Reducing and constraining the intrinsic galaxy alignment contamination to weak lensing measurements

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Abstract.

We present a method for removal of the contaminating effects of intrinsic galaxy alignments, in measurements of cosmic shear from multi-colour weak lensing surveys. The method down-weights pairs which are likely to be close in three dimensions, based on spectroscopic or photometric redshifts. Results are dramatic: the intrinsic contamination of the low-redshift Sloan photometric redshift survey could be 80 times the lensing signal, but this can be almost completely removed, leaving random shot noise errors of the order of 10%. Intrinsic galaxy alignments, although an annoying contaminant for cosmic shear studies, are interesting in their own right, and we therefore present a new observational constraint for their amplitude from the aperture mass B-mode in the Red-Sequence Cluster Survey (RCS; Hoekstra, Yee & Gladders 2002b). The small measured B-mode rules out the published intrinsic alignment models from numerical simulations, which assume no evolution in galaxy clustering.

1. Introduction

A key assumption for cosmic shear studies is that galaxy ellipticities are randomly orientated on the sky. It is possible, however, that gravitational interactions during galaxy formation could in fact produce intrinsic shape correlations between nearby galaxies, mimicking to an extent weak lensing shear correlations. This effect will limit the accuracy of cosmological parameter estimation from weak lensing studies, but to what extent is still uncertain. In this conference proceedings, we review models for intrinsic galaxy alignments, estimated from numerical simulations, and summarise an optimal galaxy pair-weighting method, detailed in Heymans & Heavens (2003), which significantly reduces the contamination of weak lensing measurements by intrinsic galaxy alignments. We propose a simple optimised scheme for multi-colour surveys and show its effect for the Sloan photometric survey design and the RCS survey design.

Current analytical and numerical estimates for the amplitude and correlation length of intrinsic galaxy alignments, although in broad agreement on their
effect on weak lensing studies, differ in the details by an order of magnitude or more, (see contribution by King in this volume). Intrinsic galaxy alignments are potentially very interesting, providing information for galaxy formation, and possibly galaxy evolution, if evolution with redshift is observed in the intrinsic alignment signal. It is therefore desirable to determine the extent of intrinsic galaxy alignments observationally. At low redshifts, where weak lensing shear correlations are negligible, galaxy ellipticity correlations have been observed in the SuperCOSMOS survey, (Brown et al. 2002), and in the Tully catalogue (Pen, Lee & Seljak 2002). With deeper multi-colour surveys, for example COMBO-17 (Brown et al. 2003), intrinsic galaxy alignments can be observationally constrained by comparing ellipticity correlations before and after their removal with the application of a close pair downweighting scheme, or by using correlation function tomography (King & Schneider 2003). An additional observational constraint that we focus on here arises from observed aperture mass $B$ modes in weak lensing measurements, which serve as a good diagnostic for the presence of non-lensing sources within the data.

2. Estimating intrinsic galaxy alignments from numerical simulations

Assuming that luminous matter forms galaxies in all dark matter halos above some minimum mass limit, it is possible to acquire a three dimensional catalogue of galaxy shapes from a large N-body dark matter numerical simulation. The shape of each luminous galaxy can be modelled as a thin disc placed perpendicular to the angular momentum vector of its parent dark matter halo, (Heavens, Refregier & Heymans 2000, HRH), or by assuming that the galaxy ellipticity, $e$, is equal to that of its parent dark matter halo, (Croft & Metzler 2000; HRH; Jing 2002). The resulting calculated three dimensional ellipticity correlations, $\eta(r) = \langle e(x)e^*(x+r) \rangle$, for galaxy pairs separated by distance $r$, show significant alignment, $\langle ee^* \rangle \approx 0.01$, between galaxies pairs closer than a few tens of Mpc. This result alone shows that in numerical simulations, there is a preferred angular momentum direction for nearby dark matter halos. Projecting $\eta(r)$ into two dimensions yields an angular ellipticity correlation function $C_I(\theta)$, which can be directly compared to weak lensing shear correlation functions.

\[
C_I(\theta) = \frac{\int dz_a dz_b \phi_2(z_a) \phi_2(z_b) [1 + \xi_{gg}(r_{ab})] \eta(r_{ab})}{\int d\phi_a d\phi_b \phi_2(z_a) \phi_2(z_b) [1 + \xi_{gg}(r_{ab})]}, \tag{1}
\]

where $\phi_2$ is the survey selection function, and $\xi_{gg}(r)$ is the two-point correlation function, which takes into account galaxy clustering.

