THE FLATNESS OF THE MASS-TO-LIGHT RATIO ON LARGE SCALES

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ABSTRACT

It has been suggested that the mass-to-light (M/L) ratio of gravitationally clustering objects is scale-independent on scales beyond galaxy clusters and may also be independent of the mass of the objects. In this Letter, we show that the scale behavior of the M/L ratio is closely related to the scaling of cosmic structures that are larger than clusters. The scale dependence of the M/L ratio can be determined by comparing the observed scaling of the richness function (RF) of multiscale-identified objects with the model-predicted scaling of the mass function (MF) of large-scale structures. Using the multiscale-identified clusters from the IRAS 1.2 Jy galaxy survey, we have made comparisons of the observed RF scaling of IRAS $r_\alpha$ clusters with the MF scalings given by simulations of three popular models: SCDM, LCDM, and OCDM. We find that the M/L ratio is basically scale-independent from the Abell radius up to about 24 $h^{-1}$ Mpc, while it seems to show a slight, but systematical, increase over this scale range. This result is weakly dependent on the cosmological parameters.

Subject headings: cosmology: theory — galaxies: fundamental parameters — large-scale structure of universe

1. INTRODUCTION

The scale dependence of the mass-to-light (M/L) ratio is always an important topic of cosmology. The M/L ratio on scales of galaxies, double galaxies, groups of galaxies, and galaxy clusters provided the first approach for evaluating the mean mass density of the universe (e.g., Faber & Gallagher 1979). The most striking result in this study is that the M/L ratio increases with the scale of the system considered (e.g., Rubin 1993). This has inspired a search for a dark matter in objects on scales larger than clusters. Yet the M/L ratio appears to be flat on scales of rich clusters and larger. This result has been employed to propose that the M/L ratio on scales larger than clusters asymptotically reaches a constant, which is approximately equal to the median M/L ratio of rich clusters, i.e., $M/L = 300 \pm 100$ $h (M/L)_\odot$ (Bahcall, Lubin, & Dorman 1995). This asymptotic M/L ratio yields $\Omega_m \approx 0.2 \pm 0.07$, suggesting a low-density universe (Bahcall & Fan 1998). That is, the behavior of the M/L ratio on large scales is directly related to the cosmological parameter $\Omega_m$.

The evidence for a flat M/L ratio on a large scale is still weak. The observed Virgo Cluster infall motion seems to be the only evidence of the flatness on the scale of the local supercluster ($\sim 10$ $h^{-1}$ Mpc) (e.g., Yahil, Sandage, & Tammann 1980). However, a direct measure of the mass-to-light ratio of the Corona Borealis supercluster gives $M/L = 560 h (M/L)_\odot$. Namely, the M/L ratio on a scale of $\sim 20$ $h^{-1}$ Mpc is higher than that of rich clusters by a factor of 2 (Small et al. 1998). On the other hand, galaxy clusters with Abell radius generally are dominated by elliptical galaxies at their centers, while larger structures have a higher fraction of spiral galaxies. Therefore, it is uncertain whether the morphological segregation leads to a variation of the M/L ratio of structures that are larger than clusters.

In this Letter, we try to approach this problem by analyzing the observed scaling of clusters on scales that are beyond clusters. We have found recently that the richness function (RF) and mass function (MF) of objects identified by multiresolution analysis are scale-invariant from the Abell radius to about $20$ $h^{-1}$ Mpc (Xu, Fang, & Wu 1998, hereafter XFW). We will show that the scale dependence of the M/L ratio is completely determined by the scaling factors of the RF and MF of these multiscale-identified objects. If the mass field traced by the observed galaxies can match the popular models of CDM cosmogony, one can calculate the M/L ratio’s scale dependence by comparing the observed RF scaling with the model-predicted MF scaling. Using the data of the IRAS 1.2 Jy galaxy survey, we find that the M/L ratio is approximately flat on scales up to at least $24$ $h^{-1}$ Mpc.

