Research Statement

In the past few years, tremendous progress has been made in our knowledge of the cosmological parameters. Most spectacular have been the measurements of anisotropies in the cosmic microwave background (Spergel et al. 2003). Combined with the measurement of distant supernova (Perlmutter et al. 1999) and the large scale clustering of local galaxies (Zehavi et al. 2004; Percival et al. 2001; Maller et al. 2005b) the cosmological parameters appear to be well measured. Furthermore, we have additional evidence that the basic cosmological model is correct. For example, in my work, I have found that the velocity of our local group of galaxies is consistent with the gravitational force of large scale structure having accelerated them for the age of the universe (Maller et al. 2003a). However, while cosmology seems to rest on a firm theoretical footing, the subfield of galaxy formation faces several fundamental challenges. Galaxy formation models routinely fail to produce the observed mass, size and type distributions of galaxies, even when poorly understood physical properties are treated in a descriptive manner. Most believe this is due to our limited understanding of the galaxy formation process instead of a problem with the cosmological model. However, without a theory that explains the formation and evolution of galaxies within the cosmological framework, cosmology will remain incomplete.

My research focuses on solving these problems of galaxy formation within the context of the cosmological model. Most of my work is theoretical, using semi-analytic models and numerical simulations, but I also have experience with observational projects, and have worked extensively with the Two-Micron All Sky Survey (2MASS) as the lead author on two recent papers. As mentioned, the theory of galaxy formation currently faces several challenges, but it is also well-poised in the years ahead to make tremendous progress, bolstered by the recent explosion in observational data from all-sky surveys, satellite missions, and 10-meter class telescopes.

The main ideas behind the current theory of galaxy formation, in fact were spelled out long ago. First, gas cools and condenses in dark matter halos (White & Rees 1978). Second, the angular momentum content of the gas determines the size of the rotationally supported galactic disk (Mestel 1963; Fall & Efstathiou 1980). Third, galaxy morphologies are set primarily by mergers – when galaxies merge their disks are transformed into spheroidal systems (Toomre & Toomre 1972). While these ideas are likely correct at some level, the time is ripe to revise many of these ideas in light of new data. Below, I detail some of my contributions to these three aspects of the theory. I then discuss my future research plan to create a publicly available code that models each of these aspects and compare them in detail against numerical simulations. I also discuss my plan to organize the various data on galaxies at different redshifts so that galaxy formation models can easily be judged against all the available data. I feel that both of these projects are crucial to developing a complete theory of galaxy formation.

Cooling in Dark Matter Halos

The dominant process in galaxy formation is gas cooling. However, standard cooling arguments and hydrodynamical simulations consistently produce galaxies more massive than observed. Some form of feedback is usually invoked to try and explain this discrepancy (Larson 1974; White & Rees 1978; Dekel & Silk 1986), but numerical simulations fail to produce such feedback especially in massive galaxies (Mac Low & Ferrara 1999; Thacker & Couchman 2000).

In a recent paper (Maller & Bullock 2004), I proposed that what previous modeling failed to account for is that cooling proceeds by a multi-phase process. A two-phase medium naturally evolves during gas cooling as has long been known (Field 1965). Instead of the gas cooling and forming the galaxy's disk as is usually assumed, some of the gas cools into warm clouds while the rest of the gas remains as a low density hot core. The warm clouds then eventually loose their kinetic energy and form the galaxy, but this process may take several billion years.

The baryonic mass of the Milky Way galaxy is explained naturally in this model, and is a factor-of-two smaller than in the standard treatment without feedback. The fraction of baryonic mass contained in the hot core component grows with halo temperature, and this gives rise to a characteristic cooled, central galaxy mass in high-mass halos. Interestingly, this is what is needed to explain the bright-end cutoff in the galaxy luminosity function. The hot gas in this core can be observed in X-ray or far UV absorption spectra and there are tentative indications that this has already been seen (Savage et al. 2000; Sembach et al. 2003; Nicastro et al. 2002).

