INFRARED MASS-TO-LIGHT PROFILE THROUGHOUT THE INFALL REGION OF THE COMA CLUSTER

K. Rines,1 M. J. Geller,2 M. J. Kurtz,3 A. Diaferio,4 T. H. Jarrett,4 and J. P. Huchra1

Received 2001 August 13; accepted 2001 September 20; published 2001 October 9

ABSTRACT

Using a redshift survey of 1779 galaxies and photometry from the Two Micron All Sky Survey covering 200 deg², we calculate independent mass and light profiles for the infall region of the Coma Cluster of galaxies. The redshift survey is complete to $K_s = 12.2$ (622 galaxies), 1.2 mag fainter than $M_r$, at the distance of Coma. We confirm the mass profile obtained by Geller, Diaferio, and Kurtz. The enclosed mass-to-light ratio measured in the $K_s$ band is approximately constant to a radius of 10 $h^{-1}$ Mpc, where $ML_{K_s} = 75 \pm 23 L_{B,0}/L_{K_s}$, in agreement with weak-lensing results on similar scales. Within 2.5 $h^{-1}$ Mpc, X-ray estimates yield similar mass-to-light ratios ($67 \pm 32 h$). The constant enclosed mass-to-light ratio with radius suggests that the $K$-band light from bright galaxies in clusters traces the total mass on scales $\leq 10 h^{-1}$ Mpc. Uncertainties in the mass profile imply that the mass-to-light ratio inside $r_{200}$ may be as much as a factor of 2.5 larger than that outside $r_{200}$. These data demonstrate that the $K$-band light is not positively biased with respect to the mass; we cannot rule out antibias. These results imply that $\Omega_m = 0.17 \pm 0.05$. Estimates of possible variations in $ML_{K_s}$ with radius suggest that the density parameter is no smaller than $\Omega_m \approx 0.08$.

Subject headings: cosmology: observations — dark matter — galaxies: clusters: individual (Coma) — galaxies: kinematics and dynamics — galaxies: photometry

1. INTRODUCTION

The relative distribution of matter and light in the universe is one of the outstanding problems in astrophysics. Clusters of galaxies, the largest gravitationally relaxed objects in the universe, are important probes of the distribution of mass and light. Zwicky (1933) first computed the mass-to-light ratio of the Coma Cluster and found that dark matter dominates the cluster mass. Recent determinations yield mass-to-light ratios of $ML_B \sim 250 h M_B/L_B$ (Girardi et al. 2000 and references therein). Equating the mass-to-light ratio in clusters with the global value provides an estimate of the mass density of the universe; this estimate is subject to significant systematic error introduced by differences in galaxy populations between cluster cores and lower density regions (Carlberg, Yee, & Ellingson 1997; Girardi et al. 2000). Numerical simulations suggest that antibias in cluster cores may cause cluster mass-to-light ratios to exceed the universal value (Kraftsov & Klypin 1999; Bahcall et al. 2000; Benson et al. 2000). However, there are few measurements of mass-to-light ratios on scales of 1–10 $h^{-1}$ Mpc (Eisenstein, Loeb, & Turner 1997; Small et al. 1998; Kaiser et al. 2001; Rines et al. 2000, hereafter R00) to test this conjecture.

Because clusters are not in equilibrium outside the virial radius, neither X-ray observations nor Jeans analysis provide secure mass determinations at these large radii. There are now two methods of approaching this problem: weak gravitational lensing (Kaiser et al. 2001) and kinematics of the infall region (Diaferio & Geller 1997; Diaferio 1999). Kaiser et al. analyzed the weak lensing signal from a supercluster at $z \approx 0.4$; the mass-to-light ratio ($ML_B = 280 \pm 40$ for early-type galaxy light) is constant on scales up to 6 $h^{-1}$ Mpc. Geller, Diaferio, & Kurtz (1999, hereafter GDK) applied the kinematic method of Diaferio & Geller (1997) to the infall region of the Coma Cluster. GDK reproduced the X-ray–derived mass profile and extended direct determinations of the mass profile to a radius of 10 $h^{-1}$ Mpc. This method has also been applied to the Shapley Supercluster (Reisenegger et al. 2000), A576 (R00), the Fornax Cluster (Drinkwater, Gregg, & Colless 2001), and A1644 (Tustin et al. 2001). R00 found an enclosed mass-to-light ratio of $ML_B \sim 300 h$ within 4 $h^{-1}$ Mpc.

