A PHOTOMETRIC AND KINEMATIC STUDY OF AWM 7

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ABSTRACT

We have measured redshifts and Kron-Cousins $R$-band magnitudes for a sample of galaxies in the poor cluster AWM 7. We have measured redshifts for 172 galaxies; 106 of these are cluster members. We determine the luminosity function (LF) from a photometric survey of the central $1.2 \times 1.2 \ h^{-1} \ \text{Mpc}$. The LF has a bump at the bright end and a faint-end slope of $\alpha = -1.37 \pm 0.16$, populated almost exclusively by absorption-line galaxies. The cluster velocity dispersion is lower in the core ($\sim 530 \ \text{km s}^{-1}$) than at the outskirts ($\sim 680 \ \text{km s}^{-1}$), consistent with the cooling flow seen in the X-ray. The cold core extends $\sim 150 \ h^{-1} \ \text{kpc}$ from the cluster center. The Kron-Cousins $R$-band mass-to-light ratio of the system is $650 \pm 170 \ h \ M_\odot/L_\odot$, substantially lower than previous optical determinations, but consistent with most previous X-ray determinations. We adopt $H_0 = 100 \ h \ \text{km s}^{-1} \ \text{Mpc}^{-1}$ throughout this paper; at the mean cluster redshift ($5247 \pm 76 \ \text{km s}^{-1}$), $1 \ h^{-1} \ \text{Mpc}$ subtends $65.5$.

Key words: galaxies: clusters: individual (AWM 7) — galaxies: luminosity function, mass function

1. INTRODUCTION

The AWM and MKW clusters were selected on the basis of the appearance of the central cD galaxy (Morgan, Kayser, & White 1975; Albert, White, & Morgan 1977). There is controversy about the history of these systems and the presumably related formation of the central galaxy. Ostriker & Tremaine (1975) suggest that a cD galaxy grows by accreting other galaxies through dynamical friction and tidal stripping; Merritt (1985) suggests that galaxies merge during the original cluster collapse. Recent N-body simulations by Bode et al. (1994) and Dubinski (1998) produce giant central elliptical galaxies through hierarchical merging. Fabian (1994) proposes that enhanced star formation at the cluster center resulting from a cooling flow may further enlarge these merged galaxies.

The AWM/MKW clusters span a broad range of velocity dispersions ($\sigma \sim 100–700 \ \text{km s}^{-1}$) and more than 2 orders of magnitude in X-ray luminosity (Beers et al. 1995; Kriss et al. 1980; Kriss, Cioffi, & Canizares 1983). Detailed study of these systems may thus discriminate among these scenarios. These systems are dynamically fairly simple in their centers, without much substructure in the central $1 \ h^{-1} \ \text{Mpc}$, although there is evidence for complexity on larger scales (Beers et al. 1995). They are sufficiently nearby that a complete sample can be analyzed to reasonable limiting magnitude with modest instrumentation. X-ray data in conjunction with optical studies provide a foundation for equilibrium mass models of these clusters.

Early optical studies of AWM/MKW systems lack extensive photometry and complete redshift samples (Beers et al. 1984, 1995 and references therein; Malumuth & Kriss 1986; Williams & Lynch 1991; Price et al. 1991; Dell'Antonio, Geller, & Fabricant 1995). AWM 7 is particularly problematic, as it spans two Palomar Sky Survey plates with rather different sensitivities, making consistent photographic magnitude determination difficult. Previous optical determinations of the mass-to-light ratio of AWM 7 (Kriss et al. 1983; Beers et al. 1984) yield values exceeding $1000 \ h \ M_\odot/L_\odot$, a result exacerbated by the cluster's high velocity dispersion. The optical data are discrepant with X-ray determinations in the range $200–500 \ h \ M_\odot/L_\odot$ (Dell'Antonio et al. 1995; Neumann & Börhringer 1995). Our new complete photometric and spectroscopic data yield $650 \pm 150 \ h \ M_\odot/L_\odot$, consistent with the range for other clusters and with the X-ray data for AWM 7. Optical mass-to-light determinations for other AWM/MKW systems by Beers et al. (1995) are generally consistent with X-ray results.

AWM 7 is the first system in our study of a complete sample of nearby AWM/MKW clusters. It is one of the nearest clusters ($\sim 5200 \ \text{km s}^{-1}$), and is the one with the largest velocity dispersion ($\sim 700 \ \text{km s}^{-1}$). We have measured 172 magnitudes and redshifts in AWM 7, making it one of the best-sampled systems in the sky.

In § 2, we discuss the data acquisition and reduction, and define the cluster sample. In § 3, we discuss the cluster kinematics and segregation by spectral type, search for substructure, and examine the velocity dispersion profile. In § 4, we discuss the photometric properties, compute the luminosity function of the cluster, and compute the mass-to-light ratio. We discuss the ramifications in § 5 and conclude in § 6.

