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THE DISTRIBUTION OF MATTER AROUND LUMINOUS GALAXIES

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Abstract

We discuss the dynamical implications of a measure proposed by Jim Peebles which is the cosmic mass density of material within some fixed distance of a luminous galaxy. If all the matter in the Universe were strongly correlated with galaxies, then this measure rises rapidly to the standard cosmic mass density as expressed in the parameterΩ. With numerical simulations we show that in both standard and low-mass CDM models only half of the mass of the Universe lies within a megaparsec or so of a galaxy of luminosity of roughly L_* or brighter. The implications of this clustering property are considerable for conventional mass measures which treat galaxies as point particles. We explore two such measures, based on the Least Action Method and the Cosmic Virial Theorem. In the former case, the method is not likely to work on scales of a typical intergalaxy spacing; however, it may perform nicely in estimating the mass of an isolated set of galaxy groups or poor clusters. In the case of the Cosmic Virial Theorem, we find that having a large fraction of the mass in the Universe located at some distance from galaxies brings in potentially severe problems of bias which can introduce large uncertainties in the estimation of Ω.

1 Introduction

The aspect of our research presented at the Moriond workshop by W. Zurek was primarily the viability of cold dark matter models in light of recent COBE measurements and observations of nearby cosmic large-scale structures. The bulk of this material is being published elsewhere (see [1] for an analysis of CDM and the redshift-space power spectrum which shows no incompatibility between the models and observations; also see [2] for a broader discussion). Hence we focus on an issue which was only lightly touched upon at the workshop but which ultimately may be important to our understanding of distribution of dark matter in the Universe.

At the Heron Island Workshop on Peculiar Velocities in the summer of 1995, Jim Peebles posed the following question: How does the of cosmic mass density that is inferred by including only the mass within some distance R of a galaxy vary with R? In a system where all of the dark matter is tightly bound to luminous galaxies, this density—call it Ω_R—rises rapidly to unity at distances corresponding to the typical size of a galaxy. In systems where the galaxy distribution does not account for the total mass, Ω_R may rise much more slowly, reflecting a situation where a significant amount of dark matter lies outside of galaxies, or perhaps in large, extended halos. It is clear that Peebles' question has important ramifications for observational cosmology. For example, many conventional measures of dynamical mass in large-scale structures are based on the assumption that galaxies are point particles. If Ω_R rises slowly with R then there may exist a large and uncertain distribution of dark matter which can seriously compromise these mass measures.

Here, we explore some properties of Peebles' measure in the context of high and low Ω cosmogonies. We consider the implications for large-scale dynamics which originally motivated Peebles to define Ω_R. Our discussion will include the Least Action Method [3, 4] and the Cosmic Virial Theorem [5].

2 The Ω_R Measure

Peebles' density measure $\Omega_R(R)$ is most easily described in algorithmic terms given above. The prescription is to determine if an infinitesimal mass element is within a distance R of any galaxy in a **Fair Sample** volume V; if so it is added to a running sum of mass which, after all such elements have been examined, is divided by the total volume in the sample. To relate this measure to other statistics of large-scale structure, we consider the following more formal definition:

$$\Omega_R \equiv \frac{\Omega(R)}{\equiv}\frac{1}{V}\left[\int_V d\vec{r}_g \rho_g(\vec{r}_g)\int_{r<R} d\vec{r}\rho(\vec{r}-\vec{r}_g) - O(\rho,\rho_g,R)\right] , \quad (1)$$

where ρ and ρ_g are the continuous mass density and discrete galaxy distribution, respectively, and the function O represents the mass which is counted more than once by integration in spheres (denoted by subscript $r < R$) which overlap. In the limit of small R, O vanishes and Ω_R can be immediately related to the galaxy-mass pairwise correlation function ξ_{gm} by taking an ensemble average of Ω_R. In this case, Ω_R will have the form of the average cumulative mass profile of a galaxy. However, in general, the volume of integration can be of complicated topology and an ensemble average will introduce dependencies on high-order correlations between galaxies and mass ($\xi_{ggg\cdots gm}$). In a metaphorical sense, Ω_R is a hybrid of a count-in-cell statistic (e.g., [6]) and the topological genus of isodensity contours [7].

