Galaxy Clustering and the Missing Mass

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Galaxy clustering and the missing mass

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The last several years have witnessed the completion of several large-scale red-shift surveys of galaxies, which have greatly increased our knowledge of the large-scale distribution of galaxies, and have shown that the superclustering phenomenon is widespread and accompanied by large holes in space that appear to be quite deficient in galaxies. The extreme lumpiness of our local Universe presents a challenge to all current theories of galaxy and cluster formation. A comparison with existing n-body simulations results in a poor match to the observations, indicating either that the initial conditions are incorrect or that additional input physics must be specified. With the large CfA red-shift survey complete to magnitude 14.5 at high Galactic latitude, it is possible to determine dynamical masses of small groups as well as large clusters, and the data set provides critical parameters for the mass measurement of the entire Local Supercluster. A trend of increasing mass:light ratio with scale size of measurement emerges from these studies, an effect that implies that dissipative processes probably played a major role in the formation of galaxies and clusters.

1. Clustering as observed in red-shift surveys

Over the past decade, our knowledge of the large-scale distribution of galaxies has grown tremendously. The systematic analysis of large galaxy catalogues and the use of the correlation function $\xi(r)$ has brought important quantitative measures of the amplitude and statistical uniformity of galaxy clustering. Thorough reviews of all this work are given in Fall (1979) and in Peebles (1980). These analyses have concentrated in the main on two-dimensional catalogues listing only sky coordinates and perhaps a magnitude estimate for each galaxy in the sample.

Much improved information on the structure and dynamics of clustering can be gained by measuring the red shift of all galaxies in selected samples, and in the past several years several such red-shift surveys have been completed. The red shift provides a precise third parameter for each galaxy, a measure of the sum of its Hubble flow expansion plus the longitudinal component of its peculiar, or non-Hubble, velocity. The resulting maps of the red-shift space distribution of galaxies are therefore distorted from the true spatial distribution, particularly in rich clusters where the peculiar motions are large.

With the data in hand, it is at once strikingly apparent that all the nearby Abell clusters such as Coma, Perseus and Hercules are very much larger than apparent from their central regions. They appear to be embedded in superclusters of 30–60 h^{-1} Mpc extent (H_0 = 100 h km s^{-1} Mpc^{-1}), and these superclusters are usually prolate structures with one axis somewhat longer than the other two. Several of the recent surveys have focused on these rich clusters and have traced their extent in several directions (Gregory & Thompson 1978; Tarenghi *et al.* 1979, 1980; Gregory *et al.* 1981). A study of our own Local Supercluster is best done with red-shift samples complete to magnitude 13. The Shapley–Ames catalogue, which is nearly complete over the entire sky to this limit, has complete red-shift data available (Sandage &

Tammann 1981), and in addition Fisher & Tully (1981) have made available a list of over 1100 galaxies with red shifts less than 3000 km s^{-1}.

To obtain a 'fair measure' of galaxy clustering it is important not to preselect the survey region towards some nearby interesting cluster, and one must probe deep enough to get beyond the effects of the Local Supercluster. The red-shift surveys of Kirschner *et al.* (1979, 1981) and of R. Ellis, G. Efstathiou & T. Shanks (personal communication 1982) were complete surveys of a few hundred galaxies to a limiting magnitude of *ca.* $17m_B$ in small randomly

