SIMULATIONS OF LARGE-SCALE STRUCTURE COMPARED TO ABELL CLUSTER DISTRIBUTION

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ABSTRACT. The amount of structure present among the Abell clusters out to redshift $z = 0.085$ has been compared with numerical supercomputer simulations (with 64^3 particles) of the isothermal, neutrino, and cold particle models for large-scale structure, assuming a flat universe and $H = 50$ km sec^{-1} Mpc^{-1}. High-density clusters of particles were identified in each simulation. Correlation and percolation tests were then used to compare the spatial distribution of these high-density points with the apparent superclustering among Abell clusters. While all of the models had some small superclusters (the neutrino model has too many), none came very close to possessing the extremely extensive structures found in the Abell clusters (generally, disagreement by 2σ or more).

A second set of simulations used the cold particle model with $\Omega = 0.2$ and 0.5. The structures found in these simulations were certainly larger than those of the $\Omega = 1.0$ cold particle case, but still $> 2\sigma$ too small in comparisons with the Abell clusters.

The spatial distribution of Abell clusters shows evidence of some very large-scale (~ 300 Mpc) structures in the Universe (*e.g.*, Oort 1983, Bahcall and Soneira 1984, Batuski and Burns 1985), and an important current question is how well models for large-scale structure can match the observed distribution of galaxies and clusters. To begin to answer this question on these very large scales, we created numerical simulations of three popular models (isothermal (IS), neutrino (NE), and cold particle (CP)) with a Cyber 205 supercomputer at Purdue University. We then looked for clusters within the simulations, and compared their spatial distributions with that of Abell clusters.

In the simulations, we used 64^3 particles, positioned on a 128^3 cloud-in-cell (CIC) grid to maximize spatial resolution. The density data were smoothed by another application of the CIC algorithm to a 64^3 grid, with each cell ~ 24 Mpc on a side. Thus, the volume for each simulation was $(\sim 1536 \text{ Mpc})^3$. The initial conditions for the simulations were the power spectra for the three models

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considered, at $z = 2.5$, prior to which time collapse of density perturbations on scales of interest was linear. The models were then evolved gravitationally to the time $z = 0$, identified as the time that the slope of the mass two-point correlation function matched that observed for galaxies.

Each simulation volume was then searched for the grid points of highest mass density, which were considered analogous to Abell clusters in the Universe. Those points were selected that were above a mass density threshold which yielded the same number density of "pseudo-clusters" as that observed for the Abell clusters. For the percolation tests performed, each simulation was sampled with a volume of the same size and shape as that containing our Abell cluster sample.

This sample consists of 226 $R \geq 0$ clusters in the largely unobscured ($l > 30°$) portion of the sky, within $z < 0.085$. The sample is 85% complete in redshift measurements, and redshifts of unmeasured clusters were estimated by magnitudes of the tenth-brightest cluster galaxies. To make the Abell cluster data as directly comparable to the simulations as possible, these data were also smoothed with the CIC algorithm, to the same grid scale as the models. We used several tests on the different samples for $\Omega = 1.0$, $H = 50$ (and also $H = 75$, but the matches of models to observations were consistently worse than at $H = 50$). In Fig. 1, the two-point correlation functions of the four samples are shown. The Abell sample is quite strongly correlated for $r \sim 1.0$, much different from CP and IS, which have essentially $\xi = 0$ for $r > 0.8$, and even more different from NE, which shows significant anticorrelation near $r = 1$. The Abell cluster data has a $> 3\sigma$ "bump" in the $2.2 < r < 3.2$ range, also very different from the $\xi = 0$ of all the models in the same range.

Fig. 2 shows the results of one of our percolation tests, where the fraction of clusters identified as supercluster members is plotted as a function of the percolation parameter (b_p) used to define the superclusters. All the samples match well for b_p large, as nearly all the clusters are "connected" into superclusters, but the neutrino model has far too many clusters in superclusters at small b_p, and IS and CP have far too few in comparison to the Abell cluster sample.

Finally, Fig. 3 provides still another view of the structures present in the samples, through a multiplicity function analysis at $b_p = 0.7$. Almost half of the Abell clusters are found in superclusters of 10 or more members, while about 65% of clusters in each of the models are in smaller superclusters (2-10 member clusters). None of the models have more than 10^{-4} probability (χ^2 test) of being drawn from the same population as the Abell clusters, with these distributions.

We also looked at the CP model for $\Omega = 0.2$ (H had to be ≥ 100 to prevent conflict with the isotropy of the microwave background) and $\Omega = 0.5$ ($H \geq 50$). These simulations contained only slighty greater amounts of structure on larger scales, still disagreeing with the Abell case at the $> 3\sigma$ level in the correlation function and multiplicity function tests.

