1. INTRODUCTION

Weak gravitational lensing of distant galaxies by foreground large-scale structure has emerged as a powerful tool for modern cosmology (see Mellier 1999; Bartelmann & Schneider 2001; Refregier et al. 2003 for reviews), which has already provided constraints on cosmological parameters (see, e.g., Hoekstra et al. 2002; van Waerbeke & Mellier 2003 for the current status) and been touted for its potential to constrain dark energy (Benabed & Bernardeau 2001; Huterer 2002; Hu 2002a, 2002b; Abazajian & Dodelson 2003; Benabed & van Waerbeke 2003; Jain & Taylor 2003; Heavens 2003; Refregier et al. 2004; Takada & Jain 2004; Bernstein & Jain 2004; Takada & White 2004).

Lensing distorts the shapes of background galaxies; the percent level distortion induced by large-scale structure is referred to as cosmic shear. As shear surveys become more powerful, systematic errors need to be understood more fully. Fortunately, nature has provided us with a means to test for some systematic errors. Since lensing arises from a scalar gravitational potential, it generates a particular type of shear pattern. For example, the shear pattern around an isolated, spherically symmetric mass is called a (positive) E-mode signal and to B-modes of varying amplitudes. Exquisite control of such systematics will be required as we approach the era of precision cosmology with weak lensing.

We use numerical simulations to model the effect of seeing and extinction modulations on weak lensing surveys. We find that systematic fluctuations in the shear amplitude and source depth can give rise to changes in the E-mode signal and to B-modes of varying amplitudes. Exquisite control of such systematics will be required as we approach the era of precision cosmology with weak lensing.

Subject headings: cosmology: theory — gravitational lensing — large-scale structure of universe

2. SEEING AND EXTINCTION

One systematic effect that has received particular attention is the correction for the point-spread function (PSF; e.g., Kaiser et al. 1995; Hoekstra et al. 1998; Kuijken 1999; Kaiser 2000; Bernstein & Jarvis 2002; Hirata & Seljak 2003; Hoekstra 2004) and its anisotropy. Here, we consider two related issues: the effects of fluctuations in seeing conditions and Galactic extinction.

Seeing circularizes the images of galaxies, thereby degrading the lensing signal. Corrections for this “isotropic” PSF effect have been studied using simulations (e.g., Bacon et al. 2001; Erben et al. 2001) and by marginalizing over the uncertain shear calibration (Ishak et al. 2004). In practice a cosmic shear survey consists of many pointings of a telescope, and seeing can vary by a factor of 2 between the best and worst pointings. Furthermore, the seeing correction is determined for each chip separately. The finite number of stars that are used to characterize the isotropic PSF and the noise in the galaxy polarizabilities lead to uncertainties in the seeing correction, which vary on the scale of individual chips. For example, in the CFH12K and Megacam data analyzed in van Waerbeke et al. (2004), corrective factors differ by as much as 10% from chip to chip. Systematic errors in the lensing measurement may therefore be introduced on the scale of the telescope pointings or of individual chips due to imperfections in this correction.

A second effect of seeing fluctuations is to modulate the depth of the survey by down-weighting smaller images that have become too circularized. This increases the noise and alters the source z-distribution and can therefore be expected to have an effect that resembles source redshift clustering (e.g., Bernardeau 1998), although on a different angular scale. The measured signal thus probes different depths in different regions of the sky. Variable galactic extinction in a magnitude-limited survey will have a similar effect, although it should not be correlated with the signal.

We note that while a better understanding of the magnitude of the errors induced by these systematics is necessary, it is not our purpose to address this complex issue here. Instead, we examine the impact on simulated E- and B-mode signals for these systematic errors, assuming simple models that are likely to span the form and magnitude of the actual effect.

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3. SIMULATIONS

In order to assess the systematic errors induced by uncorrected changes in the calibration or depth of the survey, we make use of simulated weak lensing maps. These maps are generated by ray tracing through $N$-body simulations. We use the methods described in detail in White & Vale (2003), providing only a brief summary here.

Our calculation is done within the context of a $\Lambda$ cold dark matter model (model 1 of White & Vale 2003) chosen to provide a good fit to recent cosmic microwave background and large-scale structure data. The weak lensing maps are made from an $N$-body simulation using a multiplane ray tracing code, as described in Vale & White (2003). The code computes the $2 \times 2$ shear matrix $A$, which describes the distortion of an image due to lensing by a distribution of sources. The shear matrix $A$ is decomposed as

$$ A = \begin{pmatrix} \kappa + \gamma_1 & \gamma_2 + \omega \\ \gamma_2 - \omega & \kappa - \gamma_1 \end{pmatrix}, $$

where the $\gamma_i$ are the shear components, $\kappa$ is the convergence, and $\omega$ is the rotation, which is generally small.

