ANTIBIAS IN CLUSTERS: THE DEPENDENCE OF THE MASS-TO-LIGHT RATIO ON CLUSTER TEMPERATURE

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ABSTRACT

We show that the observed mass-to-light (M/L) ratio of galaxy clusters increases with cluster temperature as expected from cosmological simulations. Contrary to previous observational suggestions, we find a mild but robust increase of M/L from poor ($T \sim 1$–2 keV) to rich ($T \sim 12$ keV) clusters; over this range, the mean $M/L_v$ increases by a factor of about 2. The best-fit relation satisfies $M/L_v = (170 \pm 30) [H_{100}]^{-0.3 \pm 0.1}$ at $z = 0$, with a large scatter. This trend confirms predictions from cosmological simulations that show that the richest clusters are antibiased, with a higher ratio of mass per unit light than average. The antibias increases with cluster temperature. The effect is caused by the relatively older age of the high-density clusters, where light has declined more significantly than average since their earlier formation time. Combining the current observations with simulations, we find a global value of $M/L_v = 240 \pm 50$ $h$ and a corresponding mass density of the universe of $\Omega_m = 0.17 \pm 0.05$.

Subject headings: cosmology: observations — cosmology: theory — dark matter — galaxies: clusters: general — large-scale structure of universe

1. INTRODUCTION

The mass-to-light (M/L) ratio of clusters of galaxies has been used for decades in the classical M/L method of estimating the mass density of the universe. In this method, the average ratio of the observed M/L of clusters of galaxies, which represent systems of relatively large scales ($\sim 1$ Mpc), is assumed to be a fair representation of the mean M/L of the universe. This ratio is then multiplied by the observed luminosity density of the universe to yield the universal mass density. When applied to rich clusters, with an average of $M/L_{cl} = 300$ $h$, the total mass density of the universe amounts to $\Omega_m \sim 0.2$ (where $\Omega_m$ is the mass density in units of the critical density; Zwicky 1957; Abell 1965; Ostriker, Peebles, & Yahil 1974; Bahcall 1977; Faber & Gallagher 1979; Trimble 1987; Peebles 1993; Bahcall, Lubin, & Dorman 1995; Carlberg et al. 1996; Carlberg, Yee, & Ellingson 1997 and references therein).

A fundamental assumption in this determination, however, is that the M/L of clusters is a fair representation of the universal value. If the M/L of clusters is larger or smaller than the universal mean, the resulting $\Omega_m$ will be an over- or underestimate, respectively. In general, if mass follows light on large scales ($M/L \propto $ constant), the galaxy distribution is considered to be unbiased with respect to mass. If mass is distributed more diffusely than light, as is generally believed, then the galaxy distribution is biased (i.e., more clustered than mass), and the above $\Omega_m$ determination would be an underestimate.

Observations of galaxies, groups, and clusters of galaxies show that the M/L function increases with scale up to a few hundred kpc (Rubin & Ford 1970; Roberts & Rots 1973; Ostriker et al. 1974; Einasto, Kassik, & Saar 1974; Davis et al. 1980; Zaritsky et al. 1993; Fischer et al. 2000) but then flattens on larger scales (Bahcall et al. 1995; Fischer et al. 2000). A comparison with high-resolution cosmological simulations (Bahcall et al. 2000) reveals an excellent agreement with the observed M/L function: the simulated M/L function increases with scale on small scales ($<0.5$ Mpc) and flattens to a mean constant value on large scales, as suggested by the data.

However, the simulations show that while M/L flattens on average on large scales, high-overdensity regions, such as rich clusters of galaxies, exhibit higher M/L values than average, while low-density regions have lower M/L ratios (at a given scale); high-density regions are antibiased in M/L, with mass more strongly concentrated than light (a higher M/L ratio) than average. Bahcall et al. (2000) show that the M/L antibias is expected to increase in simulated clusters of galaxies: higher density clusters (richer, higher mass and temperature clusters) should exhibit larger M/L ratios (especially in the blue and visual luminosity bands) than poorer, lower mass and temperature clusters. The expected effect is a factor of approximately 2 increase from poor to rich clusters. It is caused as seen in the hydrodynamic simulations, by the age of the systems: high-density clusters form at earlier times than low-density clusters; their luminosities have thus declined more significantly by the present time (if no significant recent star formation occurred), yielding a larger M/L ratio, on average, for the richer clusters.