In § 2, we calculate the mass functions of multiscale-identified clusters from simulations and calculate their scaling indices. In § 3, we derive the richness functions and their scaling indices of multiscale-identified clusters from the IRAS 1.2 Jy galaxy survey. In § 4, we study the scale dependence of the mass-to-light ratio by matching the scaling behaviors of theoretical mass functions with those of observational richness functions. In § 5, we present our conclusion.

2. MF OF $r_\alpha$ CLUSTERS FROM SIMULATION SAMPLES

The model samples of mass distribution used in this Letter are similar to the ones in XFW. They are generated by N-body simulations with the PÔM code developed by Y. P. Jing (Jing & Fang 1994). Three popular models of the cold dark matter (CDM) cosmogony, i.e., the standard CDM (SCDM), the flat low-density CDM (LCDM) models, and the open CDM model (OCDM), are employed. The Hubble constant $h = [H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}])$, the mass density $\Omega_m$, the cosmological constant $\Omega_{\Lambda}$, and the normalization of the power spectrum of the density perturbation $\sigma_8$ are chosen to be $(0.5, 1.0, 0.0, 0.62)$ for the SCDM, (0.75, 0.3, 0.7, 1.0) for the LCDM, and (0.75, 0.3, 0.0, 1.0) for the OCDM. The simulation parameters are (1) the box size $L = 310 h^{-1}$ Mpc, (2) the number of simulation particles $N_p = 64^3$, and (3) the effective force resolution $\eta = 0.24 h^{-1}$ Mpc. In this case, each particle has a mass of $3.14 \times 10^2 \Omega_m h^{-1} M_\odot$, which is small enough to resolve reliably objects with mass $M \geq 5.5 \times 10^{14} h^{-1} M_\odot$. We produce eight realizations for each model.
For the simulation results, the clusters on scales \( r_{cl} \) and with masses larger than \( M \) are identified by the multiresolution (or multiscale) analysis that is based on discrete wavelet transformation (DWT) (Fang & Thews 1998). It has been shown that the DWT-identified clusters on the Abell scale, i.e., \( r_{ab} \) clusters, are the same as those given by the friends-of-friends (FOF) method (Xu et al. 1999). That is, in terms of the \( r_{ab} \)-cluster identification, the DWT method is as good as the FOF. Thus, the DWT method can be reliably used to identify objects systematically on scales \( r_{cl} > r_{ab} \) (Xu, Fang, & Deng 1999).

With the multiscale identification of simulation samples, we have predicted, using models, the mass function of \( r_{cl} \) clusters, \( n(M, r_{cl}) \), which is the number density of \( r_{cl} \) clusters with masses larger than \( M \). The MFs of \( r_{cl} \) clusters with \( r_{cl} = 1.5, 3, 6, 12, \) and \( 24 \) h\(^{-1}\) Mpc in models of the SCDM, LCDM, and OCDM are shown in Figure 1. The middle part of the mass function, roughly in the range \( 10^{-4} > n(M, r_{cl}) > 10^{-7} \) h\(^{-1}\) Mpc\(^{-3}\), is more reliable since all the Poisson errors are relatively small.

It can be seen from Figure 1 that all the MFs have a similar shape. This is because of the MF scale invariance (XFW), which is

\[
n(M, r_{cl}) = n(M, \lambda r_{cl}),
\]

where the scaling factor \( \lambda(r_{cl}/r_{ab}) \) is only a function of the ratio \( r_{cl}/r_{ab} \) but is independent of \( M \). Obviously, \( \lambda = 1 \) when \( r_{cl} = r_{ab} \). The scaling factor \( \lambda \) is an important statistical description of clustering on large scales.

