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Cosmological Simulations of Galaxy Formation
Including Hydrodynamics

by

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B.S. (Virginia Polytechnic Institute & State University) 1988
M.A. (University of California at Berkeley) 1990

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Committee in Charge

Professor Marc Davis, Chair
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Abstract

Cosmological Simulations of Galaxy Formation
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The formation of galaxies in hierarchical cosmogonies is studied using high resolution N-body simulations. The equations of gravity and hydrodynamics are evolved for two particle fluids: a pressureless dark matter component and a dissipational baryonic component. The collapse of structure is followed self-consistently from Mpc scale filamentary structures to kpc scale galactic objects.

The simulated galaxy population has sizes, masses, and abundances in the range of those for real galaxies. A large fraction of these objects show rotationally supported disk structures. This is the first demonstration that disk formation is a natural consequence of cosmological collapse. Isolated galaxies generally grow through steady mass accretion while objects in clustered regions are more likely to undergo mergers. Galactic disks form via discrete accretion of relatively large gas clouds and viscous transport of angular momentum to the inner regions. The formation era is consistent with high redshift observations and has a peak rate near redshift 3.

Galaxies collapse as segments of filaments and then flow along the filaments toward intersections. The formation of groups and clusters of galaxies is dominated by radial, directed infall which will increase the relaxation timescales as well as the incidence of merging, tidal disruption, and gas stripping. In this specific region, biases in both the spatial and kinematic distributions of galaxies relative to the dark matter are found. Virial mass estimates give results a factor of two to three lower than the true value. However, finer modelling of the stellar fluid within galaxies will be required before these findings can be generalized.

A didactic discussion of smoothed particle hydrodynamics (SPH) is presented along with several computational tests. Density estimation is shown to be sensitive to the resolution of SPH parameter choices and can greatly affect the physical results. Initial work on the self-similar spherical accretion problem indicates the general method is sound, but further work is required to search for optimal parameter sets. Tests of several galaxy identification schemes within simulations show that SPH methods are necessary for tracing galaxies through clustering and that the phenomenon of velocity bias has not yet been convincingly demonstrated.

Chair Date

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Chapter 1 – Introduction

And word by word they handed down the light that shines today. And those who came at first to scoff, remained behind to pray.
– Alan Parsons Project, *Ammonia Avenue*

stronomy is a curiosity driven endeavor. Its simple motivation is captured in the questions “What is it?”, “How is it structured?”, and “Where did it come from?”. The puzzle is more enticing because for most observations the only data is the light transmitted to Earth. One only gets to examine the information carried in electro-magnetic radiation and is not able to handle, manipulate, or perform experiments on the objects under study. The intellectual pursuit must provide the impetus because the knowledge gained serves mainly to stretch the imagination and has little chance of practical value in everyday life. In many ways, it is a science with a philosophical bent: astronomers are trained to pose questions and search for answers, with the answers themselves being the reward.

One of the fundamental problems is galaxy formation. Galaxies are one of the elemental forms of structure. In grand context, they are the basic unit of large scale structure in the universe. Closer to home, galaxies are the characteristic assemblages of smaller structures such as stars, clusters of stars, interstellar gas, and molecular clouds. It is natural to ponder how galaxies formed.

Two viewpoints on the question can be advanced. The first view considers individual galaxy formation: how does a cloud of matter collapse into the observed structures of a spiral, elliptical, lenticular, or irregular galaxy with the corresponding distribution of components? The second view is concerned with global structure: what cosmological framework can form galaxies with the observed spatial distribution, velocity fields, abundances, clustering properties, et cetera? Each form of the question leads to immense opportunities for study and the problem of galaxy formation sits at the confluence of these two huge streams of research.

Each stream is incomplete without the other. It is not sufficient for a cosmogony to specify only the sites of galaxy formation, it must also demonstrate that galaxies like those observed can form in those sites. Likewise, creating beautiful galaxies in isolation becomes meaningful when one can show that the necessary conditions will arise in the general universe. It is the goal of this thesis to advance some modest step along the cross integration of these two streams.

By examining the overlap region, one cannot hope to cover the depth of either topic. The main concern is for the larger scale aspects of galaxies and the smaller scale aspects of cosmology. The paragraphs below will discuss only the topics most relevant to the problem at hand.

1.1 Galaxies

In constructing a theory for the formation of galaxies, the number of observations one would like to satisfy is immense. The basic shapes of galaxies are combinations of thin disk and ellipsoidal bulge components. Disk sizes are typically several hundred pc thick and a few tens of kpc in diameter while elliptical structures generally range from kpc to 10 kpc scales. A variety of galaxy eccentricities can be noted including dwarf objects, cD ellipticals, warps, rings, and tidal tails. Characteristic masses and luminosities are around 10^{12} $M_\odot$ and 10^{11} $L_\odot$ with several orders of magnitude variation.

Beyond the gross characteristics is the detailed internal structure. Measurements of radial luminosity profiles show exponential disks and de Vaucouleur $r^{1/4}$ profiles for elliptical components. The outer rotation curves of spiral galaxies are flat, indicating a profile of total mass proportional to radius. Ellipticals are not rotationally supported, but have their shapes determined by triaxial velocity dispersions. Significant differences in age and metallicity between components are also found.

The group properties of galaxies give further constraints. The luminosity function is fit by a Schechter form, with a power law at low luminosities and an exponential cutoff at the high end. Spirals dominate the population in the field, but are found at a reduced fraction in clustered regions. The rotation velocity of spiral galaxies is empirically related to luminosity as described by the Tully–Fisher relation. Similarly for ellipticals, the Faber–Jackson relation correlates luminosity with central velocity dispersion.

The above paragraphs can only give a flavor for the wide variety of observations to address. Details and other results can be found in lengthy reviews of the subject (e.g., Silk & Wyse 1993; Gilmore, Wyse, & Kuijken 1989; Efstathiou & Silk 1983). The same references plus White and Frenk (1991) will also serve to expand on the brief review of theory presented below.

The basic framework for galaxy formation theory is that of gravitational collapse. In the collisionless case, star formation is assumed to occur early in the process and the resulting structures are compared with the old populations found in ellipticals and the bulges of spirals. Though two body relaxation is negligible for galactic systems, fluctuations in the potential during collapse leads to a process of violent relaxation that mixes orbits in phase space (Lynden-Bell 1967). For the final steady state, triaxial velocity dispersions imply the existence of a third integral beyond the conservation of energy and angular momentum. The possibility that galaxy mergers are the dominant process for elliptical formation has also been raised, but mostly in connection with simulations (discussed below).