The warm clouds also explain the origin of the population of high velocity clouds detected in HI around our Galaxy (Blitz et al. 1999; Putman et al. 2002), and high-ion absorption systems detected around other galaxies at $z < 1$ (Chen et al. 2001). Furthermore, such clouds are needed to account for the high-ionization-state gas detected in damped Lyman alpha systems (neutral gas commonly associated with galactic disks) at high redshift (Maller et al. 2003b). I have produced the only model that matches the properties of these systems. Associating the high-ion gas with warm clouds in the galaxy's halo, and the low ions with neutral gas in the central and satellite galaxies, creates the observed kinematic properties (Maller et al. 2001, 2003b). The nature of these high ion systems are therefore an important test of this model.

To study them I proposed a method using gravitational lensing to determine the ratio between the total mass (baryons and dark matter) and the column density observed in quasar absorption systems (Maller et al. 2002b). This technique exploits the correlation between the column density of the absorption system with the change in the background quasar's luminosity due to weak gravitational lensing. Recently Ménard & Péroux (2003) have detected such a lensing signal which will allow one to constrain the properties of gas in and around galactic halos in the near future.

Lensing can also be used to measure the mass of the galaxy and the mass of the halo to determine how much mass does actually cool to form a galaxy. Galaxy-galaxy weak lensing can be used to measure the mass of the halo that the galaxy resides in (McKay et al. 2001). Alternatively, strong lensing around a galaxy can be used to measure the mass of a galaxy. This is particularly true in the case of spiral galaxies where the flattened geometry of the disk means that nearly edge-on systems have a projected surface density many times higher then they would have in a spherical geometry (Maller et al. 1997). I developed and demonstrated this technique finding that the disk of the spiral lens B1600+434 contributed no more then 25% of the mass in the inner parts of that galaxy (Maller et al. 2000). Subsequently Trott & Webster (2002) and Winn et al. (2003) have applied this method to other spiral galaxy lenses arriving at similar conclusions. By accurately measuring the ratio of galaxy mass to dark matter halo mass we will be able to judge if our cooling description is correct. We can then turn to understanding the sizes and Hubble types of galaxies.

Conservation of Angular Momentum and Disk Formation

Clearly, it is important to understand the role of angular momentum in galaxy formation because galactic disks are rotationally supported. If angular momentum is not transfered in the process of galaxy assembly then the sizes of disk galaxies are determined by the initial specific-angular-momentum of the baryons (Fall & Efstathiou 1980), which presumably follows that of the dark matter. However, this is not seen in simulations where galaxies lose most of their angular momentum and form disks smaller than those observed (Navarro & Steinmetz 2000; Keres et al. 2005).

Investigating the properties of damped Lyman alpha systems at a redshift of 3, I found that in order to explain the kinematic properties of these systems (Prochaska & Wolfe 1997, 1998) their sizes must be about 50 times larger than the standard angular momentum arguments would give (Maller et al. 2001). I believe that this gas is most likely not rotationally supported at this redshift, possibly because of interactions with other galaxies, or because warm clouds as discussed in the previous section have not had time to loose their excess kinetic energy. The importance of this result is that angular momentum may not be the most relevant parameter in determining the distribution of cooled gas at high redshift, instead galaxy interactions may play the dominant role.

I also developed a new recipe for angular momentum accumulation in dark matter halos based on the transfer of orbital angular momentum during a halo's merger history (Maller et al. 2002a). I found that this model produced a log-normal spin distributions as seen in N-body simulations, and it shows the same lack of correlation with halo mass, cosmology, and redshift. This model may have important implications for understanding galaxy disk sizes, including the issue of high-redshift disks described above. For example, the merger-induced picture helps explain why the angular momentum distribution of gas in low-mass galaxies differs from that measured in dark matter only simulations (Maller & Dekel 2002). Because small-mass halos preferentially contribute to the mass with low specific-angular-momentum, feedback changes the angular momentum profile of baryons by ejecting the baryons from small mass halos. Choosing a feedback scheme that gives the observed baryon fraction in dwarf galaxies also leads to angular momentum profiles in those galaxies like those observed. This paper fundamentally changes the picture that baryons simply trace the angular momentum of dark matter. Instead, it shows that how baryons cool into dark halos is intimately related to the resulting sizes of disks.

