# NUMERICAL EXPERIMENTS ON GALAXY CLUSTERING

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## ABSTRACT

A study of the way observable clustering depends on expansion history is reported. Observable shapes that result from evolving otherwise identical systems are intercompared to show differences due to different expansion histories. Four cases are compared: non-expanding, $\Omega = 1$, and two open universes with 0.10 and 0.03 as final values of $\Omega$ There is remarkably little difference in observable forms for the expanding cases. The 0.03 universe expanded by a factor 500 during the experiment. This study is an example of the way numerical experiments can be used is studies of galaxy clustering.

## 1. INTRODUCTION

Numerical experiments yield configurations that look remarkably like the observed structure of galaxy clustering when started from fairly smooth initial conditions. Several groups have run calculations of this kind. Doroskevich and Shandarin (1983) and Efstathiou (1983) have reported this kind of work at this meeting. Their papers provide references to earlier work. A remarkable feature of all this work is that everyone gets structures that he says look a lot like the observed Universe even though the details of the calculations differ substantially. This suggests that structures like those observed are easy to get through simple dynamical processes based on gravitational forces. The observational properties that catch our attention do not depend much on details of the dynamics, the cosmological history, or boundary and initial conditions. This is reassuring from the standpoint of trying to simulate the Universe but it is distressing from the alternative point of view of trying to distinguish among various

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theoretical models. This situation might have been foreseen: the fact that many different theoretical models each gave some measure of agreement with observation already indicated that observations do not constrain the models very much. We need a uniqueness proof--but there seems to be no such thing in astronomy.

Numerical experiments seem to be a popular indoor sport, but what part can they play in helping toward an understanding of the physical processes that caused the Universe to look the way it does? Numerical experiments can be a keen analytical tool in showing precisely how different models or different initial or boundary conditions affect observable properties. This in turn can help to identify observational features that will provide some leverage on the key questions of what our Universe looked like at earlier times and of what physical processes dominated galaxy clustering. We need some qualitative guides before detailed quantitative studies can be of much use. Some steps in that direction are reported here. It turns out that some of the features we had hoped would produce significant observable differences actually produce very subtle--almost indistinguishable--effects.

Two matters of viewpoint are essential. (1) The notion of numerical experiments, and (2) Heavy reliance on direct comparison with observation.

(1) A numerical experiment is the closest analogue we have to a laboratory experiment in the dynamics of galaxies and larger systems. One tries to include as much of the essential physics as possible in a kind of laboratory setup (the computer program), in ways such that possible instrumental effects (numerical errors, grid effects, different boundary conditons) can be calibrated and controlled. A series of experiments is run in this environment, varying one parameter at a time to "pick the picture apart," to identify the important physical effects. The approach is the same as in laboratory physics--it is not theory in the conventional sense. A strength of the method lies in the intercomparison of results obtained in a systematic search of the parameter space. Instrumental effects affect the various experimental runs in much the same way so differences can safely be attributed to changes in the parameters.

(2) Three dimensional forms as complex as the Universe are difficult to visualize both in experimental results and in observations. It is safest to compare experimental results and observations directly at a level as close to the basic observational material as possible. The motion picture showing a three-dimensional representation of the observed Universe shown by Einasto (1983) at this conference was prepared as part of this effort. A film showing the experimental results presented in the same way will be shown as part of the presentation of this paper [1]. The film is a vital part of the paper. We stress that apparent similarity of observed and experimental structures is necessary for the experiments to be convincing. It is not sufficient. On the other hand, while more abstract summaries of the

observational data (e.g., correlation functions) can be difficult to interpret because of different boundary conditions in the experiment and in the real Universe, the visual comparison of the two kinds of results has an unambiguous immediacy.

## 2. THE EXPERIMENTAL METHOD

The basic experimental setup is described in a paper which we hope will soon be published (Miller 1981) to which we refer for details. We summarize it briefly.

