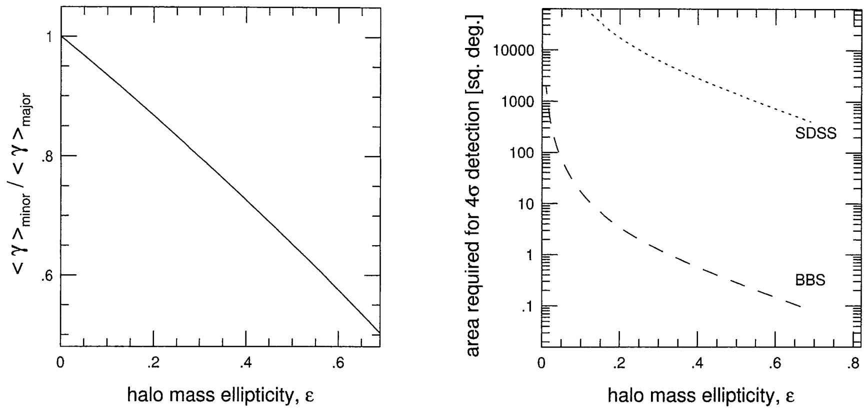

Figure 2. Left panel: ratio of the mean shear experienced by sources within $\pm 45°$ of the minor axis of an elliptical halo to that experienced by sources within $\pm 45°$ of the major axis. Right panel: Area of survey that would be needed by the original SDSS and BBS data in order to obtain a 4-σ detection of anisotropic galaxy–galaxy lensing. Note that this is a pessimistic prediction which assumes that the signal–to–noise in the final SDSS data will not be significantly improved compared to the commissioning data.

imaging surveys and should provide strong constraints on the mean projected ellipticity of dark matter halos.

To estimate the size of a survey that would be needed to detect anisotropic galaxy–galaxy lensing, consider a singular isothermal ellipsoid lens, for which the convergence is: $\kappa(r,\varphi) = \sqrt{f}/2r\Delta(\varphi)$ (e.g., Kormann et al. 1994), where $\Delta(\varphi) = \sqrt{\cos^2\varphi + f^2 \sin^2\varphi}$ and $f = b/a$ is the axis ratio of the mass distribution $(0 < f \le 1)$. If we define $\langle\gamma\rangle_{\rm major}$ to be the mean shear experienced by sources whose polar angle, φ, places them within $\pm 45°$ of the *major* axis of the lens, and $\langle\gamma\rangle_{\rm minor}$ to be the mean shear experienced by sources whose polar angle, φ, places them within $\pm 45°$ of the *minor* axis of the lens, it can be shown that

$$\frac{\langle\gamma\rangle_{\rm minor}}{\langle\gamma\rangle_{\rm major}} = \frac{\left\langle \frac{1}{\Delta(\varphi)} \right\rangle_{\rm minor}}{\left\langle \frac{1}{\Delta(\varphi)} \right\rangle_{\rm major}}. \tag{3}$$

The ratio $\langle\gamma\rangle_{\rm minor} / \langle\gamma\rangle_{\rm major}$ is plotted in the left panel of Fig. 2 for lens mass ellipticities in the range 0 to 0.7 (i.e., values of f in the range 1 to 0.3). For "reasonable" halo mass ellipticities (i.e., $\epsilon \sim 0.3$) the shear ratio is considerably smaller than a factor of 2 but, nevertheless, even such a relatively small anisotropy should be measurable with an appropriate data set.

If we define an anisotropy parameter to be $A = 1 - \left[\langle\gamma\rangle_{\rm minor} / \langle\gamma\rangle_{\rm major}\right]$ then it is straightforward to show that in order to obtain an $M\sigma$ detection of the anisotropy, the signal-to-noise in the measurements of $\langle\gamma\rangle_{\rm major}$ and $\langle\gamma\rangle_{\rm minor}$

would each need to be of order

$$\frac{\sqrt{2}M\,\langle\gamma\rangle_{\rm minor}}{\langle\gamma\rangle_{\rm major}-\langle\gamma\rangle_{\rm minor}}. \tag{4}$$

Additionally, all else being equal (i.e., the depth, seeing, and noise properties of the imaging data), the signal–to–noise in a detection of galaxy–galaxy lensing scales as the square root of the area of the data set (e.g., BBS; Natarajan & Refregier 2000). That is, if two data sets have identical imaging characteristics but differ by a factor of 2 in the area of sky that is covered, the larger survey will yield a signal–to–noise in a detection of galaxy–galaxy lensing that is a factor of $\sqrt{2}$ larger than would be yielded by the smaller survey.

