COSMIC SHEAR WITH THE CFHT

L. VAN WAERBEKE\textsuperscript{1,2}, Y. MELLIER\textsuperscript{2,3}, T. ERBEN\textsuperscript{4}, J.C. CUILLANDRE\textsuperscript{5}, F. BERNARDEAU\textsuperscript{6}, R. MAOLI\textsuperscript{2,3}, E. BERTIN\textsuperscript{2,3}, H.J. Mc CRACKEN\textsuperscript{7}, O. LE FEVRE\textsuperscript{7}, B. FORT\textsuperscript{2}, M. DANTEL-FORT\textsuperscript{3}, B. JAIN\textsuperscript{8}, P. SCHNEIDER\textsuperscript{4}

\textsuperscript{1} Canadian Institut for Theoretical Astrophysics, 60 St Georges Str., Toronto, M5S 3H8 Ontario, Canada.
\textsuperscript{2} Institut d’Astrophysique de Paris. 98 bis, boulevard Arago. 75014 Paris, France.
\textsuperscript{3} Observatoire de Paris. DEMIRM. 61, avenue de l’Observatoire. 75014 Paris, France.
\textsuperscript{4} Max Planck Institut fur Astrophysiks, Karl-Schwarzschild-Str. 1, Postfach 1523, D-85740 Garching, Germany.
\textsuperscript{5} Canada-France-Hawaii-Telescope, PO Box 1597, Kamuela, Hawaii 96743, USA
\textsuperscript{6} Service de Physique Théorique. C.E. de Saclay. 91191 Gif sur Yvette Cedex, France.
\textsuperscript{7} Laboratoire d’Astronomie Spatiale, 13376 Marseille Cedex 12, France
\textsuperscript{8} Dept. of Physics, Johns Hopkins University, Baltimore, MD 21218, USA

We present preliminary results of our cosmic shear survey currently in progress at the Canada-France-Hawaii Telescope (CFHT). We analysed 1.7 sq. degrees of high quality data (seeing below 1 arcsec), out of which we were able to measure a significant correlation of galaxy shape-orientation over several arcmin scale. We present measurements of the variance of the shear \(\langle \gamma^2 \rangle\) and of the correlation functions \(\langle e_r(\theta)e_r(0) \rangle\), \(\langle e_t(\theta)e_t(0) \rangle\), and we show that the signal is consistent with gravitational lensing by large scale structures predictions. The level of residual systematics after Point Spread Function correction is discussed and shown to be small compared to our measured signal. We outline several possible future evolutions of our work by using additional data of our lensing survey now extended to 9 sq. degrees.

1 Introduction

Since the pioneering works by \textsuperscript{3,12,19,29}, gravitational lensing by large scale structure has been recognized as a potential powerful probe of the mass distribution in the Universe at scales from 1 arcmin to several degrees. The effect we are looking for consists of a small stretching of distant galaxies by the foreground matter, with an amplitude of 1-5 percents of distortion. Since the induced distortion is very small compared to the intrinsic ellipticities of the galaxies (\(\sim 0.3\)), it
Table 1: List of the fields. Most of the exposures were taken in the I band at CFHT. The total area is 1.7 deg², and the 8 fields are uncorrelated.

| Target   | Name | Camera | Used area | Filter | Exp. time | Period | seeing |
|----------|------|--------|-----------|--------|-----------|--------|--------|
| F14P1    | F1   | CFH12K | 764 arcmin² | V      | 5400 sec. | May 1999 | 0.9"   |
| F14P2    | F2   | CFH12K | 764 arcmin² | V      | 5400 sec. | May 1999 | 0.9"   |
| F14P3    | F3   | CFH12K | 764 arcmin² | V      | 5400 sec. | May 1999 | 0.9"   |
| CFDF-03  | F4   | UH8K   | 669 arcmin² | I      | 17000 sec.| Dec. 1996 | 0.75"  |
| SA57     | F5   | UH8K   | 669 arcmin² | I      | 12000 sec.| May 1998 | 0.75"  |
| A1942    | F6   | UH8K   | 573 arcmin² | I      | 10800 sec.| May 1998 | 0.75"  |
| F02P1    | F7   | CFH12K | 1050 arcmin² | I    | 9360 sec. | Nov. 1999 | 0.8"   |
| F02P4    | F8   | CFH12K | 1050 arcmin² | I    | 7200 sec. | Nov. 1999 | 0.9"   |