2. OBSERVATIONS

AWM 7 is a poor cluster with the cD galaxy NGC 1129.
Table 1 contains the velocities and R-band magnitudes for the 172 galaxies. Column (1) lists the galaxy right ascension; column (2), the declination; column (3), the radial velocity; column (4), the uncertainty in the radial velocity; column (5), the isophotal magnitude (to 23.5 mag arcsec$^{-2}$ in $R_{\text{EC}}$); column (6), the error in isophotal magnitude; column (7), the source of the magnitude (CCD frame number or P for POSS); column (8), the spectral type (presence or absence of H$\alpha$ emission, quantified in §3); and column (9), the extinction $A_R$ along the line of sight to the galaxy.

2.1. Redshifts

We measured 140 redshifts with the FAST spectrograph on the Whipple Observatory 1.5 m Tillinghast Telescope in 1995 November–December and a further 43 with the Multiple Mirror Telescope (MMT) Blue Channel Spectrograph on 1996 December 5–6, yielding 172 galaxy redshifts. To ensure uniform spectroscopy with a well-understood error model, we obtained a new spectrum for each galaxy, despite the scatter due to the number or P for POSS); column (8), the spectral type (presence or absence of H$\alpha$ emission, quantified in §3); and column (9), the extinction $A_R$ along the line of sight to the galaxy.

2.2. Photometry

We acquired an R-band mosaic of the central 75' x 75' of the cluster with the MDM 1.3 m telescope during 1995 November. Thirty-six 6 minute 13:7 x 13:7 exposures were taken, with 1:2 overlap between frames. Conditions were photometric for most of the images; we correct the four nonphotometric images using the overlap regions with neighboring photometric frames. The rms error in the photometric solutions are 0.0196 and 0.0370 mag for the two photometric nights. We determine isophotal magnitudes with the Faint Object Classification and Analysis System (FOCAS) package. The quoted magnitudes are isophotal to $R = 23.5$ mag arcsec$^{-2}$, which is more than 2 $\sigma$ above the sky noise in each frame. We reviewed the star/galaxy separation manually for all nonstellar objects brighter than $R_{23.5} = 18.5$ to remove misclassified objects—FOCAS tends to misclassify double stars as galaxies.

FOCAS magnitudes are sensitive to the local sky. FOCAS is optimized for faint objects, and tends to underestimate the luminosity of bright extended objects systematically, assigning much of the diffuse light to the sky rather than to the object. Moreover, because the isophotes are defined by the number of $\sigma$ in excess of sky, the determination of the sky $\sigma$ in each frame is critical. There are flaws in the FOCAS software that lead to systematic errors in the sky determination. The presence of bright stars at the bottom edge of an image results in comet-like swaths of spuriously bright sky extending up the image. Blocking out the stars by hand removes this effect, but its very existence adds uncertainty to the sky determination and, hence, to the isophotal magnitudes. We thus add 0.05 mag in quadrature to the magnitude errors, derived otherwise from the rms scatter in the photometric solution; for the nonphotometric images, we also include the uncertainty in the zero point as determined from the rms magnitude error for isolated stars in the overlap regions. We quote an error of 0.25 mag for the digitized POSS magnitudes (Geller et al. 1997), although the scatter is in fact likely greater for AWM 7 because of the different sensitivities of the two plates spanned by the cluster.

### TABLE 1

| $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $cz$ (km s$^{-1}$) | $\sigma_{cz}$ (km s$^{-1}$) | $m_R$ | $\Delta m_R$ | Phot. Type | Emission Type | $A_R$ |
|------------------|------------------|--------------------|-----------------------------|------|-------------|------------|--------------|------|
| 2 49 20.60       | 40 53 17.02      | 4161               | 31.4                        | 14.99| 0.250       | P          | Ab           | 0.40 |
| 2 49 45.30       | 42 22 05.81      | 5489               | 31.3                        | 14.42| 0.250       | P          | Ab           | 0.41 |
| 2 49 45.90       | 41 27 26.10      | 19811              | 21.2                        | 15.45| 0.250       | P          | Em           | 0.45 |
| 2 49 46.10       | 41 03 06.00      | 6108               | 19.0                        | 14.98| 0.250       | P          | Em*          | 0.42 |
| 2 49 46.10       | 41 03 06.00      | 6108               | 19.0                        | 13.48| 0.250       | P          | Em*          | 0.41 |

Note.—Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

* Emission-line H$\alpha$ equivalent widths typically $\gtrsim 7$ Å.
We use galaxies in overlap regions of the mosaic to check the consistency of the magnitudes; in Figure 1, we plot the difference in the magnitude measurements for individual galaxies as determined from different mosaic fields. We plot the differences as a function of the brighter magnitude. When a galaxy appears in more than two fields, we plot the greatest difference against the brightest magnitude. The mean difference is 0.043 mag, with a scatter of 0.036 mag.

We calculate an extinction correction for each galaxy from the relation $A_R = 2.5E(B-V)$ (Zombeck 1992), with the color related to the H I column density by $\langle N(\text{H} I)/E(B-V) \rangle = 4.8 \times 10^{21}$ atoms cm$^{-2}$ mag$^{-1}$ (Bohlin, Savage, & Drake 1978). We obtain the H I column density along the line of sight to each galaxy from the Bell Laboratories H I maps (Stark et al. 1992). The extinction in the total sample of 172 galaxies ranges from 0.40 to 0.54 mag; the gradient arises from the cluster’s proximity to the galactic plane $(B_\odot = -15.6)$. Within the region with CCD photometry, the extinction ranges from 0.42 to 0.50. These values exceed those on the map of Burstein & Heiles (1982) by $\sim 0.15$ mag. The magnitudes listed in Table 1 are the measured magnitudes, uncorrected for the extinction in column (9). Calculations of the luminosity function below do account for the extinction.

