We present a measurement of cosmic shear on scales ranging from 10” to 2’ in 347 Wide Field Planetary Camera 2 (WFPC2) images of random fields. Our result is based on shapes measured via image fitting and on a simple statistical technique; careful calibration of each step allows us to quantify our systematic uncertainties and to measure the cosmic shear down to very small angular scales. The WFPC2 images provide a robust measurement of the cosmic shear signal decreasing from 5.2% at 10” to 2.2% at 130”.

Subject headings: cosmology: observations — gravitational lensing — surveys

1. INTRODUCTION

Gravitational lensing may be in principle the most powerful tool to measure the distribution of dark matter from galactic to cosmic scales. Lensing can be used to directly trace the gravitational potential of all matter, regardless of its nature, and requires only the distribution of light sources that shine through the matter distribution—unlike velocity measurements, which depend on the availability of visible tracers in situ. Considerable progress has been made in recent years in the use of weak lensing to trace dark matter associated with light, on scales ranging from individual galaxies (Brainerd, Blandford, & Smail 1996; Griffiths et al. 1996; Blandford, Surpi, & Kundic´ 2001) to clusters of galaxies (e.g., Mellier 1999; Kaiser 2001). On even larger scales, gravitational lensing can trace directly the distribution and clustering of dark and luminous matter via its gravitational signature, cosmic shear. In principle, cosmic shear can provide an unbiased measurement of the spectrum of mass fluctuations, independent of their nature and of any light associated with them. Theoretical calculations predict a signature of a few percent on arcminute scales for several models of structure formation and cosmology (Jain & Seljak 1997; Kaiser 1998; Bartelmann & Schneider 1999; Barber 2002).

Measurements of the cosmic shear have indeed been achieved over the last few years. A tentative detection was announced by our group in 1999 July (published in Casertano, Griffiths, & Ratnatunga 2001). Shortly afterward, several ground-based programs have achieved more reliable detections of cosmic shear at a level of 1%–3% on angular scales ranging from 1’ to 15’ (van Waerbeke et al. 2000; Kaiser, Wilson, & Luppino 2000; Bacon, Refregier, & Ellis 2000; Wittman et al. 2000). These measurements placed significant, if preliminary, constraints on the strength of mass clustering at z ~ 0.5 on linear scales from 0.2 to 5 Mpc (Kaiser et al. 2000). In the last year, the second generation of ground-based weak shear measurements has started to probe the power spectrum of dark matter fluctuations and constrain cosmological parameters (Bacon, Massey, & Refregier 2003; Brown et al. 2003; van Waerbeke et al. 2002). Somewhat weaker constraints have been obtained from space-based data by Refregier, Rhodes, & Groth (2002) and Rhodes et al. (2001), who use data similar to ours.

Typically, ground-based results are based on measuring the shape of marginally resolved galaxies over very large areas—up to several square degrees. The quality of the results depends critically on the correction for a number of systematic noise sources, which for ground-based data include atmospheric effects as well as those due to variations in the point-spread function (PSF) across the field of view and any other image distortion, due to either optics or sensitivity variations. Very sophisticated methods have been developed to extract this signal optimally (e.g., Kaiser, Squires, & Broadhurst 1995; Kaiser 2000; Bernstein & Jarvis 2002). Nonetheless, ground-based measurements could be affected to some extent by residual systematics, and independent confirmation from different methods on other types of data, such as those obtained with the Hubble Space Telescope (HST), is valuable. With HST, individual galaxies are substantially larger than both PSF and pixel size, and therefore instrumental effects, while present, are both smaller than and different from those found in ground-based data.

The present Letter offers a measurement of cosmic shear using 347 HST Wide Field Planetary Camera 2 (WFPC2) images collected by the Medium Deep Survey (MDS), covering a total area of 0.53 deg². The measurement is based on a new statistical technique, described and tested in detail in a companion paper (Ratnatunga, Casertano, & Griffiths 2003, hereafter RCG03), and takes full advantage of the high resolution and relative stability of the WFPC2 PSF. Our method takes properly into account observational and PSF errors, as well as statistical effects that become important on small angular scales; unique to our procedure is the ability to measure the cosmic shear signal from the distribution of observed galaxy shapes even on scales that include only a few galaxies per cell. In consequence, we measure cosmic shear over angular scales ranging from the full field of view of the camera (∼2’) down to 10”–20”, using approximately 35,000 galaxies. The procedures that we develop can be applied to other space-based samples with a larger number of galaxies and will probably allow an improvement of the quality and reliability of cosmic shear measurements with the upcoming trove of Advanced Camera for Surveys data.

