THE DISTRIBUTION OF THE GALAXIES

This topical volume examines one of the leading problems in astronomy today – how galaxies cluster in our Universe. Many observational surveys and theoretical projects are currently underway to understand the distribution of galaxies. This is the first book to describe gravitational theory, computer simulations, and observations related to galaxy distribution functions (a general method for measuring the clustering and velocities of galaxies). It embeds distribution functions in a broader astronomical context, including other exciting contemporary topics such as correlation functions, fractals, bound clusters, topology, percolation, and minimal spanning trees.

Key results are derived and the necessary gravitational physics provided to ensure the book is self-contained. And throughout the book, theory, computer simulation, and observation are carefully interwoven and critically compared. The book also shows how future observations can test the theoretical models for the evolution of galaxy clustering at earlier times in our Universe.

This clear and authoritative volume is written at a level suitable for graduate students and will be of key interest to astronomers, cosmologists, physicists, and applied statisticians.

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Gravitational Clustering in Cosmology

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Prologue

Despite appearances, it is not the Epilogue, but the Prologue that is often left for last. Only after seeing what is done, can one acknowledge and apologize. My main acknowledgments are to many students and collaborators, for they have taught me much. My apologies are to those colleagues who may not find enough of their own results in the pages still ahead. For them I can only echo Longfellow that "Art is long and Time is fleeting." The subject of large-scale structure in the universe, of which the distribution of the galaxies represents only a part, has burgeoned beyond all previous bounds as the new millennium approaches. Driven as much by the scope and depth of its questions as by new streams of data from the depths of time, there is an increasing excitement that fundamental answers are almost in reach. And there will be no stopping until they are found.

On the timescales of the physical processes we are about to consider, millennia count for very little. But on the timescale of our own understanding, years, decades, and certainly centuries have changed the whole conceptual structure surrounding our views. This may happen again when the role of dark matter becomes more transparent.

Meanwhile, this monograph is really no more than an extended essay on aspects of galaxy clustering that I've found especially interesting. It emphasizes galaxy distribution and correlation functions – but mostly distribution functions because correlations have already been discussed widely elsewhere. Besides, distribution functions contain more convenient descriptions of more information.

Both these statistics are embedded here in a broader context, but their main virtue is that, of all descriptions so far, correlations and distributions can be related most directly to physical theories of gravitational clustering. Even for gravitational clustering, I have emphasized the simplest and most fundamental problem: how gravitating point masses cluster self-consistently within the background of an expanding universe. Three general approaches – statistical thermodynamics, computer N-body experiments, and astronomical observations – all give consistent results, and all are discussed here in detail. The observational agreement suggests that this cosmological many-body problem will remain a useful and basic aspect for understanding galaxy clustering, whatever detailed scenario produced it. And we really need to understand clustering by the known gravitational forces of the galaxies alone, before adding more speculative contributions.

The cosmological many-body problem, moreover, is endlessly fascinating in its own right. Much has been learned about it since Newton's first qualitative discussion, but much more remains for future discovery. Part of this fascination comes from its inherent and essential nonlinearity. Its statistical thermodynamics hints at a deeper theory. Computer simulations can check these theories and prevent them from going too far astray. We have just begun to explore the theory of systems with ranges of masses and different initial conditions. Important new problems are easy to find.

To begin, I have sketched the historical background, from Babylonian myths until 1970. Our subject started slowly and for centuries lay well outside the mainstreams of astronomy. Nevertheless it made quiet progress, and I've selected some milestones with the hindsights of history. These lead, in Part II, to a brief general review of the main descriptions of galaxy clustering; each has its weakness and all have some virtue. Thus the first third of the book provides an overall introduction.

Next, the general theme of gravity takes over. Part III discusses its relation to correlation functions in the context of the cosmological many-body problem and reviews several topics of recent interest along with a sketch of computer simulation techniques and results. This ends with a brief description of observations. Naturally there is some repetition of the earlier introduction. Although most discussions are self-contained, my earlier book *Gravitational Physics of Stellar and Galactic Systems* (GPSGS) sometimes extends them.

In the book's second half, I discuss distribution functions for galaxy positions and peculiar velocities and how they evolve. These are the generalizations, for the cosmological many-body system, of the Poisson and Maxwell–Boltzmann distributions in a perfect gas.

Distribution functions may be less familiar than correlations and other descriptions of clustering. So I've started by summarizing their mathematical properties that are especially useful for our exploration. Then the cosmic energy equation provides a dynamical link to the cosmological distributions. Like most complex dynamics, this link is easier to follow in the linear regime of fairly weak clustering. To examine the observed range of nonlinear clustering, it helps to develop the statistical thermodynamic theory. After reviewing thermodynamics, we apply it to derive the spatial and velocity distribution functions of the cosmological many-body problem. Then we follow their quasi-equilibrium evolution as the universe expands. There are no free parameters in this theory – after all it's just gravity.