Knowing the above, we can then ask the following question. How large an area would the previous investigations have had to have covered in order to detect anisotropic galaxy–galaxy lensing? As an illustrative example, the right panel of Fig. 2 shows the area of sky that would have been needed by BBS and by SDSS in order to obtain a 4-σ detection of anisotropic galaxy–galaxy lensing in their data. Note that here I have assumed that the signal–to–noise in the final SDSS data will not be significantly better than in the commissioning data used by Fischer et al. (2000). This, of course, should not be the case since it is certainly hoped that the imaging quality will be greatly improved and the separation of lenses and sources will be based upon spectroscopic redshifts (rather than apparent magnitudes as in the Fischer et al. analysis).

It is clear from Fig. 2 that even without an improvement in signal–to–noise SDSS should be able to detect anisotropic galaxy–galaxy lensing at a statistically–significant level, provided the halos are at least as flat as the theoretically expected value of $\epsilon \sim 0.3$. However, it is not merely the extremely wide area of the SDSS that will allow a detection of this effect. The SDSS is a relatively shallow survey and a survey that covers a much smaller area of sky but is significantly deeper is a complementary approach to the problem. In particular, the BBS data were two magnitudes deeper than the SDSS data and Fig. 2 suggests that if the mean halo ellipticity is of order 0.3, only a square degree or so of imaging data with quality similar to BBS would be needed to detect the effects of halo flattening on the galaxy–galaxy lensing signal.

3.3. Bias and the Galaxy–Mass Correlation Function

The initial investigations into galaxy–galaxy lensing were largely motivated by the prospect of constraining the amount and extent of dark matter that is associated with the individual halos of the lens galaxies. However, galaxy–galaxy lensing should be able to provide direct constraints on the distribution of dark matter throughout the universe as a whole. In particular, it has long been suspected that the clustering of galaxies (i.e., the light in the universe) is biased relative to that of the underlying mass distribution such that the autocorrelation functions of the galaxies and the mass are related through $\xi_{gg}(r) = b^2(r)\xi_{mm}(r)$, where ξ_{gg} is the galaxy autocorrelation function, ξ_{mm} is the autocorrelation function of the mass, and b is a "bias factor" which may be scale-dependent in general (e.g., Kaiser 1987). Weak lensing of the galaxy population provides a direct measurement of this bias (e.g., Kaiser 1992) since the variation of the tangential shear with angular separation is, in effect, a cross-correlation between

https://doi.org/10.1017/S0074180900216367 Published online by Cambridge University Press

the galaxies and the mass distribution of the universe. In particular, since the galaxy autocorrelation function is well-fit by a power law (e.g., Loveday et al. 1995), and the variation of the tangential shear from galaxy–galaxy lensing is also well-fit by a power law, $\gamma(\theta) \propto \theta^{-\eta}$, (see, e.g., Fischer et al. 2000), the galaxy–mass correlation function will also be a power law: $\xi_{gm}(r) = (r_{gm}/r)^{\nu}$, where $\nu = \eta + 1$. Combining the Limber's equation for $\gamma(\theta)$ (e.g., Kaiser 1992) and the observed power-law dependence of the galaxy autocorrelation function (e.g., Loveday et al. 1995) yields a measurement of r_{gm}, the correlation length of the galaxy–mass cross–correlation function. To date, the only published attempt to constrain the bias using galaxy–galaxy lensing is the work by Fischer et al. (2000), who found the correlation length of the galaxy–mass correlation function to be $r_{gm} \sim 3h^{-1}\Omega_{m0}^{-0.57}$ Mpc. Given the fundamental importance of such measurements and the fact that weak lensing provides a measurement of the bias which is completely independent of other measurements (such as peculiar velocity fields), this is an application of galaxy–galaxy lensing that is sure to be exploited in the very near future.

