A weak lensing study of massive structures
Hoekstra, Harald

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Lensing by galaxies in CNOC2 fields

We have observed two blank fields of approximately 30 by 23 arcminutes using the William Herschel Telescope\(^1\). The fields have been studied as part of the Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (CNOC2), and redshifts are available for 1125 galaxies in the two fields. We use the data to study the lensing signal caused by large scale structure, and to study the halos of field galaxies.

The observed lensing signal caused by large scale structure is low, and favours a low matter density universe. Given the uncertainty in the measurement, none of the cosmological models we considered can be excluded.

We study the galaxy-galaxy lensing signal of three overlapping samples of lenses (one with and two without redshift information), and detect a significant signal in all cases. The estimates for the velocity dispersion of an L\(_{B}^*\)(z = 0) = 5.6 \times 10^{10} \text{ h}^{-2} \text{L}_{\odot} \text{ galaxy agree well for the various samples. The signal-to-noise ratio from the smaller sample with redshifts is comparable to the larger sample without redshifts. The best fit singular isothermal sphere model to the ensemble averaged tangential distortion around the galaxies with redshifts yields a velocity dispersion of } \sigma_s = 133^{+14}_{-13} \text{ km/s}, \text{ or a circular velocity of } V_c^* = 188^{+20}_{-22} \text{ km/s for an L}_B^* \text{ galaxy, in good agreement with previous studies.}

We study the extent of the galaxy dark matter halos using a maximum likelihood analysis. Making optimal use of the available data, we find \sigma_s = 111^{+12}_{-11} \text{ km/s (68.3\% confidence)} for a truncated isothermal sphere model in which all galaxies have the same mass-to-light ratio (s \propto \sigma^2). The value of the truncation parameter s has more freedom. We find s_s = 260^{+24}_{-23} \text{ h}^{-1} \text{ kpc (68.3\% confidence), with a 99.7\% confidence lower limit of 80 h^{-1} kpc. Interestingly, our results provide a 95\% confidence upper limit of 556 h^{-1} kpc. The galaxy-galaxy lensing analysis allows us to estimate the mass-to-light ratio of the field, which in its turn provides an estimate of } \Omega_m, \text{ but the result depends strongly on the assumed scaling of } s.

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\(^1\)Based on observations made with the William Herschel Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.
1 Introduction

Weak gravitational lensing is a valuable tool to study the mass distribution of a range of objects in the universe. The differential deflection of light rays by intervening structures allows us to study the projected mass distribution of the deflectors, without having to rely on assumptions about the state or nature of the deflecting matter.

Although the first attempt in the field was to detect the weak lensing signal induced by an ensemble of galaxies (Tyson et al. 1984), this area of astronomy blossomed with the successful measurement of the signal induced by rich clusters of galaxies at intermediate redshifts (e.g., Tyson, Wenk, & Valdes 1990; Bonnet, Mellier, & Fort 1994; Fahlman et al. 1994; Squires et al. 1996; Luppino & Kaiser 1997; for an extensive review see Mellier 1999). Studies of rich clusters of galaxies are an important first step in demonstrating the feasibility of weak lensing analyses, but nowadays more and more studies concentrate on blank fields.

Galaxy groups have masses intermediate between clusters of galaxies and galaxies. Recently, Carlberg et al. (2000) identified a large number of these systems in the Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (CNOC2) (Yee et al. 2000). The ensemble averaged weak lensing signal from a sample of 50 of these groups was detected by Hoekstra et al. (2000b).

Another recent result is the detection of the lensing signal caused by large scale structure (Bacon et al. 2000; Kaiser, Wilson, & Luppino 2000; van Waerbeke et al. 2000; Wittman et al. 2000), which provides important constraints on the cosmological parameters.

Weak lensing is also an important tool to study the dark matter halos of field (spiral) galaxies (e.g., Brainerd, Blandford, & Smail 1996; Griffiths et al. 1996; Dell’Antonio & Tyson 1996; Hudson et al. 1998; Fischer et al. 2000). Rotation curves of spiral galaxies have provided important evidence for the existence of dark matter halos (e.g., van Albada & Sancisi 1986). Also strong lensing studies of multiple imaged systems require massive halos to explain the observed image separations. However, both methods provide mainly constraints on the halo properties at relatively small radii.

The weak lensing signal can be measured out to large projected distances, and in principle it can be a powerful probe of the potential at large radii, constraining the extent of the dark matter halos (e.g., Brainerd et al. 1996, Hudson et al. 1998; Fischer et al. 2000). Only satellite galaxies (e.g., Zaritsky & White 1994) provide another way to probe the outskirts of isolated galaxy halos.

The lensing signal induced by an individual galaxy is too low to be detected, and one has to study the ensemble averaged signal around a large number of lenses. Redshifts for the individual galaxies are useful, because they allow a proper scaling of the lensing signal around the galaxies, and they are necessary for studies of the evolution of the mass-to-light ratio of field galaxies from lensing.

To date only Hudson et al. (1998) have made use of (photometric) redshifts in their study of the northern Hubble Deep Field, but the small area covered by the HDF limits the accuracy of their results. Fischer et al. (2000) used commissioning data of the Sloan Digital Sky Survey, and detected a very significant lensing signal, demonstrating the importance of the survey for the study of galaxy halos, in particular when photometric redshifts become available.

We use our deep imaging data of the two CNOC2 fields to study the galaxy-galaxy lensing signal of three overlapping samples of galaxies (one with, and two without redshift information). Earlier results on groups of galaxies were presented by Hoekstra et al. (2000b). We compare the results for the different samples, and study the usefulness of redshift information. We examine the mass, extent, and mass-to-light ratio of field galaxies.

The structure of the paper is as follows. In section 2 we present the observations and data reduction. In this section we also describe in detail the object analysis and the corrections for the various observational distortions. In section 3
we discuss the redshift distribution of the sources we use in this study. The smoothed shear fields and the corresponding mass reconstructions are presented in section 4, and in section 4.1 we present our measurement of the lensing signal caused by large scale structure. Our analysis of the galaxy-galaxy lensing signal is presented in section 5. In section 6 we present our estimates of the field mass-to-light ratio for different halo models. We also discuss how an independent measurement of \( \Omega_m \) can be used to constrain the sizes of galaxy halos. Throughout the paper we take \( H_0 = 100 h \) km/s/Mpc, \( \Omega_m = 0.2 \), and \( \Omega_A = 0 \).

## 2 Data

The Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (CNO2) targeted four widely separated patches on the sky to study the field population of galaxies in the universe. Redshifts of \( \sim \) 6200 galaxies down to \( R_c = 21.5 \) have been measured, resulting in a large sample of galaxies at intermediate redshifts (\( z = 0.12 - 0.55 \)). A detailed description of the survey is given in Yee et al. (2000).