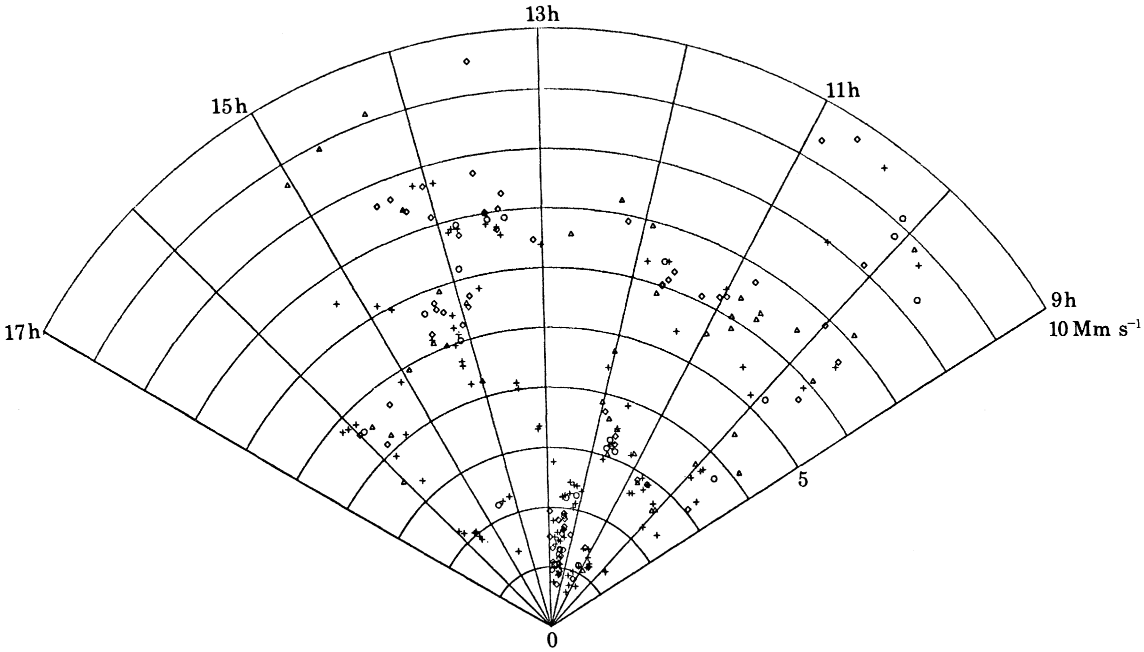

FIGURE 1. Galaxies from the CfA survey in the range $10° < \delta < 20°$, from Davis *et al.* (1982); 249 galaxies plotted. The Virgo cluster is prominent in the foreground.

chosen fields. The very large hole reported by Kirschner *et al.* (1981) was further confirmation of the large voids detected in the earlier surveys. In all these works the clustering is very strong and the red-shift distributions are very far from homogeneous.

The Harvard–Smithsonian (CfA) red-shift survey is a compromise between these very deep surveys into selected or randomly chosen regions and the shallower sky surveys. After 200 nights of 60 inch (*ca.* 1.52 m) telescope time, at Mt Hopkins, Arizona, we have completed the initial survey to $14.5m_B$ over 2.7 sr at high galactic latitude. The sample contains some 2400 galaxies, all selected from the Zwicky *et al.* (1961–8) catalogue. This sample provides detailed information on the galaxy distribution to a distance of 100 h^{-1} Mpc. Maps of the resulting distribution have been discussed by Davis *et al.* (1982) and further delineations of the most prominent clusterings are described in detail by Oort (1982).

Again the clustering is quite apparent, with long filamentary clusters and large low-density regions equally prominent. A representative slice of the survey is shown in figure 1, taken from Davis *et al.* (1982). This slice shows the data in the declination wedge $10° < \delta < 20°$ and is dominated by the core of the Virgo cluster in the foreground, stretched into a cigar along the line of sight by virial motion within the cluster. The background clumps, on the other hand, are quite diffuse and loosely connected, if at all. Careful examination of the overall distribution of galaxies seen in this survey shows a tremendous amount of randomness. The bridges defining superclusters are often so tenuous (i.e. of such low density contrast) that one must be careful not to overinterpret the distribution.

A useful approach to understanding the overall nature of the large-scale structure is to compare it with artificial distributions created by processes under our control. For example, we can use existing n-body simulations in which mass points cluster because of gravitational instability in an expanding coordinate system. The best existing simulation for comparison