Observationally, however, cluster M/L ratios have been suggested to show no dependence on cluster overdensity (as represented by cluster richness, mass, or temperature; e.g., Carlberg et al. 1997; Hradecky et al. 2000). In this Letter we investigate the observed M/L dependence on cluster overdensity (temperature) by using a well-studied sample of clusters that range from poor to rich systems. We find that the M/L ratio increases, on average, with cluster temperature, in good agreement with the prediction of cosmological simulations.

2. DEPENDENCE ON CLUSTER TEMPERATURE

We investigate the dependence of M/L ratio on cluster overdensity by using a reliable sample of clusters that ranges from poor to rich systems. The cluster overdensity is represented by the observed temperature of the cluster, $T$; the overdensity within a given radius is proportional to $T$: $\Delta \rho / \rho(1, T) \propto (M/I R)_{cl} \propto T$. As revealed by cosmological simulations (Bahcall et al. 2000), the M/L ratio of clusters is expected to increase with $T$ by a factor of about 2 (in $M/L_{cl}$ and $M/L_v$) from poor ($T \sim 1$–2 keV) to rich ($T \sim 10$ keV) clusters.

Current observations of galaxy clusters generally claim no observed dependence of M/L on cluster temperature or other cluster parameters (e.g., Carlberg et al. 1997; Hradecky et al. 2000). However, the expected effect is not large, and the observational uncertainties in M/L are significant. It is important...
therefore to use a reliable and consistent sample of clusters that spans a wide range of cluster temperatures.

We select clusters with measured temperatures in the range of \(\sim 1-12\) keV. All clusters have measured \(ML\) ratios observed within radii of typically 0.5–1.5 \(h^{-1}\) Mpc. The cluster \(ML\) measurements are based on a few self-consistent subsamples and methods. We analyze different subsamples separately in order to test the reliability of the results. The sample includes clusters with mass determinations from gravitational lensing observations (Fischer & Tyson 1997; Hoekstra, Franx, & Kuijken 2000; Squires et al. 1996a, 1996b, 1997; Tyson & Fischer 1995) and X-ray observations (from a single, carefully executed method; Hradecky et al. 2000). A sample of velocity dispersion virial mass determinations from a single method (Carlberg et al. 1997) is also shown for comparison, although this method differs somewhat in that it determines cluster virial masses within the larger (and less certain) virial radii of \(\sim 1–1.5\ h^{-1}\) Mpc. We repeat our analysis both with and without this virial subsample and find consistent results. We also repeat the analysis for individual cluster subsamples, e.g., lensing versus X-ray cluster subsamples and high-versus low-redshift cluster subsamples; all samples yield consistent results.

In addition to the cluster sample, we also include the recently observed ensemble average \(ML\) ratio of 50 groups of galaxies determined from weak gravitational lensing by Hoekstra et al. (2001). We convert the mean velocity dispersion for this group sample, \(274^{+38}_{-56}\) km s\(^{-1}\), to a mean temperature using the observed velocity-temperature relation for clusters and groups: 
\[
V_c = (332 \pm 52) T^0.65_{1000} \text{ km s}^{-1} \quad (\text{Lubin & Bahcall 1993})
\]
This yields a mean group temperature of \(T = 0.73\) keV, consistent with observations of typical groups (\(\sim 1\) keV). The total sample we use, 21 systems, is listed in Table 1. Also listed are the redshifts, the observed temperatures and \(ML\) ratios, the luminosity band of the observations (mostly V-band), the relevant radius \(R\) for the observed parameters, and the relevant references. A Hubble constant of \(H_0 = 100\ h\) km s\(^{-1}\) Mpc\(^{-1}\) is used throughout.