Here we calculate the infrared mass-to-light profile to a radius of 10 $h^{-1}$ Mpc for the Coma Cluster using photometry from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997). Within a radius of 800, the redshift survey is complete to $K_s = 12.2$ (622 galaxies), 1.2 mag fainter than $M_r$, at the distance of Coma (Kochanek et al. 2001, hereafter K01). Infrared light is a better tracer of stellar mass than optical light, at least in late-type galaxies (Gavazzi, Pierini, & Boselli 1996); it is relatively insensitive to dust extinction and recent star formation. Despite these advantages, there are very few measurements of infrared mass-to-light ratios in clusters (Tustin et al. 2001). The physical scale at the redshift of Coma ($cz = 7093$ km s⁻¹; $cz_{CMB} = 7361$ km s⁻¹) is 1° = 1.25 $h^{-1}$ Mpc ($H_0 = 100 h$ km s⁻¹, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$; we assume that Coma is at rest with respect to the cosmic microwave background [CMB] and use $cz_{CMB}$ for all calculations).

2. OBSERVATIONS

2.1. Spectroscopy

We have collected 1779 redshifts (964 new or in press) within 800 of the center of the Coma Cluster (collected from the CfA Redshift Catalog and the NASA/IPAC Extragalactic Database; van Haarlem et al. 1993; Colless & Dunn 1996; Falco et al. 1999; Castander et al. 2001; Wegner et al. 2001; M. J. Geller et al. 2001, in preparation). We measured new redshifts with FAST, a long-slit spectrograph (Fabricant et al. 1998) on
the 1.5 m Tillinghast telescope of the Fred Lawrence Whipple Observatory (FLWO). We selected targets from digitized images of the POSS I 103aE (red) plates. The redshift catalog is complete to \( E \approx 15.4 \) (845 galaxies). We later obtained a small number of redshifts (\( \sim 20 \)) to complete the \( K_s \leq 12.2 \) sample. K. Rines et al. (2001, in preparation) describes this catalog in detail.\(^7\)

2.2. The 2MASS Photometry

The 2MASS is an all-sky survey with uniform, complete photometry (Nikolaev et al. 2000) in three infrared bands (\( J, H, \) and \( K \), a modified version of the \( K \)-filter truncated at longer wavelengths). We use a preliminary version of the complete extended source catalog (Jarrett et al. 2000). Future recalibrations may change the zero points of individual scans by up to 0.03 mag. We use the default \( K_s \)-band survey magnitudes that include light within the circular isophote corresponding to \( \mu_{K_s} = 20 \) mag arcsec\(^{-2} \) (Jarrett et al. 2000). These magnitudes omit \( \sim 15\% \) of the flux (K01). The sky coverage of the catalog is complete to \( K_s = 12.2 \). We include two galaxies not in 2MASS with \( K \) magnitudes from Gavazzi & Boselli (1996).

There are 622 galaxies with \( K_s \leq 12.2 \) within \( 8'0 \) of the center of Coma; all of these galaxies have measured redshifts. We make no correction for Galactic extinction, which is negligible in the near-infrared at the north Galactic pole.

