DETECTION OF NON-GAUSSIAN SIGNATURES IN THE VIRMOS-DESCART LENSING SURVEY

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ABSTRACT

We have detected non-Gaussian signatures in the VIRMOS-DESCART weak lensing survey from a measurement of the three-point shear correlation function, following the method developed by Bernardeau, van Waerbeke and Mellier (2002). We obtain a 2.4σ signal over four independent angular bins, or equivalently, a 4.9-σ confidence level detection with respect to measurements errors on scale of about 2 to 4 arc-minutes. Both amplitude and shape are found to agree with theoretical expectations that have been investigated for two cosmological models. This supports the idea that the measure corresponds to a cosmological signal due to the gravitational instability dynamics. Its properties could be used to put constraints on the cosmological parameters, in particular on the density parameter of the Universe, but the error level as well as the cosmic variance are still too large to permit secure conclusions. 

1. INTRODUCTION

The large-scale structures of the Universe are expected to form from the gravitational growth of initial density perturbations obeying Gaussian statistics. As the Universe expands and the perturbations grow, non-Gaussian features are expected to emerge in the density field due to gravitational dynamic effects. These features can be characterized with perturbation theory calculations, which allow to compute for instance the skewness, third moment of the local density probability distribution function (Peebles 1980, Fry 1984, Bernardeau 1992). The reduced skewness of the density field has been found to be quite insensitive to the variance and the cosmological parameters (Juszkiewicz et al. 1992, Bernardeau 1994). This is not the case for weak lensing surveys since they trace the integrated mass along the line-of-sight which is roughly proportional to the density parameter of the Universe. Weak lensing by large scale structures has been measured by several teams as a distortion field of distant galaxies coherent over large angular distances (Bacon et al. 2000, Hämmerle, et al., 2001, Hoekstra et al. 2001, Kaiser et al. 2000, Maoli et al. 2001, Rhodes et al. 2001, van Waerbeke et al. 2000 and 2001, Wittman et al., 2000). The projected mass density reconstructed from the distortion field (i.e. the convergence field) can be used for non-Gaussian signatures searches, as shown in Bernardeau, van Waerbeke & Mellier (1997, hereafter BvWM97). This work and further studies (Jain & Seljak, Bernardeau & Mellier, 1999) have shown that the non-Gaussian properties of the convergence field can be used as a probe of the cosmological density parameter, with a weak dependence on the cosmological constant ΩΛ, provided that the redshift distribution of the sources is known.

However, a straight application of these theoretical considerations to real data sets turned out to be more arduous than expected. Indeed the convergence field has to be recovered from a mass reconstruction process which uses a continuous shear field obtained from a smoothed map of the discrete galaxy ellipticities. Unfortunately, surveys have a non trivial topology, with many masked areas due to light scattering, bright stars, comet-like reflections, asteroid/airplane tracks, very bright galaxies, etc.... Since the masks sizes cover a range of scales from a few arc-seconds to two degrees and are strongly anisotropic (for instance bright stars preferentially saturate along CCD columns), mass reconstruction in such data sets is still challenging. An alternative approach is the aperture mass applied to cosmic shear (Schneider et al. 1998), which allows the measurement of the skewness from the distortion field directly, bypassing the mass reconstruction process. Unfortunately, our attempts for measuring the skewness of the aperture mass lead to very noisy and un-significant results. Recently, Bernardeau, van Waerbeke and Mellier (2002, hereafter BvWM02) have proposed a new method using some specific patterns in the shear three-points function. This method has also the advantage to bypass the mass reconstruction process. Despite the complicated shape of the three-points correlation pattern, BvWM02 uncovered a specific geometrical property in it which can serve as a basis for non-Gaussian feature measurements. A detection strategy based on this method has been found to be robust.

1 Based on observations obtained at the Canada-France-Hawaii Telescope, which is operated by the National Research Council of Canada, Le Centre National de Recherche Scientifique (Institut National des Sciences de l’Univers), and the University of Hawaii.
and usable in patchy catalogs, being quite insensitive to the topology of the survey. In the following we apply this method to the VIRMOS-DESCART weak lensing survey done at the Canada-France-Hawaii Telescope.

2. Optimized 3-points Correlation Function Applied to VIRMOS-DESCART Data

2.1. Method

Let us consider a triplet of galaxies at locations $\vec{x}_1$, $\vec{x}_2$ and $\vec{x}$, and their shear estimates $\tilde{\gamma}(\vec{x}_1)$, $\tilde{\gamma}(\vec{x}_2)$ and $\tilde{\gamma}(\vec{x})$. BvWM02 introduced the shear 3-points correlation function

$$\xi_3(\vec{x}') = \langle (\tilde{\gamma}(\vec{x}_1) \cdot \tilde{\gamma}(\vec{x}_2)) \tilde{\gamma}(\vec{x}') \rangle$$