We observed the central parts of the two CNO2 patches 1447+09 and 2148-05 using the 4.2m William Herschel Telescope (WHT) at La Palma. Table 1 lists the central positions of the observed fields as well as the dates of the observations. The images were taken using the prime focus camera, equipped with a thinned 2048 \( \times \) 4096 pixels EEV10 chip, with a pixel scale of 0.237 pixel\(^{-1}\). The resulting field of view of the camera is approximately 8.1 by 16.2.

The patches observed in the CNO2 survey are much larger than the field of view of the WHT prime focus camera, and we observed a mosaic of 6 pointings. As illustrated in figure 1 our observations cover the central rectangles of the CNO2 patches. The typical integration time per pointing is one hour in \( R \) (see Table 2).

## 2.1 Data reduction

The images were flatfielded, using a master flatfield constructed from the science exposures. The images were calibrated using observations of standard stars from Landolt (1992).

The data for each pointing typically consists of 3 exposures of 1200s, which were taken with small offsets. Because of telescope distortions the exposures have to be remapped before the images are combined into the final image. We selected and measured the positions of stars in each of the exposures and used these as input for the IRAF tasks `geomap` and `geotran`. To obtain the final images that were used for the object analysis the remapped images were simply averaged to ensure that neither cosmic ray rejection or medianing changed the shape of the PSF or the galaxies in a non-linear way.

Although a remapping of the images was necessary, the camera induced distortion is small. According to the WHT prime focus observer’s manual the telescope distortion is purely radial. We compared the measured positions of bright

<table>
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Table 2—Summary of the deep WHT imaging. Column (1): identification of the pointing; (2) total integration time; (3) median seeing; (4) number of galaxies; (5) number density of galaxies; (6) 90% completeness limit in \( R \).
stars coinciding with stars from the USNO catalog, and the results agree to the published parameters within the errors. However, due to the relatively large uncertainty in the astrometry of the USNO catalog the error is substantial. To correct the observed distortion for the camera shear we follow Hoekstra et al. 1998, taking the numbers from the observer’s manual. We find that the induced shear is small: at most 0.66% in the corners of the field.

Table 2 lists the total integration time, seeing, and number of detected objects for both observed fields. The data for the 1447 field have a median seeing of ~ 0".7, whereas the data for the 2148 field are somewhat worse, with a seeing of 0".85.

2.2 Object detection and analysis

Our analysis technique is based on that developed by Kaiser, Squires, & Broadhurst (1995) and Luppino & Kaiser (1997), with a number of modifications which are described in Hoekstra et al. (1998). We analyse each pointing separately as the seeing and PSF anisotropy vary between each exposure. After the catalogs have been corrected for the various observational effects, they are combined into a master catalog which covers the complete field that is observed.

The first step in the analysis is to detect the faint galaxy images, for which we used the hierarchical peak finding algorithm from Kaiser et al. (1995). We select objects which were detected with a significance $\nu > 5\sigma$ over the local sky in the combined images. This catalog is used for the weak lensing analysis. We also run the peak finder on the images of the single exposures. We do a coincidence test on these catalogs and classify extremely small, but very significant objects as cosmic rays, which are removed from the catalog that is used for the object analysis.

For the weak lensing analysis we select objects which are detected in at least two of the shorter exposures. The objects which are detected in only one of the shorter exposures are small, faint objects, which are not useful as their shape parameters are noisy. The resulting catalogs are inspected visually in order to remove spurious detections, like spikes from saturated stars, HII regions in resolved galaxies, etc.

For all detected objects we measure the appar-
ent magnitude in an aperture that is scaled to the object's size, the half light radius, and the shape parameters (polarization and polarizabilities). We also estimate the error on the polarization following Hoekstra, Franx, & Kuijken (2000a).

2.3 PSF correction

To measure the small, lensing induced, distortions in the images of the faint galaxies it is important to correct the shapes for observational effects, like PSF anisotropy and seeing. PSF anisotropy can mimic a lensing signal, and the correction for seeing is required to relate the measured shapes to the real lensing signal.

To do so, we follow the procedure outlined in Hoekstra et al. (1998) (which is based on Kaiser et al. 1995; Luppino & Kaiser 1997). We select a sample of moderately bright stars from our observations. These are used to characterize the PSF anisotropy and seeing. Figure 2 shows a typical result for one of the pointings. We fit a second order polynomial to the shapes of the stars, and this model is used to correct for the PSF anisotropy. Figure 2 also shows the residual polarization in the stars after the correction. The residuals (as indicated in figure 2b) are small indicating that we can reliably correct for the PSF anisotropy.

The next step is to correct the shapes for the circularization by the PSF. The stars that were used to study the PSF anisotropy are also used to compute the 'pre-seeing' shear polarizability $\mathcal{P}^s$ (Luppino & Kaiser 1997). Again we follow the scheme outlined in Hoekstra et al. (1998). The measurement of $\mathcal{P}^s$ is very noisy, and we
combine the estimates of many galaxies to reduce the noise. We also found that the size of the FSE, and thus the correction, depends on the position on the chip. The variation, however, is small: about 10% maximum. To account for this, we binned the raw polarizabilities not only in bins of $r_g$, but also as a function of position. For a given $r_g$, we fitted a second order polynomial to the median $P^v$'s, and used the results to compute the $P^v$'s of the galaxies. Figure 3a shows $P^v$ as a function of $r_g$.

Objects with small values for $P^v$ require large corrections, thus increasing the noise. The weighting scheme suggested in Hoekstra et al. (2000a) gives already less weight to these objects, but in addition we exclude objects with $P^v \leq 0.1$

3 Redshifts of lenses and sources

For a given mass distribution, the amplitude of the weak lensing signal is proportional to the dimensionless mass surface density

$$\kappa(x) = \frac{\Sigma(x)}{\Sigma_{critical}},$$

where the critical surface density is defined as

$$\Sigma_{critical} = \frac{c^2}{4\pi G D_s D_{ls}} = \frac{c^2}{4\pi G D_s^3 \beta}.$$  

Here $D_s$, $D_l$, and $D_{ls}$ correspond to the angular diameter distances between the observer and the source, observer and the lens, and the lens and the source. The lensing signal depends on both the redshifts of the lenses and the sources, and the dependence on the source redshift is characterized by $\beta$, which is defined as

$$\beta = \max[0, D_{ls}/D_s].$$

If the redshift of the lens approaches that of the source, the amplitude of the lensing signal, which is proportional to $\beta$, decreases. On the other hand, if the lens is at low redshift (i.e. $D_l$ is low), the lensing signal is low as well. In general, the lensing signal is maximal if the lenses are at redshifts $z = 0.2 - 0.5$ and source redshifts $z \sim 1$ or higher.