We can estimate the behavior of Ω_R in various cosmological models with high-resolution N-body simulations. We present the results from three sets of numerical data corresponding to a COBE-normalized standard cold dark matter ($100h \equiv H = 50$ km/s/Mpc; $\Omega = 1$; $\Lambda = 0$), a standard CDM model with lower normalization ($\sigma_8 = 0.74$), and a low density CDM model in a flat universe ($h = 0.8$; $\Omega = 0.2$; $\Lambda = 0.8$). In each case, 17 million particles were used to represent the dissipationless dark matter in periodic cubes of length $250h^{-1}$ Mpc to a side; the interparticle forces were determined using a treecode with $10h^{-1}$ kpc force smoothing. Galaxy halos, candidates for realistic galaxies, are identified on the basis of local density and potential fields. (An example of output from this code can be found on the cover of this volume.)

Figure 1 illustrates our results. Evidently, the profile of $\Omega_R(R)$ is only modestly sensitive to changes in normalization of the primordial density field or to the cosmic mass density. Greater sensitivity arises from the choice of threshold mass used to identify halos. This fact is not surprising; for a given mass distribution an increase in the galaxy number density will generally steepen the Ω_R profile.

A useful length scale can also be defined for the purposes of understanding dynamics of clustering: we take $R_{1/2}$ to be such that $\Omega_R(R_{1/2}) = 0.5$. This measure gives a length that roughly characterizes the failure in the assumption that the mass of the universe can be approximated by point-like galaxies. For the full halo catalogs with ~15,000 objects with "luminosity" of roughly L_* or brighter, $R_{1/2}$ is approximately 1 h^{-1} Mpc; for the 8000 most massive objects, $R_{1/2}$ extends to 2 h^{-1} Mpc.

3 A Point-Mass Approximation?

The Ω_R profiles presented in §2 suggest that the approximation of galaxies as points may be valid only when the characteristic interaction scale between galaxies is well above $R_{1/2}$; below this value a significant fraction of the mass lies outside of galaxies and may have dynamical consequences which are neglected by the point-mass approximation.

If $R_{1/2}$ represents a lower limit to interaction distances for which a point-mass approximation is expected to work well, then interactions between objects larger than galaxies, such clusters

