Chapter 9

Summary and future Work

9.1 Summary

Population III stars play an important role in the formation of large-scale structure in the universe through their feedback of metals, kinetic energy, and radiation, and are possible seeds for the super massive black holes (SMBHs) that are observed at the centers of most massive galaxies. These stars are the first luminous objects to form after the Big Bang, and are believed to play a significant role in the ensuing generations of star formation by preprocessing large volumes of the universe with ionizing radiation and metals, which greatly enhance the ability of gas to cool, radically changing the properties of the gas out of which later generations of stars form. Their critical role in structure formation in the early universe makes an understanding of the Population III mass function and the feedback properties of these stars crucial to be able to model the formation of the first generation of galaxies from first principles. At present there are no direct observational constraints on the mass function of Population III stars. Some indirect evidence has been obtained from observations of extremely metal poor stars in the galactic halo, the extragalactic infrared background, and measurements of polarization in the cosmic microwave background. Though future observations by facilities such as the Square Kilometer Array (SKA), the Low Frequency Array (LOFAR) and the James Webb Space Telescope (JWST) may directly observe these stars, at present the only way to study their properties directly is by the use of numerical simulations.

In this thesis I have used the adaptive mesh refinement cosmology code Enzo (described in detail in Chapter 2) to study aspects of the formation and feedback processes of the first generation of stars in the universe. Chapter 3 describes the results of an extensive comparison of Enzo with the smoothed particle hydrodynamics (SPH) code GADGET. This comparison, in the context of cosmological simulations of galaxy formation, shows that it is possible to achieve very similar results with methodologies that are extremely different when one is performing simulations with only dark matter, and also when one includes non-radiative ("adiabatic") hydrodynamics. This comparison helps to verify the correctness of both codes and also lends credibility to simulation results performed in regimes where direct observational evidence is not currently available (e.g. structure formation in the early universe).

Chapter 4 presents results from high dynamical range simulations of the formation of Population III stars in a ΛCDM universe. I performed simulations varying both the simulation box sizes and random seeds (effectively changing the pattern of large scale structure in the simulation), as well as choosing a single realization and varying simulation parameters, in order to obtain further constraints on the formation and ultimate stellar mass of Population III stars. I show that the mean formation redshift of these stars, as well as the overall accretion rate onto the primordial protostar, varies systematically with the volume of the cosmological simulation, with larger box sizes tending towards lower overall accretion rates, and in principle lower overall stellar masses. The implications of this are significant – the mass estimates of Population III stars that are most commonly used in the literature have been based primarily upon the results of three-dimensional cosmological simulations using very small simulation volumes, and as a result much work has been based on assumptions of a Population III mass range that may be more massive than is implied by this work. The range of supernova energies, as well as nucleosynthetic yields, varies significantly between the inferred mass range for the largest simulation volumes described in this work ($\sim 10-100$ $M_{\odot}$) and from previous work ($\sim 30-300$ $M_{\odot}$).

Chapter 4 also presents results from simulations of the formation of Population III stars assuming a constant Lyman-Werner background. This soft ultraviolet background will photodissociate molecular hydrogen, the primary coolant in primordial gas. I demonstrate that increasing the strength of this UV background will delay the onset of Population III star formation, and may even completely prevent the formation of primordial stars in halos whose virial temperatures are less than $\sim 10^4$ K.

In Chapter 5, I discuss results from simulations of the formation of Population III stars assuming a simple warm dark matter (WDM) model. This model is quite generic in that it makes no assumptions about the mechanism which suppresses power on small physical scales. I apply suppression to the power spectrum over a range of assumed warm dark matter particle masses in order to present a more reasonable lower limit on a possible warm dark matter particle mass, and also run a cold dark matter version as a control sample. This suppression is applied on multiple simulations which all have the same large scale structure (all other simulation parameters are also identical) so that we can directly compare results. I show that simulations of the formation of Population III stars in a warm dark matter cosmology are effectively identical to the results from the fiducial ΛCDM case at $m_{WDM} \simeq 35$ keV, and that observations of polarization in the cosmic microwave background (which imply partial reionization of the universe at $z \simeq 17 \pm 5$) suggest a lower limit on the warm dark matter particle mass of ~ 15 keV, which is a factor of ~ 3 greater than previous published lower limits. This significantly tightens constraints on a possible warm dark matter particle mass.