Most of the lensing signal comes from galaxies that are generally too faint to be included in redshift surveys. To relate the lensing signal to a physical mass it is necessary to know the redshift distribution of the faint background galaxies. To this end, we use photometric redshift distributions from the Hubble Deep Fields North and South (Fernández-Soto, Lanzetta, & Yahil 1999; Chen et al. 1998). Hoekstra et al. (2000a) used these for their analysis of the distant cluster MS 1054-03 ($z = 0.83$), and concluded that these redshift distribution provide a good approximation of the true distribution. Based on the colours of the galaxies in the HDFs we have computed their $R$ band magnitude. For each lens-source pair we compute the corresponding value of $\beta$.

4 Lensing signal

In the case of lensing by massive clusters the images of the sources tend to align tangentially
to the cluster mass distribution. One of the selection criteria for the CNOC2 fields (which are described in Yee et al. 2000) is that no known nearby rich cluster should be in the field. However, the observed fields might contain distant massive clusters. In principle such clusters can be found in a weak lensing analysis, provided they are massive enough. The analysis can also find dark mass concentrations (e.g., Erben et al. 2000).

Therefore we have examined the smoothed distortion maps of the two observed fields, which are presented in figure 4. The distortion has been smoothed spatially using a Gaussian with a FWHM of 1 arcminute. To take into account the noise in the shape measurements we weight each object with the inverse square of the uncertainty in the distortion, which includes the contribution of the intrinsic ellipticities of the galaxies and the shot noise in the shape measurements (see HKF for a detailed discussion).

![Figure 4](image1.png)  
**Figure 4**— (a) Smoothed distortion field for the sample of background galaxies in the 1447 field. The distortion has been smoothed spatially with a Gaussian with a FWHM of 1 arcminute (indicated by the hatched circle). (b) Same as panel (a) but now for the 2148 field. The orientation of the sticks indicates the direction of the distortion, whereas the length is proportional to the amplitude of the signal.

![Figure 5](image2.png)  
**Figure 5**— (a) Reconstruction of the projected dimensionless mass surface density for the 1447 field. The interval between adjacent contours is 0.018 in κ (which corresponds to 1σ). (b) The mass reconstruction of the 2148 field. The interval between adjacent contours is 0.019 in κ (which corresponds to 1σ). The map has been smoothed using a Gaussian with a FWHM of 1 arcminute (indicated by the circle). In both maps ⟨κ⟩ = 0. The mass maps are consistent with noise maps.

The distortion field is consistent with a noise field. However, the distortion at a certain position is a local noisy measurement of the lensing signal. Another way to present the data is to reconstruct the map of the dimensionless surface density of the two CNOC2 fields.

To do so, we used the original Kaiser & Squires (1993) algorithm, and the images of the reconstructed dimensionless mass surface density are presented in figure 5. We have trimmed the edges of the mass reconstructions, because they are rather noisy at the edges. The resulting mass maps are consistent with noise maps. We find a few 3σ peaks, but no obvious counterparts are seen in the number counts of bright galaxies. The mass maps have been smoothed with a Gaussian with a FWHM of 1 arcminute, result-
ing in approximately 500 independent points in each map. Therefore one expects about three $3\sigma$
peaks.
It is also useful to estimate what cluster masses could have been detected from the mass reconstructions. We assume that the cluster mass profile is well described by a singular isothermal sphere (SIS):

$$\kappa = \frac{r_E}{2\pi},$$

(4)

where $r_E$ is the Einstein radius. The Einstein radius (in radians) is related to the velocity dispersion through

$$r_E = 4\pi \left(\frac{\sigma}{c}\right)^2 \beta$$

(5)

From the observed scatter in the shapes of the sources we find that the typical uncertainty in the Einstein radius $r_E$ is $\sim 2''$ (fairly independent on the range in radii where the fit is done), and thus we should be able to detect a cluster with $r_E > 6''$ (at the $3\sigma$ level). The velocity dispersion of the SIS model is given in km/s by

$$\sigma = 186.3 \sqrt{\frac{r_E}{\beta}} \text{ km/s},$$

(6)

when $r_E$ is given in arcseconds. Given the redshift distribution of our sources a cluster with a velocity dispersion of 630 km/s at $z = 0.2$ could have been detected, whereas a cluster at $z = 0.5$ should have a velocity dispersion larger than 900 km/s. Such rich clusters would be detected in the CNOC2 redshift survey. Clusters at $z > 0.5$ are even more massive. Such massive systems are very rare, and are unlikely to be in the observed fields. Based on the mass reconstructions we find no massive clusters in the CNOC2 fields.

### 4.1 Cosmic shear

The analysis of the lensing signal induced by the large scale structure provides a direct measurement of the statistical properties of the large scale mass distribution (e.g., Blandford et al 1991; Kaiser 1992; Bernard, van Waerbeke, & Mellier 1997; Schneider et al. 1998). Recently, several groups have reported detections of this signal (e.g., Bacon et al. 2000; Kaiser, Wilson, & Luppino 2000; van Waerbeke et al. 2000; Wittman et al. 2000).

To study the cosmic shear one averages the distortion in apertures of given size and shape, and repeats this for many apertures. The measurement of the variance in the average distortion can be compared to predictions for various cosmological models.

The area covered by the two CNOC2 fields is smaller than the area covered by the studies mentioned above, but it is still interesting to examine our results and compare them to the predictions. The largest aperture we can use here, is the full field covered by our observations. We use galaxies with apparent magnitudes $21 < R < 26$ as our sample of sources for the analysis. The measurements of the average distortion of the two fields are presented in table 3. The values are small, which suggest that the correction for the PSF anisotropy has worked well.

We can also study the lensing signal caused by large scale structure in smaller scales. To do so, we average the shear in circular apertures of various sizes. The signal between adjacent apertures is correlated. Ideally, one would like to use well separated apertures, but our data do not allow such an analysis. Similar to what is done by Kaiser et al. (2000) and van Waerbeke et al. (2000), we tile the observed fields with these apertures, such that they do not overlap.

The observed variance in the average shear is the sum of the signal from the large scale structure, and the noise introduced by the shapes of the sources. To recover the cosmic shear the latter has to be subtracted from the observed variance (e.g., Bacon et al. 2000; Kaiser et al. 2000; van Waerbeke et al. 2000).

