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Wide field weak lensing observations of A1835 and A2204
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We present mass reconstructions from weak lensing for the galaxy clusters A1835 and A2204 over 34 × 34 fields using data from the ESO/MPG Wide Field Imager. Using a background galaxy population of 22 < R < 25.5 we detect the gravitational shear of A1835 at 8.8σ significance, and obtain best-fit mass profiles of σv = 1233+690−575 km/s for a singular isothermal sphere model and r200 = 1550h−1 kpc, c = 2.96 for a ‘universal’ CDM profile. Using a color-selected background galaxy population of 22 < R < 25.8 we detect the gravitational shear of A2204 at 7.2σ significance, and obtain best-fit mass profiles of σv = 1035+665−71 km/s for a SIS model and r200 = 1310h−1 km/s, c = 6.3 for a ‘universal’ CDM profile. The gravitational shear at distances greater than 10 is significantly detected for both clusters. The best fit weak lensing cluster masses agree well with both X-ray and dynamical mass measurements, although the central concentration of A1835 is much lower in the weak lensing mass profile than that measured by recent Chandra results. We suggest that this lower concentration is most likely a combination of contamination of the ‘background’ galaxy population with cluster dwarf galaxies and the effect of a prolate or tri-axial cluster core with the major axis lying near the plane of the sky. We also detect a number of additional structures at moderate significance, some of which appear to be sub-haloes associated with the clusters. Gravitational lensing – Galaxies: clusters: individual: A1835 – Galaxies: clusters: individual: A2204 – dark matter
Introduction In recent years, cosmological N-body simulations have been used to obtain theoretical mass profiles for massive clusters of galaxies (NA97.6, hereafter NFW; MO99.5; JI00.1). While there is some discrepancy between the models for the mass profile at small radii (100 kpc), at large radii (1 Mpc) they agree that the mass density should decrease as r−3. This is a much steeper slope at large radii than the singular isothermal sphere (hereafter SIS) model, which falls as r−2. Measuring the mass profiles of clusters at large radii, therefore, should provide an excellent test of the predictions from N-body simulations.
Weak gravitational lensing, in which one determines the mass of an object by measuring the shear induced in background galaxies by the gravitational potential of the object, is a powerful tool for determining the mass and mass profile of clusters of galaxies. Because the gravitational shear depends linearly on the two-dimensional mass surface density, it can be used to measure mass profiles to much larger radii than X-ray observations, for which the emissivity scales as the square of the baryonic mass density. Further, the resulting mass measurements have no dependence on the dynamical state of the cluster and are not influenced by shocks caused by infalling material. To date, the primary limitation on the maximum radius to which the cluster mass profiles has been measured with weak lensing (~ 400 – 600h−1 kpc) has been the size of the detector and the fact that the depth of exposure needed to obtain a sufficient number density of background galaxies for shear analysis made large-area mosaics impractical in telescope time.
With the advent of wide-field mosaic CCD detectors LU98.1, it is now possible to obtain a weak lensing signal to large radii (2h−1 Mpc) on moderate redshift clusters in a few hours of telescope time. The mass profile for A1689 out to 2h−1 Mpc was measured by [hereafter CS01]CL01.1. Here we present the mass profiles to similar radii for two additional massive clusters, A1835 and A2204. In Sect. 2 we discuss the image reduction and object catalog generation. We analyze the weak lensing signal for A1835 in Sect. 3 and for A2204 in Sect. 4. In Sect. 5 we present out conclusions. Unless otherwise stated we assume a Ωm = 0.3, Λ = 0.7 cosmology, H0 = 100h km/s/Mpc, and that the mean redshift of faint galaxies is at zbg = 1.
Observations and Data Reduction Imaging on the fields was performed on the nights of May 29-30, 2000, with the Wide Field Imager (WFI) on the ESO/MPG 2.2m telescope in La Silla, Chile. In total, twelve 900 second exposures in R were obtained on A1835 on May 30, twelve 900 second exposures in R were obtained on A2204 on May 29, and three 600 second exposures in B and V were obtained on A2204 on May 30. The night of May 29 was photometric, while the night of May 30 was non-photometric and large changes in the
brightness of objects can be seen in consecutive images. The images were taken with a dither pattern which filled in the gaps between the chips in the CCD mosaic, resulting in the final $R$-band images having ~ 82% of their area receiving the full exposure time and the rest receiving varying amounts of lesser exposure times as the area was in the chip gap or out of the field of view for one or more of the images. The $V$ images were taken with large enough offsets to fill in the chip gaps, but the final image has ~ 12% of the area covered by a single input image. Because one of the three $B$ images is unusable due to severe extinction, the coadded $B$ image has ~ 24% of the area covered by just one input image and ~ 3% of the area is blank.