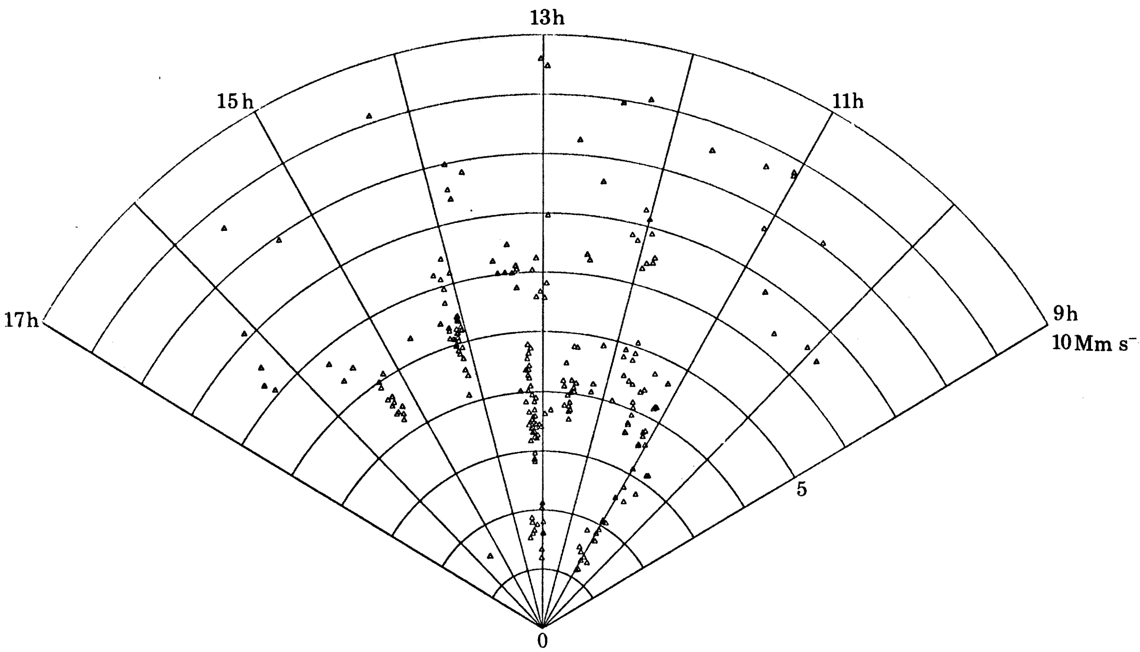

FIGURE 2. A section of the simulation of Efstathiou & Eastwood (1981) when projected in red-shift space; 229 points plotted (from Davis *et al.* 1982).

with the data is that of Efstathiou & Eastwood (1981) in which 20000 points were evolved by using Newtonian gravity in an expanding cube with periodic boundary conditions. The simulation is scaled at a given time slice so that the two-point correlation function scale length matches that of the observations (r_c = 5 Mpc); only a fraction of the points at a distance from some arbitrarily chosen central observing point are selected in a fashion consistent with the observed luminosity distribution of galaxies. The result is a catalogue magnitude limited in the same manner as the real data set.

Figure 2 shows a slice of the resulting simulation, which now has the same selection biases as the real data set seen in figure 1. Note that the clustering differs quite strongly from the real data. Large holes are present in both, but the n-body clusters are more compact, have far more obvious cigar distortion, and clusters are not as well connected in the large scale. The peculiar velocities of the points in the simulation have been scaled by a factor of $\frac{1}{3}$ to shrink the cigar extensions to reasonable levels and to bring the r.m.s. one-dimensional peculiar velocity dispersion to 350 km s^{-1}. This approximately scales the $\Omega = 1$ simulation to $\Omega = 0.09$ but is not a completely self-consistent procedure.

The difference in the clustering apparent in the figures is equally apparent when the correlation functions of the two distributions are examined. This is shown in figure 3 where we plot

$r^2\xi(r)$ for both the data and the simulation. Details of this work will be given by Davis & Peebles (1982). Note that the data roughly approximate a power law up to 10 h^{-1} Mpc but the simulation never fits a power-law model and is continuously steepening, with more power on small scales than the data and less power on large scales.

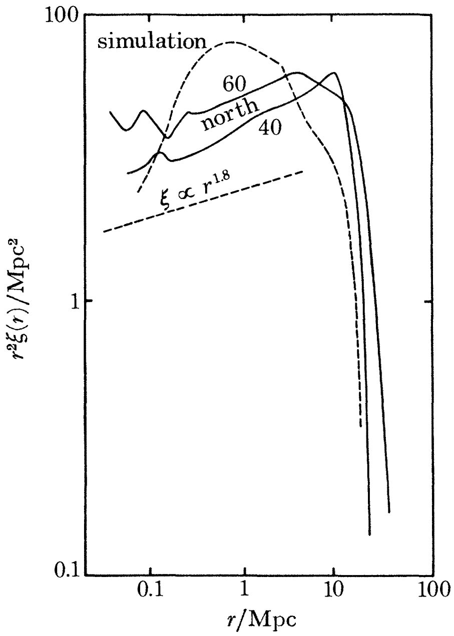

FIGURE 3. The solid lines plot $r^2\xi(r)$ in the CfA sample for catalogues volume limited to 40 or 60 h^{-1} Mpc and magnitude limited beyond. A power law $\gamma = 1.8$ is indicated (broken straight line). The broken curve is $r^2\xi(r)$ for the simulation, which does not have a power-law behaviour.