The combined results from our two CNOC2

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<td>0.00323</td>
<td>-0.00140</td>
<td>0.00254</td>
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</table>

Table 3 — Average distortion in the observed fields. The errors in the measurements are given in the last column.
fields are presented in figure 6. The observed variances are small, which is a good indication that the correction for the PSF anisotropy has worked well, because systematic errors tend to increase the scatter. The error only includes the uncertainty because of the intrinsic shapes of the sources, and does not include the contribution by cosmic variance. Also note that the points are correlated.

Given a cosmological model, the variance in the shear because of the large scale structure can be computed as a function of aperture size $R$ (Jain & Seljak 1997)

$$\langle \gamma^2 \rangle (R) = 2\pi \int_0^\infty dl \, l \, P_e(l) \left[ \frac{f_k(l R)}{\pi R} \right]^2,$$  \hspace{1cm} (7)

where $P_e(l)$ is the effective convergence power spectrum given by

$$P_e(l) = \frac{9H_0^2 \Omega_m^2}{4c^4} \int_0^w dw \left( \frac{\tilde{W}(w)}{a(w)} \right)^2 P_b \left( \frac{l}{f_k(w)} \right).$$  \hspace{1cm} (8)

![Image](image_url)

**Figure 6**— The observed variance of $\langle \gamma^2 \rangle$ as a function of the radius of the aperture in which the shear is averaged. Note that the points are correlated. Given our redshift distribution of sources the expected variance for three different cosmologies are also presented.

<table>
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<tr>
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<td>0.3</td>
<td>0.90</td>
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</table>

**Table 4**— Parameters of the cosmological models considered in the cosmic shear analysis. All three models are cluster normalized.

Here $w$ is the radial coordinate, $a(w)$ the cosmic scale factor, and $f_k(w)$ is the comoving angular diameter distance. $\tilde{W}(w)$ is the source averaged ratio of angular diameter distances $D_{ls}/D_s$ for a redshift distribution of sources $p_w(w)$

$$\tilde{W}(w) = \int_w^{\infty} dw' p_w(w') \frac{f_k(w' - w)}{f_k(w')}.$$  \hspace{1cm} (9)

The various parameters for the three cosmologies we have considered are listed in table 4. The predicted variances depend on the redshift distribution of the sources, for which we again use the photometric redshift distributions from the HDFs. Our results favour a low density universe, but given the uncertainty in the measurement (which should also include the contribution from cosmic variance) none of the models can be excluded.

## 5 Galaxy-galaxy lensing

We study the lensing signal caused by the field galaxies using two methods. First we measure the ensemble averaged tangential distortion around the lens galaxies, which provides a robust estimate of the lensing signal. We also perform a maximum likelihood analysis, similar to that of Schneider & Rix (1997), and Hudson et al. (1998).

In table 5 we present the three subsamples of lenses that we study. The ‘faint’ and the ‘bright’ sample are magnitude limited, and we use statistical redshift distributions for the lenses to infer the average halo properties. The ‘CNOC2’ sample has the same magnitude limits as the ‘bright’ sample, but consists only of galaxies with spectroscopic redshifts. It includes approximately half of the galaxies of the ‘bright’ sample. The ‘faint’ sample is comparable to
the sample of lenses studied by Brainerd et al. (1996) who used $20 < r_{\text{source}} < 23$, and $23 < r_{\text{source}} < 24$. Brainerd et al. (1996) did not use fainter sources, because they did not correct for observational distortions.

### 5.1 Lenses selected irrespective of redshift information

Figure 7 shows the ensemble averaged tangential distortion as a function of radius for the ‘faint’ and the ‘bright’ sample. For both the ‘faint’ and the ‘bright’ sample a significant lensing signal is detected. If the measured signal is caused by gravitational lensing, no signal should be observed when the sources are rotated by $\pi/4$. The results of this test are shown in figure 7b and d, and no signal is seen indeed. We fit a SIS model to the tangential distortion profiles presented in figure 7. We do not know the redshifts of the individual lenses in these samples, and consequently we can only determine the ensemble averaged Einstein radius $\langle r_E \rangle$. For the ‘faint’ sample we find a best fit Einstein radius $\langle r_E \rangle = 0\ arcmin = 0.118 \pm 0.0025$, and for the ‘bright’ sample we obtain $\langle r_E \rangle = 0\ arcmin = 0.176 \pm 0.045$. We use the effective $\beta$ for these samples (see column 6 of table 5) to derive a mass weighted average velocity dispersion $\langle \sigma^2 \rangle^{1/2} = 110^{+13}_{-12}$ km/s for the ‘faint’ sample, and $\langle \sigma^2 \rangle^{1/2} = 125^{+13}_{-15}$ km/s for the ‘bright’ sample. The corresponding circular velocity can be calculated using $V_c = \sqrt{2}\sigma$. The derived values of $\langle \sigma^2 \rangle^{1/2}$ depend on the selection of the sample of lens galaxies, and one cannot compare these results to findings of other studies, given the differences in sample selection. Instead we estimate the velocity dispersion (or circular velocity) of an $L^*_B$ galaxy. We assume a scaling relation between the velocity dispersion and the luminosity of the galaxy of the form

$$\sigma \propto L^{1/4}_B, \quad \text{or} \quad V_c \propto L^{1/4}_B.$$  

We also assume that the luminosity of a lens of given mass evolves with redshift $\propto (1 + z)$ (e.g., Lin et al. 1999). With these assumptions the average value of the Einstein radius (in radians) is given by


<table>
<thead>
<tr>
<th>(1) sample</th>
<th>(2) $R$</th>
<th>(3) source</th>
<th>(4) # lens</th>
<th>(5) $z_{lens}$</th>
<th>(6) $\langle \beta \rangle$</th>
<th>(7) $\langle r_E \rangle$</th>
<th>(8) $\langle r_E^* \rangle$</th>
<th>(9) $\sigma$</th>
<th>(10) $V^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>faint</td>
<td>$20 &lt; R &lt; 23$</td>
<td>$23 &lt; R &lt; 26$</td>
<td>8715</td>
<td>0.46</td>
<td>0.35</td>
<td>0.118 ± 0.025</td>
<td>0.159 ± 0.034</td>
<td>128$^{+13,-3}$</td>
<td>181$^{+8,-28}$</td>
</tr>
<tr>
<td>bright</td>
<td>$17.5 &lt; R &lt; 21.5$</td>
<td>$22 &lt; R &lt; 26$</td>
<td>2125</td>
<td>0.34</td>
<td>0.41</td>
<td>0.176 ± 0.045</td>
<td>0.161 ± 0.041</td>
<td>116$^{+14,-10}$</td>
<td>164$^{+2,-28}$</td>
</tr>
<tr>
<td>CNOCS2</td>
<td>$17.5 &lt; R &lt; 21.5$</td>
<td>$22 &lt; R &lt; 26$</td>
<td>1125</td>
<td>0.36</td>
<td>0.40</td>
<td>0.196 ± 0.046</td>
<td>0.196 ± 0.047</td>
<td>133$^{+14,-13}$</td>
<td>185$^{+2,-28}$</td>
</tr>
</tbody>
</table>