### 2.3. Defining the Cluster Sample

Figure 2a shows the redshift distribution for all 172 galaxies; large-scale structure is apparent behind the cluster at $\sim 20,000$ km s$^{-1}$, and more weakly at $\sim 10,000$ km s$^{-1}$. In the range 2500–7500 km s$^{-1}$ there are 106 galaxies, which we identify as cluster members; we denote this set of galaxies the “C” sample. The line under the histogram in Figure 2b indicates this range, and the dotted line indicates the redshift of the central cD galaxy. For these 106 galaxies, $cz = 5247 \pm 76$ km s$^{-1}$ and $\sigma = 783 \pm 49$ km s$^{-1}$ (Danese, De Zotti, & di Tullio 1980, 68% confidence). There is a 779 km s$^{-1}$ velocity gap between the highest redshift cluster galaxy and the lowest redshift background galaxy; this is a $\sim 1 \sigma$ gap starting 2.5 $\sigma$ above the cluster mean. There is no obvious foreground.
Eighty-two of the 106 C galaxies lie within the region with CCD photometry; Figure 2c shows their velocity distribution. This sample is 100% complete to $R = 16.3$, 99% complete to $R = 16.5$, 98% complete to $R = 16.7$, and 96% complete to $R = 16.9$ (uncorrected magnitudes); for this subsample, $cz = 5248 \pm 82 \text{ km s}^{-1}$ and $\sigma = 747_{-36}^{+56} \text{ km s}^{-1}$, clearly consistent with the larger sample. We denote this set of galaxies the “ML” sample.

There are 134 galaxies in the central $75' \times 75' (1.56 \text{ deg}^2$) with $R_{23.5} \leq 17$, of which 122 have measured redshifts; of these, the 82 ML galaxies have velocities in the range 2500–7500 km s$^{-1}$. Assuming that 82/122 of the 12 unmeasured galaxies also lie in the cluster, we estimate that there are $4 \pm 2$ additional background galaxies, for a total of $44 \pm 5$, or $28 \pm 3 \text{ deg}^{-2}$. Representing the background count by

$$n_b = C_0 \int_{-\infty}^{m_{\text{min}}} 10^{d_0} \, dm \, \text{deg}^{-2},$$

and using values of $d_0$ and $C_0$ derived from the Century Survey (Geller et al. 1997) yields $n_b = 36 \pm 6 \text{ deg}^{-2}$ for $m_{\text{min}} = 16.9$, consistent with the background we observe. The quoted errors are Poisson errors, which underestimate the true error due to clustering.

We investigate the peak in the velocity histogram (Fig. 2a) at $\sim 18,000 \text{ km s}^{-1}$. We plot the spatial distribution of the background galaxies in Figure 3; the nonuniform distribution of the background galaxies adds some uncertainty to the computation of the faint end of the LF (§ 4.3) and to the background-subtraction statistics.

3. KINEMATICS

We use the C sample to examine the kinematics of the cluster. This sample is magnitude-limited only within the area of the CCD survey.

We separate our sample by spectral type (presence/absence of H$\alpha$); the two subsamples have quite different kinematics. We test for substructure in the cluster and examine the cluster velocity dispersion profile as a function of radius.

3.1. Velocity Histogram

The velocity distribution in Figure 2b appears bimodal with an apparent peak near 4500 km s$^{-1}$. However, a Kolmogorov-Smirnov (K-S) test (Press et al. 1992) shows that the distribution is consistent with a Gaussian velocity distribution of mean 5247 km s$^{-1}$ and dispersion 783 km s$^{-1}$ ($P_{d > d_{\text{crit}}} = 0.73$).

3.2. Spectral Segregation

We separate the sample into emission (Em) and nonemission (Ab) galaxies, based on the presence or absence of H$\alpha$ emission in the spectrum. We use two criteria for including a galaxy in the Em sample. The first is that the redshift derived from cross-correlating against the emission-line template must lie within 200 km s$^{-1}$ of the redshift derived from the best-fit template; if the emission-line template fits best, this criterion is automatically satisfied. The second criterion is that the EMSAO task in the IRAF RVSAO package must detect and correctly identify H$\alpha$ given the best-fit redshift. If both criteria are satisfied, we classify the galaxy as Em; if neither, as Ab. If the first criterion is satisfied and not the second, the galaxy is classified as Ab; given the correct redshift, EMSAO would identify any strong H$\alpha$ that were present. If the second criterion is satisfied but not

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8.2. Angular distribution of the 106 C galaxies with 2500 km s$^{-1} < cz < 7500 \text{ km s}^{-1}$, both within and without the region with CCD photometry. Emission-line galaxies are circles; nonemission galaxies are crosses.
central concentration of the Ab galaxies is apparent, as is their smaller velocity dispersion. Moreover, all but one of the 13 faint (R > 16.3) cluster galaxies are absorption-line systems. We discuss the magnitude distribution in more detail in §4.