3. DEFINING THE INFALL REGION WITH CAUSTICS

Figure 1 displays the projected radii and redshifts of galaxies surrounding Coma. The expected caustic pattern is easily visible; we calculate the shape with the technique described in Diaferio (1999) using smoothing parameters \( q = 10, 25, \) and 50 to test the variation caused by the subjective choice of this parameter. GDK show that the mass profile is robust with respect to the limiting magnitude and nonuniform sampling. We recalculate the caustics based on additional redshifts collected since the calculation by GDK and find the same results. The cluster center is \( \alpha = 13^\text{h}00^\text{m}00^\text{s}.7, \delta = 27^\circ56'51" \) (J2000) and \( c_{\text{CGS}} = 7093 \text{ km s}^{-1} \) (\( c_{\text{CMR}} = 7361 \text{ km s}^{-1} \)). The center is 2'3 southwest of NGC 4884 and 5'6 east-southeast of NGC 4874. The mass profile agrees with the Navarro, Frenk, & White (1997, hereafter NFW) form but excludes a singular isothermal sphere. For the NFW profile, \( r_s \approx 0.17 \text{ h}^{-1} \text{ Mpc} \), and \( r_{200} \approx 1.5 \text{ h}^{-1} \text{ Mpc} \) (\( r_{200} \) is the radius of the sphere with an average mass density 200 times the critical density). Varying \( q \) changes the mass in the range of 6–10 \( h^{-1} \) Mpc; the NFW form provides the best fit for \( q = 10 \) and \( q = 25 \), but the Hernquist form provides the best for the choice \( q = 50 \). Unless otherwise stated, we use \( q = 25 \) in later analysis (this choice yields the largest mass in the range of 6–10 \( h^{-1} \) Mpc). GDK show that the mass profile agrees with independent X-ray mass estimates (Hughes 1989).

4. MASS-TO-LIGHT PROFILE

We subtract background and foreground galaxies (those outside the caustics) from the sample. K01 and Cole et al. (2001) use 2MASS to calculate the infrared field galaxy luminosity function (LF) and obtain nearly identical results. We adopt the values \( M_{K_s}^* = -23.39 \pm 0.05 \) and \( \alpha = -1.09 \pm 0.06 \) (K01) for 2MASS isophotal magnitudes. Measurements of the LF of the Coma Cluster yield similar values of \( M_{K_s}^* \) (Mobasher &

\(^7\) The redshift catalog is available at http://tdc-www.harvard.edu/comacz.

5. DISCUSSION

The \( K \)-band mass-to-light ratio of the Coma Cluster within 10 \( h^{-1} \) Mpc is \( 75 \pm 23 \) as estimated from the light contained in galaxies brighter than \( K_s = 12.2 \) and the LF of K01. We

Fig. 1.—Redshift vs. projected radius of galaxies around the Coma Cluster. The trumpet-shaped caustic pattern that defines the infall region is clearly visible. The dashed, solid, and dash-dotted lines show the location of the caustics for \( q = 10, 25, \) and 50, with \( 1 \) uncertainties shown for \( q = 25 \). For clarity, the uncertainties are only displayed away from the cluster.
The mass-to-light profile may be affected by departures from projection effects (Diaferio 1999); the shape of the enclosed mass-to-light ratio is constant within 10\% by a factor of 2 between the core and a radius of 4\,h^{-1}\,Mpc. We estimate that mass estimates yield estimates of 280–380\,M_{\odot} when divided by the (projected) light profile. Assuming a typical galaxy color62 for a mass-follows-light model (Hughes 1989). We use a typical galaxy color of \(B-K \approx 3.7\) (Jarrett 2000) and \((B-K)_{c} = 2.11\), we obtain \(M/L_{p} \approx 329 \pm 103\,h\), in agreement with \(M/L_{p} = 280 \pm 40\,h\) from weak lensing on a similar scale (Kaiser et al. 2001). At a radius of 3\,h^{-1}\,Mpc, \(M/L_{p} \approx 316 \pm 57\,h\), in agreement with Kent & Gunn (1982), who find \(M/L_{p} \approx 362\,h\) at this radius. X-ray mass estimates yield estimates of 280–380\,h\,Mpc for a mass-follows-light model (Hughes 1989). We use a typical galaxy color of \(R-K \approx 2.2\) and \((R-K)_{c} = 0.94\) to estimate \(M/L_{p} \approx 243 \pm 72\,h\), in agreement with caustic estimates at large radii in A576 (R00). We estimate that \(M/L_{p} \approx 91 \pm 27\,h\), in agreement with \(M/L_{p} = 82–127\,h\) in A1644 (Tustin et al. 2001).