2. THE DATA: THE MDS CATALOG OF GALAXIES

The HST MDS has resulted in a large catalog of galaxies suitable for weak lensing measurements. Extensive tests and
simulations (Ratnatunga, Griffiths, & Ostrander 1999, hereafter RGO99) show that the parameters—size, shape, and magnitude—measured for such galaxies are unbiased and have quantifiable, reliable error estimates. The MDS catalog covers several hundred fields observed with the WFPC2; this study includes 347 fields covering a total area of 0.53 deg$^2$ to a typical depth of $I = 25.5$. The object catalog for each field is produced using the standard MDS procedures, i.e., automated object location, eyeball verification, two-dimensional image fitting, and goodness-of-fit classification. We use the galaxy parameters as determined by RGO99, with a small correction for the image shear introduced by the geometric distortion of the WFPC2. The full catalog for the 347 selected fields contains 36,389 stars and 100,253 galaxies, as classified by our likelihood ratio algorithm.

We consider only objects classified as galaxies with a signal-to-noise ratio parameter $Z > 1.6$, as defined in RGO99. We further exclude about 500 very small objects with half-light radius $r_h < \text{min}(0.05, 1' \times 10^{-2.4 + 0.35 \times \mu})$. Applying these selections leaves a total of 52,433 confirmed galaxies with $21 < I < 26$, of which about 35,000 are used in the actual shear measurements.

3. MEASURING COSMIC SHEAR: GALAXY PARAMETERS AND THE EXCESS QUADRATIC ELLIPTICITY STATISTIC

Current measurements of cosmic shear are based on the correlated distortion of background galaxy images. The measurement consists of two steps: first, determine the corrected shape of the galaxies detected in those images, after accounting for instrumental and seeing effects; second, combine these single-galaxy measurements into a statistical measure of the cosmic shear.

Our shape measurements are based on the axis ratio and position angle determined in the MDS pipeline by fitting the observed image with a parametric light distribution, convolved with the PSF. RGO99 describe the fitting process in detail and provide a reliable estimate of the uncertainties in the derived image parameters for each galaxy. For ideal data, the axis ratio and position angle thus defined transform correctly under the effect of shear, and therefore are suitable for weak lensing measurements. Unlike most ground-based observations, the galaxies are generally well resolved in WFPC2 images, and the effect of the WFPC2 PSF is a small correction—about a few percent—on the measured image parameters. In § 4.2 we report on our tests of the impact of nonideal data.

For the second step, we have developed a statistical method based on the excess quadratic ellipticity $A_j = \langle e_i^2 \rangle - \langle e_i \rangle^2/N_g$, which measures the correlation between the ellipticities $e_i$ of the $N_g$ galaxies within each cell. If the galaxies are randomly oriented, the $e_i$ are uncorrelated and $A_j$ will vanish on average. A nonrandom component, in the form of a correlation between observed galaxy ellipticities, will cause a slight positive bias of $A_j$, which scales quadratically with the shear. Typically this bias is too small to be measured in a single cell; averaging a large number of cells measures the variance of the cell-averaged shear. The bias in $A_j$ is especially difficult to measure when $N_g$ is small; partly for this reason, most studies report only shear on relatively large scales, 1’ or more. However, as we show in RCG03, careful analysis of the statistical properties of the excess quadratic ellipticity enables us to measure the typical shear down to scales of 10’, where $N_g \lesssim 10$. In RCG03 we show that optimal results are obtained by using appropriate weights for each field, and we find that for our data, the relationship between $A_j$ and the shear variance is approximately

$$\langle A_j \rangle \sim (3.82 - 2.10/N_g - 3.13\langle e_i^2 \rangle - 7.35\langle e_i \rangle^2)\langle \gamma^2 \rangle,$$  

where $\langle \gamma^2 \rangle$ is the variance in the cosmic shear averaged in each cell, $\langle e_i^2 \rangle$ is the mean squared ellipticity of all galaxies, and $\sigma_i$ is the combined measurement error in each ellipticity component, estimated by combining the measurement error in both axis ratio and position angle. Since $\sigma_i$ is typically much smaller than the ellipticity itself, this latter term can usually be neglected. Note that the relationship between $A_j$ and $\langle \gamma^2 \rangle$ depends significantly on the number of galaxies for $N_g \ll 10$, and this dependence must be taken into account when averaging results for small cell sizes.