3. RF of \( r_{cl} \) Clusters from IRAS Sample

We apply the DWT multiresolution identification to the redshift survey of the IRAS galaxies with a flux limit of \( f_{\text{IRAS}} \geq 1.2 \) Jy (Fisher et al. 1995). The IRAS sample is of 2 (physical space) + 1 (redshift space) dimensions. A DWT algorithm for identifying \( r_{cl} \) clusters from the \((2 + 1)\)-dimensional samples has been developed (XFW; Xu et al. 1999). To minimize the radial effects, the data are divided into redshift intervals of \([2500, 5000]\), \([5000, 7500]\), and \([7500, 10,000]\) km s\(^{-1}\). We then identify \( r_{cl} \) clusters in each interval on scales of \( r_{cl} = 1.5, 3, 6, 12, \) and \( 24 \) h\(^{-1}\) Mpc.

The sampling rate of the IRAS sample is low. The IRAS clusters identified on the Abell scale \( r_{ab} \) contain much fewer galaxies than optical clusters, and IRAS galaxies do not populate the clusters in the same manner as optical galaxies (Fisher et al. 1995; Webster, Lahav, & Fisher 1997). This gives rise to higher Poisson errors. However, if we are interested in clusters larger than the Abell scale, this problem would be softened since structures contain more member galaxies. Meanwhile, IRAS galaxies are mostly of late type. They trace clusters on various scales of \( r_{cl} \) uniformly. Therefore, the samples of IRAS \( r_{cl} \) clusters may be less affected by morphological segregation and are good for studying the scale dependence of structures.

With the identified \( r_{cl} \) clusters of IRAS galaxies, one can find the richness function of IRAS \( r_{cl} \) clusters, \( N_{\text{IRAS}}(N_{cl}, r_{cl}, z) \), which is the number density of \( r_{cl} \) clusters containing \( \geq N_{cl} \) members of IRAS galaxies in the redshift shell \( z \). The RFs of \( r_{cl} \) clusters with \( r_{cl} = 1.5, 3, 6, 12 \) and \( 24 \) h\(^{-1}\) Mpc are shown in Figure 2, in which the errors are Poissonian (Xu et al. 1999). Despite the large errors, it is clear that the shapes of all the RFs are basically the same. This feature can be described as an RF scaling invariance in each \( z \) shell,

\[
N_{\text{IRAS}}(N_{cl}, r_{cl}, z) = N_{\text{IRAS}}(N_{cl}, r_{ab}, z).
\]

The scaling factor \( \lambda_{\text{IRAS}}(r_{cl}/r_{ab}) \) is a function of the scale ratio \( r_{cl}/r_{ab} \) but is independent of \( N_{cl} \). Obviously, \( \lambda_{\text{IRAS}} = 1 \) when \( r_{cl} = r_{ab} \). The scaling factor \( \lambda_{\text{IRAS}} \) of IRAS \( r_{cl} \) clusters as a function of \( r_{cl}/r_{ab} \) is presented in Figure 3. It shows that \( \lambda_{\text{IRAS}} \) is also independent of \( z \) within the 1 \( \sigma \) error bars.

4. Scale Dependence of MIL Ratio

By definition, the mass-to-luminosity ratio for IRAS \( r_{cl} \) clusters is the ratio between mass and luminosity of \( r_{cl} \) clusters. One can introduce the MIL ratio of the IRAS \( r_{cl} \) clusters by a mass-number relation as

\[
M = R(r_{cl})N_{G},
\]

where \( M \) is the total mass of a \( r_{cl} \) cluster and \( N_{G} \) is the total...
galaxies in the redshift shells of [2500, 5000], [5000, 7500], and [7500, 10,000] km s\(^{-1}\), with \(r_g = 1.5, 3.0, 6.0, \) \text{and} 12 h\(^{-1}\) Mpc. \(N_g\) is the number of member galaxies of the IRAS \(r_g\) clusters; \(n_{\text{ab}G}(>N_r,r_g)\) is the number density of \(r_g\) clusters with the number of member galaxies more than \(N_g\).

number of member galaxies of the \(r_g\) cluster, defined by

\[
N_G = N_g/\phi(z),
\]

where \(\phi(z)\) is the selection function (Fisher et al. 1995). The definition of \(R(r_g)\) in equation (3) has implicitly assumed that \(R(r_g)\), or the M/L ratio, is independent of the mass of the objects, since the M/L ratio of \(r_g\) clusters is found, on average, to be independent of mass (Bahcall & Cen 1993). Such independence may be caused by the fact that the scale of the luminosity-related hydrodynamical process is smaller than that of clusters. Thus, luminosity functions and M/L ratios are statistically independent of the environment on the cluster scale. Therefore, it would be reasonable to assume that the mass independence of the M/L ratio still holds on scales larger than clusters.