The shape of the enclosed mass-to-light profile differs from the one measured in the \(K\) band for A576. Instead of decreasing by a factor of 2 between the core and a radius of 4\,h^{-1}\,Mpc, the enclosed mass-to-light ratio is constant within 10\,h^{-1}\,Mpc. We propose two explanations of this difference. First, it may be a result of projection effects (Diaferio 1999); the shape of the mass-to-light profile may be affected by departures from spherical symmetry (R00). Second, if the enclosed mass-to-light profile measured in the \(K\) band is flat in A576 as in Coma, a decrease in \(R-K\) with radius leads to a decreasing profile in the \(R\) band. We expect such a trend if the star formation rate increases with radius as observed in other systems (e.g., Balogh, Navarro, & Morris 2000). Infrared light profiles should be insensitive to recent star formation and best represent the distribution of stellar mass within the infall region. CCD \(R\,(K)\) photometry for Coma (A576) would resolve this issue. The color gradient effect becomes more significant at bluer wavelengths; we expect more steeply decreasing mass-to-light ratios with decreasing wavelength (see Diaferio 1999 and Bahcall et al. 2000).

In calculating the mass-to-light profile for Coma, we assume that the LF is independent of radius; changes in the LF with radius would affect the mass-to-light profile of Coma. Balogh et al. (2001) find different LFs in field, group, and cluster environments. Our survey includes 67\%, 69\%, and 65\% of the total light in their field, group, and cluster LFs, respectively, assuming a Schechter form. Thus, uncertainties due to changes in the LF with environment contribute \(\leq 7\%\) uncertainty to the light profile. Our data provide no constraints on galaxies fainter than \(M_{K_{c}} = M_{K_{c}}^{*} + 1.2\).

6. SUMMARY

We calculate the mass-to-light ratio as a function of radius in the near-infrared \(K_{s}\) band for the Coma Cluster. This calculation is one of the first measurements of a cluster mass-to-light ratio in the infrared. The mass-to-light profile extends to 10\,h^{-1}\,Mpc and represents one of the largest scale measurements of a cluster mass-to-light ratio at any wavelength. Within 10\,h^{-1}\,Mpc, the enclosed mass-to-light ratio is \(M/L_{K_{s}} = 75 \pm 23\,h\). With appropriate color transformations, this value agrees with previous optical and X-ray estimates for Coma (Kent & Gunn 1982; Hughes 1989) and estimates at scales of 1–6\,h^{-1}\,Mpc from infall mass estimates (R00) and weak lensing (Kaiser et al. 2001) in other systems.

The enclosed mass-to-light ratio is constant on scales up to 10\,h^{-1}\,Mpc. This result implies that \(K\)-band light measured in bright galaxies traces the underlying mass distribution in clusters on scales of up to 10\,h^{-1}\,Mpc. Uncertainties in the mass profile imply that the mass-to-light ratio inside \(r_{200}\) may be as much as a factor of \(\sim 2.5\) larger than the ratio outside \(r_{200}\), possibly because of antibias. \(K\)-band light is not positively biased with respect to mass; we cannot rule out antibias. Radial gradients in the star formation rate should create stronger observed antibias at shorter wavelengths (Kravtsov & Klypin 1999; Bahcall et al. 2000; Benson et al. 2000; R00).