An n-body system in which the motions of 100,000 particles are followed self-consistently as they move under forces generated by their own self-gravitation is the basic tool. Particles and forces have periodic boundary conditons in which the periodic cell partakes of the general (externally specified) expansion. The forces that act on individual particles are derived from potentials that are obtained by solving Poisson's equation on a grid, here 64 active grid points in each direction of a cartesian lattice. This technique is often referred to as a "Fourier method," but Fourier is only a computational trick to speed up the numerical solution of the Poisson equation, and it has nothing whatever to do with the match between the computation and the physics of the problem.

The paper mentioned describes some of the first results, which include several checks on the consistency and robustness of the results. The principal features found were (1) disturbances grow at the rate given by linear perturbation theory to an accuracy of 1-2% to clumping strengths greater than those in the present-day Universe with no evident saturation. (2) The dominant visual impression on watching the dynamical development in a motion picture is one of growing voids--of opening holes that sweep material before them and pile it up in a structure that looks like superclusters with huge voids.

## 3. DEPENDENCE OF OBSERVABLE CLUSTERING ON EXPANSION HISTORY

These experiments were all started from identical runs of pseudorandom numbers in the initial load. All particles were nearly at rest. They were given small initial velocities to suppress the dying mode of linear perturbation theory. Disturbances grow at the expected rates in all experiments. Motion pictures will be shown for the expanding cases. The forms are virtually identical at equal clumping strengths. "Snapshots" of these systems are rotated to show the three-dimensional forms at stages of equal clumping strength. The similarities are remarkable.

But the similarities are even more remarkable at microscopic levels (see accompanying figures). Little particle aggregates can be recognized in each of the configurations.

Forms seen at equal clumping strengths are similar for each of these three expansion histories. This implies that values of $\Omega$ are not easily determinable from particle locations. However, since the time-dependence of clumping strength depends on $\Omega$, there may well be $\Omega$-dependent information in the particle velocities.

A careful look shows slightly sharper clumps at $\Omega = 0.03$ than at $\Omega = 1$. This results from a nonlinear effect whose nature is clarified by the non-expanding (NE) experiment. Features are not as tightly clumped in the NE experiment as in any of the others. A study of the time-dependence of clumping strength shows the cause: disturbances at high wavenumber (small wavelength) start to grow and then stop in the NE case, while they continue to grow in the remaining experiments. Particle velocities build up in the NE experiment to where the Jeans instability is suppressed at short wavelengths. This is a characteristic nonlinear effect that appears at larger clumping strengths. In the expanding cases, redshifting of the velocities diminishes the effect until, at $\Omega = 0.03$, clumping can continue at short wavelengths, producing tighter clumps.

The use of identical starting conditions, with only the expansion history varying, is the key to the sharp result obtained.

Films shown with this presentation were produced at the NASA-Ames Research Center largely through the efforts of Dr. Bruce F. Smith. Dr. Smith has been an equal partner in the galactic dynamics program since its inception. Computations leading to these results were carried out at the Max Planck Institut fur Astrophysik, whose support is gratefully acknowledged. The writer has enjoyed the generous hospitality of the European Southern Observatory as joint visitor at ESO and MPA, where this work was done while on leave from The University of Chicago. This work was partially supported by Interchange No. NCA2-OR108-902 between NASA-Ames and the University of Chicago.

## REFERENCES

Doroskevich, A., and Shandarin, S. 1983, this volume, p.387.

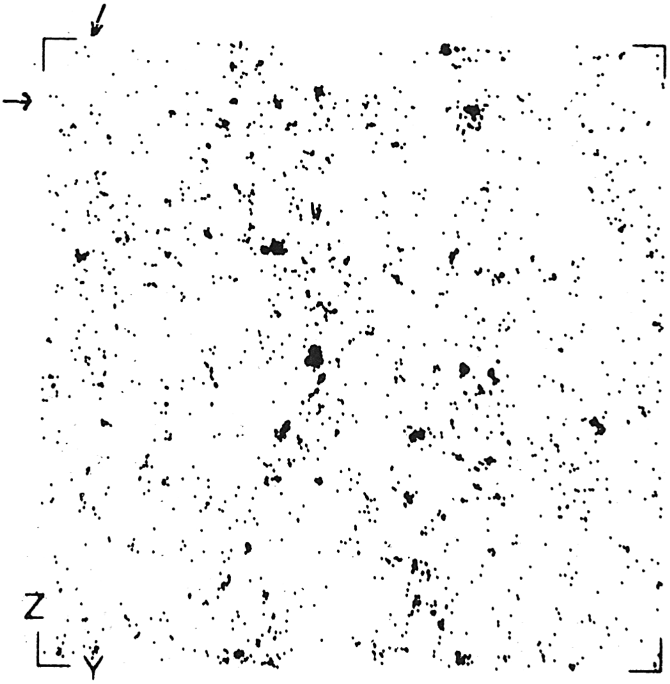
Efstathiou, G. 1983, this volume, p. 393.