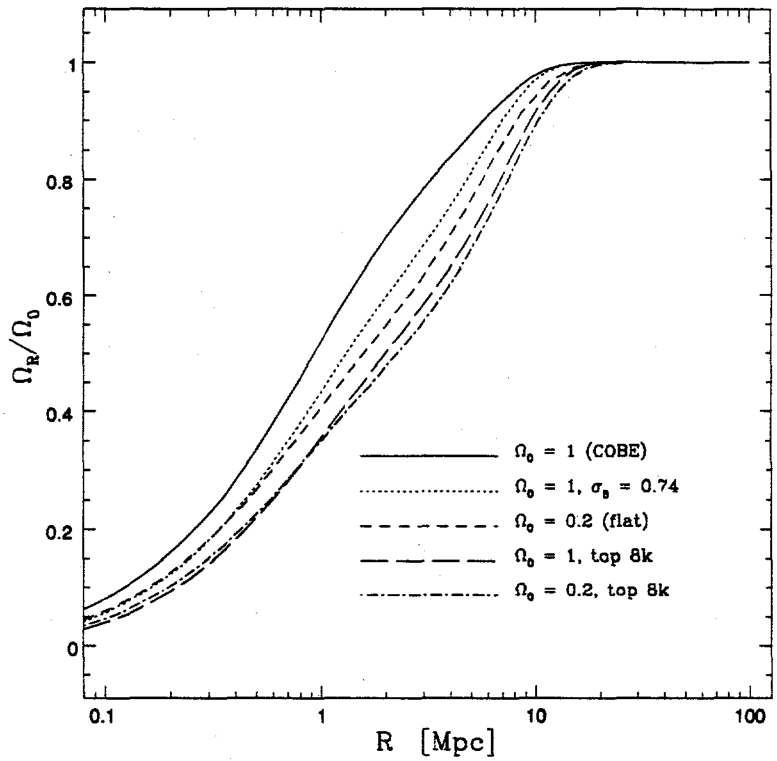

Figure 1: The profile of Ω_R versus scale. Shown are profiles from standard CDM of two different normalizations and from a cosmologically flat, low density CDM model. The two rightmost curves are taken from subsets of the low-normalization standard model and the low-density model; each subset consists of the top 8,000 most massive galaxy halos. These curves shows the sensitivity of Ω_R to the galaxy mass cutoff.

or superclusters, may be less susceptible to the effects of outlying dark matter. However, there is an obvious difficulty if the approximation is to be applied to entities which themselves consist of many galaxies. A large astrophysical object like a supercluster can generate a gravitational potential with significant high-order multipole terms; a point-mass approximation for such an object will certainly fail.

Perhaps there exists a limited range of interaction scales which is above $R_{1/2}$ yet below the limit imposed by strong multipole interactions between extended massive objects. To determine if such a range exists, we propose a way to approximate the susceptibility of a massive object to multipole interactions, based on the evolution of an object inhomogeneity with no high-order multipole moments—a spherically symmetric overdensity. The idea is that multipole interactions will be important only if an object collapses at some late time. Something which virializes at high redshift is likely to be well-approximated as a point mass, at least for the purposes of tracking interactions with similar, neighboring objects.

The spherical collapse model allows us to get a quick handle on the collapse time, here measured by z_{max}, the redshift at which an overdense region has maximum size in proper coordinates. With the definition that δ_R is the overdensity relative to the mean in a sphere of radius R, we find that

$$z_{max} \approx \begin{cases} 0.54\Omega^{0.66}\delta_R - \Omega^{-0.82} & (\Lambda = 0) \\ 0.54\Omega^{0.24}\delta_R - 0.88\Omega^{-0.17} & (\text{flat}) \end{cases}, \qquad (2)$$

for cosmogonies with negligible cosmological constant Λ (upper equation) and negligible spatial curvature (lower equation). In the spirit of the Press-Schechter theory of structure formation we suppose that collapsed objects originate from overdensities at the 2-σ to 3-σ level, where σ^2 is the variance in the primordial mass density field smoothed on a scale R. For galactic scales we find that for standard CDM $\delta_R \gtrsim 10$, leading to $z_{max} \gtrsim 5$, and a redshift of $z \gtrsim 2.8$ at time of collapse. This redshift is comfortably large–we might accept the possibility that objects which reach their maximum radius at $z_{max} = 5$ have spent a good fraction of their history in a collapsed state, neither producing excessive quadrupole potential terms nor reacting strongly to tidal fields of other neighboring objects. Of course we are neglecting a great deal of physics such as merging that arises in a hierarchical clustering scenarios.

At larger scales, the fluctuation amplitudes for a 3-σ peak get considerable smaller and the redshift of maximum expansion is accordingly reduced. On a mass scale of several megaparsecs, corresponding to the Local Group, $z_{max} \approx 3$. A cluster with a mass of 10^15 $M_\odot$reaches its maximum radius at a redshift near unity in a standard CDM scenario. The implication is that rich clusters may have formed too late to be considered as point objects over the course of their evolution, however, groups of galaxies or poor clusters may have interacted with one another as if points since a redshift of 3 or more.

This criterion, although extremely loose, gives hope of finding dynamical systems in the universe for which the actual distribution of dark matter need not be determined precisely. In this way, dynamical mass estimates may be accurately derived solely on the basis of phase-space locations of luminous objects. It remains to be determined for each such estimate whether this hope can be realized, and this calls for detailed analysis using numerical simulations.

