LOCAL GROUP DWARF GALAXIES AND THE CONTRIBUTION OF THE FIRST STARS TO REIONIZATION

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ABSTRACT

The Local Group contains some dwarf galaxies that apparently formed all their stars early, lost their gas to winds or ionization, and survive today as “fossils” from the epoch of reionization. This study presents new models of these objects based on the hierarchical chemical evolution framework of Tumlinson (2006). The model accurately reproduces the observed luminosity-metallicity relation of dwarf galaxies with minimal free parameters. When calibrated to this relation, the models show that small dark matter “minihalos” formed 2–8% of their baryonic mass into stars prior during reionization. By tracking the chemical enrichment of these early halos the models specify that metal-free first stars contributed approximately 5–10% of the ionizing photons generated by these small halos and so did not dominate reionization. Models that allow for larger relative contributions from metal-free stars may not generate enough total ionizing photons for early reionization. As significant star formation in early minihalos is a requirement of many successful models for the IGM reionization, these models can be considered to pass a key test of their validity. It appears we have as much to learn about reionization from the universe at $z = 0$ as at $z = 6$.

Subject headings: galaxies:formation – galaxies:evolution – Galaxy:formation – Galaxy:evolution – stars:abundances – stars:mass function – cosmology:theory

1. INTRODUCTION

The reionization of the intergalactic medium was a major change in the physical state of most of the baryons in the Universe, potentially a major influence on the formation and development of galaxies, and may be intimately connected with the first generations of metal-free stars. Observations by the Wilkinson Microwave Anisotropy Probe (WMAP) of the integrated Thomson scattering optical depth to the cosmic microwave background, $\tau_{\text{es}} = 0.17_{-0.07}^{+0.08}$, and the Gunn-Peterson absorption trough in spectra of high-$z$ QSOs found by the Sloan Digital Sky Survey (SDSS), together suggest that reionization had a complicated history in the interval $z = 6 - 20$, which spans $<1$ Gyr of cosmic time.1

Theoretical studies have attempted to explain these data in terms of semi-analytic reionization models that calculate the collapse of dark matter halos and track the growth of cosmological H II regions (Venkatesan, Tumlinson, & Shull 2003; Haiman & Holder 2003; Cen 2003; Tumlinson, Venkatesan, & Shull 2004, hereafter TVS04). These studies vary in their particulars, but they generally include assumptions about or ab initio calculations of three important physical quantities that have so far been unconstrained by observation. The first of these is $f_s$, the efficiency of converting virialized baryons within dark-matter halos into stars. This factor may depend on such local conditions as gas density, metallicity, and radiation feedback in unknown fashion, and as $f_s$ is difficult to calculate a priori, it is generally assumed. The second uncertain parameter is $\gamma_0$, the time-integrated ionizing photon production per baryon in stars. This quantity is essentially completely determined by the initial mass function (IMF) at a given metallicity, and ranges from $\gamma_0 = 4000$ for a Salpeter IMF at solar metallicity to $\sim 50000 - 100000$ for an IMF dominated by massive stars, as expected at low metallicity. TVS04 used detailed chemical abundances in metal-poor Galactic halo stars have favored massive star IMFs with $\gamma \sim 50000 - 80000$ for metal-free stars. Finally, the escape fraction of ionizing photons from their parent galaxies is denoted by $f_{\text{esc}}$ and has been estimated at 0.1 for bright galaxies in the local universe, but is unconstrained for small galaxies in the high-redshift universe. Thus, the three critical model inputs for reionization are all uncertain.