Two corrections are applied to the sample to bring all measurements to the same consistent system. First, the sample contains clusters at redshifts from \(z \sim 0.02\) to 0.8. Since cluster luminosities evolve with redshift, we correct all luminosities to \(z = 0\). Given the observed evolution in \(L_v\) (Kelson et al. 1997), 
\[
L_v \sim 10^{0.3z+10}\%
\]
all \(MLv\) values were corrected upward by a factor of \(10^{0.3z+10}\%\) to yield \(MLv(z = 0)\). Similarly, \(MLp\) values were corrected by a factor of \(10^{0.4z+10}\%\) (van Dokkum et al. 1998), and \(ML\) values were corrected by a factor of \(10^{0.15z+10}\%\) (Carlberg et al. 1996).

Second, four of the 21 clusters are observed in the blue-band luminosity, \(L_b\), and six are observed in the \(r\)-band luminosity, \(L_r\) (all others are observed in \(L_v\)). We convert \(L_b\) to \(L_v\) at \(z = 0\) using \(L_v = 1.15L_b\), based on the typical cluster color of \(B-V = 0.8\) [and solar \((B-V)_\odot = 0.65\)]. Similarly, we convert \(L_r\) to \(L_v\) using \(L_v = 0.935L_r\), following \((B-r)_{\odot} = 0.915\) and \((B-r)_z = 0.692\) (Jorgensen, Franx, & Kjærgaard 1995). These corrections have no significant impact on the final results. In addition, all cluster values (and the evolution correction) are corrected to the same cosmology of \(q_0 = 0.15\) (following van Dokkum et al. 1998). The resulting \(MLv\) values at \(z = 0\) are listed in Table 1. The error bars represent the convolved error bars of the observations and the evolutionary correction.

The sample includes cluster \(ML\) ratios measured within radii of \(\sim 0.5–1.5\ h^{-1}\) Mpc. The results are not significantly affected by the different radii; we test this by comparing a subsample of clusters measured at a fixed radius (0.5 \(h^{-1}\) Mpc) and find consistent results. The cluster \(ML\) ratio is nearly constant over this range of radii within a given cluster.

The observed \(MLv(z = 0)\) ratios are plotted as a function of cluster temperature for all clusters in Figure 1. While the scatter is large, a clear correlation of increasing \(MLv\) with \(T\) is apparent. The best-fit linear and power-law relations are as
follows:

\[
\left(\frac{M}{L_{\nu}}\right)_{z=0} = 142 \pm 32 + (23 \pm 5)T_{\text{keV}} h
\]

\[= (142 \pm 32)[1 + (0.16 \pm 0.05)T_{\text{keV}}] h, \quad (1)
\]

\[
\left(\frac{M}{L_{\nu}}\right)_{z=0} = (173 \pm 29)T_{\text{keV}}^{0.30 \pm 0.08} h. \quad (2)
\]

These best-fit relations are shown in Figure 1. Also shown in the figure is the relation predicted by the cosmological simulations (Bahcall et al. 2000). The agreement between data and simulations is excellent; both show an increase in \(M/L_{\nu}\) by a factor of about 2 on average, from ∼200 to 450 h, as \(T\) increases from ∼1 to 12 keV. While the simulation \(M/L_{\nu}(T)\) trend is insensitive to \(\Omega_m\), the normalization, or absolute value of \(M/L\) at a given \(T\), is proportional to \(\Omega_m\). The simulation results plotted in Figure 1, which best fit the data, correspond to \(\Omega_m = 0.17\) [using the observed \((M/L_{\nu})_{\text{critical}} \approx 1400 h^3 Mpc}\) as the simulation normalization; see Bahcall et al. 2000].

