Chapter 5

Epilogue

This thesis has investigated the problem of galaxy bias from the point of view of hydrodynamic simulations, making a number of predictions about the relative clustering of different types of galaxies and the evolution of that clustering with redshift; I have also tested some of these predictions using the Las Campanas Redshift Survey (LCRS; Shectman et al. 1996). In this Epilogue, I discuss the (mostly future) prospects of developing models of galaxy formation and testing their predictions.

1. Current and Future Simulations

I will first briefly mention the future of the predictions themselves. Improved versions of the hydrodynamic simulations used here are already being run, at 1.5 times the current resolution, and continuing improvement of the algorithms and hardware ensure steady progress in this area. Since the rate of cooling is proportional to $p^2$, if the simulation cannot resolve gas clumping it may be systematically underestimating star-formation rates, and it is important to test whether such effects are affecting our results. In addition, other approaches to cosmological gasdynamics are currently being vigorously pursued. As mentioned in the Introduction, Katz, Hernquist, & Weinberg (1992; 1998) have performed Smoothed Particle Hydrodynamics (SPH) simulations of galaxy formation using $64^3$ particles, using criteria for star-formation quite similar to those used in Chapters 2 and 3. As part of the VIRGO consortium, Pearce et al. (1999) have performed $128^3$ SPH simulations and have examined the clustering evolution of galaxies. Other SPH codes, such as the Parallel TreeSPH code of Davé, Dubinski, & Hernquist (1997), will soon be able to integrate $128^3$ particles to $z = 0$ and, if outfitted with star-formation criteria similar to those used here, would provide an alternative test of some of the effects we found in Chapters 2 and 3. Similarly, the Adaptive Mesh Refinement (AMR) hydrodynamic codes, which have been used to study the formation of individual galaxies in a cosmological context.
by Bryan & Kepner (1998), can in principle be adjusted to follow any number of galaxies (though not at as high resolution) and implement star-formation in the manner used here.

In the meantime, I am currently working on using the results of this thesis to develop an particle-particle/particle-mesh (P³M) N-body code which incorporates the patterns of star-formation observed in the hydrodynamic simulations (e.g. the dependencies on temperature and density). The idea is to see if the gross properties of star-formation in the simulations, such as the sharp decline at low redshifts and the shift of star-formation from dense regions to the field, can be reproduced by making star-formation proportional to a simple function of density and temperature. If such a simple model were possible, it would also one to investigate larger volumes in both parameter and real space, as well as to create realistic mock catalogs of large redshift surveys for comparison with observation.

Semi-analytic models which are harnessed to N-body simulations continue to benefit from increases in computing power as well. The VIRGO Consortium is currently running the largest simulations along these lines, using a P³M code with 256³ particles and a softening length of \( \sim 30 \, h^{-1} \) kpc (Couchman, Thomas, & Pearce 1995; Pearce & Couchman 1997; Jenkins et al. 1998; Benson et al. 1999; Kauffmann et al. 1999). The virtue of the semi-analytic models is their ability to probe large volumes of parameter space quickly, and they should continue to be of use in understanding the consequences of new ideas about the nature of galaxy formation, such as the burst model of Somerville, Primack & Faber 1998. They are also flexible enough to incorporate dependence on the local IGM temperature, as measured by the local galaxy velocity dispersion, and its effect on infall, along the lines of Oh & Ostriker (1999), though none of the simulations include these effects yet.

Finally, the approach of Narayanan & Weinberg (1999) is to use assumptions about the bias of local galaxies and about cosmological parameters to reconstruct initial conditions which, when run forward to \( z = 0 \), correspond to the local galaxy density field. One can test different assumptions by checking to see how well each choice can reproduce the observed galaxies at \( z = 0 \). How dependent the results are on the particular method of reconstructing the initial conditions is not yet known. It will likely be useful in the future to use alternative methods of reconstruction, for instance the Perturbative Least Action approach of Goldberg & Spergel (1999), which may also be able to probe more nonlinear scales, in order to explore this issue.

As I found in Chapter 4, clearly a necessary step for a comparison to observations (once the underlying physics in the simulations is understood) is to observe these simulations in the same way as the real universe is observed. While it is important to attempt to understand the theoretical results on their own terms (as I do in Chapter 2 and for most of Chapter 3), it is necessary to understand the observational complications to observing the
interesting properties in each simulations, including such nasty details as surface brightness selection, incomplete sampling, etc. In particular, the simulation of observations is the playing field on which different theoretical models of galaxy formation will compete.

2. Measuring Bias in the Universe

Tests of the predictions from all of these simulations will be made using the masses of data being collected in large-angle redshift surveys such as the Sloan Digital Sky Survey (SDSS; Gunn & Weinberg 1995, the Two-degree Field (2dF; Colless 1998), as well as the angular Two-Micron All-Sky Survey (2MASS; Beichman et al. 1998). Also important are deeper, narrower surveys which can evaluate the nature of galaxies and their clustering at high redshift, such as: the Canada-France Redshift Survey (Lilly et al. 1995); the survey of Lyman-break objects at $z \sim 3$ or greater (Steidel et al. 1998); sub-millimeter observations which observe high-redshift star-forming galaxies (Blain et al. 1999; Lilly et al. 1999); and the Deep Extragalactic Evolutionary Probe (DEEP; Davis & Faber 1998), which aspires to observe $\sim 30,000$ galaxies in the vicinity of $z \sim 1$.