Dissipational collapse is envisioned to form spiral galaxies and many of the dominant ideas are outlined by White and Rees (1978). Cooling by radiative processes allows the gas to dissipate thermal pressure support. The mass scales where cooling is efficient determines the characteristic mass scale of galaxies (Silk 1977; Rees & Ostriker 1977). Rotation in the initial cloud slows the collapse in the plane perpendicular to the angular momentum vector and naturally leads to flattened disks. A dark collisionless component is assumed in addition to the gaseous component to account for the flat rotation curves of the final object. The differences in ages and metallicities of the bulge and disk populations is accounted for by separate episodes of star formation; the first occurs during collapse and enriches the metal content of the interstellar material while the second episode happens after the disk forms (Eggen, Lynden-Bell, & Sandage 1962). Assuming that the dark halo and the gas initially had the same angular momentum leads to the conclusion that the disks have collapsed by a factor of order ten relative to the halos (Fall & Efstathiou 1980). Significant modifications to this picture can occur when considering the energy injected from supernova explosions and the effects of a background ionizing radiation field.

Many tests of these ideas have been pursued via N-body simulations. Collisionless simulations are able to reproduce elliptical galaxy profiles with systems that are initially flattened and slowly rotating (Aarseth & Binney 1978). Violent relaxation does not sphericalize the systems, requiring a third integral. The angular momentum induced by tidal torques of neighboring perturbations gives low dimensionless spin parameters of $\lambda \approx 0.07$ with $\lambda = J|E|^{1/2}G^{-1}M^{-5/2}$ and J is the angular momentum, E is the total energy, M is the mass (Efstathiou & Jones 1979). Such values of the spin parameter, when combined with the idea of a dark halo about spiral galaxies, predict the order of magnitude collapse for disks and reconcile the collapse time of a disk with the age of the universe (Fall & Efstathiou 1980).

The most detailed spiral galaxy formation simulations are those by Katz and Gunn (1991) and Katz (1992). Their simulations included both dark matter and baryonic fluids, the physics of gravity, hydrodynamics, and heating and cooling processes, plus an algorithm to model star formation with feedback. The simulated galaxies they produced had thin disks, stellar spheroids, exponential surface mass density profiles, and flat rotation curves. To the resolution of their model, results were consistent with the basic scenario outlined above.

Assuming disks are the natural result of a collapse, one might suppose that ellipticals form by the merging of disk components. A recent review article by Barnes and Hernquist (1992) covers the details of these arguments (see also Wielen 1990). The simulations find that the merger hypothesis generally works well and estimates of the fraction of ellipticals formed by mergers range from some to most. Incomplete violent relaxation allows the centers and outskirts of merger remnants to be composed mostly of particles from the centers and outskirts of the initial objects, consistent with the metallicity gradients seen in ellipticals. The merging cross section is governed by the extent of the dark halos with the luminous parts eventually merging after the halos have decelerated the systems. Gas in the initial objects is driven inward by tidal effects and winds up in the core of the merger possibly providing bursts of star formation or forming small disks. Mergers provide natural explanations for the slow rotation of giant ellipticals, double nuclei cD galaxies, and mass shells in some ellipticals. Several open questions concern the specific number of globular clusters and the expected core radii in merger remnants.

The main question about these simulations is whether or not the initial conditions they use are realistic. The distribution of mass before the collapse is usually assumed to have simple symmetries and one may question whether such conditions are likely to arise in the general universe. For example, the work of Katz and Gunn (1991) assumed a spherical cloud in solid body rotation and then added small scale fluctuations to imitate hierarchical effects. Even with the high frequency power, the situation is dominated by symmetry and angular momentum, making disk formation somewhat guaranteed by the physics. Merging simulations often use models of fully formed galaxies for the initial objects, although one might expect merging to occur well before the formation process is complete. One needs to gauge the appropriate conditions for galaxy formation from large scale models and establish a connection to cosmology.

1.2 Cosmology

Cosmology is an expansive and quickly changing field. One testament to its range, and an excellent reference for most of the subjects below, is the recent 700 page tome by Peebles (1993). Other good general references include Kolb and Turner (1990) and Peebles (1980). By comparison, only a meager outline is feasible here.

The same initial conditions problem discussed above is expanded to a global scale in cosmological studies. Much of the effort in this field is expended in trying to characterize the nature of the primordial density fluctuations in the universe. First attempts used optical surveys, such as the Lick catalog, to estimate on what scale the universe appeared homogeneous and isotropic. Redshift surveys, which sport many acronyms like CfA, IRAS, APM, and QDOT, add a third dimension to better probe the distribution and motions of galaxies. Large area surveys map the cosmographic features of the local universe and directed 'pencil beam' surveys look for very large scale properties. Observations of the cosmic microwave background radiation field, most notably the COBE results (Smoot et al. 1992), confirm the isotropy of the universe on very large scales and have begun to provide a baseline measurement of the conditions in the early universe that can be used to normalize theories. Measurements of the global density and Hubble parameters constrain the growth of density fluctuations.

These global concerns are not the focus of this thesis. The more relevant observations are those closer to galaxy scales. Perhaps the most fundamental are the correlation function and velocity dispersion of galaxies in the local universe. These observations set the scale for the level of clustering and the motions of galaxies. The existence of quasars at high redshift fixes a minimum timescale in which at least some objects must collapse. The clouds of the Lyman alpha forest give clues to the nature and distribution of compact objects back to the era of quasars. Number counts of faint galaxies and the Butcher–Oemler effect argue for significant recent evolution of the galaxy population.

Also pertinent are observations of clusters of galaxies. The dynamical state of clusters, particularly the presence of substructure, can be used to estimate the mass scale of objects that have had time to relax in the universe. The distribution and velocity dispersion of galaxies can give an estimate of the mass in the cluster. Scaling the mass estimate by the luminosity density of the universe divided by the luminosity of the cluster gives an estimate of the global mass density, with typical values of $\Omega \sim 0.2$ where Ω is measured in units of the closure density. X-ray observations show the presence of a hot intra-cluster medium with a total mass of the same order as that in the cluster galaxies. Based on this and related cluster data, one may estimate that baryons comprise about 25% of cluster mass (White et al. 1993). Recent higher resolution x-ray data indicate the presence of substructure even in large clusters (White, Briel, & Henry 1993).