The cluster Abell 576 shows similar behavior (Mohr et al. 1996a); there too the Em galaxies are less spatially concentrated, have a greater velocity dispersion, and are systematically fainter than the Ab galaxies, but they are not offset from the cluster center. The core velocity dispersions of the Ab galaxies are \( \sim 530 \, \text{km} \, \text{s}^{-1} \) in both AWM 7 and A576, but the velocity dispersion profile rises more steeply and to a higher value in A576; at 1 Mpc, \( \sigma_{A576} \sim 1000 \, \text{km} \, \text{s}^{-1} \). The ratio of Em to Ab galaxies is larger in A576 (79:142).

We follow the procedure adopted by Mohr et al. (1996a) and consider the Em and Ab samples separately below. We base our estimates of the mass-to-light ratio on the Ab galaxies only.

### 3.3. Substructure

We use the Dressler-Shectman (D-S) statistic (Dressler & Shectman 1988) to test for substructure in the cluster. They define the statistic

\[
\Delta_0 = \sum \delta_i,
\]

where the summation is over all galaxies and

\[
\delta_i = \frac{n}{\sigma_g^2} \left[ (\bar{v}_g - \bar{v}_i)^2 + (\sigma_g - \sigma_i)^2 \right]^{1/2}
\]

is a measure of the deviation of the local mean velocity and dispersion \((\bar{v}_i, \sigma_i)\) from the global cluster values \((\bar{v}_g, \sigma_g)\). For each galaxy, \(\delta_i\) is a function of the number of nearest neighbors \(n\) entering into the calculation of the local \(\bar{v}_i\) and \(\sigma_i\). We evaluate the significance of \(\Delta_0\) for each \(n\) by randomly shuffling the velocities of all galaxies 5000 times, and recalculating \(\Delta_0\) each time. We thus obtain a distribution of \(\Delta_0\) against which to compare the actual value.

A D-S test with \(n = 11\) indicates that there is substructure in the northwest of the cluster, where the Em galaxies predominate. Because the \(\Delta_0\) statistic characterizes local deviations of the mean and dispersion from the overall cluster values, this substructure reflects the larger dispersion of the Em galaxies seen in Figure 5. The significance of the substructure detection is marginal. Figure 7 shows the D-S statistic for the 106 C galaxies as a function of subgroup size \(n\) for \(5 \leq n \leq 90\) in the top panel, with the probability of an equal or greater D-S statistic arising by chance (determined from the 5000 Monte Carlo simulations for each \(n\)) in the bottom panel. A low \(P_{\text{false}}\) indicates a high significance for the substructure detection. The substructure is most significant for \(n = 13\), but even then there is still a greater than 2% chance of an equal or greater \(\Delta_0\) arising by chance. When we exclude the Em galaxies and perform the D-S test on the...
remaining 88 Ab galaxies, there is no discernible substructure for any value of n (not shown); the distribution of Ab galaxies is smooth. This analysis supports the idea that the Em galaxies are a dynamically distinct population of late-type galaxies; our sample does not contain enough Em galaxies to determine their large-scale dynamics. It may be that, as in A576, they are infalling.

3.4. Velocity Dispersion Profile

Figure 8 plots the velocity dispersion of the 88 non-emission C galaxies as a function of cluster radius. We take the cD as the geometric center of the cluster; Neumann & Böhringer (1995, hereafter NB) find that the cD coincides exactly with the maximum of the X-ray emission. The plot extends to to 2200", the radius to which our photometric and kinematic data are both complete.

Each point in the top panel of Figure 8 represents the velocity dispersion of 11 galaxies ranked sequentially in distance from the cD; neighboring points are thus correlated, but represent annuli of different widths. Uncorrelated points are distinguished by 68% confidence level error bars. The middle and bottom panels plot the velocity and magnitude dispersion of 11 galaxies ranked sequentially in distance from the overall cluster median; however, the cluster core has relatively few faint galaxies and median values of and for the remaining 88 Ab galaxies, there is no discernible substruc-

so that the core is cooler than the outskirts, but only at the ~1 σ level. The evidence for a cold core from σ(r) alone is thus present, but weak. The scale of the core matches the scale of the X-ray cooling flow seen by NB.