Table 5—Properties and results for the different samples of lens galaxies: (1) the range in apparent magnitude of the lens galaxies; (2) range in apparent magnitude for the sources; (3) number of lenses; (4) median redshift of the lenses; (5) average value of $\beta$ based on the redshift distribution of the lenses and sources. (7) best fit Einstein radius; (8) estimate for the Einstein radius of an $L_B^*$ galaxy; (9) best estimate for the velocity dispersion of an $L_B^*$ galaxy; (10) corresponding circular velocity.

\[
\langle r_E \rangle = \frac{4\pi}{c^2} \frac{\sigma^2}{L_B^\text{obs}(z=0)} \langle \beta \rangle \left( \frac{L_B^\text{obs}}{1+z} \right),
\]

(11)

where $L_B^\text{obs}$ is the observed intrinsic luminosity of the galaxy. We also introduce $\langle r_E^* \rangle$

\[
\langle r_E^* \rangle = \frac{4\pi}{c^2} \sigma^2 \langle \beta \rangle,
\]

(12)

which is the Einstein radius of an $L_B^*$ galaxy at the average redshift of the sample of lenses.

The redshift distribution of the sources and the ‘faint’ lens sample are derived from the photometric redshift distributions of the HDF North and South ((Fernández-Soto, Lanzetta, & Yahil 1999; Chen et al. 1998). We showed earlier that this approach works well (HFH). For the ‘bright’ sample we use the redshift distribution from the CNOCS2 survey with the proper weighting to take into account the incompleteness of the survey. To determine the restframe $B$ luminosities we use template spectra for a range of spectral types and compute the corresponding passband corrections as a function of redshift and galaxy colour.

Lin et al. (1999) have studied the field galaxy luminosity function at intermediate redshift from the CNOCS2 survey, and they find $M_B^*(z = 0.3) = -19.18 + 5 \log h$, which corresponds to a luminosity of $7.3 \times 10^9 h^{-2} L_{B,0}$. With our assumed luminosity evolution, this results in $L_B^*(z = 0) = 5.6 \times 10^9 h^{-2} L_{B,0}$. We adopt this value in the rest of the paper.

Column 8 in table 5 lists the derived Einstein radii of an $L_B^*$ galaxy for the ‘bright’ and the ‘faint’ sample. For the ‘bright’ sample the observed $\langle r_E^* \rangle$ is actually very close to $r_E^*$. For the ‘faint’ sample we find that the observed $\langle r_E^* \rangle = 0.74 \langle r_E^* \rangle$. Columns 9 and 10 list the velocity dispersion and circular velocity for an $L_B^*$ galaxy. The results for the two samples agree well.

5.2 Lenses with redshifts from CNOCS2

Redshifts for the lens galaxies are useful because they allow a proper scaling of the signals around the lens galaxies. Intrinsically faint (and therefore low mass) galaxies, or galaxies with redshifts comparable to the source galaxies are given lower weights. We scale the observed distortion of each galaxy, as well as its error, such that it corresponds to that of an $L_B^*$ galaxy at the median redshift of the ‘CNOCS2’ sample

\[
S_T^\text{scale} = \frac{5.6 \times 10^9(1+z)}{L_B} \left( \frac{0.4}{\beta} \right)^{1/2},
\]

(13)

where we assumed that the luminosity scales with the fourth power of the velocity dispersion. The value of $\beta$ is calculated for each galaxy separately, based on its redshift, and the redshift distribution of the sources. The sample of lenses consists of 1125 galaxies with spectroscopic redshifts, and $17.5 < R_{lens} < 21.5$. Figure 8a shows the resulting average tangential distortion as a function of radius around an $L_B^*$ galaxy at $z = 0.36$. A significant galaxy-galaxy lensing signal is detected.
5.3 Sizes of galaxy halos

Another way to study the galaxy halos is to use a model for the mass distribution of individual galaxies and compare the predicted distortions to the observed distortion field. This way one makes use of both components of the distortion. A useful model to describe a truncated halo is (Schneider & Rix 1997)

$$
\Sigma(r) = \frac{\sigma^2}{2Gr} \left( 1 - \frac{r}{\sqrt{r^2 + s^2}} \right),
$$

where $s$ is a measure of the truncation radius. The total mass of this model is finite, and half of the mass is contained within $r = \frac{s}{4}$. The total mass is given by

$$
M_{\text{tot}} = \frac{\pi \sigma^2}{G} s = 7.3 \times 10^{12} \left( \frac{\sigma}{100 \, \text{km/s}} \right)^2 \left( \frac{s}{1 \, \text{Mpc}} \right).\quad (15)
$$

For the mass model we use again $\sigma \propto L_\text{B}^{1/4}$, which is based on both dynamical and observational considerations. The situation is different for the truncation parameter $s$, because there are no observational constraints. Here we will explore several options.

If all halos have the same value for $s$ the total mass-to-light ratio scales as $(M/L)_{\text{tot}} \propto L^{1/2}$ (where we assume that $L \propto \sigma^4$). Thus the mass-to-light ratios of more massive objects are higher. Another option is to take $(M/L)_{\text{tot}} = \text{constant}$ for all galaxies. This choice is equivalent to taking $s \propto \sigma^2$ (e.g., Brainerd et al. 1996; Hudson et al. 1998). The last relation we examine is $s \propto \sigma^4$, which gives $(M/L)_{\text{tot}} \propto L^{-1/2}$.

The scatter in the polarizations of the galaxies is approximately constant with apparent magnitude, and it can be well approximated by a Gaussian distribution. In that case the log-likelihood function is given by the sum over the two components of the polarization $e_i$ of all the source galaxies

$$
\log \mathcal{L} = \sum_{i,j} \left( e_{i,j} - \frac{g_{i,j}(\sigma_s, \sigma_e) P_{i,j}}{\sigma_e} \right)^2, \quad (16)
$$
where $g_{ij}$ are the model distortions, $P^j_i$ is the shear polarizability, and $e_{i,j}$ are the image polarizations for the $j$th galaxy.

In figure 9 we present the results for the ‘CNOCS2’ sample, for which the redshifts of the lenses are known. It shows the likelihood contours for the parameters $\sigma_s$ and $s_s$ jointly. The result for a constant $s$ for all galaxies is presented in figure 9a, and the result for $s \propto \sigma^2$ is shown in figure 9b. We omit the likelihood plot $s \propto \sigma^4$, but we list the best fit parameters (68.3% confidence limits) for all three models in table 6a.