Interpretation of these data begins with gravitational collapse theory. Starting with a density field in the early universe, one can follow the evolution of fluctuations in this field. Assuming the initial fluctuations are small, a perturbation approximation gives the growth in the linear regime, $\delta\rho/\rho < 1$ where $\delta\rho$ is the fluctuation and ρ is the mean density. For Gaussian random fields, the statistics of peaks of the field, which are the expected sites of galaxy formation, can be considered in detail (Bardeen et al. 1986). A simpler approximation that predicts the number of collapsed objects of a given mass scale is given by the Press–Schechter formalism (Press & Schechter 1974). Extra freedom is added by noting that galaxies, as peaks of the distribution, may be more correlated than the underlying mass; an effect known as biasing.

These tools are applied to a wide variety of structure formation models. The main element of such models is a description of its mass and energy components. The fraction in baryons is constrained well by nucleosynthesis calculations to $\Omega_B \approx 0.0125\, h^2$ where h is the present Hubble parameter in units of $100\,\mathrm{km\ s^{-1}\,Mpc^{-1}}$. The dark component comes in two standard flavors, cold and hot, depending on whether its thermal velocities at the time of matter domination are non-relativistic or relativistic. The dark matter is assumed to interact only via gravitation and the amount is governed by one's choice of Ω in the model. Inflationary models and the prejudices of theorists favor $\Omega = 1$. Open models assume the lower observational value and curvature dominated models do both, assuming the observational value for matter and filling out to unity with a vacuum energy density. From these assumptions and the class of perturbations (adiabatic or isocurvature) one generates a spectrum of initial fluctuations by considering evolution through to the time of decoupling of baryonic matter and radiation. Alternatively, one may motivate a fluctuation spectrum from other considerations such as topological defects or large scale cosmic explosions.

Because galaxies are density enhancements with $\delta\rho/\rho \gg 1$, linear theory does not address their formation. In probing the predictions of various cosmological models in the non-linear regime, N-body simulations have become an indispensable tool. By following the evolution of representative regions of the universe and identifying the likely sites for galaxy and cluster formation, one can 'observe' the simulations in similar fashion to real observations and specify the model predictions. Work of the so-called "gang of four" was influential in shifting focus onto the cold dark matter (CDM) model (Davis et al. 1985; White et al. 1987b). A standard CDM model developed with $\Omega = 1$, $h = 0.5$, and a reasonably well constrained range of normalizations for the power spectrum.

In recent years, various objections have been raised. The comparisons with redshift surveys find more power on large scales than standard CDM would predict (Maddox et al. 1990; Efstathiou et al. 1990; Vogeley et al. 1992). Large simulations suggest that CDM forms an excessive number of large mass clusters and requires low normalizations to fit galaxy velocity dispersions (Gelb 1992). More definitively, the COBE observations appear to require a normalization of the CDM power spectrum on large scales that is much higher than the usual range of normalizations on galaxy scales. The current status appears to be that cold dark matter has been knocked down as king of the hill, but no successor model has risen to take its place (see Davis et al. 1992; Frenk 1991; Ostriker 1993). Various patches to standard CDM with low Ω, a cosmological constant, or a mixture of cold and hot dark matter have been proposed to provide a larger ratio of large scale to small scale power that seems to be required (Efstathiou, Sutherland, & Maddox 1990; Davis, Summers, and Schlegel 1992; Klypin et al. 1993).

It is important for this work to note that the success of standard CDM is on the galaxy to cluster scales. The main problem on these scales is that the inferred velocity dispersions are much higher than those observed in the local universe. However, enough uncertainties remain (see the next paragraph) that CDM's strengths outweigh its weaknesses in this regime. Regardless of which theory supplants CDM, it will have to be sufficiently CDM-like on the galaxy to cluster scales. Because only these scales will be addressed, one feels comfortable using CDM as a representative of hierarchical structure formation for the problem at hand.

Most of the simulations discussed above assume that the dark matter is gravitationally dominant and only follow the evolution of a single dissipationless dark matter fluid. Because baryons are not included, one can not directly identify where galaxies would form in the simulations. The unknown bias in the distribution of galaxies versus the distribution of the dark matter is what allows a range of normalizations in standard CDM. It has also been suggested that the velocities of galaxies will be systematically different from those of the dark matter; an effect dubbed velocity bias. Additionally, objects composed of collisionless particles quickly lose substructure when merging and the sites of galaxy formation in cluster regions are washed out by what is called overmerging. Considering these caveats, there is a large amount of leeway when interpreting the simulations and falsifying a cosmogony can be quite difficult. It has sometimes seemed as if CDM was the theory that would not die.

An important class of simulations has worked to remedy these problems by including both dark matter and baryonic components. These simulations have examined the state of the intracluster medium (Evrard 1990; Thomas & Couchman 1992) and the intergalactic medium (Ryu, Vishniac, & Chiang 1990; Cen & Ostriker 1992a). In cosmology, Cen and Ostriker have evaluated various scenarios with the two fluid approach, but without the dynamic range necessary to study galaxy formation. Using a Lagrangian hydrodynamics code, two groups have been able to resolve objects with galactic densities within small scale cosmological simulations (Summers, Davis, & Evrard 1991; Evrard, Summers, & Davis 1994; Katz, Hernquist, & Weinberg 1992). These simulations and the complex modelling involved are a nascent field, but they offer the promise of cutting through the biasing fog and being able to identify galaxies directly.

1.3 Galaxies within Cosmology

The stage is now set for this work. Individual galaxy formation simulations have progressed to the point where one can produce quite reasonable galaxy representations on the computer. Large scale structure investigations have identified a class of models that predict reasonable sites for galaxy formation. Computational methods have developed the tools that can begin to handle the severe constraints of the problem. From this point of view, a thesis such as this one was inevitable.

Although the problem is of huge proportions, the goals of this project must be more modest. The approach will be to look at the small scale cosmological simulations (several Mpc) and try to resolve large scale galaxy phenomena (several kpc). The two fluid, Lagrangian hydrodynamic simulations will serve as the appropriate vehicle and cold dark matter will serve as a suitable example of hierarchical structure formation. As alluded to above, one must first determine whether or not galactic density objects will form under the conditions of the model. Then one can check the population of those objects to see if they are sufficiently "galaxy-like". Success in that endeavor allows one to examine the process of galaxy and cluster formation with confidence that the results will be useful and applicable when probing galactic and cosmological questions. The intricate physics involved in galaxy formation means that one can not hope to model the complete process in every detail, rather it is prudent to start with the basic physical processes: gravity, hydrodynamics, shock heating, and radiative cooling. Further work can include other important processes, such as star formation and energy feedback from supernovae, and characterize their effects by comparison to the baseline results. These investigations should provide a significant first step toward merging the two streams of research outlined above.