A number of approaches to measuring bias in these new surveys have been proposed. The main difficulty is that the usual probe of any gravity field, the peculiar velocities of objects falling through that field, does not contain enough information in this case to determine the amplitude of mass density fluctuations. This insufficiency occurs because the amplitude of velocities are proportional to $\beta \equiv \Omega_0^{0.6} \sigma / \sigma_g$, where $\sigma$ is the amplitude of mass fluctuations, $\sigma_g$ is the amplitude of galaxy fluctuations, and $\Omega_0$ is the currently uncertain density parameter of the universe (see Strauss & Willick 1995 for a complete summary of this subject). Thus, measuring a complementary combinations of $\Omega$ and $\sigma$ can put constraints on the bias of galaxies, since, in combination with velocity field measurements and measurements of $\sigma_g$, these three measurements can determine $\Omega_0$, $\sigma$, and $b \equiv \sigma_g / \sigma$.

An example of this is the observation of the evolution of the mass function of clusters with redshift, which can determine $\Omega_0$ (Fan, Bahcall, & Cen 1997; Gross et al. 1997). Other methods of determining $\Omega_0$, such as using the baryon fraction in clusters in combination with estimates of the baryon fraction of the universe, can serve the same purpose (Evrard 1990; Cen & Ostriker 1993; White et al. 1993; Lubin et al. 1996). Similarly, schemes to combine many observations, such as the Cosmic Microwave Background, Supernovae Ia observations at high redshift, weak lensing, etc., can constrain bias, along with a number of other cosmological parameters (Eisenstein, Hu, & Tegmark 1999). I cannot discuss all possible ways of constraining all possible parameters in the space here. Thus, in this section, I will restrict myself to discussing the approaches to bias and galaxy formation which use observations of galaxies, their velocities, and their clustering properties.
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One approach is to assume that one knows some property of the mass fluctuations which one can then compare to the galaxy fluctuations; the comparison will reveal something about the nature of the relationship between the two density fields. A straightforward example is given by Dekel (1998), who suggests assuming based on N-body simulations that the density distribution function of the mass is log-normal; the extent to which the observed galaxy distribution differs from log-normal then reveals the effects of bias (although this method would probably not provide constraints on the amplitude of bias but on its degree of nonlinearity).

A number of investigators instead assume only that the initial conditions are Gaussian and structure formation proceeds according to gravitational instability, assumptions which are likely more robust than that given in the above paragraph. Using perturbation theory one can then predict the relationship in the mildly nonlinear regime between the second moment of the density field (expressed as the variance, the power spectrum, or the correlation function) and the third moments of the mass density field (expressed as the skewness, the bispectrum, or the three-point correlation function). Because of the distinctive nature of the nongaussianity arising from gravitational instability, it turns out that comparing these predictions to observations of the moments of the galaxy density field can constrain the nature of bias, especially if the shape-dependence of the three-point statistics is exploited. Variants on this approach have been developed by Frieman & Gaztañaga (1999), who use the angular three-point correlation function, Buchalter & Kamionkowski (1999), who use the redshift-space three-point correlation function, Verde et al. (1998), who use the redshift-space bispectrum, and Szapudi (1998), who uses cumulant correlators instead of the moments of the density fields. As noted in the introduction, the application of this method in Frieman & Gaztañaga (1999) to the APM galaxies finds little evidence for bias in the galaxy density field on scales greater than about ~ 10 h⁻¹ Mpc. These tests of bias will become ever more powerful as new angular and redshift surveys, such as SDSS, 2dF, and 2MASS, are completed.

In a similar way, looking at velocity fields in the mildly nonlinear regime can also break the degeneracy between Ω and b. For instance, a number of authors have pointed out that the nature of the transition of redshift-space distortions from the linear to the nonlinear regimes encodes information about the value of σ independent of Ω₀ (Cole, Fisher, & Weinberg 1994). Similarly, while the relationship between density and velocity fields in neither the linear nor the nonlinear regime can break the degeneracy between Ω and b, the relationship in the mildly nonlinear regime may be able to (Bernardeau et al. 1997; Chodorowski 1999; Juszkiewicz, Springel, & Durrer 1999). Unfortunately, these methods tend to require velocity field data much better than is currently available or will be available in the near future.
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Instead of using the velocity fields as tracers of mass, it is also possible to use weak gravitational lensing as a probe of the density field. A number of investigations have shown that large-scale weak lensing maps can provide information about the mass power spectrum and bias (Kaiser 1998a; Refregier et al. 1998; van Waerbeke 1998). On the other hand, it is also possible to look at individual objects, such as clusters and superclusters, and compare these maps to galaxy maps and evaluate how mass is related to light in a particular spot in the universe. Such studies can evaluate how well the light traces the mass in detail; an interesting example of this kind is the weak-lensing map of a supercluster measured by Kaiser (1998b), which shows that the supercluster mass is traced well by the early-type galaxies. There is an increasing number of weak lensing maps of clusters, and they should yield insight into how mass and light are related to each other.