In all cases the velocity dispersion is well constrained, and in good agreement with the results from the ensemble averaged tangential distortion. The value of the truncation parameter has significant freedom, and the value of $s_s$ depends strongly on the assumed scaling relation. We find that the value of $s_s$ decreases when $s$ scales with a high power of the velocity dispersion. The minimum $\chi^2$ for the three models are comparable, and no scaling relation for $s$ is preferred over the other ones. Table 6a also lists the best estimate and the 68.3% confidence limits for the total mass and mass-to-light ratio of an $L_V^*$ galaxy. The total galaxy mass is not well constrained, mainly because of the large uncertainty in the value of the truncation parameter $s_s$.

The mass model uses only half of the galaxies with $17.5 < R < 21.5$, and therefore it ignores the contributions of the other galaxies (they are given zero mass). If the remaining galaxies were distributed randomly they would only introduce noise, but we know that galaxies are clustered. Consequently the mass model will associate the mass of the galaxies without redshifts with the galaxies in the ‘CNOCS2’ sample that have measured redshifts.

To examine this in more detail we study the ‘bright’ sample, which is selected irrespective of redshift information. Even this selection is not ideal, neighbouring galaxies that are fainter than the applied magnitude limits are still excluded. If a substantial fraction of the mass is in these galaxies both the values of $\sigma_s$ and $s_s$ are overestimated.
Figure 10 shows the resulting likelihood contours. To obtain figure 10 we have assumed that all halos have the same velocity dispersion, and the same value for s in arcseconds. We find \( \langle s^2 \rangle^{1/2} = 117^{+13}_{-15} \text{ km/s} \) and \( \langle s \rangle = 88^{+43}_{-27} \text{ arcseconds} \) (68.3% confidence). At the average redshift of the lenses, this corresponds to \( \langle s \rangle = 284^{+139}_{-87} h^{-1} \text{ kpc} \). The estimate for \( \langle s \rangle \) is a complicated average over the s for all the galaxies, which are all at different redshifts. The interpretation of the result is not straightforward for the various options for the scaling relation of s.

To infer the best estimates for \( \sigma_s \) and \( s_s \) of the bright sample one has to perform a maximum likelihood analysis in which the redshift of each individual galaxy is a free parameter, which has to be chosen such that it maximizes the likelihood. This approach is computationally not feasible, and we use another approach to obtain estimates for \( \sigma_s \) and \( s_s \).

Thanks to the CNO2 survey we know the statistical properties (redshifts and intrinsic luminosities) of the galaxies in the 'bright' sample. We create mock redshift catalogs for the full sample of 'bright' lenses. The redshifts are randomly drawn from the CNO2 survey based on the apparent R magnitude of the galaxies in the 'bright' sample, and we take into account the incompleteness of the survey. For this mock redshift catalog we determine the best estimates for \( \sigma_s \) and \( s_s \), based on a maximum likelihood analysis of the observed distortion field. We repeat this procedure 25 times, and use the average \( \chi^2 \) surface to obtain the best estimates for \( \sigma_s \) and \( s_s \) (see table 6b).

This procedure does not provide the formal maximum likelihood estimate for \( \sigma_s \) and \( s_s \), but it does yield an unbiased estimate. We verified this by simulating the procedure described above. It also allows us to estimate the uncertainty introduced by the lack of observed redshifts for the lenses. We used the derived values of \( \sigma_s \) and \( s_s \) (see table 6) as input values for the simulations. For the simulation where \( s \propto \sigma^2 \) we find that the lack of redshifts increases the uncertainty in \( s_s \) by \( \sim 45 h^{-1} \text{ kpc} \), and the uncertainty in \( \sigma_s \) by \( \sim 3 \). The amplitude of the noise in \( s_s \) depends on the assumed scaling relation for \( s_s \) and we find that the fractional error is approximately the same for all models.
Comparison with the results obtained for the CNOC2 sample shows that the estimate of \( s_x \) is smaller, as well as that of the velocity dispersion, but the results are consistent. The agreement with the results from the direct averaging method is good.

The difference between the results from the two methods could have various causes. Firstly, the direct averaging method does not take into account the clustering of the lenses, which can introduce a slight bias in the result. Also the SIS model is fitted to the averaged tangential distortion out to 2 arcminutes, whereas the maximum likelihood analysis uses the full observed field. In the maximum likelihood analysis we have ignored the contribution from lenses outside the field of view (e.g., Hudson et al. 1998). This tends to lower the resulting \( \sigma_x \) and \( s_x \) somewhat. The area covered by our observations is much larger than the HDF North studied by Hudson et al. (1998), and the bias in our estimates of \( \sigma_x \) and \( s_x \) is small.

The analysis of the ‘bright’ sample has ignored any available redshift information. To make optimal use of the available information, we redo the analysis. For the galaxies with redshifts we use the observed values, but for the remaining galaxies we draw redshifts and luminosities from the CNOC2 survey randomly (as was done previously for all galaxies in the ‘bright’ sample). As before, we create mock catalogs which are analysed. This procedure improves the accuracy in the estimates of \( \sigma_x \) and \( s_x \). The results are presented in table 6c. Simulations show that the incomplete redshift information increases the uncertainty in \( \sigma_x \) by 18\% and the uncertainty in \( s_x \) by 10\%, compared to the situation where full redshift information is available.

### 5.4 Effect of galaxy groups

It is well known that galaxies cluster, and most of the galaxies reside in groups of galaxies. If the matter in galaxy groups is associated with the halos of the group members (i.e. these halos are indistinguishable from the halos of isolated galaxies) the analysis presented above gives a fair estimate of the sizes of galaxy halos. However, if a significant fraction of the dark matter in galaxy groups is distributed in a common group halo, the interpretation of the results becomes difficult.

Fischer et al. (2000) argued that galaxy groups complicate the interpretation of the galaxy-galaxy lensing signal. They measured the lensing signal out to large projected distances, and find a non vanishing distortion at large radii. It will be interesting to see if this result can be confirmed with more data.

Compared to Fischer et al. (2000) we have the advantage that a number of galaxy groups have been identified in the CNOC2 fields (Carlberg et al. 2000). The weak lensing signal of these groups was studied by Hoekstra et al. (2000b). They derived a mass weighted group velocity dispersion of \( \langle \sigma_{\text{group}}^2 \rangle^{1/2} = 273 \pm 56 \text{ km/s} \).