The number-mass conversion coefficient \(R(r_g)\) is proportional to the mass-to-light ratio \(M/L(r_g)\) for IRAS galaxies on a scale of \(r_g\). We then have

\[
M/L(r_g) = M/L(r_{ab}) = R(r_g)/R(r_{ab}).
\]

Using equations (3) and (4), one can find the mass function of IRAS \(r_g\) clusters as

\[
n_{\text{IRAS}}(>M, r_g, z) = N_{\text{IRAS}}[>[M\phi(z)/R(r_g)], r_{cl}, z].
\]

Therefore, the RF scaling (eq. [2]) will further yield an MF scaling of IRAS \(r_g\) clusters as

\[
n_{\text{IRAS}}(>M, r_{cl}, z) = n_{\text{IRAS}}(>\lambda_{\text{IRAS}}^{\text{MF}} M, r_{ab}, z),
\]

where the MF scaling factor \(\lambda_{\text{IRAS}}^{\text{MF}}\) is given by

\[
\lambda_{\text{IRAS}}^{\text{MF}}(r_{cl}/r_{ab}) = \lambda_{\text{IRAS}}^{\text{MF}}(r_{cl}/r_{ab})[R(r_g)/R(r_{ab})],
\]

or

\[
M/L(r_{cl}) = M/L(r_{ab}) \times \lambda_{\text{IRAS}}^{\text{MF}}(r_{cl}/r_{ab})^{1/2}.
\]

Namely, the scale dependence of the M/L ratio is completely determined by the ratio between the MF and RF scaling factors of the IRAS \(r_g\) clusters.

However, despite the fact that we have the observed scaling factor \(\lambda_{\text{IRAS}}(r_{cl}/r_{ab})\), we lack the observed \(\lambda_{\text{IRAS}}^{\text{MF}}(r_{cl}/r_{ab})\). This problem can be overcome by matching the traced mass field of the IRAS galaxy with popular models of CDM cosmology. With properly selected parameters, CDM cosmogony models have been found to provide a good approximation to many observational properties of large-scale structures, especially the mass function of optical and X-ray clusters (e.g., Jing & Fang 1994; Bahcall, Fan, & Cen 1997, and references therein). On the other hand, some individual clusters and superclusters from optical surveys have been identified from the IRAS data (Fisher et al. 1995; Webster et al. 1997). Therefore, it is reasonable to assume that the mass field of the CDM cosmogony model provides a description for the mass field traced by the IRAS galaxies. Thus, the statistical properties of the simulated \(r_g\) clusters should be the same as that of the IRAS \(r_g\) clusters. We
then have
\[ \lambda(r_{\text{cl}}/r_{\text{sab}}) = \lambda_{\text{IRAS}}(r_{\text{cl}}/r_{\text{sab}}); \] (10)
i.e., the scaling factors of \( n(> M, r_{\text{cl}}) \) and \( n_{\text{IRAS}}(> M, r_{\text{cl}}) \) are the same. Using equations (9) and (10), we have
\[ \frac{\text{MIL}(r_{\text{cl}})}{\text{MIL}(r_{\text{sab}})} = \frac{\lambda(r_{\text{cl}}/r_{\text{sab}})}{\lambda_{\text{IRAS}}(r_{\text{cl}}/r_{\text{sab}})}. \] (11)
Thus, the MIL ratio can be determined by the ratio between the model-predicted \( \lambda(r_{\text{cl}}/r_{\text{sab}}) \) and the observed \( \lambda_{\text{IRAS}}(r_{\text{cl}}/r_{\text{sab}}) \).

This result is weakly dependent on the specific parameters of models of the CDM cosmogony. The \( \chi^2 \) goodness is larger than 98% for all the three CDM models.

