CAUSTIC AND WEAK-LENSING ESTIMATORS OF GALAXY CLUSTER MASSES

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ABSTRACT

There are only two methods for estimating the mass distribution in the outer regions of galaxy clusters, where virial equilibrium does not hold: weak gravitational lensing and identification of caustics in redshift space. For the first time, we apply both methods to three clusters: Abell 2390, MS 1358.4+6245, and Cl 0024+1654. The two measures are in remarkably good agreement out to ~2 h−1 Mpc from the cluster centers. This result demonstrates that the caustic technique is a valuable complement to weak lensing. With a few tens of redshifts per square comoving megaparsec within the cluster, the caustic method is applicable for any z ≤ 0.5.

Subject headings: cosmology: miscellaneous — cosmology: observations — galaxies: clusters: individual (Abell 2390, Cl 0024+1654, MS 1358.4+6245) — gravitational lensing

1. INTRODUCTION

The relative distributions of mass and light in the universe have remained a profound and central mystery in cosmology for more than 70 years. Since Zwicky’s pioneering use of the virial theorem to discover dark matter in the Coma Cluster (Zwicky 1933), the range and sophistication of methods for estimating cluster masses and mass profiles have increased to include a host of dynamical measures, X-ray estimates, and strong and weak gravitational lensing determinations.

Different mass estimators applied to rich clusters of galaxies constrain the mass distribution on different scales. Strong lensing generally provides constraints on very small scales (≤0.1 h−1 Mpc). Virial mass estimates, including Jeans analysis, assume dynamical equilibrium and apply only within the virial radius. Mass estimates based on X-ray observations assume hydrostatic equilibrium and rarely extend beyond one-half of the virial radius (Majerowicz et al. 2002; Pratt & Arnaud 2002).

At larger clustercentric radii where equilibrium assumptions break down, there exist only two techniques for mass estimation: weak lensing (Kaiser et al. 1995) and the redshift-space caustic technique (Diaferio & Geller 1997; Diaferio 1999, hereafter D99). Both techniques enable determination of the mass distribution from the cluster center to distances larger than the virial radius.

The caustic technique has been applied to many local clusters (Rines et al. 2003 and references therein). At small clustercentric radii, caustic estimates agree well with the traditional virial analyses in the optical and X-ray bands. At larger radii the caustic technique is still valid, but its mass estimates were tested against N-body simulations only (D99).

Here we discuss the first comparison of mass estimates from the caustic technique and weak lensing. Only recently have sufficient lensing and spectroscopic data become available to make this comparison. Both techniques have known systematic uncertainties: these comparisons test the importance of these systematics. In this Letter, we examine mass-profile measure-
certainties are smaller for real clusters than in the simulations. The small scatter (∼30%) around the equivalence relation between X-ray and caustic masses (Rines et al. 2003) suggests that the simulations indeed overestimate the errors in the caustic technique at small radii. If 30% represents a rough estimate of the correct caustic mass uncertainty at all radii, the D99 recipe typically overestimates this uncertainty by a factor of 2. Nevertheless, because it is the only available prescription for evaluating the error, we use the conservative D99 prescription. Comparison of gravitational lensing and caustic measurements for large samples of clusters in the redshift range 0.2–0.8 will test the accuracy of this recipe.

3. MASS COMPARISON

Mass-profile estimates of high-redshift clusters depend on the assumed cosmological parameters: physical distances and X-ray and weak-lensing cumulative mass profiles scale as the angular diameter distance $D_A$. Moreover, if one derives a best-fitting NFW (Navarro et al. 1997) density profile $\rho(r,z) = \delta_c \rho_{crit}(z) (r/r_s)^{-1} (1 + r/r_s)^{-2}$, with $\rho_{crit}(z) = 3H^2(z)/8\pi G$ the critical density of the universe, $H^2(z) = H_0^2(1 + z)^3 + (1 - \Omega_M - \Omega_k)(1 + z)^2 + \Omega_\Lambda$), $\delta_c = c^2(200/3)\ln(1 + c) - c(1 + c)^{-1}$, and $c = r_{\text{vir}}/r_s$, the concentration parameter, $c$ also depends (nonlinearly) on $D_A$, because $\delta_c \rho_{crit}(z)$ scales as $D_A^2$. Below, all quantities assume $\Omega_M = 0.3$, $\Omega_k = 0.7$, and $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Figure 1 shows the redshift diagrams of the three clusters with the caustic location (top) and the mass profiles estimated with the caustic technique, gravitational lensing, and X-ray data (middle and bottom). Gravitational lensing measurements all the mass projected onto the sky along the line of sight. Therefore, we distinguish between three-dimensional (middle) and projected (bottom) cumulative mass profiles. Radial distances are three-dimensional $r$ or projected onto the sky $R$.