For shallow surveys, for example the Sloan photometric survey with median redshift $z_m \sim 0.2$, it is generally agreed that correlations from intrinsic galaxy alignments will far exceed the correlations expected from weak gravitational lensing. For deeper surveys with $z_m \sim 1.0$, assuming weak evolution in galaxy clustering, contamination can contribute up to 10% of the lensing signal.
Intrinsic galaxy alignments

3. An optimal method to remove the contamination from intrinsic galaxy alignments

If an accurate estimate of the intrinsic ellipticity correlation strength did exist, then it would be possible to subtract it, leaving ellipticity correlations induced purely by lensing. In the absence of a good estimate for the intrinsic correlation function it is obvious that one can reduce the contamination from intrinsic alignments by down-weighting nearby galaxy pairs. This is done at the expense of increasing the shot noise contribution from the distribution of individual galaxy ellipticities and therefore it is best to apply an optimised weighting scheme.

Given accurate galaxy redshifts, the optimal weighting for a galaxy pair $p$, derived in Heymans & Heavens (2003), is given by;

$$W_p = 1 - \frac{J_p \Lambda_1}{1 + \Lambda_2} \quad (2)$$

where

$$\Lambda_n \equiv \sum_q J_q^2 \quad (3)$$

$$J(r) \equiv \frac{fI(r)}{\sigma_{\text{pair}}} \quad (4)$$

$\sigma_{\text{pair}}$ is the shot noise error, and $fI(r)$ is the predicted intrinsic ellipticity correlation from a galaxy pair at separation $r$, multiplied by a fractional error $f$, which takes into account the uncertainty in the intrinsic alignment model. In practice, to guarantee the removal of any intrinsic alignment signal, the conservative approach is to set $f = 1$ and choose the strongest plausible intrinsic alignment model for $I(r)$.

We apply this scheme to the Sloan spectroscopic survey design comparing two intrinsic alignment models from HRH, and Jing (2002). Figure 1 shows that this optimal weighting scheme can largely remove the contamination by intrinsic alignments leaving almost pure shot noise. The shallow depth of this spectroscopic sample however, still prevents its use for weak lensing studies as the remaining shot noise exceeds the expected weak lensing signal.

4. Application to multi-colour surveys

The optimal weighting scheme is only applicable to spectroscopic surveys. More often surveys have estimates of galaxy distances from photometric redshifts, $\hat{z}$, with associated errors, $\Delta_z$. These errors are much larger than the scale over which galaxy shapes are intrinsically correlated. We therefore propose a semi-optimal weighting scheme dependent on estimated redshifts such that for a pair of galaxies with estimated redshift $\hat{z}_a$ and $\hat{z}_b$ we assign a zero weight if $|\hat{z}_a - \hat{z}_b| < \alpha \Delta_z$ and a weight of one otherwise. $\alpha$ is chosen to minimise the total error on the shear correlation function and will depend on the angular scale, and survey specification. With good photometric redshifts, this simple procedure does almost as well as the theoretical optimum where all galaxy distances are known, and is similar to a method simultaneously proposed by King & Schneider (2002).
Figure 1. Reduction in the error from intrinsic alignments and shot noise for the Sloan spectroscopic sample. The upper curves show the error in the shear correlation function for two intrinsic alignment models, Jing (triangles) and HRH (circles), assuming all galaxy pairs are weighted equally. With optimal weighting (filled), both intrinsic alignment signals are reduced close to shot noise (shown dashed) producing a negligible increase in shot noise. The expected weak gravitational lensing correlation function for a ΛCDM model, (dotted), is still dominated by shot noise for this shallow $z_m = 0.1$ sample.
Figure 2. Reduction in the error from intrinsic alignments and shot noise for photometric SDSS and RCS. The semi-optimal weighting, (filled circles), has reduced the unweighted HRH intrinsic alignment error (circles) to well below the expected amplitude of the weighted weak lensing shear signal, (dotted). The effect of semi-optimal weighting can be compared to the optimally weighted error, (dashed), attainable with spectroscopic redshifts.