**Image Reduction**

The image reduction technique for the $R$-band images is identical to that given in CS01. Treating each chip as its own separate camera, we de-biased the images from a master bias taken at the beginning and end of each night, and corrected for bias drift during the night by subtracting a linear fit to the residual of the overscan strip. The images were then flattened by a 9th by 17th order two-dimensional polynomial fit to the twilight flats. The fit to the twilight flat was performed in order to remove the sky interference fringes present in the $R$-band data. All of the long exposure $R$-band images from each night were then normalized with the mode sky value of the image and medianed together. The resulting night sky super-flat was also fit with a 9th by 17th order polynomial, and the images were flattened with this polynomial. The flattened images were re-normalized and medianed again to produce an image of the fringes, which have a peak-to-peak amplitude of ~ 10%, which was then scaled to each images’ mode sky value and subtracted. As this technique tends to incorrectly subtract regions of low quantum efficiency, such as dust spots, such regions were masked by hand. As was mentioned in CS01, due to the large number of input images and the dithering between the images, the lensing results from this technique are indistinguishable from those produced by simply dividing by the nightsky flatfield with the fringes left in place. This technique, however, should more accurately preserve the photometry of the objects than by dividing by the fringes, particularly around the edge of the image where few input images were averaged. **We note that neither of these methods is in principle correct, but lacking the means to separate the fringes from the flat-field for this data set, these two methods were chosen to determine if the miscorrection of the fringes or pixel variations could produce a noticable systematic error in the lensing results. Because the lensing data from the two methods are statistically indistinguishable, we therefore conclude that any systematic error produced is much smaller than the noise in the data.** The $B$ and $V$-band images were flattened with a medianed flat without the fitting procedure above as the fringes are present only in the $R$-band data.

The sky level in each image was determined by detecting minima in a smoothed image. An image containing only the minima was then smoothed by a 128 pixel, ~ 307, FWHM Gaussian and divided by a similarly smoothed image containing the number of minima (1 or 0) in each pixel. This produced an image of the sky smoothed on the ~ 30 scale, which was then subtracted from the original image. This process was repeated on the sky-subtracted image using 96, 64, 48, and 32 pixel FWHM Gaussians. The first sky-subtracted image which only subtracts sky variations on the ~ 30 scale was subsequently used for the photometric measurements of cluster galaxies, while the final sky-subtracted image which removed sky variations on a ~ 75 scale, along with extended wings of bright stars and many of the larger galaxies, was used for the weak lensing measurements. The $B$ and $V$-band images had only the first sky-subtraction performed, as they are used only for photometry. The sky-fitting routine performed in CS01 could not be used on these fields due to the presence of several large stellar reflection rings in each field.

Stellar reflection rings are quite predominant on the WFI images. Every saturated star with blooming in the core has two reflection rings, roughly 48 in diameter, centered a few arcseconds from the star, radially away from the center of the image with the offset increasing with distance from the center of the image, with typically 2 offset between the two rings. Stars which are bright enough to have the blooming extend beyond the stellar core also have a visible third fainter reflection ring, ~ 92 in diameter, which is centered about twice as far from the star and in the same radial direction as the two smaller rings. Exceptionally bright stars, however, reveal far more reflection rings. A star in the SW corner of the A1835 image, listed as $V = 7.4$ in the USNO-A2.0 catalog USNO, has three additional reflection rings: a 318 diameter ring centered 140 NE of the star, a 232 diameter ring centered 287 NE of the star, and a very faint ring ~ 10 in diameter centered ~ 1 NNE of the star. A star in the WSW edge of the A2204 image, $V = 7.8$ in the USNO-A2.0 catalog, has two observable reflection rings, similar in size and offset to the first two given above. A $V = 5.6$
star located only a few arcminutes SW of the A2204 cluster near the center of the image also has the same three additional rings, although the first is centered roughly on the star, the second about 10 NE of the star, and the larger third ring centered ~ 4 SSW of the star. In addition, there appear to be a number of smaller reflection rings, ~ 3 in diameter, located ~ 7 SSW of this star which overlap each other sufficiently to make it impossible to determine an accurate count.

The sky-subtraction process above was able to remove the largest reflection ring such that we were confident of being able to accurately measure both magnitudes and second moments of the surface brightness for objects in this ring. For the other two larger rings, the sky-subtraction software was unable to remove the edges of the ring, including the spider shadows, so objects in these regions had their magnitudes and colors measured, but were excluded from the lensing analysis. The regions containing the three brighter rings found around all the stars were excluded from all subsequent analysis, both lensing and photometric.