The solid lines in the middle and bottom rows of Figure 1 show the best-fitting NFW profile with parameters listed in Table 1. To compute these fits, we only used the data points within $r_{\text{lim}} = 1 \text{ h}^{-1} \text{ Mpc}$, a conservative radius beyond which the NFW mass profile might not be a good description of the actual profile. For all clusters, the data points beyond $1 \text{ h}^{-1} \text{ Mpc}$ do indeed agree with the NFW model, indicating that the correct choice of $r_{\text{lim}}$ is irrelevant. In any case, the fit parameters and their errors are only indicative, because the individual data points are correlated. Moreover, the NFW fit parameters are correlated even with independent data points. Keeping one of the two parameters, $c$ or $r_s$, fixed in our fits reduces their relative errors to ∼10%.

For each cluster, we also show the best fits determined from the weak-lensing (dashed lines) and X-ray (dotted lines) measurements. We now comment on each cluster separately.

A2390.—This is a rich cluster at $z = 0.228$ with optical (Le Borgne et al. 1991; Yee et al. 1996), X-ray (Böhringer et al. 1998; Allen et al. 2001), and both weak (Squires et al. 1996) and strong (Pelló et al. 1991; Pierre et al. 1996) gravitational lensing observations. Squires et al. (1996) compared the weak-lensing data within ∼260′ with a singular isothermal model with velocity dispersion $v = 1093 \text{ km s}^{-1}$ taken from Carlberg et al. (1996). The isothermal model underpredicts the amount of mass actually measured in the range 0.46–0.67 h−1 Mpc (Fig. 1, bottom left); however, this model is in good agreement with the best-fitting NFW mass profile derived by Allen et al. (2001) from Chandra observations. They find $r_s = 0.44_{-0.22}^{+0.76} h^{-1} \text{ Mpc}$, $c = 3.6_{-1.1}^{+1.6}$, and $r_{\text{vir}} = 1.6_{-0.3}^{+0.7} h^{-1} \text{ Mpc}$.

By using the galaxy redshift survey by Yee et al. (1996) and assuming dynamical equilibrium, Carlberg et al. (1996) estimate a mass $M(3.3 h^{-1} \text{ Mpc}) = (2.7 ± 0.4) \times 10^{15} h^{-1} M_\odot$. The caustic mass (1.4 ± 1.2) $\times 10^{15} h^{-1} M_\odot$ and the mass 1.8 $\times 10^{15} h^{-1} M_\odot$ extrapolated from the weak-lensing isothermal...
model are 48% and 33% smaller than this virial mass, but within its 3 σ uncertainty.

At smaller radii, A2390 sports spectacular arcs and arclets (Pelló et al. 1991), some of which have measured redshifts (Bézecourt & Soucail 1997; Frye & Broadhurst 1998; Pelló et al. 1999). Pierre et al. (1996) used the brightest strongly lensed arc and its surrounding shear to derive the projected total enclosed mass $M(<97 h^{-1} \text{ kpc}) = (8.0 \pm 1.0) \times 10^{13} h^{-1} M_\odot$ ($\sigma = 0.3$ and $\bar{z}_r = 0.7$; $D_c$, $D_s$, and $D_l$ are the angular distances to the cluster, to the source of the lensed image, and between the cluster and the source, respectively).

The X-ray and weak-lensing mass models agree within ~0.8 $h^{-1}$ Mpc but underestimate the strong-lensing mass derived by Allen (1998). The fact that the weak-lensing mass provides only a lower limit to the mass profile and the caustic mass is in excellent agreement with the strong-lensing measurement suggests that the caustic mass provides the correct mass profile of MS 1358 out to ~2 $h^{-1}$ Mpc.