(1)

for a fixed $|\vec{x}_2 - \vec{x}_1|$ distance. At fixed separation $\vec{x}_{12}$, $\xi_3$ is expected to scale like the square of the shear 2-point correlation function, $\xi_2(\vec{x}_{12}) = \langle \tilde{\gamma}(\vec{x}_1) \cdot \tilde{\gamma}(\vec{x}_2) \rangle$. Its dependence on the cosmological density parameter ($\Omega$) is expected to be similar to the convergence skewness ($\approx \Omega^{-0.8}$), with an additional dependence on the slope of the mass power spectrum. The dependence of $\xi_3(\vec{x}')$ on $\vec{x}'$ is in general complicated although asymptotic properties can be obtained analytically. However $\xi_3(\vec{x}')$ has been found to be rather uniform, and perpendicular to $\vec{x}_{12}$, over an elliptic area that covers the segment joining $\vec{x}_1$ to $\vec{x}_2$. This central pattern turns out to be robust against different cosmologies and smoothing scales, with an amplitude which can be related to the cosmological parameters. The results obtained by BvWM02 in synthetic catalogs suggested that present-day cosmic shear surveys were already large enough to allow a detection. We have undertaken such a measurement in the VIRMOS-DESCART lensing survey.

We consider the geometrical average,

$$\bar{\xi}_3(\vec{x}_1 - \vec{x}_2) = \int_{\text{Ell}} \frac{d^2\vec{x}'}{V_{\text{Ell}}} \xi_3(\vec{x}')$$

(2)

which corresponds to the average three-point function inside an elliptic area where it is expected to vary weakly. An optimum selection of pair points, where close pairs and highly elliptical galaxies are rejected, turns out to provide an optimal information on non-Gaussian features in simulated catalogues. BvWM02 checked that different sources of noise produced by the intrinsic ellipticity distribution of galaxies, by realistic galaxy shape measurements and PSF corrections and by masking effects do not affect the result. In all configurations the global signal to noise remains higher than 5 for scales between 30 arc-seconds to 5 arc-minutes for simulated catalogues containing as many galaxies as real data, with ellipticity distribution, PSF anisotropy and masking templates similar to the VIRMOS-DESCART sample.

2.2. The VIRMOS-DESCART Sample

The VIRMOS-DESCART sample used in this work is part of the DESCART cosmic shear programme which uses the VIRMOS photometric/imaging survey for wide field cosmic shear. It covers 11.7 deg² of CFH12K images spread over four uncorrelated fields. All data were obtained in I-band up to a limiting magnitude of $I_{AB} = 24.5$ (within 5 arc-second aperture, 5-σ), which is consistent with a mean source redshift of $z \approx 0.9$. The data contain all observations used by van Waerbeke et al (2001) plus new fields obtained in September and November 2000. All images were processed as described in van Waerbeke et al (2001) at the TERAPIX data center. From an initial detection we build up a sample containing 1.6 millions objects. After masking and all galaxy selection processes, it reduces to 580,000 galaxies, covering an effective area of 8.5 deg². Close-pairs with angular separation smaller than 10 arc-seconds can produce systematics and are rejected (see van Waerbeke et al 2000).

Following standard notation, the shear is defined as the mean source ellipticities

$$\gamma_1 = \langle \cos(2\theta) \rangle, \quad \gamma_2 = \langle \sin(2\theta) \rangle$$

(3)

where $\theta$ is the angle between the major axis of the source galaxy and the $x$ axis, and $\epsilon = (a - b)/(a + b)$ is determined by the major axis length $a$ and minor axis length $b$. It is computed according to the rules and weighting schemes given in Pen et al. (2001). In particular, we consider in this Letter the decomposition into $E$ and $B$ modes described in Pen et al. (2001) which is used for residual systematics checks for the 2-points statistics. However an improved PSF anisotropy correction based on a better map of the star anisotropy was used here, which is presented elsewhere (van Waerbeke et al. in preparation).

The statistical estimators for the binned two and three point functions are given by

$$\xi_2(d_{ij}) = \frac{\sum_{ij} w_i w_j (\vec{e}_i \cdot \vec{e}_j)}{\sum_{ij} w_i w_j}$$

(4)

$$\bar{\xi}_3(\vec{d}_{ij}) = \frac{\sum_{ijk} w_i w_j w_k (\vec{e}_i \cdot \vec{e}_j) e^{ij}_k}{\sum_{ijk} w_i w_j w_k}$$

(5)

where $e^{ij}_k$ is the tangential component of the ellipticity of galaxy $k$ with respect to the $(\vec{x}_j - \vec{x}_i)$ direction, the summations are made for pairs or triplets such that $d_{ij} = |\vec{x}_i - \vec{x}_j|$ is in the chosen bin, $\vec{x}_k$ lies within the ellipse defined by $|\vec{x}_k - \vec{x}_j| > 1.1 |\vec{x}_i - \vec{x}_j|$ and $w_i$ are weights associated to each galaxy according to the scheme discussed in BvWM02.