Theoretical studies attempting to explain the reionization data have varied in their specific treatment of these uncertain parameters, specifically with regard to their assumptions about “minihalos”. TVS04 achieved $\tau_{\text{esc}} = 0.12$ with $f_s = 0.05$, $f_{\text{esc}} = 0.05$, and an IMF with $M > 10 - 100 \, M_\odot$, but did not vary $f_s$ and $f_{\text{esc}}$. Haiman & Holder (2003) combined the three factors into a single efficiency parameter, $\epsilon_{\text{halo}} = f_s \gamma_0 f_{\text{esc}}$, and varied this to achieve reasonable fits to the WMAP and Gunn-Peterson data. Cen (2003) studied the feedback effects of X-ray emission from early SN remnants and black hole accretion and found that low-mass halos could form stars efficiently enough to reionize the universe completely by $z = 17$. Though they differ in their details, the theoretical studies cited above generally agree that dark matter “minihalos” (with virial temperatures $T = 10^3 - 10^4$ K, or $M = 10^6 - 10^8 \, M_\odot$ at $z = 6 - 15$), which could probably cool only by molecular hydrogen ($H_2$), are essential to explaining the WMAP data on $\tau_{\text{esc}}$. The reasons are the cumulative nature of $\tau_{\text{esc}}$ and the bottom-up nature of structure formation. If the universe is completely ionized only at $z < 10$, $\tau_{\text{esc}} \approx 0.08$. High levels of ionization at $z > 10$ are therefore necessary to match the WMAP constraint, which corresponds to complete ionization to $z = 17$. In the range $z = 10 - 17$, minihalo hold most

1 I assume the cosmological parameters derived from first-year WMAP data by Spergel et al. (2003): $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$, $\Omega_b = 0.044$, and $H_0 = 71\, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$.
of the collapsed baryons in the ΛCDM cosmology. At $z = 15$, 3.3% of all baryons reside in collapsed halos with $T_{\text{vir}} \geq 10^4$ K, but only 0.7% are in objects with $T_{\text{vir}} \geq 10^4$ K. If $\sim 80\%$ of the baryons do not participate in star formation, extreme assumptions about $\gamma_0$ and $f_{\text{esc}}$ would be necessary for $\tau_{\text{es}} = 0.17$ or the models may fail altogether.

Dark-matter “minihalos” apparently need to form stars with efficiency $f_* \geq 0.01$ to match the key data on reionization. However, these objects have the most uncertain physics of gas cooling and star formation and are likely to be too faint to be constrained by independent observation at high redshift. Some hydrodynamical simulations (Abel, Bryan, & Norman 2000, 2002; Bromm, Coppi, & Larson 1999, 2002) have followed $H_2$ cooling in these objects and determined that they likely form only very massive stars (VMSs; $M \gg 100 M_\odot$) with low efficiency ($f_* \sim 0.001 \rightarrow 0.01$) and then rapidly dissociate the $H_2$ in their neighboring halos, thereby suppressing further the average minihalo efficiency. Other authors (Ricotti et al. 2002; Cen 2003) have argued that the feedback of soft-UV and X-ray photons is likely to be positive, such that minihalos can experience significant star formation over long periods. In light of all these results, efficient star formation in these halos can be taken as a prediction of successful reionization models, most of which would fail without the participation of minihalos.

This study extends previous work (particularly by Ricotti & Gnedin 2005, hereafter RG05) to argue that these predictions can be tested already using dwarf galaxies in the Local Group (LG), and that these dwarf galaxies likely formed as “minihalos” at high redshift and contributed significantly to the reionization of the IGM. Section 2 of this Letter briefly describes the framework of Tumlinson (2006), concentrating on the modifications needed to study LG dwarfs. Section 3 reviews the data on Local Group dwarfs and presents models for their luminosity, metallicity, and star formation efficiency. Section 4 summarizes the conclusions.

2. METHODS

Tumlinson (2006, hereafter Paper I) presented a new chemical evolution code that works both within the hierarchical context of galaxy formation and in the stochastic limit of low-metallicity Galactic evolution. Paper I focused on primordial IMF constraints using Galactic halo stars, but the framework is adaptable to model halos at arbitrary mass and redshift and so is well suited to modeling pre-Galactic halos that form before reionization.