In addition to the scientific aspects, several computational issues need to be addressed. The hydrodynamic method that will be used, smoothed particle hydrodynamics, is being applied to a new regime and its performance should be tested. A knowledge of how the variations in the method used by different researchers can affect the results is imperative for making comparisons. One should also compare the new results with results one would have obtained by previous methods to show what consistencies and conflicts arise. Indeed, because the hydrodynamic methods are computationally very expensive, one wants to justify the need for their use. Progress in the computational methods leads to new avenues of exploration of the science.

The field of galaxy formation is changing rapidly. It is unlikely that the results presented here will be definitive. The most one can hope for is that they serve as the current best answer for a brief time, enabling other research to build on it and progress to a slightly higher level of understanding yet again. The amount of intellectual effort and just plain work involved in achieving the modicum of advance presented here makes one keenly appreciative of the historical groundwork laid down by so many. The future is sometimes just an elaboration on the past.

Chapter 10 – Summary and Discussion

He's dead, Jim.
– Dr. McCoy, *Star Trek*

He's not dead, he's just resting.
– Pet Store Owner, *Monty Python's Flying Circus*

I'm not dead yet.
– Old man in Scene 2, *Monty Python and the Holy Grail*

We are able to rule out all $\Omega = 1$ cold dark matter models for $\sigma_8 > 0.5$ . . .
– Gelb 1992, Ph.D. Thesis

(these results) are difficult to reconcile with the 'standard' $\Omega = 1$, scale-invariant, cold dark matter model . . .
– Efstathiou et al. 1990, *Large-scale Clustering of IRAS Galaxies*

Better understanding of galaxy formation is needed before the demise of cold dark matter is declared.
– Davis et al. 1992, *The End of Cold Dark Matter?*

t is an idealized view that represents a thesis as an isolated, compact, and complete piece of research. The simple facade of collecting work into book form gives the impression that there exists a beginning, a middle, and an end. Such clean divisions are never so apparent in reality. A line of study is continuous; inheriting from previous work and extending into future efforts the ideas, methods, and knowledge of the present. The boundaries drawn by discrete documents are somewhat artificial. One might also suppose that when a project can be truly completed, it will no longer be a forefront enterprise and becomes an unlikely candidate for a thesis topic.

This work started as a small scale extension to the cosmological dark matter simulations by the so-called 'gang of four' (Davis et al. 1985) as well as to the hydrodynamic cluster simulations of Evrard (1990). Along the way, it became apparent that the simulation would really begin to address galactic scales and thus could make a connection to the isolated galaxy formation simulations, such as those by Katz (1992). Extensions in the form of adding star formation and other physics, increasing the dynamic range, and applying these techniques to larger and smaller scale problems could now clearly be envisioned. Though many months had been spent on learning simulation techniques and hundreds of supercomputer hours had already been burned, it was only at the point when a continuous path was identified that the project took on a well defined shape. Crystallization occurred upon establishing context.

This chapter, in combination with the first, is an attempt to define and describe that context. The pages in between represent another step along the way, work that shall be collated and correlated here. The various paths toward future work will be outlined. Individual results take on both greater and lesser meaning when viewed as part of a larger progression: greater, because the reason for their significance becomes apparent, and lesser, because they are viewed as one step in a long series.

10.1 Summary

This section will have to serve a dual purpose. For those who have read the previous chapters, it should provide a reminder of the important results. For those reading only this summary chapter, it should provide enough depth to foster appreciation of the results. The compromise is likely to be too heavy in detail for the first group and too thin on background for the second. The aim is for a proper balance, perhaps a bit more detailed than a paper abstract, in the capsule chapter summaries below.

10.1.1 Chapter Two

Chapter 2 presents the simulation methods in detail. The algorithms and equations of the P3MSPH code are described in a manner geared toward non-specialists. Emphasis is placed on basic underpinnings of the methods and upon covering the important elements of all areas of the code. Special care is taken to motivate aspects of the mesh and SPH methods, as well as provide connections between them, by discussing an example in depth. Because SPH techniques are relatively new, some variations of the choices in the method are explored to promote a feel for its implementation. The chapter finishes with a discussion of the limitations of the code due to the necessary numerical compromises.

10.1.2 Chapter Three

A broad overview of the main simulations of this thesis is given in Chapter 3. The motivations and goals are discussed along with the specific implementation. Technical parameters are dispensed in enough detail to allow others to replicate the procedure. As a preemptive strike against over- and mis-interpretation, limitations of what the simulation does and does not address are explicitly outlined in advance. Mass resolution is identified as a critical enabling factor for the simulation and some related aspects are discussed.

The results of Chapter 3 concern the range of physical regimes addressed in the simulation. The standard filamentary structures of hierarchical collapse are found in the 16 Mpc co-moving cubic region, with a large group of galaxies forming at the vertex of three filaments. The two particle fluids, representing dark matter and baryonic components, trace roughly the same structures on large scales, but deviate strongly below scales of a few hundred kpc. The baryons cool efficiently and, by radiating their thermal pressure support, collapse to overdensities characteristic of galaxies. These high density baryonic objects have small cross sections and do not suffer the excessive merging seen in the dark matter when clustering to form a group. The dark matter can be characterized as a single phase fluid peaked at high temperatures and moderate overdensities, while the baryons exhibit a three phase structure: a hot component in the halos of groups of galaxies, a cold, low density component in 'voids', and a cold, high density component in collapsed objects. The simulation aim of covering the smaller cosmological scales (several Mpc) down to the larger galaxy scales (several kpc) is confirmed.

10.1.3 Chapter Four

Chapter 4 explores the details of the high density baryonic objects and their suitability as a simulated galaxy population. The identification of these galaxy-like objects, or globs for short, is straightforward due to their high density contrast. In comparison, definition of a dark matter halo population is less clear cut because of its smooth, single peaked distribution in density.

The globs and halos have a varied distribution and reasonable abundances. Of the roughly 200 objects, one third are in groups of two to nineteen globs, while the rest represent a 'field' population. Masses of the objects range from about 1/30 the Milky Way to a cD-type value for the largest object of the largest group. The evolution of number density shows the behavior characteristic of Gaussian random fields and of hierarchical structure formation. The total mass within collapsed objects turns out to be several times higher than observations and may indicate a problem for $\Omega = 1$ hierarchical models. Comparisons of a glob mass function to the observed galaxy luminosity function are complicated due to the unknown mass to light ratio, the constrained overdensity in our simulated region, and necessary final redshift ($z = 1$) of the simulation. The faint end mass slope is found to be -1.4, more consistent with a luminosity function corrected for low surface brightness galaxies (≈ -1.6) than with the bright galaxy data (≈ -0.95). The mass distribution within objects, as given by the circular velocity curves, indicates that the baryons dominate the central regions while the dark matter governs large scales.