can be observed only statistically by measuring the averaged orientation and elongation of several galaxies. Unfortunately telescope imaging defects (like optical distortion, tracking errors, etc...) induce also a significant coherent elongation of the galaxies, very similar to the gravitational lensing effect we wish to measure. Therefore the most challenging part of the analysis is the correction of the intrinsic telescope defects (which makes the Point Spread Function anisotropic) down to a level smaller than the expected lensing signal. This problem prevented the detection of the lensing effect in the earlier searches. Recently a significant measurement of the galaxy alignment was found thanks to the improvement of the image quality, but the analyzed fields were small, and yet it was not clear what sort of mass distribution was responsible for the lensing effect.

The fundamental importance of a clean PSF correction pushed many groups to design specific methods of image analysis. During the preparation of our cosmic shear program, we tested intensively the Kaiser, Squires and Broadhurst (KSB) correction scheme on highly realistic simulations. We found that the KSB method can easily reach the 1% accuracy PSF correction even for severely deteriorated PSF’s as we obtain in real observations. A 1% accuracy might be not sufficient to measure the gravitational lensing effect at the degree scale, but at the arcmin scale the gravitational lensing signal is enhanced by the non-linear evolution of the large-scale-structures, and the variance of the shear \( \kappa^2 \) can be as high as 3 – 5%. We are therefore confident that the present day technology is enough to detect the cosmic shear effect, even if significant improvements remain to be done to fully exploit the scientific case.

Four independent groups almost simultaneously reported a significant detection, and a new detection is coming with VLT data. Here, we present our own detection and discuss different aspects of the PSF correction and of the statistical measurement. Next we compare the measurements with the predictions and discuss their consistency. We show how our cosmic shear program will hopefully improve the situation very shortly: we outline the new measurements and the new tests of PSF correction we plan to do next.

2 From the data set to the galaxy catalogues

Table show the list of the fields used in our cosmic shear detection. Despite the relatively large differences in the filter and the exposure time, the mean redshift depth is approximately 1 according to the deepest spectroscopic surveys done so far, with a dispersion probably very large (\( \sim 1 \)). It is impossible to give a more accurate determination of redshifts as we do not have enough colors for this. A complete scientific interpretation of our signal would require the missing redshift information, but in the early stages of the work we were more interested in a detection of the cosmic shear effect rather than its scientific exploitation. As discussed in the last Section, the scientific analysis requires some crucial issues to be addressed first.
The thick solid line show the measured $\langle \gamma^2 \rangle$, and the error bars are calculated using randomized ellipticity orientations. The dashed lines show the $\pm 1\sigma$ levels. From left to right: (a) the thin solid lines are $\langle \gamma^2 \rangle$ measured in bins of $N$ galaxies, where the galaxies are chosen with respect to the star ellipticity strength $e_1$ and $e_2$. The number of galaxies is then converted into a fictive scale which is used to make the plot. (b) The $N$ galaxies are chosen with respect to the optical distortion amplitude. (c) The $N$ galaxies are chosen with respect to the CCD lines and columns.

The total field covers about 6300 arcmin$^2$ and has a number density of galaxies of about $n_g \simeq 30$ gal/arcmin$^2$. However, after a proper weighting of the galaxies their effective number density is about half (details are in the original paper). Our procedure of shape measurement using IMCAT is described in details elsewhere so it is unnecessary to give it here, therefore we assume that we have already a catalogue of PSF corrected ellipticities for the galaxies.