Our method is in principle quite similar to other methods that rely on estimating the correlations between ellipticities of galaxies that are proximate on the sky; see, e.g., Seitz et al. (1998) and Rhodes, Refregier, & Groth (2000). Our key improvements are (1) considering explicitly the number of galaxies per cell, as in equation (1) above, which allows us to obtain unbiased shear estimates for small cells including only a handful of galaxies each, and (2) using extensive simulations to validate the statistical properties of our method, which allow us to derive the uncertainty in our measurements with high fidelity. More details are reported in RCG03.

4. COSMIC SHEAR FROM THE MDS DATA

4.1. Measured Shear

Figure 1 shows the cosmic shear estimated on scales from 10” to 130” on the WFPC2 data. Cells larger than 65” are L-shaped as the WFPC2 field of view, with a gap of 10”–30” between the detectors to avoid edge effects. For homogeneity, we do not include PC data in our analysis.

The measured variance of the cosmic shear, represented by the filled squares, is based on the calibration of the $A_j$ statistic given in equation (1). The error bars reflect the 1 $\sigma$ uncertainty in the shear variance determined by the simulations described in RCG03; we find that the presence of shear increases only slightly the measurement uncertainty, and therefore the 1 $\sigma$ errors in Figure 1 apply to a null measurement as well. The open circles show the estimated contribution of PSF errors, while the crosses indicate the inferred shear variance from simulations.
in which no shear was included. Error bars in this case show the uncertainty in the mean effect, based on several thousand simulations, rather than the dispersion in individual simulations.

Our data yield the strongest evidence of cosmic shear on a single-detector scale, 65°, where the measured value \( \langle \gamma^2 \rangle = 0.0007 \) is about 4 \( \sigma \) from a null result. The measured shear increases on smaller scales, although individual measurements have lower significance; the detection at 10° has a significance of about 2 \( \sigma \).

4.2. Possible Sources of False Signal

The image fitting method that we adopt to determine galaxy shapes and orientations has been shown (RGO99) to yield measurements of galaxy properties that are not affected by detectable systematic biases, even in the presence of image pixelation. However, the cosmic shear measurement is sensitive to other effects because of an imperfect knowledge of the observations. We discuss briefly three such effects: errors in the adopted PSF; uncorrected differential aberration in parallel \( HST \) observations, and fields with special properties, such as unknown galaxy clusters.

WFPC2 has a difficult-to-characterize PSF with significant variations over its field of view. The PSF is temporally stable except for its dependence on the \( HST \) focus, which is known to vary systematically over a single orbit as well as over longer timescales. However, the focus dependence affects primarily the core of the PSF; our tests show that even a substantial focus error affects the shape of a typical galaxy in our sample, as measured via the MDS procedures, by much less than 0.1%. Of more concern is a systematic mismatch between the true PSF and the model that we adopted, which is based on the Tiny Tim code (Krist 2000). If improperly accounted for, the intrinsic asymmetry of the PSF could produce an artificial correlation between measured ellipticities and thus affect our cosmic shear measurement. We test for such a correlation in two ways. First, we generate artificial catalogs in which each galaxy retains its observed size, orientation, and position in detector coordinates but is assigned randomly to another observation. When analyzed exactly as the true catalog, the artificial catalogs yield a very small residual shear, less than 0.03% on all scales, as shown by the open circles in Figure 1. This test is also sensitive to other persistent instrumental errors, such as the assumed geometric distortion. Second, we compute the mean ellipticity of the galaxies that fall in each 100 \times 100 pixel region of the WFPC2 field of view in all observations. A significant nonzero mean would indicate residual instrumental effects, such as uncorrected PSF; we find instead a typical rms value of 2.9% for each ellipticity component, compared to an expected value of 3.0% \pm 0.2% from the same number of randomly oriented objects in each cell. It is worth noting that an earlier version of the MDS catalog, based on a 3 \times 3 grid of PSF models for each detector instead of the 7 \times 7 grid used here, fails this test, returning a mean ellipticity \~1% with an rms variation of 3.8%.