A. Diaferio (1997, private communication) proposes a simple dynamical explanation for a cold core. Under the assumption of virial equilibrium (probably valid for the Ab-type galaxies in the core),

\[ \sigma^2 \propto \frac{GM(<r)}{r} \]

Replacing the radial mass density profile by a power law \( \rho(r) \propto r^{-\alpha} \) yields

\[ M(<r) \propto \int_0^r \rho(x)x^2dx \propto r^{3-\alpha} , \]

so \( \alpha < 2 \) results in a rising \( \sigma(r) \) profile, and \( \alpha > 2 \) in a falling profile. The mass model of Navarro, Frenk, & White (1995) posits \( \rho(r) \propto r^{-1}(r + r_s)^{-2} \), which behaves as \( r^{-1} \) for small \( r \), giving \( \sigma(r) \propto r^{1/2} \), a rising profile. Alternatively, the common \( \beta \)-model (Cavaliere & Fusco-Femiano 1978) has \( \rho(r) \propto [1 + (r/r_s)^2]^{-3/2} \), implying constant density for \( r < r_s \) and so \( \sigma(r) \propto r \) in this regime. NB find \( r_s = 51 \pm 3 \) h^{-1} kpc for AWM 7. Thus the \( r \)-dependence of \( \sigma \) in the core \( (r < r_s) \) would only be detectable with very dense sampling of the cluster core to overcome small-number Poisson statistics, the sensitivity of \( \sigma \) to outliers, and the small angular extent of the core. Our sampling is too sparse to characterize any rise within \( r_s \), as more representative of one model density profile or the other; a deeper sample could in principle discriminate between them. However, the cluster core has relatively few faint galaxies, and the core sampling may never be dense enough to discriminate.

4. PHOTOMETRIC PROPERTIES

Figure 9 shows the differential and cumulative magnitude distribution of the 82 ML galaxies, with the Em galaxies alone as the dotted histogram. Here we correct the magnitudes for extinction. At the mean sample redshift of 5247 km s^{-1}, \( m = M + 33.60 - 5 \log h \). A fiducial absolute magnitude for the field \( M_{kr} = -20.7 \) in the R-band from the Century Survey yields a corresponding \( m_{kr} = 13.35 - 5 \log h \). AWM 7 contains three galaxies substantially brighter than \( m_{kr} \), and seven of comparable magnitude.

The distribution of the Em galaxies is flat as a function of magnitude; significantly, only one galaxy fainter than 16.3 is an emission-line galaxy. The median magnitude of the Em sample is \( R = 15.44 \); the median of the Ab sample is \( R = 14.67 \). The offset between the magnitude distributions probably reflects the \( \Delta(B - R) \sim 1 \) mag color difference between late- and early-type galaxies. At B, the Em and Ab galaxies would have more concordant magnitude distributions, consistent with field measurements (Marzke et al. 1994). A similar offset between the spectral types is seen in A576.

4.1. Surface Brightness

Figure 10 shows the mean and central surface brightness for the 82 sample galaxies. The core surface brightness is determined in the most luminous 3 x 3 pixel grid in the object, corresponding to an area 1.33 square on the sky; we
compute the mean surface brightness within the $R = 23.5$ isophote. We plot E1 galaxies as triangles and A1 galaxies as squares. There is a clear trend of decreasing surface brightness with increasing magnitude. This trend makes the observation of fainter objects more difficult, and leads to some undercounting of faint sources, artificially depressing the faint end of the luminosity function.

The brightest galaxy (the cD NGC 1129) is anomalous. A cD galaxy is a giant elliptical with an extended low surface brightness envelope (Oemler 1976). This envelope lowers the mean surface brightness within the $R = 23.5$ isophote for NGC 1129, since it occupies a large fraction of the area within the limiting isophote. The distended envelope also makes the isophotal magnitude more sensitive to the sky subtraction because the brightness profile approaches the sky level more gradually.

4.2. Magnitude Segregation

Magnitude (or equivalently luminosity) segregation is usually interpreted as an indicator of mass segregation; the more massive (and hence more luminous) galaxies are more centrally concentrated and move more slowly than less massive (luminous) ones. Den Hartog & Katgert (1996) find luminosity segregation in 25 of their sample of 71 clusters, with a strong signal in 10.

The middle panel of Figure 8 shows $m_R$ as a function of cluster radius in AWM 7, with a moving 11 galaxy average superposed. The median magnitude of galaxies within $r < 0.1 h^{-1}$ Mpc is brighter than the median outside this radius, although the significance is low because of the small sample size. The radial extent of this luminosity excess is roughly coincident (within a factor of 2) with NB's value of $r_c = 51 \pm 3$ kpc for the X-ray core. The extent of the excess also matches the region of reduced velocity dispersion, suggesting that the cold X-ray core, the reduced velocity dispersion, and the luminosity excess are related physical effects.

4.3. Luminosity Function

The most striking feature of the luminosity function (LF) of AWM 7 is the peak near $R_D = 13.7$ and the subsequent dip in galaxy counts near $R_D = 14.5$ ($M_R = -19.1$). The cumulative distribution shows that although the peak is enhanced by the binning, the dip is not an artifact. A similar feature appears in the Coma Cluster (Bernstein et al. 1995; Biviano et al. 1995), in three of four moderate-redshift Abell clusters studied by Wilson et al. (1997), and in a sample of 20 Abell clusters studied by Gaidos (1997). Biviano et al. determine Coma Cluster membership spectroscopically (unlike Bernstein et al., Wilson et al., and Gaidos, who do so statistically), and suggest that this feature may be common to rich clusters.