Of special note are the morphologies of the collapsed objects. Numerical effects will damp velocity dispersions and do not allow the simulation of elliptical galaxies, halo components, or tidal heating. Galactic disk structures, linear tidal features, and objects collapsed to unresolved scales are all predicted and seen. A variety of different structures is found with more merging and tidal interactions suggested in groups. Moment of inertia analysis finds disk structures in almost all of the well resolved, isolated objects. With a condensed baryonic component in the core, the shapes of the dark matter halos are more spherical in two fluid simulations than in dark matter only simulations.

Detailed analysis of the disk structures finds several good features. The sizes, rotation speeds, and the presence of warps of simulated disks agree well with observed spiral galaxy characteristics. Measured rotation curves of the particles confirm that the well resolved disks are rotationally supported. Though pushing the interpretive boundaries, one does finds a tight Tully-Fisher type relationship and can examine its consequences.

10.1.4 Chapter Five

In Chapter 5, the formation process of the galactic objects is investigated. The globs are traced from output to output following the appearance of new objects, mergers between objects, and dispersal of objects. The galaxy formation rate, as tracked by the new objects, peaks at a redshift of $z = 4.0$ for a baryonic mass scale of $3 \times 10^9\ \mathrm{M}_\odot$ and at $z = 2.5$ for $10^{11}\ \mathrm{M}_\odot$ in baryons. These early collapse epochs can easily account for the existence of high redshift quasars, subject to resolution caveats and the unknown method of powering such phenomena. Consistent with the expectations of hierarchical structure formation, the merging rate for these objects is delayed with respect to the formation rate. Significant merging also appears correlated with the formation of the large central group.

The formation sequence for disk objects is followed in detail and a generic process for hierarchical collapse is identified. Initial collapse proceeds by the formation of a filament, segmentation of the filament, and collapse along the filament axis of the local segment. This one dimensional collapse does not produce significant angular momentum. Angular momentum is transported into the interior regions of the forming galaxy by the accretion and dissipation of gaseous clouds. After that, a large fraction of the final mass is gained by slow accretion of low density material.

The disk formation process by discrete accretion of gas clouds seems a natural consequence of hierarchical collapse and differs strongly from the simple and symmetric analytic picture. While many accretion events would destroy a disk, the process works because hierarchical formation requires only a couple significant events to build the next level. To ensure dissipation, it is important that the clouds remain gaseous during infall and the timing of star formation could determine the viability of this process.

With a two fluid simulation, the correspondence between galactic objects and the dark matter halos can now be pursued. Small mass halos often do not contain a collapsed baryonic object because the gas has not had sufficient time to cool to very high overdensities. For well resolved and isolated systems, there is a good one to one correspondence between globs and halos. Larger mass globs are found in regions of higher galaxy density. However, the total mass of globs in group systems is a decreasing function of halo mass because a larger percentage of the gas is shock heated to form a hot intra-group medium.

Abundant merging is characteristic of hierarchical formation. The globs in the group environments generally undergo more merging interactions, but there is large individual object variance. The dark matter halos see more mergers than the globs and, for merger events that correlate with glob mergers, the halo mergers occur about a crossing time or so earlier. Halo mergers also tend to have larger mass ratios between objects than found in glob mergers. With a reduced number of mergers and smaller mass events, disk formation in globs can proceed without too much disruption. Growth histories of the globs can be used to divine a nominal mass accretion rate of $10\,M_\odot\,yr^{-1}$, but one which is highly variable due to merging.

10.1.5 Chapter Six

Progressing to larger scales, Chapter 6 looks at how the simulated galaxies aggregate into groups. In appearance, a striking comparison is presented between one of the groups in the simulation and a real group of galaxies from the Palomar plates. Such visual recognition fosters confidence in the numerical results. For the formation process, a detailed sequence is traced. The first stage is the collapse of a few objects in a dense region and their agglomeration to form the core of the group. Concurrently, the filaments around the group region collapse, segment, and align toward the core. The next stage is radial infall of the simulated galaxies from the specific filament directions. Further accretion will be of groups and small clusters of galaxies, as higher levels of the hierarchy are assimilated into the dominant structures.

This formation process has several implications for groups and clusters in hierarchical scenarios. The prominence of filaments implies that linear structures should indicate an unvirialized structure in the infall regime and that projection effects can be severe. Radial orbits would increase both the relaxation time of the cluster as well as the frequency of mergers, tidal interactions, and gas stripping from galaxies.

The distribution of the baryons relative to the dark matter can also be studied for the group environment. Baryons dominate the mass on galaxy scales, but relax to cosmic proportions on scales of a few hundred kiloparsecs. No evidence of segregation of the two fluids is seen on large scales, suggesting that large baryon fractions in clusters of galaxies denote problems for $\Omega = 1$ models. The cooling of gas into glob structures is less efficient in larger groups because the individual galaxy gas halos are ram pressure stripped by the intra-group medium and heated to the inefficient cooling regime.

Further exploration of the distribution and dynamics of globs within clusters is needed to address biasing questions. In our small simulation, the globs are more correlated than the dark matter at high redshift and less correlated at the final output. A counts-in-cell analysis indicates that most of the signal for this 'anti-bias' arises in the dense central group region where merging has suppressed clustering on 1 Mpc scales and increased it on 100 kpc scales. A scale dependent, but time invariant, velocity bias (the ratio of glob to dark matter velocity dispersions) is found with a value of 0.7 at the 1 Mpc scale. The mild time dependence of the velocity bias downplays the role of dynamical friction, but no conclusive source can be identified. One must be careful not to interpret these results as general predictions because the simulation models a small and constrained region of the universe and probably overstates the hydrodynamic effects.

The important comparison with observations is the group mass estimates. Using the glob population, virial mass estimation of the large group produces an estimate a factor of two lower than the true binding mass. Part of this value is due to the small scale clustering of globs and part to the reduced velocity dispersions. Assuming that luminosity is proportional to mass in globs, one can scale the group mass estimate to a global estimate of Ω. Since larger objects form preferentially in groups, an additional reduction in the estimate occurs and one finds an example of an $\Omega = 0.3$ estimate within an $\Omega = 1$ cosmology. Unfortunately, this example is only a large group that is known to be unrelaxed and not a rich, virialized cluster.