The large holes in the simulation are easy to understand in view of the large velocity fields present in the simulation (particularly if the velocities are not adjusted as in figure 2). However, in the real data set it is not so obvious that the velocity field is large enough to have created the observed voids. The fact that the clustering is stronger on small scales in the simulation makes the resulting velocity field easier to spot than in the real data where the clustering is relatively stronger on large scales, which should result in velocity fields with a large coherence length that would be difficult to identify in the red-shift maps.

2. Evidence for missing mass

The existence of the linearly growing dark mass is by now quite well established for spiral galaxies of all types (Rubin *et al.* 1980), but this only establishes the existence of a mysterious halo out to a scale of roughly 20–50 kpc. The next largest systems to study are isolated binary galaxies, which have projected separations in the range 10–100 h^{-1} kpc. In an analysis of new, accurate red-shift data for the complete Turner sample of 156 pairs, White *et al.* (1982) show that the mean velocity difference for pairs that are likely to be true binaries is approximately 75 km s^{-1} but that there is virtually no correlation between luminosity, velocity difference or projected separation. This result is quite inconsistent with Kepler's law and strongly favours an isothermal-type halo of dark matter. The lack of observed correlation between the measured luminosity and mass of the binary systems argues that the ratio of dark to luminous matter within this scale size may be large and that a galaxy's measured luminosity is a poor measure of its mass.

As one measure of the dynamics of the clustering on larger scales still, the CfA sample can be searched for groups of galaxies and the virial theorem applied to all the resulting groups. Press & Davis (1982) have done this for the CfA sample, using a group selection procedure that

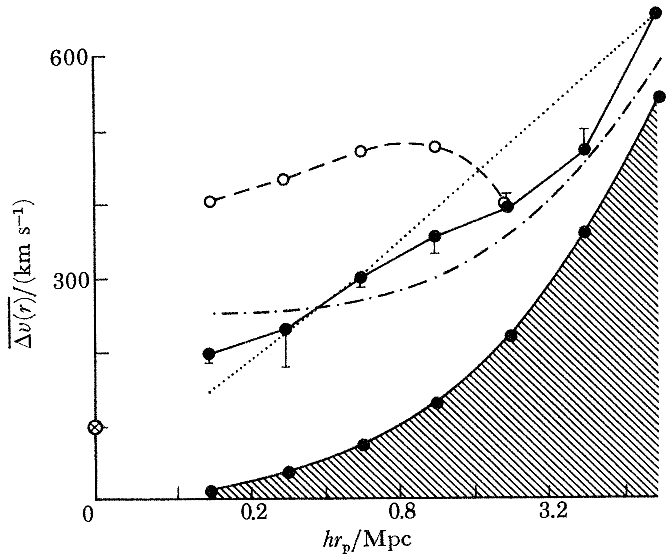

FIGURE 4. First moments of the velocity difference distribution of clustered pairs as a function of projected separation of the pairs. Various models of the behaviour of the dispersion σ are indicated: solid points, data; open points, simulation; ⊗, Turner binary sample; stippled area, Hubble-flow limit; ·—·, σ = 300; · · ·, $400r^{\frac{1}{2}}$.

selects physical associations with crossing times less than 30% of the Hubble time. For such systems the virial theorem should apply at least approximately, although of course the measure is very unreliable for individual clusters. The procedure is calibrated against the simulation for various cosmological densities and correctly predicts the underlying density. However, in the real data set, the virial results show a persistent trend in the sense that the measured mass per galaxy is a linear function of the measured size of the group, as though the massive halo has still not converged on these scales. This trend is completely absent in the simulations. Thus no simple measure of an average mass per galaxy, or equivalently a mean mass density, can be derived from this analysis unless one is prepared to interpret the meaning of the trend-line, which extends from scales of 50 kpc to 3 Mpc.

One criticism of this result has been raised on the basis that early-type galaxies may dominate the larger clusters and late-type systems may dominate the smaller clusters, so that at least part of the trend would be caused by an intrinsic difference in the mass per galaxy of early-type and late-type systems (see Davis (1982) for a discussion). Such an effect could perhaps explain a factor of 2 variation in the curve, whereas the observed effect extends over a factor of nearly 100. Furthermore, such a trend has been noted before in different catalogues and different group-selection procedures (Rood & Dickel 1979). The only advantage of the new analysis is that it is performed over a uniform quality data set and is calibrated against simulations for which the internal dynamics is known.