Initially the applicability of gravitational thermodynamics to the cosmological many-body problem was rather surprising. To paraphrase Mark Twain, it gratified some astrophysicists and astonished the rest. This apparent impasse arose because thermodynamics is essentially an equilibrium theory, whereas gravitational clustering is a manifestly nonequilibrium phenomenon. What this seeming contradiction failed to appreciate, however, is that under a wide range of conditions, cosmological many-body clustering can evolve through a sequence of equilibrium states. This quasi-equilibrium evolution enables thermodynamics to provide a very good approximation.

Computer N-body experiments, which directly integrate the mutual orbits of many galaxies in an expanding universe, show that gravitational thermodynamics does indeed apply for a variety of initial conditions in different universes. Part V describes these tests. They also determine the conditions under which gravitational thermodynamics fails to give a good description of clustering and the reasons for this failure. We still need more diverse computer experiments to explore the whole range of the theory.

Naturally, the grandest experiment of all is the analog computer in the sky. In our own Universe, the initial conditions and detailed evolution of galaxy clustering remain controversial and highly uncertain. Here the cosmological many-body problem is perhaps the simplest model of this process. It assumes, in this application, that when the galaxies clustered most of the dark matter that affected their orbits was associated with the individual galaxies, either inside them or in halos around them. Thus galaxies acting effectively as point masses dominated the clustering. Other types of models are dominated by vast quantities of unobserved dark matter whose growing large-scale inhomogeneities determine the clustering, and galaxies merely go along for the ride. More than thirty years of increasingly ingenious and sensitive searching have failed to reveal the specific forms of dark matter these other models require.

As a model for galaxy clustering, the cosmological many-body theory describes the observed galaxy distribution functions remarkably well, as Part VI discusses. This suggests that the clustering effects of intergalactic dark matter are small, or that they have contrived to mimic many-body clustering. Consistency between models and observations is a good sign, but it is not proof. History has shown that our Universe is complex, and so a final decision here will have to await further developments.

Part VII introduces some aspects of clustering that may unfold in the future. These generally involve more complicated modeling than simple gravitational clustering, but such models are necessary to understand many detailed astrophysical consequences, including galaxy formation itself. No one doubts a connection between galaxy formation and clustering, but the nature and strength of this link is still so uncertain that at present I think it wise – or at least expedient – to consider clustering as a separate problem. The formation of galaxies (not a particularly well-defined process) sets the initial conditions for their clustering, which I assume are subsumed by those studied here. If not, we will have to modify them. Optimistically there is hope that eventually the fluctuations of the cosmic microwave background will lead to a clear solution of the origins of clustering.

The work of determining galaxy distribution functions from observations, numerical simulations, and gravitational theory in which I've participated has benefitted greatly from discussions with dozens of astronomers, physicists, and mathematicians. Most of the results have come from many collaborations over the years and over the world. Although some collaborators were officially called students, they quickly outgrew any secondary role and became equal participants. In a young subject, everyone rapidly reaches frontiers. It is adventurous and all great fun. For these collaborations, I especially thank Sverre Aarseth, H. M. Antia, Kumar Chitre, Paul Coleman, Phil Crane, Naresh Dadhich, James Edgar, Fan Fang, Andrew Hamilton, Shirin Haque-Copliah, Shogo Inagaki, Makoto Itoh, Sanjay Jain, Leo Krzewina, Ofer Lahav, Sunil Maharaj, Hojung Mo, Somak Raychaudhury, Yoel Rephaeli, Ravi Sheth, Trinh Thuan, and David Valls-Gabaud. In addition, I am happy to thank Ian Du Quesnay for helpful advice on the Greek philosophers; Arthur Haberman, E. R. Harrison, Ofer Lahav, Morton Roberts, and Mark Whittle for their detailed comments on substantial parts of the manuscript; and especially David Valls-Gabaud for reading and commenting on the entire manuscript. In the University of Cambridge I am very grateful to Pat Cassidy at Jesus College and to Judith Moss at the Institute of Astronomy for their exceptionally fine work, which converted the manuscript with its occasionally complicated equations into a form directly suitable for the printers. And both Jesus College and the Institute of Astronomy provided, as they have for many years, conditions especially conducive to creative research. I am glad to thank George Kessler at NRAO for producing many diagrams with an ideal blend of modern electronics and old-fashioned skill. Richard Sword's enthusiastic and interactive artistry designed the book's cover. It has also been a pleasure, as I expected it would be, to work with Simon Mitton, Adam Black, and the staff of the Cambridge University Press.