We attempt to characterize the cluster LF in terms of the Schechter (1976) function parameters $\alpha$ (logarithmic faint-end slope) and $M_*$ (characteristic luminosity). Measured values of $\alpha$ in clusters range from $-1.0$ (López-Cruz et al. 1997; Gaidos 1997) to $-2.2$ in $B$ and $I$ (De Propris et al. 1995); the inclusion of dwarf galaxies and low surface brightness galaxies increases the faint-end slope (López-Cruz et al. 1997; Sprayberry et al. 1997). In the case of Coma, the inclusion of dwarf galaxies boosts the estimate of $\alpha$ from $-1.35$ to $-1.7$ (Trentham 1997). Trentham (1997) argues that since only dwarf spheroidal galaxies obey a power-law distribution, the faint-end slope of the LF is a misleading indicator, dominated primarily by its coupling to $M_*$. He notes that other galaxy types have bounded LFs, yet it is precisely these other types that enter into most cluster LF determinations.

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The Schechter function describes the LF of AWM 7 poorly; it cannot accommodate the peak and subsequent dip in the distribution. Maximum-likelihood fitting (Efstathiou, Ellis, & Peterson 1988) of a Schechter function to the magnitude distribution (not shown) forces $M_*$ to the peak near $R = 14$ and results in an ill-fitting declining faint end, in contrast to the increasing counts seen in the last
three complete bins of the actual distribution. Therefore, we obtain an estimate of the faint-end slope of the LF by extrapolation. We subtract a background field galaxy count, given by $n(m) \propto 10^{0.6m}$ $dm$ $deg^{-2}$ and normalized to the Century Survey, from the observed galaxy counts (with or without measured redshifts) to $R = 17.5$ (corrected for extinction), and fit a power law to the residual in the range $15.0 < R < 17.5$. We plot the result in Figure 11. The upper magnitude limit of the fit is set by the incompleteness of the galaxy counts at faint magnitudes due to poor star-galaxy separation on the CCD images with bad seeing. The best-fit power law corresponds to a Schechter parameter $\alpha = -1.37 \pm 0.16$, with formal $\chi^2/v = 3.57/6$.

We conclude that, like Coma, AWM 7 has a LF with a bump at the bright end and a steep faint end. The steep faint end seen in field galaxy surveys (e.g., Marzke et al. 1994; Marzke & da Costa 1997) is caused by blue galaxies. In AWM 7, the LF is steep and red, populated by absorption-line systems. Mobasher & Trentham (1998) find that the steep ($\alpha \sim -1.4$) $K$-band LF in Coma is caused by dwarf spheroidals. The issue is complicated by surface brightness selection effects: low surface brightness galaxies may be missing from field surveys, which consequently underestimate their contribution to the faint-end slope.

### 4.4. Mass-to-Light Ratio

Owing to the absence of precise photometry over a large area, the mass-to-light ratio of AWM 7 has been poorly known. Estimates have ranged from $160$ $\pm 0.25$ $Mpc$ to $600$ $h^{-1}$ $Mpc$ by extrapolation, along with the profile determined by NB from a $ROSAT$ temperature profile and a data point from Dell’Antonio et al. (1995). The mass enclosed within 0.25 $h^{-1}$ Mpc is $\sim 9 \times 10^{13}$ $M_\odot$, rising to $\sim 2 \times 10^{14}$ $M_\odot$ within 0.6 $h^{-1}$ Mpc. Our profile is in good agreement with the value derived by Dell’Antonio et al. (1995) from X-ray data, estimated at $8 \times 10^{13}$ $h^{-1}$ $M_\odot$ within 0.25 $h^{-1}$ Mpc; it also lies within the errors of the NB profile for radii up to $\sim 0.5$ $h^{-1}$ Mpc. Beyond this radius, Dell’Antonio et al.’s mass estimates exceed ours; Figure 12 shows their profile diverging from ours increasingly at large radii. They derive the mass profile beyond $\sim 600$ $h^{-1}$ Mpc by extrapolation, however, and their luminosity, taken from Beers et al. (1984), is an underestimate that increases the computed $M/L$ ratio.

We compute the mass from the virial estimator appropriate for the case of galaxies embedded in a diffuse distribution of dark matter, with the added assumption that the galaxies trace the dark matter distribution. We exclude the $Em$ galaxies from the computations on the grounds that they constitute a dynamically distinct population superposed on the virialized, Ab-populated cluster. The appropriate estimator (Binney & Tremaine 1987) is

$$M_{\text{est}} = \frac{3nN}{2G} \sum_{i=1}^{N} \sum_{j<i} \frac{v_i^2}{|R_i - R_j|^r},$$

where $v_i$ is the radial velocity relative to the cluster mean, and $R_i$ is the projected distance from the cluster center. This estimator assumes that the galaxies are in dynamical equilibrium within the cluster potential, and that the galaxies trace the total mass. If the dark matter is more extended than the galaxy distribution, this prescription underestimates the $M/L$ ratio. This mass estimate is also very sensitive to the inclusion of foreground or background galaxies. We estimate the error in the mass profile by the statistical “jackknife” procedure (Diaconis & Efron 1983) as follows: within each projected radius, we calculate the mass independently for all $n$ subsets of $n - 1$ galaxies, where $n$ is the total number of galaxies within said radius, and with the velocities shuffled randomly for each subset. We define the standard deviation about the mean of the $n$ masses thus computed to be the error in the mass estimate within that projected radius.