Further evidence that something is amiss in the mass distribution of the observed Universe comes from a pair-weighted analysis of the velocity field (Davis & Peebles 1982). Preliminary results of this analysis are shown in figure 4 in which is plotted the mean absolute velocity difference of clustered galaxies in the CfA sample as a function of their projected separation. At small scales, 100–200 h^{-1} kpc, the mean difference is less than 200 km s^{-1}, whereas for large projected separation (more than 3 h^{-1} Mpc) the difference grows to over 500 km s^{-1}. The mean Δv of the Turner binary sample is shown in the lower left corner of figure 4. The interpretation of this graph requires some understanding of the galaxy covariance function $\xi(r)$, for which we have a good measure. If galaxies were clustered but not dynamically interacting they would be expanding apart by Hubble flow, and galaxies at large projected separation would have sizeable velocity difference simply from the Hubble-flow expansion. If this were so, the velocity curve plotted against projected scale would behave as the heavy lower curve in figure 4, which is derived simply by integrating the correlation function along the line of sight at a given projection. Thus, particularly at scales less than a few megaparsecs, there is no doubt that the pairs of galaxies are dynamically interacting, since the mean velocity differences far exceed the Hubble-flow limit. The other dotted curves in figure 4 are the result of assuming that the r.m.s. velocity difference of pairs varies as their physical separation to the power δ. The expected behaviour at a given projection is then calculated with the $\xi(r)$ broadened isotropically according to either gaussian or exponential broadening. The Hubble-flow effect is also accounted for by assuming that it is cancelled on the mean at small scales and is only 50% cancelled at the scale where $\xi(r) = 1$. Such a behaviour is expected on the basis of similarity solutions for the time evolution of $\xi(r)$ (Davis & Peebles 1977) and is approximately observed in the n-body simulations (Efstathiou & Eastwood 1981). The details of this correction are uncertain but are of very minor importance to the resulting curve.

Note that $\delta = 0$ provides a very poor fit to the observations at any chosen mean velocity. To fit the small-scale velocity difference requires an r.m.s. Δv of 200 km s^{-1}, but such a choice predicts far too small a Δv at projections of 1 Mpc. The best fit to the curve is obtained if $\Delta\bar{v}(r) \approx 350\ (r\ h^{-2}/1\ \text{Mpc})^{0.3}$ km s^{-1}, and exponential broadening provides a better fit to the distribution function shapes than does gaussian broadening. In a gravitational hierarchy with all levels on this scale in approximate virial equilibrium, one would expect $\delta = \frac{1}{2}(2-\gamma) \approx 0.1$ (Peebles 1980), where γ is the covariance function slope, observed in this sample to be 1.8 over the scales of interest here.

However, the analysis of the clustering hierarchy assumes that the galaxies are fair tracers of the underlying mass distribution, and if this assumption is violated, with the dark mass less tightly clustered than the luminous interacting galaxies, then the behaviour of figure 4 is expected. For the simulations, $\Delta v(r)$ is observed to be nearly flat over most of the measured scale and to decrease at large separations, in agreement with the analysis of Efstathiou & Eastwood (1981). This can be understood as the result of the steeper correlation function for this sample. Thus the analysis procedure is not necessarily biased to find $\Delta v(r)$ to increase. This analysis suggests that massive halos continue beyond the scale of binary galaxies and confirms the similar conclusions of Press & Davis (1982) based on virial analysis of individual groups. The advantage of this procedure is that no group assignment need be done; all pairs of galaxies are counted equally. This type of analysis has been criticized in the past as weighting the pairs in rich clusters heavily but, as a test, we deleted all galaxies in the cores of the Virgo, Coma and Abell 1367 clusters, with resulting $\overline{\Delta v(r)}$ shown as the error bars in figure 4. The changes are small and random, so that the rich clusters do not dominate this statistic. These tests lead us to believe that the evidence for the missing mass fraction to *increase* up to scales of 1 Mpc is solid and must be taken seriously.