Cl 0024+1654.—Significant tension exists between lensing (Bonnet et al. 1994; Tyson et al. 1998) and X-ray (Soucail et al. 2000; Ota et al. 2004) mass estimates of this cluster. Kneib et al. (2003) combine their weak-lensing measurements from wide-field imaging with the strong-lensing measurement by Broadhurst et al. (2000) to derive the best-fitting NFW profile, with $r_s = 54 \pm 2 h^{-1} \text{ kpc}$, $c = 18.7_{-4.1}^{+5.4}$, and $r_{200} = 1.01_{-0.23}^{+0.41} h^{-1} $ Mpc. According to their Figure 12, the uncertainty in their mass estimate is always ≤10%. Our Figure 1 also shows the NFW profile that fits recent Chandra data (Ota et al. 2004). These authors derive the NFW profile from a β-model fit. According to its parameters, we find $r_s = 0.56 \pm 0.02 h^{-1} \text{ Mpc}$, $c = 1.8 \pm 0.3$, and $r_{200} = 1.02 \pm 0.18 h^{-1} \text{ Mpc}$. Our caustic estimate (based mostly on the spectroscopy of Czoske et al. 2001) lies between the lensing and the X-ray fits at $r < 0.2 h^{-1} \text{ Mpc}$, but it is in excellent agreement with the lensing estimate outside ~0.5 $h^{-1}$ Mpc.

In the cluster central region there are two strong-lensing measurements, which yield comparable masses. However, the very small errors claimed make them inconsistent with each other: $M(<0.114 h^{-1} \text{ Mpc}) = (1.30 \pm 0.04) \times 10^{14} h^{-1} M_\odot$ (Broadhurst et al. 2000) and $M(<0.119 h^{-1} \text{ Mpc}) = (1.563 \pm 0.002) \times 10^{14} h^{-1} M_\odot$ (Tyson et al. 1998). We scaled the mass reported by Tyson et al. (1998) by assuming $z = 1.675$ for the arc, as measured by Broadhurst et al. (2000). By construction, the NFW profile of Kneib et al. (2003) agrees with the former [it yields $M(<0.114 h^{-1} \text{ Mpc}) = 1.13 \times 10^{14} h^{-1} M_\odot$] and therefore disagrees with the latter [it yields $M(<0.119 h^{-1} \text{ Mpc}) = 1.17 \times 10^{14} h^{-1} M_\odot$]. The caustic profile gives smaller, but consistent, masses in both cases: $(7.9 \pm 3.8) \times 10^{13}$ and $(8.5 \pm 4.0) \times 10^{13} h^{-1} M_\odot$, respectively. The NFW fit to the X-ray data yields even smaller masses: $3.8 \times 10^{13}$ and $4.2 \times 10^{13} h^{-1} M_\odot$ with a ~30% typical error. Czoske et al. (2002) suggest that the peculiar-redshift distribution of the galaxies within ~3.5 $h^{-1}$ Mpc of the cluster center can be explained by a high-speed collision along the line of sight between Cl 0024 and a less massive cluster. This model implies that the X-ray mass estimate based on dynamical equilibrium is unreliable. Because the caustic and lensing mass estimators are both independent of the dynamical state of the cluster, it is reasonable that they agree with each other but disagree with the X-ray mass.

4. CONCLUSION

For the first time, we compare the only two cluster mass estimators that do not rely on the dynamical equilibrium of the system: weak gravitational lensing and caustics in redshift space. We estimate the caustic mass of A2390, MS 1358, and Cl 0024 within ~2 $h^{-1}$ Mpc of the cluster centers. The caustic mass profiles are in very good agreement with the lensing profiles. We confirm that the discrepancy between lensing and X-ray mass in Cl 0024 is probably a consequence of the unrelated state of the cluster, which invalidates the X-ray analysis. Weak lensing requires accurate photometric wide-field surveys in excellent seeing; moreover, the cluster sample is somewhat limited to clusters at distances where the lensing signal is sufficiently strong. Weak lensing measures all the mass pro-

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jected along the line of sight, resulting in a minimum 20% uncertainty in the cluster mass estimates (de Putter & White 2005). The caustic technique, which requires dense wide-field redshift surveys, provides a complementary measurement of the three-dimensional mass profile of individual clusters at moderate redshift; it also yields robust mass profiles for clusters in the local universe.

Future comparison of these techniques for large samples of clusters, covering a range of redshifts, will constrain systematic uncertainties in the methods and may provide insight into the change in the relative amounts of mass in the infall regions and cluster cores as a function of look-back time.

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