Differential velocity aberration can affect parallel observations because the \( HST \) pointing is corrected for velocity aberration at the location of the primary target of the observation. As a consequence, parallel observations are convolved with a potentially asymmetric kernel that is generally less than 0.01 but can occasionally be as large as 0.035 (Ratnatunga et al. 1995). The effect of velocity aberration is expected to have two characteristic signatures: as a convolution, it should affect small galaxies more than large ones, and its impact should vary depending on the location of the primary target of the observation. We find no significant variation in our results as a function of either galaxy size or location of the primary target, suggesting that differential velocity aberration is not significant within our measurement accuracy. More accurate measurements of cosmic shear, based on many more galaxies than we have considered here, might require a correction for this effect.

Large concentrations of mass, such as galaxy clusters, produce a shear signature much larger than its typical value. Truly random observations should include galaxy clusters as often as they occur over the whole sky; on average, the cosmic shear variance measured via random observations should be an unbiased representation of the variance of cosmic shear. However, a small number of cluster-affected fields can skew the measured shear significantly. We have verified that the distribution of \( \mu \) measured from individual pointings is regular and is not dominated by a small number of outlying points. To be safe, we have excluded two fields with somewhat larger than normal values of \( \mu \), without any measurable effect on the derived value of the shear variance. We conclude that our results are not dominated by a small number of fields with high correlation.

5. Discussion

The cosmic shear that we measure for the \~0.5 deg\(^2\) covered by the MDS data is generally consistent with the measurements obtained from other data, as well as with the results of the Refregier et al. (2002) analysis of essentially the same observations. Our procedures are substantially different from those of other authors: we measure image parameters via image fitting, including PSF convolution, and follow a different, carefully calibrated analysis process (see RGO99 and RCG03 for more details). Thanks to our methods, we can measure cosmic shear on very small scales, down to 10°, into the regime of a very small number of galaxies per cell. On scales where our measurements overlap those of other authors, we find a somewhat larger cosmic shear signature; for example, we find a value of \( \gamma \) about 30% larger than Refregier et al. (2002) measured on very similar data, and the difference is about twice the combined 1 \( \sigma \) uncertainty.

Measurements of the cosmic shear by various authors are shown in Figure 2: space-based results are shown with solid error bars, ground-based are dashed. The curve represents the Jain & Seljak (1997) predictions for an \( \Lambda \)CDM cosmology with \( \sigma_8 = 0.6 \) and source redshift 1.0; the functional approximation used is questionable below 1°, where the curve is dashed. Several authors (e.g., Brown et al. 2003) offer a more detailed comparison of the cosmic shear measurements with model predictions and discuss the more detailed constraints that can be obtained from improved samples. Indeed, the statistics of large-area ground-based measurements are beginning to approach the regime in which specialized weight functions can be applied to measure the strength of the density fluctuations on specific scales; see, e.g., the discussion in Schneider et al. (2002) and van Waerbeke et al. (2002).

Among these results, space-based data maintain a unique value even when compared with large-area, statistically impressive ground-based measurements. First, space-based measurements can probe smaller scales than has been possible from the ground thus far; the small-angle regime is uniquely sensitive to nonlinear growth effects and thus can serve to discriminate between broadly similar cosmological models that differ in the nonlinear regime. Second, space-based measurements are more direct, requiring much less averaging and PSF correction; there-
before they suffer from different systematics than ground-based measurements and can be applied more easily to galaxies of small angular size. Third, the space can, at least at present, probe to fainter source magnitudes and thus in principle gain an understanding of the growth of structures at higher redshift. Note that, for example, Barber (2002) predicts a significantly different scaling of the cosmic shear with both angular scale and redshift than Jain & Seljak (1997). Our results are based on a fairly large sample of HST data; however, the next few years will see an explosive growth in the amount of data taken by HST that can be used to measure cosmic shear, thanks to the Advanced Camera for Surveys and, later, the Wide Field Camera 3. We therefore expect a substantial improvement in space-based measurements of cosmic shear, which will probably help further constrain cosmology and the growth of dark matter structure in both the linear and the nonlinear regimes.

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