Figure 2 represents the same data as Figure 1, but with the data binned in several temperature bins (3 keV each). The average \(M/L_{\nu}\) for each bin is shown. The best-fit relations, also plotted, are consistent with those obtained for the full sample (Fig. 1 and eqs. [1] and [2]). The best-fit results and their \(\chi^2\) values are summarized in Table 2.

To test the sensitivity of the results to the cluster selection method and to the radius used, we repeat the analysis for two subsamples of the full sample: (1) we omit the clusters with dynamical determination of virial masses (to \(R_v \sim 1–1.5 h^{-1} \text{Mpc}\) based on velocity dispersion data (Carlberg et al. 1997), and (2) we use only clusters measured within a fixed radius of 0.5 h^{-1} Mpc. The best-fit results obtained for each of these subsamples are consistent with the results of the full sample; they are summarized in Table 2. The results for the \(R = 0.5 h^{-1} \text{Mpc}\) subsample are shown in Figure 3.

We further test the results by analyzing other subsamples of clusters: clusters with gravitational lensing masses versus clusters with X-ray mass determinations, as well as clusters at low redshift (\(z < 0.1\)) versus clusters at intermediate redshift (\(z \sim 0.15–0.33\)). All subsamples yield consistent results (within 1 \(\sigma\)). These tests reinforce the robustness of the results.

The above results are in excellent agreement with the pre-
diction of cosmological simulations, showing an increase in cluster $\frac{M}{L}$ ratio with cluster temperature (or overdensity).

3. SUMMARY AND CONCLUSIONS

We show that the $\frac{M}{L}$ ratio of clusters of galaxies increases, on average, with cluster temperature. Contrary to previous observational suggestions of a constant $\frac{M}{L}$ ratio for clusters—indepedent of temperature, velocity dispersion, or other observational suggestions of a constant ratio for clusters on average, in rich clusters (Bahcall et al. 2000; see also Jing, Mo, & Borner 1998). This antibias increases with cluster richness (temperature).

This trend is in excellent agreement with the prediction of cosmological simulations (Bahcall et al. 2000; see Figs. 1–3 for comparisons between data and simulations). While the scatter is large, the underlying trend is clear.

The observed correlation is important for several reasons:

1. It confirms the predictions originally made from cosmological simulations (Bahcall et al. 2000) of increasing cluster $\frac{M}{L}$ ratio with cluster overdensity (temperature). As seen in the simulations, this trend is caused by the “age effect”; higher density systems formed earlier, and their luminosities, especially in the blue and visual bands, have decreased more significantly by the present time relative to the younger, lower density systems. This results in larger $\frac{M}{L}$ ratios for the older, higher temperature clusters.

2. The simulated results, confirmed by the current observations, show that rich clusters are antibiased in their $\frac{M}{L}$ ratios—that is, rich clusters have higher $\frac{M}{L}$ ratios than average. This implies that mass is more concentrated than light, on average, in rich clusters (Bahcall et al. 2000; see also Jing, Mo, & Borner 1998). This antibias increases with cluster richness (temperature).

3. Antibias in the cluster $\frac{M}{L}$ ratio directly affects the measurement of the mass density of the universe, $\Omega_m$. Classically, $\Omega_m$ determinations use the observed $\frac{M}{L}$ ratio of the richest clusters (which are easiest to observe) and assume it to be representative of the global value. The observed antibias, however, shows that this method overestimates $\Omega_m$, since rich clusters have larger $\frac{M}{L}$ ratios than average. Comparing the observed dependence of $\frac{M}{L}$ on $T$ with results from the cosmological simulations (Bahcall et al. 2000), shown in Figures 1–3 [using $(\frac{M}{L})_{\text{crit}} = 1400 \pm 20\%$ for the simulation normalization; see Bahcall et al. 2000], we find a global mass density parameter of $\Omega_m = 0.17 \pm 0.05$. The mean representative $\frac{M}{L}$ ratio for the universe is $\frac{M}{L} = 240 \pm 50$, comparable to that exhibited by groups and poor clusters.

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