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New results from weak-lensing surveys

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Abstract. The deflection of light coming from background galaxies by the gravitational potential associated to the large scale structure of the universe produces a coherent alignment of galaxy ellipticity. This ellipticity is an unbiased estimator of the cosmic shear field. The properties of this field can be completely predicted as a function of the cosmological scenario and initial power spectrum of density perturbations. Measuring the cosmic shear allows the determination of different cosmological parameters, mainly Ω_m and σ_8. The basic principles of the cosmic shear theory are described as well as the present status of observations and the future perspectives of the CFHT Legacy Survey.

Key words. gravitational lensing, large scale structure, cosmological parameters

1. Introduction

All light rays undergo a deviation in their trajectory when they go through a gravitational potential. All the objects observed in the sky, except those at very low redshift, are distorted due to this property. This distortion can be very spectacular, as in the case of giant arcs and Einstein rings but it is present for every observed galaxy with the only condition that its rays cross an overdensity of matter before arriving at the telescope.

The observation of this distortion is only a question of sensitivity of instruments and control of systematics and can give a lot of information on the properties of the lensing object.

Cosmic shear is the coherent distortion (that is in the same direction) of the background galaxies by the large scale structure of the universe in the weak lensing regime.

Observed for the first time five years ago, the cosmic shear is one of the most recent and promising tool to investigate the matter distribution in the universe and to measure the 3D power spectrum of dark matter and the most important cosmological parameters.

This paper presents a short description of the most important theoretical and observational aspects of cosmic shear as well as the present results and future perspectives for the cosmic shear surveys. A more detailed discussion on cosmic shear can be found in Van

Waerbeke & Mellier (2003), Réfrégier (2003), Hoekstra (2003).

2. The convergence and shear fields

Assuming an isotropic and homogeneous universe described by the FRW metric, the physical distance, $\boldsymbol{\xi}$, of two rays coming from the same distant source in a empty universe is given by $\boldsymbol{\xi} = f_K(w_S)\ \mathrm{d}\boldsymbol{\theta}$ where $f_K(w_S)$ is the angular diameter distance of a source at radial distance w_S and $\mathrm{d}\boldsymbol{\theta}$ is the observed angular vector between the two rays (see Figure 1).

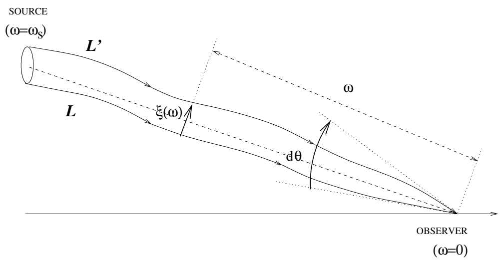

Fig. 1. A light bundle and two of its rays. $\boldsymbol{\xi}(w)$ is the physical diameter distance, which separates the two rays on the sky, viewed from the observer ($w = 0$).

Due to the presence of matter along the line of sight the vector $\boldsymbol{\xi}$ changes in a more complicated way:

$$\begin{aligned} \boldsymbol{\xi} &= f_K(w_S)\mathcal{A}\ \mathrm{d}\boldsymbol{\theta} \\ &= f_K(w_S)\begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} \mathrm{d}\boldsymbol{\theta} \end{aligned} \quad (1)$$

where $\mathcal{A}$ is the amplification matrix and describes the effects of the gravitational distortion through the scalar field, κ, called convergence field, and the pseudovectorial field, $\boldsymbol{\gamma}$, called the shear field. The amplification matrix as well as the fields κ and $\boldsymbol{\gamma}$, can be expressed as a function of the gravitational potential responsible for the gravitational lensing. Using a first order expansion for $\mathcal{A}$ and the gravitational potential Φ, we obtain:

$$\mathcal{A}_{ij}(\boldsymbol{\theta}) = \delta_{ij} + \mathcal{A}^{(1)}_{ij}(\boldsymbol{\theta}) = \delta_{ij} - \frac{2}{c^2}$$

$$\times \int_0^w \mathrm{d}w'\, G(w,w')\Phi^{(1)}_{,ij}(f_K(w')\boldsymbol{\theta}, w') \quad (2)$$

where

$$G(w,w') = \frac{f_K(w-w')f_K(w')}{f_K(w)} \quad (3)$$

is the geometrical factor containing the distances lens–object, observer–lens and observer–object, the second factor is the second order derivative of the first order expansion of the gravitational potential and the amplification matrix is computed for a single object at a distance w. This equation is valid in the Born approximation where the integral is computed along the unperturbed light path.