Nevertheless, in Figure 4, we can see a slight but systematic increase of MIL with scale. A linear fitting by
\[ \log \left[ \frac{\text{MIL}(r_{\text{cl}})}{\text{MIL}(r_{\text{sab}})} \right] = a + b \log r_{\text{cl}} \]
yields a \( \chi^2 \) goodness that is larger than 99.9% for all the three models. The least-square–fitted slope \( b \) is found to be 0.19 ± 0.17 for the OCDM, 0.21 ± 0.17 for the LCDM, and 0.41 ± 0.17 for the SCDM. That is, the MIL ratio on a scale of \( \sim 20 \ h^{-1} \) Mpc is probably larger than that of \( r_{\text{sab}} \) by a factor of 1.7 for the LCDM and OCDM (or a factor of 2.9 for the SCDM). These results for the OCDM and LCDM are consistent with the MIL ratio measurement of the Corona Borealis supercluster. Namely, the MIL scale dependence given by IRAS galaxies is consistent with the optical data.

5. CONCLUSION

The RF scaling factor of the multiscale-identified \( r_{\text{cl}} \) clusters is fundamentally important as a statistical measure for clustering on scales larger than clusters. Since these RFs depend only on the number of member galaxies of \( r_{\text{cl}} \) clusters, they can be detected directly from a galaxy redshift survey regardless of the mass distribution of individual objects.

The MIL ratio of gravitationally clustering systems that consist of luminous objects and dark matter depends only on the scale of the system and not on the total mass (Bahcall & Cen 1993). This is actually a scaling of cosmic gravitational clustering. Therefore, the scale dependence of the MIL ratio is closely related to the other scaling indices of these objects. We have shown that the scale behavior of the MIL ratio is determined by the RF and MF scaling factors of \( r_{\text{cl}} \) clusters.

By comparing the mass function scaling of simulated samples with the richness function scaling of IRAS 1.2 Jy galaxies, we conclude that the assumption of MIL flatness is basically correct in the range from 1.5 to 24 \( h^{-1} \) Mpc. This conclusion is weakly dependent on the cosmological parameters we have considered.

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REFERENCES

Bahcall, N. A., & Cen, R. Y. 1993, ApJ, 407, L49
Bahcall, N. A., & Fan, X. 1998, Proc. Natl. Acad. Sci., 95, 5956
Bahcall, N. A., Fan, X., & Cen, R. Y. 1997, ApJ, 485, L53
Bahcall, N. A., Lubin, L. M., & Dorman, V. 1995, ApJ, 447, L81
Faber, S. M., & Gallagher, J. S. 1979, ARA&A, 17, 135
Fang, L.-Z., & Thews, R. L., eds. 1998, Wavelets in Physics (Singapore: World Scientific)
Fisher, K. B., et al. 1995, ApJS, 100, 69
Jing, Y. P., & Fang, L.-Z. 1994, ApJ, 432, 438
Rubin, V. C. 1993, Proc. Natl. Acad. Sci., 90, 4814
Small, T., Ma, C.-P., Sargent, W., & Hamilton, D. 1998, ApJ, 492, 45
Webster, M., Lahav, O., & Fisher, K. 1997, MNRAS, 287, 425
Xu, W., Fang, L.-Z., & Deng, Z. 1999, ApJ, in press (astro-ph/9905156)
Xu, W., Fang, L.-Z., & Wu, X.-P. 1998, ApJ, 508, 472 (XFW)
Yahil, A., Sandage, A., & Tammann, G. A. 1980, ApJ, 242, 448

Fig. 4.—The ratio \( \lambda(r_{\text{cl}}/r_{\text{sab}})/\lambda_{\text{IRAS}}(r_{\text{cl}}/r_{\text{sab}}) \) or \( \text{MIL}(r_{\text{cl}})/\text{MIL}(r_{\text{sab}}) \) as a function of scale \( r_{\text{cl}} \). The symbols are the same as those in Fig. 3.