We make maps of the shear and the convergence at a range of source redshifts from $z \sim 0$ to 3 in steps of $\Delta z = 0.5$. In each case, a $2048^2$ grid of rays subtending a field of view of 3° is traced through the simulation. The two shear components and the convergence are output at each source plane; for a distribution $d\rho / dz_s$, the weight given to source plane $j$ is

$$ w_j = \frac{dp}{dz_s} \left| H(z_j) \Delta \chi \right|. \quad (2) $$

We use a source distribution of the form (Brainerd et al. 1996)

$$ \frac{dp}{dz_s} \propto z_s^{2/3} \exp \left[-(z_s/z_0)^{2/3}\right]. \quad (3) $$

For this distribution $z_0 = \Gamma(8/3)z_{0.5} = 1.5z_{0.5}$. We use $z_0 = 0.5$ for our base model and include fluctuations in $z_0$ where appropriate.
4. MODELING SYSTEMATICS

We want to study modulations in the amplitude of the shear and the $z_s$-distribution, as described above. We test the first effect by generating two "modulation maps." The first is a smooth horizontal gradient running from 0.9 to 1.1, while the second has the map divided into 64 regions, 22' on a side, each of which is randomly assigned a value of 0.9 or 1.1. This second modulation has sharp edges, as we expect will occur for chip of which is randomly assigned a value of 0.9 or 1.1. This second modulation gives rise to a modulation map with a scale of 4 and the $z_s$-distribution described above. For the second "Gaussian" modulations, we compute the aperture mass statistics from modulations in the mean source redshift, using a coherence scale in the modulation map of .

5. RESULTS

To quantify the changes in the $E$- and $B$-modes caused by these modulations, we compute the aperture mass statistics $M_{ap}$ and $M_l$ from the shear maps. The former should be sensitive only to $E$-modes, while the latter is sensitive only to $B$-modes. We use the $\ell = 1$ form of $M_{ap}$ described by Schneider et al. (1998),

$$M_{ap}(x_i; R) = \int d^2 x \gamma_t(x + x_i) G \frac{|x|}{R},$$

where $x_i$ is the position on the sky, $R$ is the angular scale, $\gamma_t = - (\gamma_i \cos 2\phi + \gamma_r \sin 2\phi)$ is the tangential shear, and

$$G(y) = \frac{6}{\pi R^2} y^2 (1 - y^2) \text{ for } y \leq 1$$

is the radial kernel, which vanishes for $y > 1$. On the smallest scales (less than 2'), the convolution is not well approximated by the sum over pixels, but this is not an issue for the larger scales that will be of most interest to us. To compute $M_l$, we interchange $\gamma_1 \rightarrow \gamma_2$ and $\gamma_2 \rightarrow -\gamma_1$ before computing the integral in equation (4).

An example of an $M_l$ map, excluding the regions within $R$ of the map edges, is given in Figure 1. Note that even the unmodulated maps contain some $B$-modes, as expected from effects such as lens-lens coupling and violations of the Born approximation (Jain et al. 2000; Vale & White 2003). However, modulations of the amplitude of the shear signal and of the $z_s$-distribution both significantly enhance the $B$-modes. While the $B$-modes are concentrated in regions where the amplitude or depth changes abruptly, there is additional structure in the lensing signal that makes the pattern somewhat complex.

In order to quantify these effects further, we compute the variance of the $M_{ap}$ and $M_l$ maps. This variance probes a narrow range of wavemodes in the power spectrum, peaked at roughly $R/3$. We show the effect of modulations in the amplitude of the shear in Figure 2. The smooth gradient modulation generates very small $B$-modes and a change in the $E$-mode power on all scales. This is not unexpected: the initial $B$-mode is very small. If the transformation from shear to convergence ($E$-mode) was completely local, then rescaling the shear would not generate any $B$-mode. The figure of merit is thus how much the gradient changes across the "nonlocal" scale in converting shear to convergence. Whatever the reason, the $B$-mode is much smaller in amplitude than the change in the $E$-mode, also shown in Figure 2.

A sharp modulation in amplitude gives a larger $B$-mode sig-
nal, with a similar change in the $E$-mode signal (Fig. 2). Below 25', the $B$-mode signal in this realization does not track the change in the $E$-mode signal, which is decreasing for angles large compared to the modulation. However, the amplitudes are more comparable than above, becoming very similar at the largest scales probed.

The inclusion of fluctuations in the $z_z$ distribution can increase the large-angle $B$-modes by as much as 2 orders of magnitude, as can be seen in Figure 3, where we have shown results for the Gaussian modulation map. The amplitude of this effect on scales larger than the modulation scale is (almost) independent of the angular scale of the modulation but is an increasing function of the modulation amplitude in all cases. The change in the $E$-mode variance also increases with increasing modulation but not as significantly as does the $B$-mode. In extreme cases, this effect can be as large as 1% of the $E$-mode variance (i.e., 10% of the amplitude). Although we do not show the results here, the picture is quite similar for the sharp edged and extinction modulations. For the former the $E$- and $B$-modes are similar to those seen in Figure 3, while for the latter the $E$-mode is similar while the increase in the $B$-modes is negligible unless a 100% error is made in the extinction correction.

6. CONCLUSION

We have used numerical simulations to model the effect of seeing and extinction modulations on weak lensing surveys.

We find that fluctuations in both the shear amplitude and the source $z_z$-distribution can give rise to changes in the $E$-mode power and to large-scale $B$-modes, with sharp changes in amplitude or fluctuations in the $z_z$-distribution giving the larger $B$-modes. Since the $B$-modes do not closely track the changes in $E$-mode power, they cannot be used to “correct” for the above effects. In the case of strong $B$-mode enhancement, however, they can be used as a monitor for the effect.

As we move from first detections into scientific exploitation of cosmic shear, effects such as this will need to be carefully controlled. Photometric redshift information offers a likely means of monitoring large-scale fluctuations in the survey depth while offering many scientific advantages. The stable and excellent observing conditions from space can be expected to largely eliminate effects from pointing and seeing fluctuations. Regardless of the route, it is clear that systematic errors such as those we have discussed here must be controlled if we are to realize the full power of upcoming weak lensing surveys, which will help usher in a new era in precision cosmology.

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