10.1.6 Chapter Seven

A new direction is taken in Chapter 7. Some of the important processes one wants to examine are dependent on whether the baryons are gaseous, and thus dissipational, or stellar, and behave as a collisionless fluid. A rough parametrization of star formation processes is introduced to study how the transformation from collisional to collisionless fluid affects the simulation. Because the resolution limits are well above real star formation scales, a simple prescription is employed. The main parameters are that gas particles are converted to star particles when their density exceeds $0.1\,\mathrm{cm}^{-3}$ and their temperature is below $3 \times 10^4\,\mathrm{K}$. Thermal energy is injected from supernovae at a rate of 10^{51} ergs per 100 solar masses of star formation. To maintain a reasonable rate in high density regions and preserve hydrodynamic resolution, the densest gas particles are turned into star particles first with nearby candidates being quenched.

The star particles form in the same high density regions that define the globs. The glob population in the star formation run shows the same distribution as that in the two fluid run except for some variance in group regions. The star particles do not remain tightly bound to the glob overdensities, with only 62% of the star particles found in globs. Individual globs range from purely gas particles, in some just collapsed objects, to purely star particles, with the well resolved globs averaging a 75% star particle fraction. The collisionless distribution of the star particles smooths out the central peaks of the circular velocity curves seen in Chapter 4.

The collapse of density peaks proceeds pretty much as in the two fluid simulation, but the energy feedback of supernovae slows the final stages and produces a slightly later peak of glob formation, $z = 3.5$. Star particles generally form after the initial collapse of the object and then continue to be created throughout the life of the glob. The formation of disks is not disrupted by the presence of star particles with most of them being converted in the inner 10 kpc of the forming glob. The discrete accretion scenario for disk formation is roughly the same because the infalling clouds remain mostly gaseous. Elliptical glob formation is now possible and a cD-like elliptical forms at the center of the large group. A small problem with the quenching process becomes apparent only for this very large object, due to its high rate of gas accretion.

The dynamics of the central group are affected in several ways. First, some small globs that dissipate to the center in the two fluid run, now survive for much longer and continue their orbits as star particles. Second, the larger globs have their gas content ram pressure stripped during radial orbits and proceed on looser, collisionless orbits. The role of ram pressure in the dynamics of purely gaseous globs stands in sharp relief. For globs of star particles, it is tidal dispersion that becomes a strong process, enough so that it is the standard route through which mergers occur. Finally, the sink of gas particle mass to star particle mass also acts as a pressure sink in the inner regions and the overlying structure relaxes inward.

The star formation algorithm generally works well with only minor modifications necessary at this level of resolution. However, significant points, such as the relative distributions of stars and gas within a galaxy, will require marked resolution increases. These increases will require only straightforward modifications to the algorithm, but should be accompanied by what appear to be complex changes in the physics modelled.

10.1.7 Chapter Eight

Chapter 8 considers a computational question directly related to the results of this thesis: "How well can one trace galaxies in current simulations?" In particular, is the extra modelling and computational expense of the SPH simulations necessary? A set of criteria that a suitable galaxy tracer population should meet are defined. Various methods of tracing sites of galaxy formation are applied to the dark matter only run, for collisionless algorithms, and the two fluid run, for hydrodynamic algorithms. Each method is evaluated against the criteria and then compared against each other.

None of the collisionless algorithms prove satisfactory. The methods considered are the grouping of particles into halos, the tracking of peaks in the initial density field, an algorithm proposed by Couchman and Carlberg (1992), and a new method, dubbed the most bound algorithm, developed here. The most bound algorithm is a complex attempt to avoid the problems of the previous methods, but it seems thwarted by the nature of collisionless interactions. The perturbations in a collisionless fluid only survive in the central group for a crossing time or so before they are dispersed by scattering. Dissipation to very large overdensities and high resolution appear to be required for a collisionless grouping to maintain coherence.

The SPH methods get passing marks and are reasonably robust. The definition of globs in this work is compared to the galaxy tracers defined by Katz et al. (1992) and both methods produce consistent results. The main arguments against these methods are that the complete baryonic physics is not included and thus the statistics of the population could be systematically biased.

When comparing all of these methods on the statistical measures of the correlation function and velocity dispersion of the galaxy tracers, some interesting points arise. The collisionless algorithms tend to undersample the correlation function in cluster regions as noted by previous workers. An exception is the Couchman & Carlberg algorithm which finds an enhanced correlation at all scales, because it follows only those peaks which have collapsed by an early epoch. Estimates of the velocity dispersion are anything but straightforward. In particular, all methods examined would predict a velocity bias in these simulations, but for very different reasons. Considering the methods and the scale of simulation used to present velocity bias results, we conclude that no reliable prediction of velocity bias as a general phenomenon has been presented.

10.1.8 Chapter Nine

Two tests of the SPH method are presented in Chapter 9. The first concerns estimating the density field of a particle distribution and how the various choices in SPH can affect the results. The second is a dynamical test: the self-similar collapse of an uncompensated top hat perturbation.

The density tests reveal a lot about resolution in SPH methods. The rms scatter in density estimates between methods with fixed equivalent resolution is of order 15%. When the resolution of methods differs, the estimates generally get larger with increased resolution. A very small percentage of particles, $\lesssim 1\%$, can experience order of magnitude changes in their density estimates when SPH choices are varied. It seems clear that some estimate of the resolution of various sets of SPH choices is needed.

The self-similar infall tests provided much information, but only general conclusions. The reason is that an error in setting a numerical parameter did not allow the solution to grow properly and prevents detailed tests of SPH choices. The results here show that the code handles the basic gravitational collapse of a collisional gas well and maintains consistency for large ranges in length, mass, and time scales. Smoothing and artificial pressure produce only the expected effects. Different methods for increasing the resolution produce consistent results. Future work will complete this study.

10.2 Discussion

From the above summary of results, it is clear that the basic goals of this thesis have been met. The model covers sufficient dynamic range to address galactic scale phenomena within a cosmological scale simulation. The collapse of density perturbations to overdensities characteristic of galaxies is followed self-consistently and these regions cleanly mark the expected sites of galaxy formation. These results are almost taken for granted throughout much of this work, but are the key elements upon which the rest is based.

Building on that foundation, one may then examine the simulated galaxy population. The objects formed are reasonably galaxy-like, with sizes, masses, and abundances in the range of those for real galaxies. Concerning morphologies, galactic disks are formed for the first time from cosmological initial conditions and elliptical objects can be simulated when star formation is included. These galactic objects do not suffer from the excessive merging seen for dark matter halos and can be followed through clustering. This population of objects forms the best set to date of galaxy tracers in a cosmological study.