Perhaps the best test for missing mass is the Virgo infall test, which measures our deceleration towards the Local Supercluster and provides an estimate of the total mass interior to our Virgocentric distance, roughly 15 Mpc. This test gives dynamical information on a scale totally inaccessible to the types of arguments above and is a vital link in understanding the behaviour of the missing mass. The requirements for this cosmological test are first that the mean overdensity within our Virgocentric distance be known, and second that we have a reliable estimate of our infall velocity to Virgo. The CfA sample provides the best estimate of the overdensity, since it includes the Local Supercluster in the foreground and yet samples deep enough beyond to provide a reliable background estimate. Davis & Huchra (1982) have considered the problem in detail and conclude that the mean overdensity is $\bar{\delta} = 2.0 \pm 0.2$ and that the effects of the non-spherical distribution of the Local Supercluster do not significantly change the conclusions of the spherical models. What is measured is of course the overdensity of the light or the total number of galaxies, and one presumes that on this scale the underlying mass distribution follows the light. For a measured infall of $v(p)$, the estimate of the cosmological density is approximately

$$\Omega = (v(p)/650)^{1.6}.$$

Estimates of $v(p)$ range from 220–520 km s^{-1} with derived Ω values in the range 0.18–0.70. Work continues on the difficult problem of the measurement of the infall, and perhaps in a few years' time there will be agreement over its value. As a comparison, if the universal mass : light ratio were like that of galaxies in the Coma cluster, then Ω would be between 0.1 and 0.2. This is a fairly typical value for rich clusters, as measured in their core regions of size *ca.* 1–2 Mpc. Depending on the value of $v(p)$, mass per galaxy may increase beyond this scale size but, for any reasonable value of $v(p)$, the Virgo infall test gives estimates of mass per galaxy that are considerably below the extrapolated linear trend evident on small scales.

3. Constraints on cosmogonic scenarios

The above quick sketch can be summarized into four key features that emerge from the data, and which must be incorporated within any successful model for the formation of the large-scale structure.

First, the present galaxy distribution has a power-law correlation function with prolate structures predominating. Oblate pancakes are not prominent, if they are present at all. Second, the velocity field of the galaxy distribution is small on small scales. Third, there is evidence to suggest that the dynamical mass per galaxy increases with scale size up to at least 10 Mpc and, fourth, the estimates of Ω derived from small-scale measurements are typically $\Omega \approx 0.1$, but larger-scale measurements suggest $\Omega > 0.2$, and Ω is considerably larger if our Virgo infall velocity exceeds 300 km s^{-1}. These high cosmological density estimates are in strong contradiction to the upper limit on $\Omega_b h^2$ set by the nucleosynthesis constraints, where $\Omega_b h^2 < 0.025$, and Ω_b is the cosmological density parameter of baryons (Steigman 1982).

If all these arguments are to be taken at face value, then several very strong constraints immediately follow. First, the dominant matter in the Universe is non-baryonic, and could be either primordial black holes, massive neutrinos of some flavour, or an exotic remnant of supersymmetry theories such as gravitinos (Blumenthal *et al.* 1982). In such an event experimental confirmation is highly uncertain, a very distressing thought.

Secondly, the increasing dynamical mass/galaxy with scale size suggests that non-gravitational, dissipative effects have probably played a major role in separating the dark halo from the luminous galaxies. Conceivably dynamical friction can assist in this segregation (Barnes 1982) but is unlikely to be capable of the extent of the segregation.

Finally, it does not appear that the white-noise initial spectrum simulations give an adequate picture of the present large-scale structures. Perhaps a different spectral index or an edge in the initial power spectrum would give better results.

The presence of a short-wavelength cutoff of initial perturbations in neutrino-dominated universes (Bond *et al.* 1980) is the primary motivation for the present versions of the Zel'dovich pancake scenario (Doroshkevich *et al.* 1980), in which very large galaxy clusters collapse before the formation of individual galaxies. Recently full three-dimensional n-body simulations of dissipationless particles have been performed to study the effects of such a cutoff (Klypin & Shandarin 1982; Frenk *et al.* 1982). The results are somewhat surprising in that no oblate structures form at all. Furthermore, the resulting clusters that form bear a striking resemblance to the observed galaxy distribution with reasonably small velocity fields, in sharp contrast to the initial white-noise simulations. While these models are certainly not unique and pose several interpretational problems, they are highly suggestive. Inclusion of dissipative forces will probably cause the baryonic components to settle toward the densest regions of the collapsed filaments in a process similar to that described by White & Rees (1978). In such a scenario one might expect the dissipative baryons to be tightly coupled to the dissipationless halo only on scales larger than the smallest dimensions of the filaments, which seems to be roughly 15–20% of the size of the imposed cutoff. Further work on these and other models is essential for a better understanding of the mysterious dark matter in the Universe.

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