For the year that Neal Katz was in Australia on sabbatical, I supervised his student Dusan Keres. We studied the angular momentum situation in numerical simulations (Keres et al. 2005) and found that the problem of angular momentum loss is of a rather different nature then usually claimed (Navarro & Steinmetz 2000). While we saw evidence for some transfer of angular momentum from baryons to dark matter, this amounted to less than half of the baryons angular momentum (instead of 90% as claimed by Navarro & Steinmetz 2000). However, we found evidence that the baryons that form a galaxy have transfered much of their angular momentum to the hot baryons in the halo. Thus hydrodynamical interactions play a significant role in the apparent loss of angular momentum. It may be that implementing multi-phase cooling as described above can alleviate this angular momentum loss. Currently we are studying how the angular momentum of a galaxy is effected by its merger history and plan to test the prescription of Maller et al. (2002a). We hope that by studying the merger history we will be able to determine when the galaxy looses it angular momentum which should help us understand the physical processes responsible.

Mergers and Spheroid Formation

The last important process in galaxy formation is the conversion of spiral disks into spheroids during galaxy mergers. While long suspected to be the dominant process in determining a galaxy's Hubble type, I have performed the first investigation into the actual merger rates that occur in a cosmological hydrodynamical simulation to test if such a scenario is in fact plausible (Maller et al. 2005a). I produce merger trees of each galaxy identified in the simulation at redshift zero, tracing back their progenitors until they fall below the mass resolution of the simulation. From these merger trees I derive measurable quantities that can be compared to observations, or to semi-analytic recipes of galaxy assembly. Such quantities include the probability of a merger as a function of redshift and mass, the distribution of times since a galaxy's last major merger, the distribution of the total number of major mergers that a galaxy undergoes, and the total number of progenitors of a galaxy at a given redshift.[1]

If major mergers convert galaxy disks into spheroids then I can determine a bulge-to-disk ratio for each of our simulated galaxies based on its merger history. Dividing our simulated galaxies into spirals and spheroids around a bulge-to-disk ratio of 50%, I find that the spiral galaxy fraction is a strong function of the galaxy's mass. However, even for our most massive galaxies, I find that $20 - 25\%$ have never undergone a major merger. The dependence of the spiral fraction on galaxy mass has the same slope as seen in observations (Bell et al. 2003), but is offset by a factor of two in mass. This offset is another example of the over cooling problem mentioned above that to much gas cools in hydrodynamical simulations. If all masses where reduced by a factor of two, I would find excellent agreement with the observational data on Hubble type. Therefore, it appears that Hubble type can be understood as a consequence of a galaxy's merger history.

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[1] Movies of the galaxy mergers can be found at http://www.astro.umass.edu/∼ari/mergers.html

Future Research Plans

My main scientific interest is understanding if dark matter halos can be populated with galaxies in a way consistent with observational data. This is a fundamental test of cosmology and the first step to understanding the galaxy formation process. It is also the framework in which all extragalactic phenomena occur and therefore useful for a wide range of observations and theoretical modeling of interest to NASA. Understanding how galaxies are related to dark matter will point the way to which physical processes are important in galaxy formation and allow for them to be studied in more detail. To accomplish this goal it is necessary to create recipes that can approximate the physics that we do not understand, and compare models to all available data.

The Galaxy Formation Cookbook

The formation of galaxies is a complicated process involving nonlinear processes on scales ranging from the size of galaxy clusters to that of individual stars, more than 15 orders of magnitude. Therefore, it is hard to describe both analytically and with numerical simulations. One solution has been to try and find descriptive recipes that approximate the true physics. When applied to a full galaxy formation model this has come to be known as semi-analytic modeling (Kauffmann et al. 1993; Cole et al. 1994).

Unfortunately, most of this work has focused on the production of models that fit some aspect of the observational data instead of constraining possible recipes of the physical properties I have described above. I believe this approach is fundamentally wrong. Instead the goal should be to find the most accurate recipes we can for those processes that we believe we can simulate numerically and provide error estimates of how accurately the recipe matches the simulations. For physics that we can not simulate numerically, the goal should be to explore as large a parameter space as possible to find what recipes produce results consistent with all of the observational data. Only this way can we constrain the possible recipes for describing the galaxy formation process and give confidence levels as to the accuracy of these recipes.

To give a concrete example: currently, to calculate the mass of a galaxy that will inhabit a dark matter halo, modelers choose a recipe for the cooling of the gas, the star formation rate of the galaxy, the mass function of the stars, the feedback efficiency of supernova, and how that reheated gas is distributed outside of the galaxy. Obviously, it is difficult to place constraints on recipes for these poorly understood physical processes. Instead, it would be better to explore recipes for the effective cooling rate in a dark matter halo or the resulting galaxy luminosity, which can be directly constrained from measurements of galaxies and of the dark halos they inhabit.