The asymptotic value of \(M/L_{K_{s}} = 75 \pm 23\,h\) implies that \(\Omega_{m} = 0.17 \pm 0.05\) using the K01 field galaxy LF. Because we calculate magnitudes in the same manner as K01 from similar data, many potential systematic effects should affect our sample and the field galaxy LF equally. A recent study of variations

![Figure 2](image-url)

**FIG. 2.—** Filled squares: Enclosed mass-to-light ratio as a function of radius. Solid lines: 1 \(\sigma\) uncertainties. Open squares: Mass-to-light ratio in each spherical shell. Dash-dotted line: Best-fit projected Hernquist mass profile divided by the (projected) light profile. Asterisks: Mass-to-light profile from X-ray photometry for Coma (A576). This calculation is one of the first measurements of a cluster mass-to-light ratio at any wavelength. Within 10\,h^{-1}\,Mpc, the enclosed mass-to-light ratio is \(M/L_{K_{s}} = 75 \pm 23\,h\). With appropriate color transformations, this value agrees with previous optical and X-ray estimates for Coma (Kent & Gunn 1982; Hughes 1989) and estimates at scales of 1–6\,h^{-1}\,Mpc from infall mass estimates (R00) and weak lensing (Kaiser et al. 2001) in other systems.

### TABLE 1

**Radial Variations in \(M/L_{K_{s}}\)**

| \(q\) | \(M_{200}\) \((\times 10^{14}\,h^{-1}\,M_{\odot})\) | \(M(> r_{200})\) \((\times 10^{14}\,h^{-1}\,M_{\odot})\) | \(M(L_{K_{s}})(< r_{200})\) \((h\,M_{\odot}/L_{K_{s}})\) | \(M(L_{K_{s}})(> r_{200})\) \((h\,M_{\odot}/L_{K_{s}})\) | \(M(L_{K_{s}})(< 10\,h^{-1}\,Mpc)\) \((h\,M_{\odot}/L_{K_{s}})\) |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 10 | 8.0 ± 0.6 | 7.7 ± 1.3 | 71 ± 9 | 60 ± 12 | 65 ± 14 |
| 10 (Hernquist) | 9.7 | 4.7 | 87 | 36 | 60 |
| 25 | 8.1 ± 0.8 | 10.2 ± 2.8 | 72 ± 10 | 79 ± 23 | 75 ± 23 |
| 25 (Hernquist) | 10.1 | 5.6 | 91 | 43 | 65 |
| 50 | 8.5 ± 1.8 | 6.7 ± 3.3 | 76 ± 18 | 51 ± 26 | 63 ± 35 |
| 50 (Hernquist) | 10.1 | 5.5 | 91 | 42 | 64 |

*Projected best-fit Hernquist profile.*
in the LF with environment (Balogh et al. 2001) suggests that environmental effects contribute \( \approx 7\% \) uncertainty to the light profile. Estimates of possible variations in \( M/L_k \) with radius (Table 1) suggest that the density parameter is no smaller than \( \Omega_m \approx 0.08 \). Similar studies of more distant clusters can produce better constraints if combined with weak-lensing estimates.

This project would not have been possible without the 2MASS team (in particular M. Skrutskie, T. Chester, R. Cutri, J. Mader, and S. E. Schneider) or the assistance of P. Berlind and M. Calkins, the remote observers at FLWO, and S. Tokarz, who processed the spectroscopic data. K. R., M. J. G., M. J. K., and J. P. H. are supported in part by the Smithsonian Institution. A. D. was supported by an MPA guest postdoctoral fellowship when this work began. This publication made use of data products from 2MASS, a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, funded by NASA and the NSF.