Thus, we conclude that the currently popular models for large-scale structure can not provide enough structure to match the observed distribution of Abell clusters. It is possible that incompleteness in the cluster sample contributes to the apparent large-scale structure. However, with the data currently available, some new model appears necessary, perhaps one employing cosmic strings to generate the required spectrum of very large-scale density perturbations (*e.g.*, Zel'dovich 1980).

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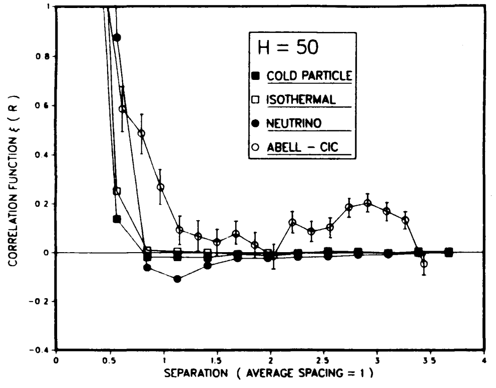

Figure 1 Two-point correlation functions for three simulations at $h_{100} = 0.50$, compared with $\xi(r)$ for the Abell clusters. Error bars on the Abell cluster curve reflect assumption of Poisson errors in numbers of pairs found in each separation bin. The scale for r is in terms of the average separation of nearest neighbors within the $R \geq 0$ Abell cluster sample, $r_{ave} \equiv \rho^{-1/3} = 42.5h_{100}^{-1}$ Mpc, where ρ is the average number density of the Abell clusters.

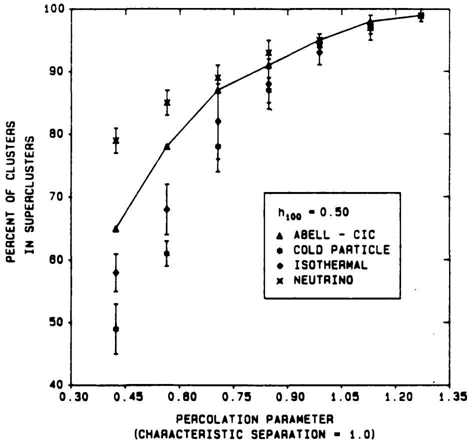

Figure 2 Percentage of pseudo-clusters in the models that were linked together into superclusters as a function of the maximum separation two pseudo-clusters could have and still be linked - the percolation parameter, b_p. Error bars represent the 1σ variation in four samples for each model. Observed function for the smoothed $R \geq 0$ Abell clusters sample is shown by the connected symbols.

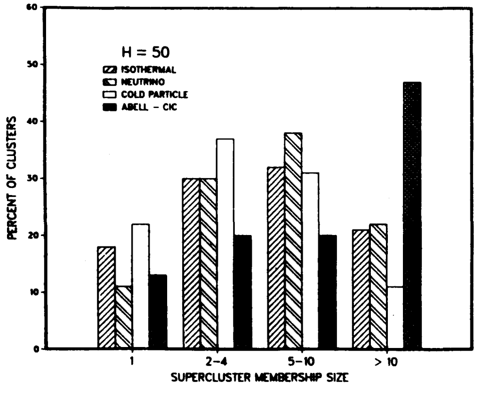

Figure 3 Average percentage of pseudo-clusters found in superclusters of various sizes in the models compared to superclusters found among the $R \geq 0$ Abell cluster sample population. Bins are number of clusters per supercluster, with a membership of "1" representing isolated clusters. The percolation parameter for the definition of a supercluster was $b_p = 71\%$ of the average nearest-neighbor separation of the Abell clusters, *i.e.*, for $h_{100} = 0.50$, $b_p = 60$ Mpc. Variations in the four samples of each of the models were roughly $\pm 9\%$ (one standard deviation) in the > 10 bin and $\pm 3\%$ in the other bins.

DISCUSSION

DEKEL: My feeling is that cosmic strings, which looked very promising at first as a way to explain the strong clustering of clusters, has become recently a theory which requires as much 'patching' as the other theories. For example, I don't think we understand why the cluster correlation function should be $\xi_{cc} \propto r^{-1.8}$ and of high amplitude. The loops about which clusters accrete don't seem to be distributed like 'beads along strings' as once thought, and the segments of infinite strings seem to be anticorrelated.

BATUSKI: I am disappointed to hear this. I had recently become quite excited about the possibility that cosmic strings could explain very large-scale structure.

ULMER: I doubt there is much effect, but I wonder how literally we should take the Abell Catalog given that some are superposition of line of sight clusters and that some clusters break up into unbound clumps when redshifts are measured.

BATUSKI: I also do not think that the effect is very large, in part because we have smoothed the Abell cluster data with the CIC algorithm, removing some of the details of the cluster distribution. Such superposition effects, as well as possible incompleteness of the $R \geq 0$ clusters with galactic latitude and redshift (even with the latitude and redshift limited sample we used to minimize the incompleteness), suggest that the Abell catalog does need observational refinement. These clusters are still the best available probes of the scales under consideration, however.