In principle, this mass estimate should be adjusted by a surface term (The & White 1986), because the entire system is not included in the observed sample. Inclusion of this term requires knowledge of $\sigma(r)$, $N(r)$, and the dark matter profile. The first two factors can be constrained from the data, and the dark matter profile can be reasonably described by model fits to hierarchical clustering simulations, as in Navarro, Frenk, & White (1997). However, our data set is not extensive enough to support this analysis robustly; we do not have broad enough angular coverage to self-consistently compute the core radius. We have calculated the surface term, and find that the error is comparable to the value of the correction itself. Thus the masses we quote below do not incorporate a surface term.

The top panel of Figure 12 shows our integrated mass profile, computed by applying the virial mass estimator to successively larger radii, along with the profile determined by NB from a $ROSAT$ temperature profile and a data point from Dell’Antonio et al. (1995). The mass enclosed within 0.25 $h^{-1}$ Mpc is $\sim 9 \times 10^{13}$ $M_\odot$, rising to $\sim 2 \times 10^{14}$ $M_\odot$ within 0.6 $h^{-1}$ Mpc. Our profile is in good agreement with the value derived by Dell’Antonio et al. (1995) from X-ray data, estimated at $8 \times 10^{13}$ $h^{-1}$ $M_\odot$ within 0.25 $h^{-1}$ Mpc; it also lies within the errors of the NB profile for radii up to $\sim 0.5$ $h^{-1}$ Mpc. Beyond this radius, Dell’Antonio et al.’s mass estimates exceed ours; Figure 12 shows their profile diverging from ours increasingly at large radii. They derive the mass profile beyond $\sim 600$ $h^{-1}$ Mpc by extrapolation, however, and their luminosity, taken from Beers et al. (1984), is an underestimate that increases the computed $M/L$ ratio.

We compute the $R$-band light by adding up the luminosities of the galaxies in our sample and correcting for incompleteness. The correction is required, because for any magnitude-limited sample, the observed luminosity is nec-
and that the data point from Geller, & Fabricant the dotted.

Dell'Antonio, & Fabricant (1995); the dotted lines indicate the profile of Neumann & Böhringer (1995). Errors on the mass are statistical jackknife estimates; they scale uniformly to errors on M/L. The data point for NGC 1129 is from Bacon, Monnet, & Simien (1985). Note that M/L = 1.58 M/L for Em galaxies with B−R = 1.5, and that M/L ≈ h.

essarily an underestimate of the total cluster luminosity because the faintest galaxies are not observed. We correct for this incompleteness by integrating the extrapolated luminosity function to infinite magnitude. For a Schechter function, the observed fraction of the total luminosity is given by \( \Gamma(x+2, L_{\text{min}}/L_*)/\Gamma(x+2) \), where \( L_{\text{min}} \) and \( L_* \) are the luminosities corresponding to the completeness limit and \( M_* \), respectively, and \( \Gamma(x,y) \) is the incomplete gamma function. The completeness limit \( R = 16.5 \) is 3.6 mag fainter than \( M_0 = -20.7 \), yielding an observed luminosity fraction of ~90%. A 0.5 mag error in the completeness limit corresponds to a 5% error in the observed luminosity fraction in this regime. We observe \( 2.6 \times 10^{11} L_\odot \) in the R band within a projected radius of \( 0.6 \ h^{-1} \) Mpc, yielding a corrected total luminosity of \( 2.9 \times 10^{11} L_\odot \). The cD alone contributes ~14% of the R-band luminosity within this radius.

We plot the M/L profile in the bottom panel of Figure 12. The data point for NGC 1129 is from Bacon, Monnet, & Simien (1985), who tabulate mass-to-light ratios for 197 ellipticals. The mean M/L in their sample is 13; the NGC 1129 ratio of M/L = 94 ± 31 is the largest in their sample. We derive an M/L ratio of \( \sim 600 \ h M_\odot/L_\odot, \) for the cluster that remains fairly constant outside a projected radius of 0.3 \( h^{-1} \) Mpc, rising to \( \sim 650 ± 170 \ h M_\odot/L_\odot \) near 0.45 \( h^{-1} \) Mpc. We include only the errors on the mass. For comparison, note that M/L = 1.58 M/L, because \( B−R = 1.0 \), but for elliptical galaxies typically \( B−R = 1.5 \). Our value of the mass-to-light ratio is at the low end of the range of NB, where values are based on extrapolations of X-ray temperature profiles to 1°. Within 0.25 \( h^{-1} \) Mpc, Dell'Antonio et al. (1995) report 430 h in the B band, corresponding to 272 h in R; we find 530 h. Given the agreement in mass, the discrepancy arises from differences in luminosity; Dell'Antonio et al. (1995) do not directly measure the luminosity in the cluster, but instead determine cluster membership by background subtraction, and then calibrate magnitudes derived from POSS plate scans against Zwicky et al. (1962) magnitudes, whose scatter is ~0.3 mag (Bothun & Cornell 1990; Geller et al. 1997). Their largest source of error is the plate photometry, particularly in light of the considerable variation of the photographic sensitivity across the cluster, which introduces a large systematic error in addition to the intrinsic scatter in the calibration magnitudes.