To achieve this, I plan to develop a publicly available set of recipes, which I call a cookbook, to meet these goals. The first step will be to have recipes to describe the gravitational processes that can be simulated numerically. There is already a great deal of work on this subject with people providing recipes for the halo mass function, the merger histories of halos, the dynamical evolution of satellite galaxies and the clustering properties of halos. While these recipes have been compared to dark matter only simulations they generally have not been compared against one another nor has their uncertainty been estimated. I will determine the uncertainty in these recipes so that the errors in the gravitational sector can be estimated and propagated to other modeling. Also I will test these recipes against simulations with gas where the cooling of baryons changes the dynamics of galaxies.

The next step will be to include recipes for the effective cooling of gas. With observations of the masses of galaxies and the dark halos they occupy this can be reasonably well determined. Measurements of the galaxy correlation function (e.g., Maller et al. 2005b; Zehavi et al. 2004;

Percival et al. 2001) along with the galaxy luminosity function place very tight constraints on how galaxies can occupy dark matter halos. Furthermore, we can use quasar absorption systems and X-ray observations to measure the the amount and state of gas that has not yet cooled onto the galaxy. These observations as a function of redshift directly measure the cooling rate in dark halos.

Turning to recipes for the sizes and Hubble type distribution of galaxies, I have discussed above a model for the growth of angular momentum in dark matter halos. Comparing it with simulations we can determine its accuracy and look for other recipes. Additionally, I am involved with a project to perform disk-bulge decomposition on the 10,000 brightest 2MASS galaxies (McIntosh et al. 2002) that should give us detailed knowledge about the disk-to-bulge ratios and sizes of nearby galaxies.

Such a set of recipes will be useful not only for understanding galaxy formation, but also for modeling all extra-galactic phenomena. Therefore, I believe it is important to make such a code publicly available so that other researchers can use the most accurate recipes to model quasars, supernova and gamma ray burst rates, super massive black hole growth and collisions which produce gravitational waves, and the production and injection of metals into the inter-galactic medium. This will make it easy to attract funding since so many NASA missions will require such a code.

The Galaxy Report Card

We now have an overwhelming wealth of data about the properties of galaxies; so much data that it is difficult to keep track of it all. However, to best constrain galaxy formation it is necessary to use all of the available data. Unfortunately, too many models attempt to fit some subset of the available data, but by doing so are in conflict with other observations. This is partially because it is difficult to gather and synthesize all of the data that may be used in constraining galaxy formation. To make this possible, I propose creating a website that will take the results of a galaxy formation model and return a goodness of fit to the available data. In this way, it will be easy to see where a model performs well and where it is having problems. For example, a model may perform well when compared to local data, but perform poorly at higher redshift. If there are conflicting observational results, the user will be able to select among them and see how this effects their models agreement. I will encourage observers to send their results to the website so that it will be constantly updated with the newest data. Also, there is substantial value in having different galaxy formation models compared in a uniform way instead of each modeler choosing the data that they favor.

Such an effort is necessary because the measurements of galaxy properties are all intertwined. If there are less baryons in galaxies then there will be more gas in galaxy halos, which should be seen in X-ray observations or in quasar absorption systems. If disk size and spheroid mass are related to merger history, then the bulge-to-disk ratio and disk size should be correlated. Making a change in a model will tend to have repercussions for many different observable properties. With a galaxy report card this should become straightforward enough that it will become standard practice in the field.

I believe that a galaxy formation model based on recipes that are in agreement with all observational data can be formulated in a few years. This will tell us what recipes combined with the cosmological model can fit the data. The challenge will then be to understand the underlying physics that the recipes approximate. Of course it may be that no set of recipes can be found that match the data within the cosmological model. This would place serious doubts on the validity of the cosmological model and spur investigation into other possibilities. In either case the benefit of completely modeling the uncertainties of galaxy formation and fitting all of the available data are clear. It will provide the framework for interpreting the next generation of space and ground based observations, test the cosmological model, and create a simple language for describing the galaxy formation process.

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