We now consider the implications of Ω_R for two specific measures of cosmic mass, the Least Action Method and the Cosmic Virial Theorem, both proposed by Peebles.

4 The Least Action Method

Peebles [3, 4] proposed that trajectories of galaxies in the Local group could be derived from an action principle operating in an expanding cosmological background spacetime with assumed cosmological parameters. An estimate of Ω then results from a best-fit between the actual phase-space locations of the galaxies (or some subset of coordinates defined in either real or redshift space) and the least action prediction. This Least Action Method (LAM), treats galaxies as point masses and its reliability hinges upon the extent to which this approximation is valid.

From Figure 1 and the discussion in §2 above, it seems unlikely that the LAM should succeed on the submegaparsec scales characteristic of intergalaxy separations within the Local Group, at least for the case of CDM cosmogonies. Simply too much mass lies outside of galaxies for the point-mass approximation to be valid on these scales. This inference from the behavior of Ω_R is actually made in retrospect. Dunn & Laflamme [8] demonstrated that that in CDM cosmogonies the LAM is seriously affected by the presence of mass outside of galaxy halos. In the context of N-body simulations, they labeled dark matter particles which are dynamically important but which are not associated with a particular galaxy halo as "orphans". Their conclusion was that the orphans cause the LAM to underestimate Ω by a significant factor.

We note that Dunn & Laflamme considered only dissipationless CDM models. The difficulties with the LAM that arise from the orphaned particles are expected to be worse in cosmogonies with hot dark matter, as the mass around galaxies is even more diffuse than for

CDM. On the other hand, models with high baryonic mass fractions admit the possibility that material can cluster more densely around galaxies than in dissipationless CDM or HDM models. In this case the LAM may work well.

The LAM may also fare better when applied to objects associated with larger mass scales. As mentioned above, perhaps isolated systems of galaxy groups or poor clusters may be immune to the problems created by orphaned dark matter. We are investigating this possibility with numerical simulations although preliminary results are ambiguous.

5 The Cosmic Virial Theorem

Measures of kinetic and potential energy in cosmological systems are found in the pairwise radial velocity dispersion, σ_v, and the two-point correlation function, ξ_2, respectively. The Cosmic Virial Theorem (CVT) provides a means to relate these two. The mechanism is provided by the BBGKY equations which give σ_v as a function of both the two- and three-point correlation functions. Dependence on ξ_2 alone can arise only in the context of a clustering model; for example, in hierarchical models, the three-point correlation function ξ_3 has the form

$$\xi_3(\vec{x}_1, \vec{x}_2.\vec{x}_3) = Q\left[\xi_2(|\vec{x}_1 - \vec{x}_2|) + \text{cyc.}\right] . \tag{3}$$

Virtually all incarnations of the CVT in the literature (e.g., [5, 9, 10]) are based upon an assumption of hierarchical clustering.

If hierarchical clustering is assumed, the CVT can be expressed as

$$\sigma_v(r) = \kappa Q r^2 \xi_2(r) I(r) \Omega \tag{4}$$

where $I(r)$ has weak dependence on r, and the evaluation of the constant κ is critical to the success of the CVT as a measure of Ω.

There is a recent article by Bartlett & Blanchard [10] which discusses the CVT and the effects of using ξ_2 and σ_v as inferred from galaxies when the real issues are the velocity and spatial correlations between the galaxies and the mass in the Universe. The conclusion reached in their paper is that the distribution of matter around galaxies is extremely important for the CVT if it is based on ξ_2 and σ_v as measured from galaxies. In particular, they claimed, the low Ω value inferred from the CVT with the observed ξ_2 and σ_v for galaxies is not necessarily incompatible with an $\Omega = 1$ universe because of the presence of large, extended galaxy halos.

We can add somewhat to the discussion of Bartlett & Blanchard first by noting that the σ_v value of 350 km/s they used from the Davis & Peebles [9] analysis of the CfA I survey has been revised upward on the basis of reanalysis of the old data [11, 13, 12] and new data [14, 15]. The more recent estimates place σ_v above 700 km/s, giving a factor of 4 boost to the inferred Ω from the CVT.