The mass-to-light ratio of AWM 7 is lower in the center than at the periphery, because the depressed central velocity dispersion lowers the mass estimate, and because there is excess luminosity in the core. It is interesting to note that the M/L profile at small radii approaches the value for the cD. The profile also flattens outside \( \sim 0.3 \ h^{-1} \) Mpc, rising only another 10% out to 0.6 \( h^{-1} \) Mpc, suggesting that the dark matter is less concentrated than the light. The mass-to-light ratio levels off at roughly twice the projected radius at which the velocity dispersion does.

Our calculated mass-to-light ratio for AWM 7 is in close agreement with the values determined by Mohr, Geller, & Wegner (1996b) for the clusters A 2626 and A 2440: they find \( M/L \sim 610 \ h \) and 660–880 h, respectively, from a joint X-ray and optical study of the clusters. Carlberg et al. (1996) and Carlberg, Yee, & Ellington (1997) overlay 14 clusters to form an aggregate whose M/L ratio they find to be \( 289 ± 50 \ (M/L)_\odot \) in Gunn r, Cirimele, Nesci, & Trevese (1997) overlay 12 Abell clusters and find \( M/L \) in the range 140–440 h. Measurements of M/L ratios for distant clusters using weak lensing yield a similar range of values: Tyson & Fischer (1995) find \( M/L = 400 ± 60 \ (M/L)_\odot \) for A 1689 at \( z = 0.18 \), while Carlberg, Yee, & Ellington (1994) report \( 225 \ h \) in the V band for a cluster at \( z = 0.325 \), and 275 h for Coma, corrected for “modest” evolution of the galaxy LF. In this context, AWM 7 no longer appears so exceptional.

5. DISCUSSION

Our optical and spectroscopic survey of the central 1.2 × 1.2 \( h^{-1} \) Mpc of AWM 7 yields a velocity dispersion profile, mass profile, luminosity function, and mass-to-light profile of the cluster. There is threefold evidence for a cold core in the cluster: the central velocity dispersion is depressed, there is luminosity segregation on the same scale, with excess luminosity in the core, and there is a cold X-ray core with similar scale. The optically determined mass is in good agreement with X-ray determinations by NB and by Dell'Antonio et al. (1995). Despite the offset in X-ray isophotes seen by them, we find no kinematic evidence for substructure. The luminosity function of AWM 7 is peculiar: there is a dearth of galaxies with \( R \sim 14.5 \), an excess of galaxies just brighter, and a steeply rising faint end. The faint end is populated almost exclusively by red, absorption-line galaxies, in contrast to the blue Magellanic Irregulars that dominate the steep faint end in the field (Marzke et al. 1994).

5.1. Evolution of the Luminosity Function and Formation of the cD

The formation of cD galaxies is closely tied to questions of LF evolution, universality, and mass segregation. Theories of cD formation include merging of dwarf galaxies through dynamical friction (Ostriker & Tremaine 1975;
White 1976; Ostriker & Hausmann 1977), cannibalization of neighboring galaxies (Gallagher & Ostriker 1972; Richstone 1975, 1976), primordial origin (Merritt 1984), and mergers of large, bright galaxies early in the cluster history, with additional growth from accretion of tidal debris or from cooling flows (Fabian & Nulsen 1977; Cowie & Binney 1977; Fabian, Nulsen, & Canizares 1984).

Active merging in a cluster would result in substantial evolution of the LF. Thus, the LF could in principle be used as an estimator of the dynamical age of the cluster. Although the traditional "cannibalization" merger scenarios held that dwarf galaxies agglomerate into larger clusters with low velocity dispersion, where mergers are a priori unlikely due to the high σ, and (2) mergers of dwarfs to form the cD would deplete the faint end. Unless AWM 7 initially had an even steeper faint end, this scenario seems unlikely.

### 6. CONCLUSION

Our study of AWM 7 reveals two important features: the cluster has a cold core, and the steeply rising faint end of the LF is populated predominantly by absorption-line galaxies, in contrast to the emission-line galaxies that populate the faint end of the field LF. In AWM 7, the emission galaxies are probably a dynamically distinct infalling population superposed on the relaxed system of absorption-line galaxies; the little substructure that is apparent in the velocity data is entirely attributable to the emission galaxies. We have resolved the anomalous earlier mass-to-light ratio calculated for AWM 7; our value (~ 650 ± 170 h M⊙/L⊙, at 0.45 h−1 Mpc) is concordant with those of similar systems. The mass-to-light ratio approaches the central cD’s value at small radii, and is flat at large radii.

The proximity of AWM 7 allows for direct determination of the LF with redshifts rather than by statistical background subtraction well below L*, since L* corresponds to R ~ 13 at 5000 km s−1. A deeper survey will result in denser sampling in the core of the cluster, aiding in discriminating between dynamical models, and will boost the signal in the various tests we have performed here. Deeper surveys will also yield direct measurements of the faint-end slope of the LF.

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