3.4. $N(z)$ for Distant Galaxies

Much of the motivation for pursuing investigations of galaxy–galaxy lensing has been to learn about the lenses, but it is equally interesting to use galaxy–galaxy lensing to learn about the *sources*. In particular, weak lensing of the faint galaxy population can yield strong statistical constraints on the shape of the redshift distribution of galaxies which are sufficiently distant that optical spectroscopy is unlikely (i.e., due to both their faintness and their unfortunate redshifts which result in a paucity of spectral features in the optical). Weak lensing by massive clusters has been used to place some statistical constraints on $N(z)$ for galaxies beyond $z \sim 1$ (e.g., Kneib et al. 1996) but it may be that weak lensing by galaxies could provide even stronger constraints simply because the number of sources is potentially so much larger than would be seen through a cluster lens.

Consider the region of the Hubble Deep Field (North) which has been the subject of deep redshift survey by Cohen et al. (2000). In addition to the spectroscopy of $\sim$ 600 galaxies, Cohen et al. have also obtained extensive multi–colour photometry and, hence, both the distances and restframe blue luminosities of these galaxies are effectively "known". By a simple scaling of the halo velocity dispersions with intrinsic luminosity (i.e., a Faber–Jackson relationship), it is possible to predict the shear field that these galaxies would produce. Shown in Fig. 3 is the result obtained for a politically–correct cosmology in which the halos of L^* galaxies are assumed to have velocity dispersions of 155 km/s and truncation radii of 50 kpc. These predictions are based upon the simple assumption that all source galaxies lie in a single plane in redshift and the plane has been varied from $z_s = 0.5$ to $z_s = 2.0$. Fig. 3 simply shows the increasing complexity of the shear field as the redshift of the sources is varied. However, using a maximum likelihood technique it will be possible to constrain the shape of the redshift distribution of the faint galaxies in the HDF by determining the most probable redshift for each galaxy, given its observed shape parameters and the lensing properties of the galaxies with known redshifts.