2.3. The VIRMOS-DESCART 2 and 3-points Correlation Functions

Figure 1 shows the estimated 2-points (top) and reduced tangential 3-points (bottom) correlation functions. Measurements have been made in regularly spaced bins of width 400 pixels (e.g. 1.3 arcmin). For comparison, the thick dotted lines shows the corresponding quantity for a $\tau$CDM and the thick dashed line for an OCDM model with a sources redshift of unity, which is not far from our mean source redshift of 0.9. In this plot the error bars are the measurement errors and do not include the cosmic variance (see BvWM02). The dot-dashed line represents the signal corrected from the residual systematics (the $E$-mode subtracted from the $B$ mode contribution, $E-B$, as discussed in Pen et al. 2001), while the solid line shows
the total \((E + B)\) measured signal. The closeness of the two curves reveals the small amount of residual systematics still present in the 2-points correlation function.

A quality assessment of the 3-points function measurements can be done by studying the effect of PSF correction. This correction is inferred from the star shapes (they ought to be round) following the standard procedure described initially in Kaiser et al. (1995). It can be thought as a star shear field that has to be subtracted off the measured galaxy shapes. One can then measure the 2- and 3-points correlation functions of the star field and compare them to the PSF corrected data set. This is presented on Figure 2. The solid line in the top and bottom plots respectively show the star two and three points functions, which are compared to the same quantities measured on the corrected galaxies (dashed lines and dashed-dot line for the corrected \(E\)-mode 2-points function). The star two-points correlation function is significantly larger than the galaxy’s signal, but this is known not to be a problem for the two-points function: Erben et al. 2001 and Bacon et al. 2001 have shown that the PSF correction can account for star anisotropies as large as 10% (the stars r.m.s. anisotropy is 6% in our data) to a precision better than than one percent. This is also demonstrated in BvWM02 using cosmic shear simulated data. The smallness of the \(B\)-mode is another proof of the robustness of the correction.

Fig. 1.— Results for the VIRMOS-DESCART survey (dot-dashed lines: \(E - B\) mode, solid line: \(E + B\) mode , top: two points correlation function, bottom: reduced three point function) compared to \(\tau\)CDM and OCDM results (dotted and dashed lines respectively) from Jain, Seljak & White (2000).

Fig. 2.— Results for the VIRMOS-DESCART survey (dashed lines: \(E + B\) mode, dot-dashed line: \(E - B\) mode) compared the properties of the star anisotropy field statistics (solid lines).

BvWM02 have also shown that the correction scheme works for the shear three-points function. We see that the situation for the three-point function (Figure 2, bottom panel) is far more interesting than the two-points function: the correction is smaller (that is in principle more robust), and the angular dependence of the star three point function does not bear any resemblance with the galaxy three-point function. If our three-point function signal were dominated by systematics it would likely not fit the expected signal as we can see from Figure 1, but would be more similar to Figure 2, bottom panel (solid line). Finally we have checked that cuts in magnitudes do not significantly affect the results. We have thus some evidences that what is observed is genuinely cosmological.

Another issue, not taken into account in the error bars, is the so-called cosmic variance, that is the amount by which such a signal can vary in surveys of finite size. The complete theory of cosmic variance for such a survey is yet to be done (and given the topology is nothing but easy!). Figure 3 shows the cosmic variance obtained from a set of 7 ray-tracing realizations of the open CDM model (Jain et al. 2000). Note that then the error-bars in the different bins are correlated. A rough examination of the situation shows that while the cosmic variance dominates the error budget for the two-point function, observational errors and cosmic variance are of similar amplitude for the three-point function.

A \(\Lambda\)CDM is well within the error bars whereas other models such as \(\tau\)CDM or OCDM are more marginal. However none of these conclusions can yet be firmly established.
3. DISCUSSION

The result shown on Figure 1 is the first detection of non-Gaussian features in a cosmic shear survey. The signal is detected with a 2.4-σ confidence level on 4 independent bins which gives a 4.9-σ global confidence level. Such a result opens the route to break the degeneracy between $\Omega_m$ and $\sigma_8$ in a way which is independent on assumptions beyond the solely hypothesis that large-scale structures grows from gravitational instability of an initial Gaussian field.

We note that the amplitude of the reduced tangential 3-point correlation function exhibits an angular dependence which is in agreement with theoretical expectations. It supports the interpretation of these results as genuine effects of the gravitational dynamics.

The signal is however still too noisy to provide reliable information on cosmological parameters. Moreover, several obstacles have yet to be overcome. It is first important to understand to which level the measurements are contaminated by systematics. This can be done through consistency checks yet to be invented (a statistic which cancels the signal in a non-trivial way, like the 45 degrees rotation test for the aperture mass will have to be found for the three-point function). We have already checked with the anisotropy of the stars that our signal is unlikely to be dominated by systematics since it would otherwise exhibits a totally different angular dependence. In the next stages, the scientific interpretation of the three-point function measurements will require a significant improvement over several issues:

- The knowledge of the redshift distribution of the sources is crucial for the third order statistics (see BvWM97);
- The source clustering effect might bias the measurement in a significant way (Bernardeau 1998, Hamana et al. 2001) if the width of the source distribution is too large;
- Intrinsic alignment of galaxies have a completely unknown effect on the non-Gaussian properties of the shear field.

Resolving these issues will require progress from both the theoretical/simulation side and from the observations, which are already on their way.

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