A reliable population allows one to describe the relationship between the (presumably) luminous baryonic matter and the gravitationally dominant dark matter. Generally good correspondence is found between the positions and sizes of galactic objects and dark matter halos, subject to the local cooling timescale. More data is necessary to quantify trends of cooled mass and number of collapsed objects versus halo mass. Circular velocity curves do not indicate an obvious edge to the halos around galactic objects. These results help develop a feel for the possible distribution of the unseen component of the universe.

Another opportunity is the study in detail of the hierarchical formation processes of both individual galaxies and groups of galaxies. Galactic disks form via discrete accretion of gas clouds which transport angular momentum to the inner regions. The collapse of groups of galaxies is dominated by radial infall along filamentary structures. In hierarchical structure formation, it must be recognized that infalling material does not remain static, but will collapse and sub-cluster during the time of infall.

In addition to the scientific results enumerated above, one also develops feedback on the methods, ideas, and practices of producing results. Some points clarify existing questions, some arise unexpectedly, and others highlight aspects previously not emphasized. These concerns are often the most valuable ones because they serve to guide the direction of future work. Several areas of such acquired knowledge are described below.

10.2.1 Methods

SPH methods of this thesis will continue to be a productive tool for quite some time. The results of Chapter 8 confirmed that SPH techniques are both sufficient and necessary for following galaxy formation in these types of simulations. Standard collisionless methods produce continual scattering interactions in clustered regions that steadily disperse sub-perturbations. Carlberg (1993) has suggested that increased resolution, such that very high overdensities can naturally be resolved in the collisionless component, may ameliorate the problem. The star formation runs of Chapter 7 do show less dispersal of star particle objects when first hydrodynamically collapsed to high density. However, the radial orbits inherent in the process still produce significant dispersal of collisionless objects and one might argue the need for still higher resolution. Even granting that, collisionless methods have a distinct disadvantage in that the correspondence between halos and collapsed baryonic objects is dependent on the state of the gas and thus not easily discernible from dark matter only simulations.

On the other hand, the best formulation of SPH for the problem is not yet defined. The self-similar spherical infall test of §9.2 indicates that the method handles the basic collapse problem well, but only partial information is available on which parameter choices are optimal. When feasible, one would favor the fixed method of setting smoothing lengths because of its stability to variation of kernel and smoothing formalism as shown in the density tests of §9.1. Further confidence could be gained at little cost by combining the fixed method with a density dependent criteria as described in §9.1.4. The infall test points out the need for a dynamical test to gauge the viscosity parameters against each different set of SPH choices. Although not conclusive, the linear viscosity parameter of the simulations, α_1, should probably be increased in the future. The choice of smoothing formalisms is found to be unimportant. No preference is indicated for increased resolution in either the smoothing kernel or the smoothing lengths, but other resolution considerations are discussed next.

10.2.2 Resolution

It is identified early on (§3.5) that sufficient resolution is a key ingredient in producing many of these results. Later, in the SPH tests, one notes that the density estimates are dependent on the resolution even for the same particle configuration. As the cooling of gas scales as the density squared, one worries that the structures formed will be controlled by numerical parameter choices. While higher resolution simulations should see more collapsed structures, it would be unsettling if one could produce such results by changing only one parameter and not the full set of related choices.

Two questions arise. First, how does one set a ‘proper’ resolution level in an SPH simulation? And second, what is the correct measure of resolution for a set of SPH choices?

The proper resolution level should be directly related to the level of physical modelling in the simulation. One must identify the range of structures one hopes to resolve, but only those for which the relevant physical processes are included. These structures should be related to the length scales of the gravitational softening and the hydrodynamic smoothing. The mass resolution should consider the total mass of a resolved object, about 30 particles for SPH. The relevant temporal criteria are the dynamical and crossing times of the structures. Above all, these parameters must form a consistent set and should not be viewed as a bunch of numerical dials that can be tuned independently.

As an example, one can check the main simulation of this thesis. The mass per baryonic particle is about $10^8\,\mathrm{M}_\odot$, giving a total mass in a minimally resolved structure of about $3 \times 10^{10}\,\mathrm{M}_\odot$. Such structure is modelled through collapse only down to a temperature of $10^4\,\mathrm{K}$ and sub-galactic structure is not handled. Minimum values of 7 kpc for the gravitational softening and 3.5 kpc for the hydrodynamic smoothing produce an appropriate 10 kpc length resolution. The timestep of 6 Myr ensures that a velocity of 500 km/s covers only a third of a length scale in one timestep. Velocity dispersions of small objects are much lower, but relative velocities in large potential wells are of this order. One element that is not modelled correctly is that the cooling timescales can be very short, but this occurs only for high density objects and does not pose much of a problem.

The SPH choices, unfortunately, do not yet have a quantitative measure of their resolution. Perhaps a standardized density test could be devised. A more relevant test for the galaxy formation problem might be one that checks at what level cooling is resolved. For our choices of SPH parameters, we find that significant cooling is resolved with a minimum resolved mass near or below $10^{12}\,\mathrm{M}_\odot$. This figure agrees with CDM expectations (e.g., Blumenthal et al. 1984) and indicates SPH resolution consistent with the 30 particle level. Sharper kernels and smaller smoothing lengths may resolve the hydrodynamics at an inconsistent level.

10.2.3 Physics

One thing a simulationist must always recognize is that even the best numerical effort will contain an incomplete physical model. The results will always be subject to caveats. Section 3.2 is an attempt to outline the major caveats in advance for the simulations of this thesis. In this section, it will serve to examine the processes behind those caveats.

Chapter 7 provides a short investigation of the effects of star formation. More accurately, the consideration is for what happens upon turning the gas particles into collisionless particles than for the impossible feat of including a realistic star formation model. The results point out that ram pressure effects may be overstated in the two fluid model. Though one can now follow galaxy evolution internal to clusters, the dynamics and distribution are not yet fully reliable. Star formation runs will have to be further studied to get a handle on the dispersal rates of galactic objects and the relative strengths of ram pressure and dynamical friction.

Further modelling of star formation will require only straightforward changes to the simple model of Chapter 7. The one problem that surfaces can be fixed without trouble. The ideas presented by Katz (1992) and Navarro and White (1993) can be implemented when the resolution justifies their inclusion and should suffice in the foreseeable future. Although we are a long way from molecular cloud scales, some thought may have to be given to the star formation in globular clusters. Here we note the reciprocal of the advice of the previous section, the modelling should be geared to the resolution scale.