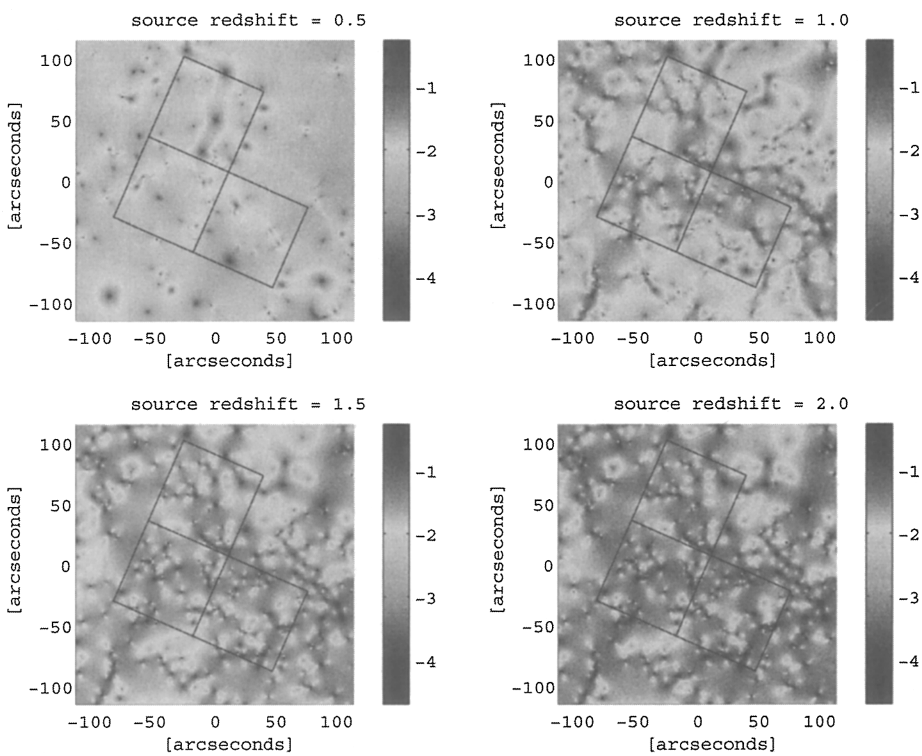

Figure 3. Theoretical shear field in the region of the Hubble Deep Field (North). The colour map shows the logarithm of the shear. The lenses are the galaxies in the HDF and flanking fields for which redshifts are publicly–available and in each of the panels the sources are assumed to lie in a plane of redshift z_s, where z_s ranges from 0.5 to 2.0. A cosmology with parameters $H_0 = 65$ km/s/Mpc, $\Omega_0 = 0.3$ and $\Omega_{\Lambda 0} = 0.7$ has been adopted.

https://doi.org/10.1017/S0074180900216367 Published online by Cambridge University Press

4. Conclusions

It is fair to say that we have not learned anything completely new from the recent detections of galaxy–galaxy lensing. That is, all of the constraints on the nature of dark matter halos which have been obtained from galaxy–galaxy lensing agree well with previous constraints that were obtained by more conventional methods. These studies have, however, demonstrated quite conclusively that galaxy–galaxy lensing is a viable technique by which the dark matter distribution on the scales of individual galaxies (i.e., proper distances of order a few 100 kpc) may be directly constrained. As a result, it is clear that galaxy–galaxy lensing holds the promise to be a unique and powerful tool by which some of the most fundamental questions about galaxy and structure formation may be addressed with forthcoming wide–field imaging data.

References

Brainerd, T. G., Blandford, R. D. & Smail, I. 1996, ApJ, 466, 623
Cohen, J. G., Hogg, D. W., Blandford, R. et al. 2000, ApJ, 538, 29
Dell'Antonio, I. P. & Tyson, J. A. 1996, ApJ, 473, L17
Dubinski, J. & Carlberg, R. G. 1991, ApJ, 378, 496
Ebbels, T. 1998, PhD Thesis, University of Cambridge
Fischer, P. et al. (the SDSS collaboration), 2000, AJ, 120, 1198
Geiger, B. & Schneider, P. 1999, MNRAS, 302, 118
Griffiths, R. E., Casertano, S., Im, M. et al. 1996, MNRAS, 282, P1159
Hoekstra, H., 2000, PhD Thesis, University of Groningen
Hudson, M. J., Gwyn, S. D. J., Dahle, H. & Kaiser, N. 1998, ApJ, 503, 531
Jaunsen, A. O. 2000, PhD Thesis, University of Oslo
Loveday, J., Maddox, S. J., Efstathiou, G. et al. 1995, ApJ, 442, 457
Mellier, Y. 1999, ARA&A, 37, 127
Kaiser, N. 1987, MNRAS, 227, 1
Kaiser, N. 1992, ApJ, 388, 272
Kneib, J.-P., Ellis, R. S., Smail, I. et al. 1996, ApJ, 471, 643
Kormann, R., Schneider, P. & Bartelmann, M. 1994, AA, 284, 285
Natarajan, P., Kneib, J. P. & Smail, I. 1998, ApJ, 499, 600
Sackett, P. 1999, in *Galaxy Dynamics*, ASP Conf. Series 182, eds. D. R. Merritt, M. Valluri & J. A. Sellwood, 393
Smith, D., Bernstein, et al. 2000, ApJ, submitted (astro-ph/0010071)
Tyson, J. A., Valdes, F., Jarvis, J. F. & Mills, A. P., 1984, ApJ, 281, L59
Warren, M. S., Quinn, P. J., Salmon, J. K. & Zurek, W. H. 1992, ApJ, 399, 405
Wilson, G., Kaiser, N. et al. 2000, ApJ, in press (astro-ph/0008504)