REFERENCES

Andreon, S., & Pelló, R. 2000, A&A, 353, 479
Bahcall, N. A., Cen, R., Davé, R., Ostriker, J. P., & Yu, Q. 2000, ApJ, 541, 1
Balogh, M. L., Christlein, D., Zabludoff, A. I., & Zaritsky, D. 2001, ApJ, 557, 117
Balogh, M. L., Navarro, J. F., & Morris, S. L. 2000, ApJ, 540, 113
Benson, A. J., Cole, S., Frenk, C. S., Baugh, C. M., & Lacey, C. G. 2000, MNRAS, 311, 793
Carlberg, R. G., Yee, H. K. C., & Ellingson, E. 1997, ApJ, 478, 462
Castander, F. J., et al. 2001, AJ, 121, 2331
Cole, S., et al. 2001, MNRAS, 326, 255
Colless, M., & Dunn, A. M. 1996, ApJ, 458, 435
de Propris, R., Eisenhardt, P. R., Stanford, S. A., & Dickinson, M. 1998, ApJ, 503, L45
Diaferio, A. 1999, MNRAS, 309, 610
Diaferio, A., & Geller, M. J. 1997, ApJ, 481, 633
Drinkwater, M. J., Gregg, M. D., & Colless, M. 2001, ApJ, 548, L139
Eisenstein, D. J., Loeb, A., & Turner, E. L. 1997, ApJ, 475, 421
Fabricant, D., Chemets, P., Caldwell, N., & Geary, J. 1998, PASP, 110, 79
Falco, E. E., et al. 1999, PASP, 111, 438
Gavazzi, G., & Boselli, A. 1996, Astrophys. Lett. Commun., 35, 1
Gavazzi, G., Pierini, D., & Boselli, A. 1996, A&A, 312, 397
Geller, M. J., Diaferio, A., & Kurtz, M. J. 1999, ApJ, 517, L23 (GDK)
Girardi, M., Borgani, S., Giuricin, G., Mardirossian, F., & Mezzetti, M. 2000, ApJ, 530, 62
Hernquist, L. 1990, ApJ, 356, 359
Hughes, J. P. 1989, ApJ, 337, 21
Jarrett, T. H. 2000, PASP, 112, 1008
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S., Skrutskie, M., & Huchra, J. P. 2000, AJ, 119, 2498
Kaiser, N., Wilson, G., Luppino, G., Kofman, L., Gioia, I., Metzger, M., & Dahle, H. 2001, ApJ, submitted (astro-ph/9809268)
Kent, S. M., & Gunn, J. E. 1982, AJ, 87, 945
Kochanek, C. S., et al. 2001, ApJ, 560, 566 (K01)
Kravtsov, A. V., & Klypin, A. A. 1999, ApJ, 520, 437
Mobasher, B., & Trentham, N. 1998, MNRAS, 293, 315
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 599, 493 (NFW)
Nikolaev, S., Weinberg, M. D., Skrutskie, M. F., Cutri, R. M., Wheelock, S. L., Gizis, J. E., & Howard, E. M. 2000, AJ, 120, 3340
Reisenegger, A., Quintana, H., Carrasco, E. R., & Maze, J. 2000, AJ, 120, 523
Rines, K., Geller, M. J., Diaferio, A., Mohr, J. J., & Wegner, G. A. 2000, AJ, 120, 2338 (R00)
Skrutskie, M. F., et al. 1997, in The Impact of Large Scale Near-IR Sky Surveys, ed. F. Garzón et al. (Dordrecht: Kluwer), 25
Small, T. A., Ma, C., Sargent, W. L. W., & Hamilton, D. 1998, ApJ, 492, 45
Tustin, A. W., Geller, M. J., Kenyon, S. J., & Diaferio, A. 2001, AJ, 122, 1289
van Haarlem, M. P., Cayon, L., Guiterrez de la Cruz, C., Martinez-Gonzalez, E., & Rebolo, R. 1993, MNRAS, 264, 71
Wegner, G., et al. 2001, AJ, in press (astro-ph/0109101)
Wright, E. L. 2001, ApJ, 556, L17
Zwicky, F. 1933, Helvetica Phys. Acta, 6, 110