Another relevant process is the effects of a background radiation field. The proximity effect of Lyman alpha clouds near quasars indicates that a substantial amount of background ionizing radiation exists in the early universe (Bechtold 1993). This radiation would have no heating effect on the current simulation because temperatures below 10^4 K are not modelled. The major change would be in shifting the gas away from collisional ionization equilibrium and significantly altering the cooling curve. Adding photoionization will decrease the rate of collisional ionizations and drop the amount of thermal energy radiated. While large objects would attain sufficient densities to shrug off these effects, small perturbations may cool much less efficiently. The era of galaxy formation would be expected to be delayed.

The most difficult physical elements to include involve the processes below a temperature of 10^4 K. A complex set of atomic and molecular radiation processes are necessary to cool gas to much lower temperatures. The extra variables necessary to store species fractions will create significant memory problems. The timescales involved are much shorter than the simulation timesteps and produce stiff equations. In addition, one needs to model a process of cooling for primordial gas and then keep track of metallicity from supernova enrichment. These prospects seem challenging, but realistic modelling of the internal structure of galaxies is dependent on it.

10.3 Future Paths

This thesis has emphasized the direct results from computer simulations, but they are not an end in themselves. The best role of simulations is to provide insight and guide one's intuition in developing theoretical understanding. The natural follow-on to this work is to re-examine the formation theories in the light of the processes identified here. The idea of creating galactic disks through discrete accretion of gas clouds will have to be considered in detail to see if it can produce the standard features like thin and thick disks, warps, and the observed radial gas distribution, as well as the unusual characteristics such as counter-rotating or bi-directional stellar disks. One should also pursue the implications of filament dominated infall for cluster formation and interpretation of those observations. These studies will provide a significant evaluation of hierarchical structure formation.

Further simulation work can delve into the regions not adequately covered here. The most important extension is a simulation of an unconstrained region of space evolved to the present day. The processes identified in this work should be present in a lower density volume, but may be delayed and proceed more slowly. Because the current simulation ends at approximately one third of the age of the universe, the stability of structures and the merging histories can be followed for considerably longer. Comparisons between the numerical results and present day observations will be facilitated.

One would also like to explore processes on other scales. Larger volumes will consider more levels of the hierarchy and will address cosmological concerns better. Smaller volumes can study the high resolution formation of a few objects. Each scale will have the attendant concerns about resolution and physical modelling.

Star formation algorithms will be employed where appropriate, but emphasis should be placed on studies of clusters of galaxies. In particular, it is very important to understand the relative roles of ram pressure, dynamical friction, and tidal disruption in order to make predictions about the possible biases between the distributions of the galaxies, the x-ray gas, and the dominant mass. These factors enter heavily in the interpretation of cluster observations and their implications for global structure.

A final scientific point to address is the effects of varying the cosmological model. Recent observational results have led to the general belief that cold dark matter requires some adjustments, but no single model has emerged as a favorite. On the scale of these simulations, one can check such things as the timing of galaxy formation and the variations in the formation processes for mixed dark matter or low Ω models. Most work on these models has been done with poor resolution of galaxy scales and these questions become very important for the viability of the models.

Modifications to the computer code will follow the guidelines of the previous section. Increases in resolution and physical modelling will progress together. Investigations of including a background ionizing radiation field have been started by Weinberg (private communication) while detailed radiation processes have been explored by Cen (1992).

To accommodate extended dynamic range and modelling, one will also have to increase the speed and efficiency of the code. In work on adapting a P3M code to parallel machines, Ferrell & Bertschinger (1993) have parallelized the particle mesh part in generalized fashion, but Bertschinger (private communication) finds that the direct summation implementation varies in method and efficiency among different machines. SPH will introduce some constraints on the algorithms because one must ensure that a direct summation is performed at each particle over a set minimum number of neighbor particles. Parallel architectures have historically been a shifting target, but the development of High Performance FORTRAN and the MPP FORTRAN programming model (Pase et al. 1993) are leading toward standardization. Another way to attack the problem is through specialized hardware. The GRAPE processor boards (Ito et al. 1991) perform a direct summation gravity calculation in hardware and accumulate lists of neighboring particles for SPH calculations. The current production version has a Plummer force law hardwired and is well suited to a combination Aarseth and SPH code (Umemura et al. 1993). We are investigating whether it can be adapted to the combination of force laws needed in P3M codes. Production versions of GRAPE boards with a programmable force law are expected in the next year or so.

The tests of the SPH code in Chapter 9 should be continued and augmented. The self-similar infall tests are now at a point where quantitative tests of parameter choices can be done. The relationship between density estimates, resolution, and cooling needs to be explored. The first approach would be a well defined problem, such as estimating the density in a power law distribution. After that, a series of small cosmological simulations with varying SPH choices could provide direct feedback on the processes relevant to galaxy formation studies.

The projects outlined above will follow through on the context envisioned in the introduction of this chapter. The flow of research should always progress through the current state toward future goals. The importance of this work lies as much in the new paths to which it leads, as in the old questions it answers.

10.4 Some Final Remarks

At the culmination of any long and involved journey, one is oft given to philosophizing. The broad exposition of events, details, and results yields to a more personal and introspective interpretation. Even when the presumed goal is rational, objective, and quantifiable scientific knowledge, the essence of being human exerts itself in the need to pass final judgement based on a purely subjective measure of individual enrichment. Permit me a small indulgence of these desires.

I hold some very different views now than when I started my thesis work. I began by imagining how grand it would be to follow the collapse of galactic density perturbations, to really visualize the collapse process, and to gain intuition for the details and subtleties. The prospect of becoming expert in simulation codes and producing realistic models was exciting indeed. And even with wide-eyed ideas, the project still surpassed my expectations. But now, the goals have shifted their stature.

Familiarity and intimate knowledge are without peer in granting perspective. Within the global context of a rich field of research and the local context of assumptions and caveats, lofty ideals are softened. My original aims are now viewed in their relative merit to the progress and prospects of the field. Enthusiasm is undamped, but I focus on exploring new regimes, rather than achieving specific targets. My hopes for the future are simply that it lives up to the promise of the past.

And thus, in a personal sense, this thesis is not so much the story of scientific research as it is the story of the person doing that work: a rite of passage from inexperienced graduate student, learning from those gone before, to (somewhat) knowledgeable researcher, able to join one's peers in disseminating new information. The personal journey is the most valuable lesson, and one which cannot be embodied in a thesis or granted by a Ph. D. diploma. It never ends. We shall always be students to experience.

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