The next step is to simultaneously combine the eight CCD images into a single image, move it to a common reference frame from all the images of a given field, and remove any distortion in the image introduced by the telescope optics. To do this we assumed that each CCD of the mosaic could be mapped onto a common detector plane using only a linear shift in the x and y directions and a rotation angle in the x-y plane. We also assume that these mappings are the same for all the data. In doing so we are assuming the CCDs are aligned sufficiently well vertically that there are no changes in depth at which the focal plane is sampled across the chip boundaries and that the CCDs do not move relative to each other when the instrument is subjected to thermal variations or flexure during the night. These assumptions are verified later by the inability to detect a change in the point spread function (PSF) across the chip boundaries.

We then used a bi-cubic polynomial to map the detector plane for each exposure to a common reference frame for each field. The parameters for the two coordinate mappings were determined simultaneously by minimizing the positional offsets of bright but unsaturated stars among the images of the same field and with the USNO-A2.0 star catalog. A downhill simplex minimization method with multiple restarts was used to minimize the 21 free parameters in the CCD-to-detector plane mapping, while at each step in the simplex the detector plane-to-sky mapping was determined with a LU decomposition PR92.1 of a $\chi^2$ minimization matrix. The resulting best fit mappings had a positional rms difference of .06 pixels, 0015, among the images of the same field and 055 between the images and the USNO-A2.0 star catalog coordinates, which is the positional uncertainty of this catalog. No large scale collective offsets between the final stellar positions and those of the USNO-A2.0 catalog were seen in any portion of the fields. We also attempted the mappings using fourth to seventh order two-dimensional polynomials for the detector plane to sky mappings, but the resulting rms dispersions in stellar positions did not improve over the bi-cubic mapping. A discussion of this technique in greater depth can be found elsewhere CL02.2.

Each CCD image was then mapped onto the common reference frame using a triangular method with linear interpolation which preserves surface brightness and has been shown not to induce systematic changes in the second moments of objects in the case fractional pixel shift CL00.1. To attempt to minimize the non-photometric conditions for the $R$-band of A1835 and $B$ and $V$-bands on A2204, the images were multiplied by a factor determined from comparing the fluxes of bright but unsaturated stars to those of the image with the brightest fluxes. For A2204 $R$-band, all twelve of the images were within 2% of the brightest, thus confirming the photometric conditions of the first night’s data. For A1835 $R$-band, four of the twelve images were within 10% of the brightest with the remainder at 60-80% of the brightest image. Further, three of the twelve images had stellar FWHM significantly higher than the others, so these were excluded from the summed image. For the $B$ and $V$-band images of A2204, all of the images were within 10% of the brightest. The images were then averaged using a sigma-clipping algorithm to remove cosmic rays.

Catalog Generation and Lensing Analysis

For object detection and photometry in the final images, we used SExtractor BE96.1. For the photometric catalog, SExtractor was used on the images with the 30 smoothed sky subtraction to detect objects which had at least 5 pixels with fluxes greater than twice the signal-to-noise of the sky after smoothing with a 3 pixel FWHM Gaussian. The sky around each object was measured using a 32 pixel thick annulus around the object, and magnitudes were measured both down to a limiting isophote equal to the signal-to-noise of the sky and in a 2 radius aperture. The best-fit Gaussian FWHM and maximum pixel flux were also generated to distinguish stars from galaxies. For the A2204 $B$ and $V$-band images, SExtractor was used in two image mode, in which objects were detected and had the outer isophote determined in the $R$-band image, but the
magnitudes were measured in the appropriate passband. Unless otherwise stated, all magnitudes and fluxes are measured using the isophotal magnitudes and all colors are from the 2 radius aperture magnitudes. All magnitudes are measured in the Vega system and determined from LA92.1 standard star fields observed at various times during the nights.

figure !H3633F1.ps Above is a plot of one of the two components of the stellar PSF ellipticity both before (top) and after (bottom) subtracting the best fit two-dimensional seventh order polynomial ellipticity model for the stars. The stars are binned into 8 vertical bins, and each bin is plotted with a 0.1 offset in ellipticity from the others. As can be seen, the fit adequately removes the large scale variation in the psf ellipticity, and no sudden change in the psf due to chip boundaries can be seen anywhere in the image. The same is true for the other component of the ellipticity, and is also true when using horizontal bins and checking the ellipticity for vertical spatial variation. The psf has also been studied in globular cluster fields with ~ 20 times greater stellar density than is present in this image, which also fails to detect a change in the psf across the chip boundaries CL02.2. psffig