3 From the galaxy catalogues to the cosmological parameters

3.1 What is the relevant information?

The easiest quantities to measure for the detection of the cosmic shear effect are the variance of the shear $\langle \gamma^2 \rangle$ and the ellipticity correlation functions. For a simplified cosmological model (zero cosmological constant, power law power spectrum with slope $n$ and normalization $\sigma_8$, and a single redshift plane $z_s$), we can show that:

$$\langle \gamma^2 \rangle^{1/2} \simeq 0.01\sigma_8 \Omega_0^{0.75} z_s^{0.75} \left( \frac{\theta}{\text{arcmin}} \right)^{\left(\frac{n+2}{2}\right)},$$

where $\Omega_0$ is the density of the Universe and $\theta$ the measurement scale in arcmin. There are similar relations for the correlation functions, but we can define several types of correlation functions. Here we are interested in $\langle e_t(\theta)e_t(0) \rangle$, $\langle e_r(\theta)e_r(0) \rangle$ and $\langle e_t(\theta)e_r(0) \rangle$, where $e_t$ and $e_r$ are the tangential and the radial component of the shear respectively:

$$e_t = -\gamma_1 \cos(2\theta_{gal}) - \gamma_2 \sin(2\theta_{gal})$$

$$e_r = -\gamma_2 \cos(2\theta_{gal}) + \gamma_1 \sin(2\theta_{gal}),$$

where $\gamma_i$ are the Cartesian components of the shear and $\theta_{gal}$ is the position angle of the pair of galaxies. The correlation functions mentioned above have a particular interest because of the specific signatures induced from weak lensing by large scale structures. From the scalar nature of the gravity we can show that $\langle e_t(\theta)e_r(0) \rangle$ should vanish, that $\langle e_t(\theta)e_t(0) \rangle$ is positive and $\langle e_r(\theta)e_r(0) \rangle$ should become negative for a finite range of scale.

*See Nick Kaiser’s home page at [http://www.ifa.hawaii.edu/~kaiser/](http://www.ifa.hawaii.edu/~kaiser/).
3.2 Measurements and amplitude of the residual systematics

We assumed that we already have a catalogue of galaxy ellipticities $e$ corrected from the PSF anisotropy. We call $\sigma_e$ the ellipticity dispersion. From a set of $N$ galaxies at positions $\theta_k$ with ellipticities $e_\alpha(\theta_k)$ we can built an estimate of the variance of the shear at the position $\theta_i$

$$E[\gamma^2(\theta_i)] = \sum_{\alpha=1,2} \left( \frac{1}{N} \sum_{k=1}^{N} e_\alpha(\theta_k) \right)^2,$$

whose the ensemble average is $\langle E[\gamma^2(\theta_i)] \rangle = \sigma_e^2/N + (\gamma^2)$. The term $\sigma_e^2/N$ can be removed either by measuring it on randomized catalogues, or by choosing and unbiased estimate equal to Eq.(3) without the diagonal elements.

An estimate of the correlation function $E[e_i(0)e_j(r)]$ (where $i$ and $j$ are either $t$ and/or $r$) is built by summing $e_i(0)e_j(r)$ for all the possible pairs of galaxies separated by a distance $r$.

Figure 1 shows the measured variance of the shear in our survey. The signal (thick line) exhibits the characteristic power law scale dependence as predicted from Eq.(1), and the amplitude of the signal has the correct order of magnitude. However, as we shall see in the next Section, the cosmic variance and the error bars are too large to put tight constraints on the cosmology.

We have shown in our original paper\cite{paper26} that the corrected ellipticity of the galaxies are uncorrelated with the ellipticity of the stars, which demonstrates the low level of residual systematics present in the catalogues\cite{catalogue}. We have reproduced in Figure 1 (thin solid lines) the variance of the shear measured when the galaxies are picked up according to the local star ellipticity instead of taking the galaxies falling into a given smoothing window. Each estimate of the shear variance is done using Eq.(3), where the $N$ galaxies have in common a similar PSF anisotropy amplitude on the data. It is then easy to convert $N$ to a scale $\theta$, since the number density of galaxies is roughly constant. The resulting shear variance is shown as the thin solid lines on Figure 1 for three cases of possible source of residual systematics (see caption for details). It shows that any residual systematic cannot be due to star ellipticity, optical distortion and CCD frame alignment.