We will use the groups to examine their effect on the galaxy-galaxy lensing results for the galaxies with redshifts from the CNOC2 survey. In
addition to the galaxies, we include the lensing signal from galaxy groups to our mass model. The groups are placed at their observed positions, and the groups are modeled as singular isothermal spheres. To study the effect of the groups on the galaxy-galaxy lensing results we increase the velocity dispersion of the ‘groups’ from 0 km/s (the result without groups) up to 300 km/s. For each choice of the group velocity dispersion we perform a maximum likelihood analysis and determine the best estimates for \( \sigma_g \) and \( s_g \).

For \( \sigma_g < 150 \) km/s the best estimates for \( \sigma_g \) and \( s_g \) vary by a few percent. For larger group velocity dispersions the value for \( \sigma_g \) and \( s_g \) decrease slowly with increasing \( \sigma_g \). For a group velocity dispersion of 300 km/s, the value of \( \sigma_g \) has dropped by \( \sim 10\% \), and the value of \( s_g \) has decreased by \( \sim 20\% \). We note that the minimum \( \chi^2 \) has increased significantly for \( \sigma_g = 300 \) km/s, compared to \( \sigma_g = 0 \) km/s.

Ideally one would like to use different halo models for the group members and the ‘isolated’ galaxies and study the difference in the best parameters for these two types of galaxies. With the current data we cannot perform such an analysis, because the number of group members is too low. However, our results are based on approximately one quarter of the full CNOC2 data set. An analysis of the full survey will improve the signal-to-noise ratio of the measurements by a factor \( \sim 2 \), and will allow a better study of the effect of galaxy groups. Also numerical simulations can be useful to examine if, and how one can separate the contribution of the galaxy halos and the smooth group halos.

5.5 Comparison with other studies

An exact comparison with other studies is difficult, because different scaling relations have been used, the assumptions about luminosity evolution are different, the samples of lenses are different, and different cosmologies have been considered. However, some information about the other samples is available to enable a crude comparison. In the comparison we use our results from the maximum likelihood analysis.

We first compare our results to findings of Hudson et al. (1998). The typical lens galaxy in their sample \( (z = 0.6; M_B = -18.5 + 5 \log h; \sigma_0 = 0.5) \) has a circular velocity of \( 210 \pm 40 \) km/s. Given our assumptions (cosmology, luminosity evolution), the luminosity of the fiducial galaxy studied by Hudson et al. (1998) corresponds to a luminosity of \( L_B(z = 0) \sim 3.2 \times 10^9 h^{-2} L_{\odot} \). According to our analysis a galaxy with that luminosity has a circular velocity of \( V_c = 119 \pm 12 \) km/s, quite lower than the value found by Hudson et al. (1998). The two results are inconsistent at the \( \sim 2\sigma \) level, but the direct comparison is difficult, and the cause of the difference is not clear.

The uncertainty in the results presented by Fischer et al. (2000) is much smaller compared to Hudson et al. (1998). Fischer et al. (2000) find for their sample of lenses an average mass weighted velocity dispersion of \( \langle \sigma^2 \rangle^{1/2} = 145 - 195 \) km/s (95% confidence). Most of the signal comes from galaxies with luminosities around \( L_g = 8.7 \times 10^9 h^{-2} L_{\odot} \) (Fischer 2000, private communication). We use an average \( B - V = 0.55 \) and the transformations from Fukugita et al. (1996), and find that the adopted \( B \) band luminosity of our \( L_g \) galaxy corresponds to a \( g' \) band luminosity of \( L_{g'} = 6 \times 10^9 h^{-2} L_{g'\odot} \).

Based on our lensing analysis we derive a velocity dispersion of \( \sigma = 129_{-14}^{+12} \) km/s (68.3% confidence) for a galaxy with \( L_g = 8.7 \times 10^9 h^{-2} L_{\odot} \). Given the uncertainties of the comparison, we conclude that our results are in fair agreement with the findings from Fischer et al. (2000).

The results from Fischer et al. (2000) indicate that the galaxy halos are large. They find a 95% confidence lower limit of \( s_{\min} = 260 h^{-1} \) kpc for their fiducial \( L_g = 8.7 \times 10^9 h^{-2} L_{\odot} \) galaxy. As they do not use any scaling for \( s \) (they assume all halos are the same) their result should be compared to our results for constant \( s \) for all galaxies. We obtain an estimate of \( s = s_\odot = 337_{-109}^{+138} \) in good agreement with the lower limit from Fischer et al. (2000).
6 Mass-to-light ratio and $\Omega_m$

A well known method to estimate the matter density of the universe was proposed by Oort (1958): $\Omega_m$ is the product of the average mass-to-light ratio of the universe, and its luminosity density.

Carlberg et al. (1997) used this method to infer $\Omega_m$ from the mass-to-light ratios of rich clusters of galaxies, and they found $\Omega_m = 0.19 \pm 0.06$. The galaxy properties of rich clusters are different from those of the field, and a large correction is needed to relate the cluster mass-to-light ratio to that of the field. Smaller corrections are required when one uses galaxy groups. From their weak lensing analysis of a sample of 50 groups, Hoekstra et al. (2000) determined $\Omega_m = 0.19 \pm 0.1$. The uncertainty in this measurement is dominated by the intrinsic shapes of the sources used in their analysis, but using the full sample of groups found in the CNOC2 survey (Carlberg et al. 2000), one expects a factor of two improvement in the accuracy of the measurement.

The results from the maximum likelihood analysis can be used to estimate the average mass-to-light ratio of the field, i.e., the universe as a whole. An important advantage over the methods discussed above is that no additional corrections for the differences in stellar populations are required. The problem with this method is already apparent from column 7 in table 6: the total mass-to-light ratio depends on the assumed scaling relation for the truncation parameter $s$.

Lin et al. (1999) have determined the luminosity function of field galaxies from the CNOC2 survey, and we use their results to estimate the average mass-to-light ratio of the field. The results are listed in table 7 (column 4). When $s \propto \sigma^2$, the average mass-to-light ratio equals that of an $L^*_B$ galaxy. In the case that all halos have the same value for $s$, we already found that the resulting mass-to-light ratio of an $L^*_B$ galaxy high, but in addition, fainter galaxies have even higher mass-to-light ratios. This results in a very high field mass-to-light ratio. On the other hand, if $s \propto \sigma^4$, faint galaxies have low mass-to-light ratios, and the field mass-to-light ratio is somewhat lower than that of an $L^*_B$ galaxy.

To estimate the luminosity density of the universe we use the results from Lin et al. (1999), which are also based on the CNOC2 survey. We convolve the redshift distribution of the galaxies with the redshift dependent luminosity density from Lin et al. (1999), which yields $j = (3.0 \pm 0.6) \times 10^9 h L_{B,J} Mpc^{-3}$. We use this result, and our estimates for the average field mass-to-light ratio at $z = 0.34$ to derive the corresponding values of $\Omega_m$, which are listed in column 6 of table 7.