Using the Poisson equation and considering the more realistic case of a redshift distribution $p_w(w)\mathrm{d}w$ for the lensed objects we can write the convergence field as a function of the mass density contrast δ:

$$\kappa(\boldsymbol{\theta}) = \frac{3}{2}\frac{H_0^2}{c^2}\Omega_0 \int_0^{w_{\mathrm{H}}} \mathrm{d}w\, g(w)\, f_K(w)\frac{\delta(f_K(w)\boldsymbol{\theta}, w)}{a(w)} \quad (4)$$

where

$$g(w) = \int_w^{w_{\mathrm{H}}} \mathrm{d}w'\ p_w(w')\,\frac{f_K(w'-w)}{f_K(w')} \quad (5)$$

w_H is the horizon, H_0 is the present Hubble costant, Ω_0 is the mean density parameter and a is the expansion factor.

For a given cosmological model and an initial power spectrum of matter perturbations, we can compute the properties of the convergence field with the main practical difficulty of computing the non linear evolution of the power spectrum. Viceversa, we can investigate the cosmological parameters and the 3D power spectrum of the dark matter measuring the lensing fields.

¿From the observational point of view, the convergence produces a magnification of the original image while the shear produces an elongation of the object shape. Of course, we have to know exactly the shape and the size of the unlensed object to measure the effects of the lensing fields. While this is impossible for a single object, the situation changes when averaging on many objects. The mean unlensed size is still difficult to know but we can assume a circular original shape accepting the hypothesis of no preferred direction for the intrinsic ellipticity of galaxies.

For this reason the properties of the shear field can be directly measured while for the convergence we have to exploit shear measurements through mass reconstruction.

To measure the shear field we define the galaxy ellipticity as a function of the second moments of the surface brightness $f(\boldsymbol{\theta})$:

$$\mathbf{e} = \left(\frac{I_{11} - I_{22}}{Tr(I)}; \frac{2I_{12}}{Tr(I)} \right) \tag{6}$$

with

$$I_{ij} = \int \mathrm{d}^2\theta W(\theta)\theta_i\theta_j f(\boldsymbol{\theta}) \tag{7}$$

$W(\theta)$ is a window function used to suppress the noise contribution far away from the object.

Before computing the shear from the observed galaxy ellipticities, we must correct them for the point spread function (PSF) which smears the lensed images. The most used method, developed by Kaiser, Squires & Broadhurst (1995), adopts a perturbative approach to correct for the PSF convolution (see also Luppino & Kaiser (1997) and Hoekstra et al. (1998)). The corrected ellipticity is an unbiased estimator of the shear field.

Investigating the statistical properties of cosmic shear, the easier quantity to measure is its power spectrum that is equal to the convergence power spectrum and therefore it is directly connected to the 3D power spectrum of the dark matter.

Three different two points statistics methods are generally used: the variance of the shear, computed using a top–hat filter, the aperture mass variance, $M^2_{\rm ap}$ (Schneider et al. 1998), computed using a compensated filter, and the two points correlation functions.

For all these methods two different components of the measured field can be defined: the E and B modes, respectively a curl–free and a curl component. Nevertheless, this separation can be done in an unambiguous way only for the aperture mass variance that is insensitive to the mass sheet degeneracy, while for the other two methods the separation is done up to an integration constant (Van Waerbeke, Mellier & Hoekstra 2005).