A robust test of the gravitational lensing origin of the signal is to measure the correlation function as indicated above. Figure 2 shows the two relevant correlation functions $\langle e_t(\theta)e_t(0) \rangle$ and $\langle e_r(\theta)e_r(0) \rangle$. The third one, not shown here, $\langle e_t(\theta)e_r(0) \rangle$ is zero as we expect from the scalar origin of the gravitational field. This results from the fact that systematics are almost non-existent in the galaxy catalogue, which is a strong supports for the cosmic origin of our signal.

\cite{however} However we found a constant bias of $\langle e_1 \rangle \simeq -0.01$ for all the galaxies which we corrected for. The source of the bias is still unclear.
Figure 3: The thick solid line is drawn from Figure 2 without the measurement error bars. The dashed lines show the prediction of $\langle \gamma^2 \rangle$ from ray-tracing simulations and the cosmic variance obtained from several realizations. From top to bottom: $(\Omega_0, \sigma_8) = (1., 1.); (0.3, 0.85); (0.3, 0.6)$. The source redshift is 1 and the power spectrum CDM-type.

However the survey size is still too small to have a low noise measurement of these quantities, and to extract the useful cosmological information. Instead, we shall see this detection as a success showing the feasibility of the cosmic shear searches.

### 3.3 Cosmological constraints

Although it is hard to calculate the cosmic variance of the measured quantities at small scale, we can use ray tracing numerical simulations in order to compare our measurement with some realistic scenario. Such numerical simulations are available and provide several realizations for a set of cosmological models, thus allowing a first analysis of the cosmic variance. Figure 3 is a comparison of our shear variance measurement (thick solid line) with three different models: $(\Omega_0, \sigma_8) = (1., 1.); (0.3, 0.85); (0.3, 0.6)$ from top to bottom (see the caption for details). The error bars show the cosmic variance measured out of several realizations for each model. Although we can only marginally reject the two extreme models, this figure shows that the data are already in favor of cluster normalized models, as suggested by the simplified analytical estimate Eq.(1).

### 4 Future prospects

The aim of the above Section was to present a condensed view of our recent cosmic shear detection with the first stream of data obtained at CFHT. All the relevant technical details can be found elsewhere; here we emphasized the control of the systematics to a reasonable level and that the signal is consistent with the gravitational lensing predictions, although we are not yet in good position to put tight constraints on the cosmology. However, we now have 9 sq. degrees in I (instead of 2), ready for scientific analysis, of comparable image quality of the data discussed here, and the numerical simulations indicate that this is enough to make a very significant measurement of various lensing statistics.

It is worthwhile to ask what can be done next. The next step is the confirmation of the cosmological nature of the signal over many different aspects. There are two areas with significant room for improvement:

1-Beating the systematics: following the same strategy in our cosmic shear paper, we can search for systematics by binning the data in various ways. With 9 sq. degrees we can bin the
data in a much refined way than we did before. We can study the alignment of the galaxies with the stars in bins of magnitude, size or other parameter. We can also split the survey into smaller parts and analyze independently the different parts.

2-Search for specific gravitational lensing signatures: this was done with the correlation function, but we can do much more with 9 sq. degrees. Of course the signal-to-noise of the correlation function will be much better, and we can study its shape as a function of size and magnitude of the galaxies. The variance of the shear measured with another filter than top-hat will be possible: for instance the Map statistic is known to have a specific angular dependence if induced by gravitational lensing. With a 9 sq. degrees survey we can also measure the skewness of the convergence, which is a direct probe of the cosmological parameters. Such measure would require accurate mass reconstruction in non-trivial topologies (non-straight edges and holes in the field), and preliminary studies show that such reconstructions give stable and unbiased mass maps. Peak statistics is also accessible with a good signal-to-noise with such a survey size. Measurement of the shear power spectrum will be done in order to check that the power is distributed over the different scales like what weak lensing theory predicts (and do not dominate at one specific scale for instance).

It has recently been suggested that galaxies might have an intrinsic ellipticity correlation. Although this could also be tested using specific lensing statistics (yet to be developed), we can completely get rid of the effect by measuring the correlation between different source redshift planes. Since our full survey will be 16 sq. degrees in four colors, we hope to have the luxury to work with many different redshift planes (using photometric redshifts) and to extract without ambiguity the cosmic shear information and the intrinsic correlations.

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