We apply this scheme to the Sloan photometric survey design, SDSS, with $z_m = 0.2$, where the photometric redshifts are taken to be accurate to $\Delta z = 0.025$. We also apply this scheme to the RCS (Hoekstra et al. 2002a), with $z_m = 0.56$, where the photometric redshifts are taken to be accurate to $\Delta z = 0.3$. Figure 2 shows the correlations we expect to find for each survey from HRH derived intrinsic alignments and the best reduction that can be achieved with this method. The most startling result comes from the SDSS where, due to the wide sky coverage and accurate photometric redshift information it is possible to reduce intrinsic alignment systematic errors that are 80 times the lensing signal, to a random error, introduced by shot noise, that is only 10% of the lensing signal. For the RCS survey, even with fairly inaccurate photometric redshifts it is still possible to remove a significant systematic error, exceeding the lensing signal at angular scales $\theta < 10$ arcminutes. This results in a 20% random error arising from shot noise. Deeper surveys have also been investigated, resulting in 10% systematic errors being reduced to less than 1% random errors.

5. Aperture mass B modes. An observational constraint for intrinsic galaxy alignments

A good diagnostic for determining the level of systematic errors present in weak lensing measurements, is to decompose the shear correlation signal into E and B modes. This was first proposed by Crittenden et al. (2002), and is now a standard statistical test for the presence of non-lensing contributions to weak lensing measurements. Weak gravitational lensing produces curl-free distortions (E-type), and contributes only to the B-type distortions at small angular scales,
\( \theta < 1' \), due to source redshift clustering (Schneider, Van Waerbeke & Mellier, 2002). A significant detection of a B-type signal in weak lensing surveys is therefore an indication that ellipticity correlations exist either from residual systematics within the data and/or from intrinsic galaxy alignments which are thought to have no preferred distortion pattern. It is therefore possible to use observed B modes as upper limits for the B mode contribution from intrinsic galaxy alignments, provided all data systematics produce positive ellipticity correlations.

The decomposition for the RCS survey has been carried out using the aperture mass statistic, \( M_{ap} \), (Hoekstra et al. 2002b), which can be directly calculated from angular ellipticity correlation functions, (Crittenden et al. 2002; Schneider et al. 2002). Assuming that intrinsic galaxy alignments have no preferred tangential or radial alignment it is possible to calculate the expected intrinsic alignment aperture mass B mode from the angular projection of an intrinsic alignment model, \( C_I(\theta) \).

\[
\langle M_{\perp}^2(IA) \rangle = \frac{1}{2} \int_0^\infty d\theta \frac{\theta}{\theta^2} \left[ \xi_+^2(\theta) + T_+^2(\theta) \right] \tag{5}
\]

where \( \xi_+^2(\theta) = \frac{1}{4}C_I(\theta) \) and a useful analytic expression for \( T_+^2(x) \) is given in Schneider et al. (2002).

Figure 3 shows the intrinsic alignment contribution from an HRH model, to the aperture mass B mode, calculated assuming no evolution in galaxy clustering. Comparing this result with the observed RCS B mode, considered as an upper limit, clearly rejects this type of model, providing evidence that the assumptions made for estimating intrinsic galaxy alignment models from numerical simulations are too simplistic, or that assuming no evolution in galaxy clustering is incorrect.

6. Conclusion

This contribution and the contribution by Lindsay King have shown that with some redshift information it is possible to separate galaxy ellipticity correlations induced by weak gravitational lensing from contaminating intrinsic ellipticity correlations, thereby removing an unknown systematic error from cosmic shear analysis. We have presented a new observational constraint from the aperture mass B mode statistic, prompting the need for a re-assessment of the assumptions made when estimating intrinsic galaxy alignment models from numerical simulations. This constraint suggests that intrinsic alignments are a less significant contaminant at high redshifts than was previously predicted from numerical simulations. Intrinsic galaxy alignments can be directly constrained observationally at low redshifts, for example in the Sloan survey, although we have also shown here that this survey could now potentially be used as a weak lensing survey with the application of an optimised close galaxy pair down-weighting scheme. Deeper surveys with photometric information can also now be used to constrain intrinsic galaxy alignments, potentially providing valuable information for galaxy formation and evolution studies.
Figure 3. HRH intrinsic alignment model contribution to the aperture mass B mode $\langle M^2 \rangle$ for the RCS survey, compared to the measured RCS B mode.

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