The E and B modes separation is very important for cosmic shear: the signal being produced by a scalar gravitational potential, only E modes can be generated by gravitational lensing. The presence of B modes in the signal can be associated with an intrinsic alignment of the galaxy ellipticities but the current interpretation is that this effect is negligible and B–modes are a powerful tool to control the presence of residual systematics (Pen, Van Waerbeke & Mellier 2002).

3. Observational results

Cosmic shear was detected for the first time in year 2000 (Bacon et al. 2000; Kaiser, Wilson & Luppino 2000; Maoli et al. 2001; Van Waerbeke et al. 2000; Wittman et al. 2000). In these five years the detection was confirmed by a lot of groups with 11 different instruments, covering more than 150 deg^2 in the sky with more than 200 uncorrelated fields. Three of these measurements were from space, the rest from the ground.

The improvements in sky coverage, in surveys deepness, and in data analysis techniques produced the first interesting constraints on cosmological parameters.

With a good estimation of the source redshift distribution and with a prior for H_0, the shear variance mainly depends on the mean matter density, Ω_M, and the normalization of the power spectrum, σ_8. Putting together all the available measurements of cosmic shear we obtain:

$$\Omega_M = 0.30 \pm 0.10 \quad \sigma_8 = 0.85 \pm 0.15 \tag{8}$$

at 99% confidence level.

Using only Virmos–Descart (Van Waerbeke, Mellier & Hoekstra 2005) and RCS (Hoekstra 2003) data, jointly with CMB data (from WMAP and CBI), we get better constrains:

$$\Omega_M = 0.30 \pm 0.07 \quad \sigma_8 = 0.85 \pm 0.06. \tag{9}$$

To go further towards an era of precision cosmology, a new generation of cosmic shear surveys, able to compete with the results of CMB and type Ia supernovae experiments, must be planned. The CFHT Legacy Survey has been designed to comply with these requirements.

Using the unique capability of MegaCam, a 36 CCDs array with 1deg^2 field of view, the CFHTLS Wide survey will cover 170 deg^2, spread over three uncorrelated fields. The main advantages of the Wide survey are:

- improve the statistic by increasing the number of galaxies by a factor 10;
- improve the k-space coverage observing larger patches in the sky and probing all the angular scales up to 7 degrees;
- improve the photometric redshift estimate observing in five different optical filters (u*, g', r', i', z'); a follow up in the NIR region is planned in the near future using the WIRCAM facility.

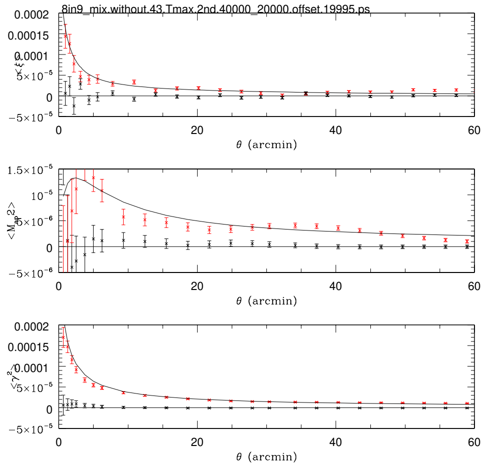

Fig. 2. Weak lensing analysis of CFHTLS Wide data. from top to bottom: E (red) and B (black) modes derived from the 2–point correlation function, the $M_{\rm ap}$ variance and the top-hat variance.

A preliminary analysis of the first data release is shown in figure 2. The cosmic shear is clearly detected with all the three statistical methods. B modes are negligible except at very small scales showing a good control of systematics.

4. Conclusions

After the first detection of cosmic shear and the first results in contraining the value of some cosmological parameters, a new generation of survey started. The CFHTLS first results proofs its capability to improve the precision in cosmological parameters determination: when all the data will be available, CFHTLS will be able to constrain with high precision the values of the Ω_M, σ_8, as well as the slope, n_s, of the primordial mass power spectrum, the running spectral index, α_s, the Hubble parameter, h, and the barionic matter density, ω_b. CFHTLS will allow to study higher order moments of the shear field and to investigate time dependent dark energy models using redshifts informations to measure the cosmic shear in different redshift slices of the universe (tomography).

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