The measurement error in the value of $\Omega_m$ is large. Additionally, the uncertainty in the scaling relation of $s$ makes it impossible to obtain a good estimate for the matter density of the universe. Furthermore, the lensing signal is not changed by adding a sheet of constant surface density (Gorenstein, Shapin, & Falco 1988).

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### Table 7

<table>
<thead>
<tr>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>scaling $s$</td>
<td>scaling $M/L_B$</td>
<td>$M_{\text{tot}}/L_B^* (z = 0)$</td>
<td>$\langle M/L_B \rangle (z = 0)$</td>
<td>$\langle M/L_B \rangle (z = 0.34)$</td>
<td>$\Omega_m$</td>
</tr>
<tr>
<td>$\propto \sigma^0$</td>
<td>$\propto 1/\sqrt{L_B}$</td>
<td>$500^{+214}_{-143}$</td>
<td>$850^{+364}_{-234}$</td>
<td>$634^{+272}_{-161}$</td>
<td>$0.69^{+0.30}_{-0.20}$</td>
</tr>
<tr>
<td>$\propto \sigma^2$</td>
<td>constant</td>
<td>$393^{+214}_{-123}$</td>
<td>$393^{+214}_{-123}$</td>
<td>$293^{+200}_{-130}$</td>
<td>$0.32^{+0.12}_{-0.10}$</td>
</tr>
<tr>
<td>$\propto \sigma^4$</td>
<td>$\propto \sqrt{L_B}$</td>
<td>$286^{+214}_{-189}$</td>
<td>$240^{+150}_{-75}$</td>
<td>$168^{+102}_{-31}$</td>
<td>$0.18^{+0.12}_{-0.06}$</td>
</tr>
</tbody>
</table>
Thus a uniformly distributed form of dark matter cannot be detected in our analysis. Consequently, our estimate for $\Omega_m$ is a lower limit. Information on the halo truncation itself is also important. Determinations of $\Omega_m$ using other techniques, such as combined constraints from high redshift supernovae and CMB measurements, can be used to exclude some of the allowed scaling relations for $s$.

It is interesting to note that the average mass-to-light ratio that corresponds to $\Omega_m = 0.2 - 0.3$ is comparable to the value found for rich clusters of galaxies. Carlberg et al. (1997) find for their sample of 16 rich clusters an average mass-to-light ratio of $M/L_v = 237 \pm 41$ M$_\odot$/L$_\odot$. Converting their estimate to the $B$ band, and correcting for luminosity evolution to $z = 0$, the average cluster mass-to-light ratio is 438 $\pm$ 76 M$_\odot$/L$_\odot$. This suggests that the smooth dark matter halos of clusters of galaxies are made up from the merged halos of the member galaxies (e.g., Bahcall, Lubin, & Dorman 1995).

7 Conclusions

We have observed two blank fields of approximately 30 by 23 arcminutes using the William Herschel Telescope. The fields have been studied as part of the Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (CNOC2) (e.g., Yee et al. 2000; Carlberg et al. 2000), and spectroscopic redshifts are available for 1125 galaxies in the two fields. Earlier results on groups of galaxies, based on these data, were presented by Hoekstra et al. (2000). We have examined the lensing signal caused by large scale structure. The observed signal is low, and the errorbars are large, because the area covered by our observations is small. Other studies (Bacon et al. 2000; Kaiser et al. 2000; van Waerbeke et al. 2000; Wittman et al. 2000) have reported detections of the lensing signal by large scale structure, based on observations that cover more area on the sky. Our results favor a low matter density universe, and also demonstrate that the corrections for the PSF anisotropy have worked well.

Weak lensing is a powerful tool to study the dark matter halos of field galaxies, as it can probe the mass distribution out to large projected distances. We have studied the ensemble averaged tangential distortion around three subsamples of lenses. In all three cases a clear lensing signal is detected. We relate the lensing signal to an estimate of the velocity dispersion of an L* galaxy, and find that the results for the three samples agree well with each other. For the sample of galaxies with redshifts from the CNOC2 survey we derive $\sigma_v = 133^{+14}_{-13}$ km/s (or $V_* = 188^{+20}_{-25}$ km/s).

Another way to study the dark matter halos of field galaxies is by means of a maximum likelihood analysis. We have used this technique to study both the velocity dispersion and the extent of field galaxies. We find that the velocity dispersion is well constrained, and that it does not depend on the assumed scaling relation for the truncation parameter $s$. The truncation parameter has more freedom, and the value depends strongly on the assumed scaling relation. Galaxy groups complicate the interpretation of the truncation parameter $s$. We examined how galaxy groups affect our results, and we find that their effect is fairly small. Our data are not sufficient for a detailed study, but the full CNOC2 data set can be useful to this end, as well as studies of numerical simulations.

If all galaxies have the same total mass-to-light ratio, we find for the velocity dispersion of an L* galaxy a value of $\sigma_v = 111^{+12}_{-11}$ km/s. For the truncation parameter we find $s_* = 260^{+124}_{-73}$ h$^{-1}$ kpc, with a 99.7% confidence lower limit of 80 h$^{-1}$ kpc, and a 95% confidence upper limit of 556 h$^{-1}$ kpc. For this model we find that the average field mass-to-light ratio at $z = 0$ is $3.93^{+1}_{-1}$ M$_\odot$/L$_\odot$, comparable to what is found for rich clusters of galaxies (Carlberg et al. 1997) and galaxy groups (Hoekstra et al. 2000b).

The field mass-to-light ratio provides an estimate of $\Omega_m$, the matter density of the universe. The results from the weak lensing analysis provide a lower limit on $\Omega_m$, because lensing cannot detect dark matter that is distributed uniformly through the universe. Our es-
timate of the field mass-to-light ratio, and consequently the derived value of $\Omega_m$, depends strongly on the assumed scaling of $s$. In principle, an independent measurement of $\Omega_m$ can be used to exclude some of the allowed scaling relations for the truncation parameter $s$.

Our results are based on approximately one quarter of the CNOC2 survey. An analysis of the full survey will improve the accuracy of the results by a factor $\sim 2$. Furthermore, many large imaging surveys are currently underway. These will also provide important constraints on the dark matter halos of field galaxies.

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References

Oort, J.H. 1958, in La Structure et L’évolution de L’Univers, Onzième Conseil de Physique, ed. R. Stoops (Solvay: Bruxelles), 163
van Albada, T.S., & Sancisi, R. 1986, RSLPT, 320, 447