Einasto, J. 1983, this volume.

Miller, R. H. 1981, Astrophys. Journ.

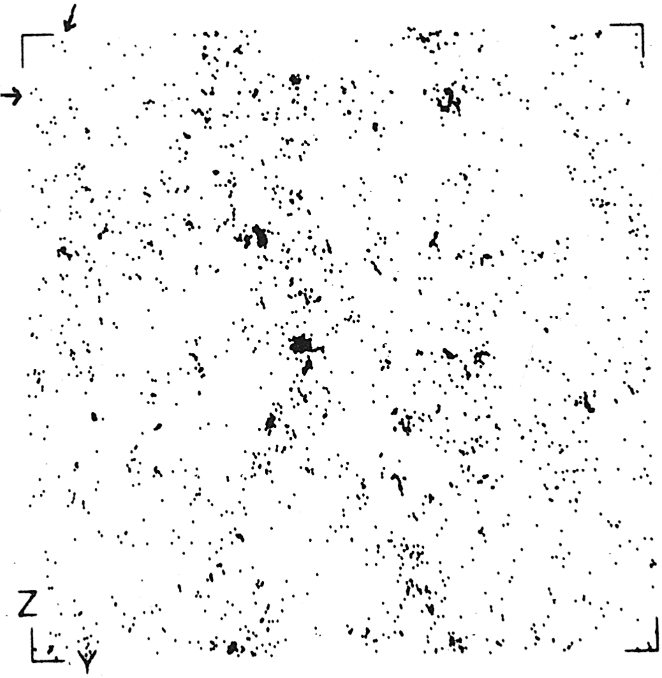
## FOOTNOTE

(1) Prints of these and other films are available at cost. Write Astronomy Department, University of Chicago, requesting ordering information for Miller's films.



One view of the configurations from each of two different experiments at the same clumping strength. The upper figure shows the $\Omega = 1$ experiment at an expansion of 35 past the initial condition. The lower figure shows the same view for the $\Omega = 0.03$ experiment at an expansion of 500 past the initial condition.

Notice the nearly identical particle aggregates like the marked triples in the upper left-hand corner or the pair near the upper right-hand corner brackets. Many more such associations can easily be found. Clumps are somewhat tighter in the $\Omega = 0.03$ experiment.



## Discussion

*Efstathiou:* I object to the statement that the two-point correlation function does not tell you much about the clustering pattern. The numerical models with $\Omega = 1$ and $n = 0$ give a correlation function which is too steep compared to the observations. The disagreement is more apparent if $\Omega << 1$ and $n = 0$.

*Miller:* I said correlation functions are not sensitive to the features that catch the eye in the observed clustering. They do not describe the filamentary pattern that is so striking in the observations. I agree with you that they provide one statistic that is useful in numerical comparisons with observed clustering.

*Dekel:* What is the cell size in your simulations, in comparison with the size of the clusters?

*Miller:* Clusters typically have diameters of at least 8 - 12 of the cells used for the potential calculation. We don't trust features only 1 - 2 cells across.

*Bhavsar:* One must remember when comparing the N-body simulations with observations that we are comparing the mass distributions of the simulations with the light distribution of the real universe. The extent to which light is a good tracer of mass will depend on the uniformity of the mass-to-light ratio.

*Miller:* Good point. Our motion pictures and analyses trace the active mass distribution. This need not be the same as the observable luminosity distribution. They do, however, trace the stuff that controls the dynamics.