Most of these methods, except for the last, have treated galaxies as objects with just two properties: position and velocity. However, if the question one is interested in is not just, “How do I fix my galaxy power spectrum so it matches the mass power spectrum?”, but “How did all of these galaxies form, anyway?”, there are many more interesting properties of galaxies to consider. In particular, the hydrodynamic simulations in this thesis, as well as other models of galaxy formation, do make predictions about the nature of star-formation in galaxies and its relationship to the cosmic environment as well as the relative clustering of different galaxy types. By testing some of these predictions, one can perhaps probe the nature of galaxy formation in a more revealing way than one can by measuring the bias relative to the dark matter.

A good example is the prediction of the relationship between different galaxy types. The hydrodynamic simulations of Chapter 2 predict that there should be considerable scatter in the relationship between old and young galaxies. In fact, as I found in Chapter 4, there appears to be rather little scatter (a correlation coefficient $r \sim 0.9-0.95$), at least on scales of tens of megaparsecs in the Las Campanas Redshift Survey (LCRS). Naturally, there are problems in interpretation. The hydrodynamic simulations cannot truly resolve galaxies from each other in the dense regions, let alone resolve the structure inside of galaxies. Thus, we weight the galaxy density field in the simulations by stellar mass, and we crudely map galaxy ages to galaxy morphologies. It is likely that one of these procedures (or some combination of the two) is causing a mismatch with observations. For instance, it could simply be that the youngest galaxies are not included among the $R$-selected LCRS galaxies. Alternatively, there could be something fundamentally wrong with the model for forming galaxies in the simulations. It is too early to tell which of these possibilities is the case. More tests need to be done, such as using a survey with a wider range of galaxy types, one which includes low surface brightness galaxies, probing smaller scales, and perhaps weighting the galaxy fields by star-formation rate (as measured by the [OIII] equivalent width, for example) in order to consider that quantity directly, as the simulations do. On
the theoretical side, improving resolution will help resolve some of these issues, as well. It could be informative to use smaller boxes and thus probe higher resolution in order to evaluate the dependence of the star-formation rate on resolution. The main point is that analyzing in detail the nature of morphological segregation on large scales has the power to constrain models of galaxy formation.

There are other predictions of these simulations which should be addressed, as well. For instance, it may be possible to test whether indeed star-formation declines in regions where the gas has a high ambient temperature. First, one can consider dense clusters of galaxies. It is well-known that galaxy morphology depends on density inside clusters, as well as on radius. In the case of spherical, smooth clusters, density and radius are equivalent. However, since many clusters are not perfectly spherical and also contain substructure, there is some controversy as whether density or radius correlates better with morphology (Whitmore, Gilmore, & Jones 1993). Since many clusters now have had X-ray maps taken of them, it may be worth examining as an alternative the dependence of galaxy morphology (or color) on surface density and X-ray emission. If there was a dependence on X-ray emission independent of the local density, it could indicate that the gas temperature is playing a determining role in the properties of the galaxies.

Another way of asking the same question in cases where X-ray data is unavailable is to examine the star formation rate inside compact groups of galaxies. In these groups, the velocity dispersion is low but the galaxy density is as high as in high velocity dispersion clusters. Again, this result could show whether star-formation depends on local temperature independent of the local density. Work using Hickson Compact Groups has had promising results along these lines, indicating that higher velocity dispersion groups have weaker star-formation (Severgnini & Saracco 1999).

Finally, as discussed in detail in Chapter 3, there is the possibility of observing the redshift dependence of the clustering of star-formation found in the hydrodynamic simulations. Deep redshift surveys such as the SDSS and 2dF may be able to detect the first traces of an evolution in the clustering of star-formation; deeper, narrower surveys such as DEEP may be able to do a better job. As described in Chapter 3, one may also be able to constrain some of these processes by using photometric estimates of both redshift and galaxy type in the photometric catalog of the SDSS. Similarly, the predictions of various models of galaxy formation will benefit from a better understanding of the nature of the Butcher-Oemler (1978; 1984) effect by using the clusters found in these surveys, particularly the Bright Red Galaxy catalog of the SDSS, which will reach redshift 0.5.

In conclusion, the problem of the bias of the galaxy density field relative to the mass may be intimately tied to the nature of galaxy formation. Therefore, in addition to being able to detect the effects of bias on large scale structure by analyzing the positions
and velocities of galaxies, the images and spectra from these surveys contain far more
information than is expressed in the galaxy density field, and can themselves constrain the
nature of galaxy formation, and, by extension, bias.

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