I present results of the formation of a second generation of Population III stars in a halo which has been ionized by the formation of a nearby extremely massive primordial star in Chapter 6. This scenario is a likely one, as $\sim 10^6 M_\odot$ halos are highly clustered in the early universe, and it is plausible that several nearby halos will be ionized by the first Pop III star to form in a given cluster of halos, assuming that this star is very massive (at least ~ 100 M$_\odot$). In this chapter I show that the ionization of gas due to the first star to form in a region actually enhances the formation of molecular hydrogen in nearby halos (after the death of the first star) and allows star formation to take place in a halo that would not otherwise form a Population III. This suggests a possible positive feedback effect due to Population III star formation. Additionally, the star that forms in the ionized halo has a much lower accretion rate than the first star to form in the simulation volume, which is most likely due to the higher overall angular momentum of the halo that this star forms in. This lower accretion rate implies a relatively low stellar mass ($\sim 5 - 20$ M$_\odot$) and presents an additional plausible scenario for the formation of Population III stars with masses lower than the "fiducial" range of $30 - 300$ M$_\odot$ that is typically assumed in the literature.

Chapter 7 presents very preliminary results of adaptive mesh refinement simulations of the supernovae from Population III stars. We examine the enrichment of metals in a cosmological context by applying a standard Sedov-Taylor supernova solution to the core of a halo in which a Population III protostar forms for two representative stellar masses, 30 and 250 M$_\odot$, which effectively bracket the range of possible Population III supernova energies ($10^{51} - 10^{53}$ ergs). The less massive star is capable of spreading metals throughout a region almost a proper kiloparsec across (at $z \sim 18$), and it seems reasonable that the more energetic supernova will have a proportionally greater effect. Initial analysis of the 30 M$_\odot$ supernova simulation indicates that though a very large mass of gas is enriched by the supernova, the level of enrichment varies widely. It is unclear at present if the cores of neighboring halos (which are presumably the sites of the next generation of star formation) are appreciably enriched with metals. Though these results are qualitative at present, this method is a very promising approach to determine the metallicities of the first generation of metal-enriched stars.

The results of simulations which model the feedback of metals from a large number of Population III stars are presented in Chapter 8. This work, which attempts to model the effects of Population III stars on the overall metallicity of the Lyman-α forest, assumes a very optimistic scenario for Population III metal enrichment: every halo with a dark matter mass of at least 5×10^5 M$_\odot$ or higher is assumed to form a Population III star with a mass of 260 M$_\odot$ at $z = 15$. These stars are assumed to produce ~ 130 M$_\odot$ of metals which are spread uniformly over a sphere one proper kiloparsec in radius. The evolution is then followed to $z = 3$ and the metallicity of the IGM is compared to current observations of the Lyman-α forest. This work shows that, even with an extremely optimistic scenario, it is impossible to explain the metallicity of the Lyman-α forest (as inferred by measurements of CIV absorption lines) at densities higher than the cosmological mean density by metal enrichment from Population III stars alone.

The work presented in this thesis, and summarized in the previous paragraphs, contributes directly to the greater understanding of the formation of Population III stars and the effects that they have on their surroundings via radiative, chemical, and mechanical feedback. This work is critical to the accurate modeling of the formation and evolution of galaxies from first principles, since Population III stars are responsible for preprocessing regions of space which will eventually become galaxies. Additionally, Population III stars may be the seeds of the super massive black holes that are observed at the centers of many galaxies. Thus, understanding the mass range of these stars is also significant for research in both the formation and evolution of super massive black holes, as well as work with active galactic nuclei (AGN), which are believed to be powered by these black holes. Finally, understanding the Pop III IMF and the resulting feedback from these stars can be useful in interpreting observations the extragalactic infrared background as well as the recent WMAP observations of polarization in the cosmic microwave background. Population III stars may also be the progenitors of extremely high redshift gamma ray bursts (GRBs), and predictions of the IMF may place constraints on the frequency of Pop III GRB events which are observable by the current and future generations of gamma ray satellites.

9.2 Future Work

The work presented in this thesis is extendible in many ways. The code comparison project in Chapter 3 discusses simulations that have dark matter only, or have dark matter with a non-radiative gas component. While an important first step, galaxy formation (which is the context of the comparison) is heavily dependent upon the cooling processes of gas in the collapsing dark matter halos as well as the formation of stars and their feedback of metal and thermal energy into the interstellar and intergalactic medium. An obvious extension of this project would be to incrementally include radiative cooling, star formation, and then star formation plus feedback, with the goal at each step of understanding and attempting to reconcile the differences between the two simulation methods. A portion of this work (simulations that include radiative cooling) is already in progress.