However good this news may seem for those who favor a high-Ω value, caution is due to any observational estimate based on the CVT. We have worked with the CVT in numerical simulations and hold perhaps stronger views on the possible biases that can effect the CVT. Not only are there biases in σ_v and the normalization of ξ_2 between galaxies and the total matter, but Q and the power law index γ for $\xi_2 \sim r^{-\gamma}$ inferred for galaxies can be different from the mass distribution. Furthermore, even something as fundamental as the hierarchical nature of the galaxy clustering may not hold for the mass. In our simulations of structure formation in CDM we have found that all of these problems exist.

In a comparison of the simulated galaxies to the mass particles we find that (1) the galaxies have a significantly reduced σ_v profile, an affect which gets more pronounced at scales below a megaparsec; (2) the two-point correlation function of galaxies is well-fit by a power law with index $\gamma = 1.8$ on scales of ~ 10 kpc to ~ 10 Mpc, while ξ_2 for mass has a steeper slope, $\gamma \approx 2$, which holds down to a "core" radius of ~ 100 kpc; (3) the correlation length for galaxies is $\sim$20% less than that of the mass; and (4) the Q values for mass and galaxies differ, with Q near unity for galaxies over a broad range of scales, while Q is a function of characteristic separation for mass, and rises steeply from unity below a megaparsec. This latter difference indicates that even though the galaxies may appear hierarchically clustered, the mass may not exhibit the same broad clustering property. Since the CVT as it appears in equation (4) is derived from the assumption that mass is hierarchically clustered, it is perhaps not appropriate for the CDM models. We must caution that this departure from the hierarchical clustering paradigm in the mass distribution may be a numerical artifact, most likely the result of finite time steps in the evolution code which can wash out structure in the densest (and hottest) regions.

Despite these problems, we applied the CVT to both the mass and galaxy halo distributions in our simulations. In the case of mass, for which the CVT should work best, we found that an effective Q value near 3 gave a reasonably flat curve for Ω as a function of pair separation on scales of a megaparsec and below, suggesting that equation (4) holds despite the deviation from hierarchical clustering at small scales.

When we applied the CVT to the galaxy halos, using parameters derived from the halo distributions alone, we found that the inferred Ω was near zero for separation much above and below a megaparsec. But near the peak of the curve, at the canonical scale for applying the CVT, the inferred Ω is near unity. Unfortunately this holds true not only in the standard CDM simulations but in the model with the true Ω value of 0.2. Thus we have come up with an example, complementary to that of Bartlett & Blanchard, wherein the CVT *overestimates* Ω in a low density universe.

6 Conclusion

On the basis of a simple curve, the density of mass within a distance R of a luminous galaxy we have argued that extreme caution must be exercised in the application of mass measures that treat galaxies as point-particles. For CDM models, the distance $R_{1/2}$ which contains half of the total mass of the Universe about L_* galaxies is around a megaparsec. It is this scale below which the point mass approximation is likely to break down.

Indeed, the numerical results for two particular mass measures, based on the Least Action Method and the Cosmic Virial Theorem, are less than promising. With the LAM, there is hope of success when it is applied to objects larger than galaxies but smaller than superclusters—perhaps isolated poor clusters may work best—because the distance between such objects are above $R_{1/2}$. However this remains to be confirmed in simulations. The CVT seems more problematic, because it depends on integral expressions that mix a range of scales, including those below $R_{1/2}$. The principle difficulty is that the presence of matter at some distance from galaxies may render fundamental parameters of the mass phase-space distribution (e.g., the correlation function index γ and the pairwise velocity dispersion, σ_v) irretrievable from observations of galaxies alone. However we do not reject the possibility that the CVT can be calibrated for galaxies, or perhaps a certain class of galaxies, using high-resolution numerical simulations.

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