The study of Population III stars in a ΛCDM universe discussed in this thesis (Chapter 4) is limited by physics when the gas in the dark matter halo that the stars formed in reaches approximately 10^{12} particles per cubic centimeter. At this point one of the main assumptions concerning the cooling in the gas, namely, that the gas is optically thin to cooling radiation, becomes invalid. Recent work by Ripamonti & Abel [47] has shown that for several more orders of magnitude in density the effects of opacity are local, meaning that minor corrections to the chemical rate equations are all that is necessary to accurately model the collapsing cloud. These fixes are already implemented into Enzo, and are a logical extension of the work presented here. In addition, all of the work in this thesis completely ignores the effects of magnetic fields. While it is widely assumed that B-fields are dynamically unimportant in the formation of Population III stars, this can be tested. The equations of magnetohydrodynamics are currently being implemented into the Enzo code, and the examination of the effect of magnetic fields on the formation of a Pop III protostar will be one of the first applications of this code. Finally, it is unclear if the observed relationship between increased box size and decreased protostellar accretion rate has converged at the largest box size studied in this work. Extension of the study to even larger box sizes would help to determine whether this result is converged.

The simulations of the collapse of a halo in a cosmology with warm dark matter (Chapter 5) are of a single cosmological realization. A straightforward (though computationally expensive) extension to make the predictions in Chapter 5 more robust would be to perform the same set of simulations for multiple random realizations and for several different box sizes, as was done in Chapter 4. This would serve to reduce issues involving small-number statistics and would also provide an attempt to disentangle the effects of the suppression of the power spectrum and issues involving the box size. Similarly, the results involving the formation of a second generation of primordial stars (Chapter 6) should be extended by performing multiple random realizations in order to increase the statistical robustness of the results. The HII region models that are used are also very simple, and rely on the one-dimensional output from a radiation transport code. This presents an inherent problem, since the universe is manifestly three-dimensional! Also, to accurately model the evolution of the HII region (particularly when the ionization front encounters nearby halos) it is important to model the time-dependent three dimensional evolution of the HII region rather than using a static density field, since hydrodynamic effects may be significant, particularly in the neighboring halos which are of most interest in this situation. Unfortunately, this is currently beyond the capabilities of our cosmology code (not to mention incredibly expensive computationally, even if the tools existed). However, one can perform computationally feasible models in two dimensions and possibly even in somewhat idealized three dimensional situations that will lend insight to the problem.

The simulations of Pop III supernovae shown in Chapter 7 are first attempts, and can stand to be improved in many ways. In particular, the models that we are using for the supernovae are somewhat simplistic, being Sedov-Taylor blast waves. Work is in progress to take the output from three dimensional models of supernova explosions and use this as the initial conditions for cosmological simulation. This work is already in progress. Additionally, the metal-enriched gas from these supernovae would have significantly enhanced cooling compared to gas of primordial composition. Implementing cooling models that include the cooling effects from metals would allow one to study the enhanced fragmentation of enriched gas, and improve our estimates of the properties of second generation metal-enriched stars. Finally, the existence of several grid-related numerical artifacts suggests that these calculations are somewhat under-resolved. Improving the spatial resolution of the calculations, though computationally costly, is important if we wish to accurately model the mixing of metals into the intergalactic medium and in neighboring halos, which is crucial to the understanding the properties and metal distribution of the first generation of metal-enriched stars.

Finally, the simulations of the pre-galactic enrichment of the IGM by Population III stars discussed in Chapter 8 can be extended in several significant ways. The simulation volumes used in the study presented are somewhat small, and it is computationally feasible to increase the size of the volume to 1024^3 cells at the same physical resolution, allowing us to increase the overall volume by a factor of 64 and significantly improving our statistics. In addition, it would be useful to explore scenarios where the simulations are enriched by Pop III stars at multiple epochs rather than only once. Finally, since we know that star formation took place after the Population III epoch was over, it would be useful to do similar calculations with the effects of post-Pop III star formation included so that one can understand their relative effects on metal enrichment of the IGM, as well as to explore the possibility of differences in QSO spectra that might allow observers to attempt to separate Lyman-α clouds which have been enriched only by Population III stars from those which have been enriched by a combination of Pop III and later generations of star formation. Much of this work is already in progress, and the results will be presented in a forthcoming paper.