The framework uses the common technique of halo merger trees (Somerville & Kollatt 1999) to decompose the Galaxy into its precursor halos working backward in time. It then calculates the history of star formation and chemical enrichment in these objects working forward in time, keeping track of all individual metal-producing supernovae and assigning metallicity to new star formation stochastically from all prior generations. Stars are formed with a constant efficiency over timestep, $\epsilon_*$, such that the mass formed into stars $M_* = \epsilon_* M_{\text{gas}} \Delta t$ in time interval $\Delta t$. At metallicities below the critical value for normal star formation, $Z_{\text{crit}} = 10^{-3.5} Z_\odot$ (Schneider et al. 2002; Santoro & Shull 2006), the IMF is a log-normal function with characteristic mass $m_*$ and width $\sigma_{\text{IMF}}$. Above $Z_{\text{crit}}$, a power-law IMF with Salpeter slope ($\alpha = -2.35$) is assumed, with $0.5 \rightarrow 140 M_\odot$. IMFs with higher $m_*$ or steeper $\alpha$ are more “top-heavy”, while $Z_{\text{crit}}$ effectively sets the time over which the top-heavy IMF persists. In the small halos of interest, metallicity is correlated with time but does not increase monotonically over short times.

The Paper I method is changed slightly to model dwarf galaxies in the Local Group. The model dwarf galaxies are like their real-world counterparts in that they virialized early, formed stars for a short period, and then lost their gas, were ionized by internal or external sources, or otherwise had their star formation truncated at some redshift, $z_{\text{end}}$, the redshift of the root halo in the tree. After this redshift they evolve no further. In the real universe, these dwarf galaxies may continue to evolve dynamically by accretion into larger objects, tidal stripping, or they may remain in isolation, but they do not appear to evolve chemically beyond the loss of their gas. A large grid of models was produced with $M_\bullet = 10^7 \rightarrow 10^9 M_\odot$, $\epsilon_* = 0.1 \rightarrow 3.0 \times 10^{-10} \text{yr}^{-1}$, and $z_{\text{end}} = 6 \rightarrow 16$. The output quantities of interest are sensitive to these quantities but not to the choice of IMF below $Z_{\text{crit}}$ or to the interstellar mixing rates.

3. LOCAL GROUP DWARFS AND REIONIZATION

The roughly 40 known Local Group dwarf galaxies span a range of types (from spheroidal to elliptical to irregular), have generally low metallicity, and dynamical mass from $10^6 \rightarrow 10^9 M_\odot$ (Mateo 1998). Prompted by the old age of many dSph populations, and by the discrepancy between CDM predictions for dwarf galaxy numbers and the known population, recent theoretical studies have posited a close connection between reionization and the early evolution of LG dwarf galaxies. Bullock, Kravtsov, & Weinberg (2001) suggested that the suppression of star formation in small halos by ionizing photons at $z > 6$ could explain the relatively small number of LG dwarfs compared with the CDM prediction.

RG05 examined this “reionization hypothesis” in hydrodynamical simulations that included $H_2$ cooling and radiative feedback. They were able to reproduce many of the observed properties of the LG dwarfs in simulations that stopped at $z = 8.3$, with no further evolution in the galaxies of interest. They proposed a classification scheme in which LG dwarfs are divided into three categories: “survivors” massive enough to retain their gas and continue forming stars robustly after reionization, “polluted fossils” that were affected by reionization but managed to continue forming stars at a modest level, and “true fossils”, which formed most of their stars before reionization and essentially none afterward. I adopt this scheme here and use the “true fossils”, those galaxies with exclusively old stellar populations, roughly 1% solar metallicity, and $M_\bullet \geq 12$, to constrain the star formation efficiency of small halos at high redshift and assess the star formation efficiency of minihalos.

The first result of this study is that the observed luminosity-metallicity ($L - Z$) relation of LG dwarfs is reproduced exactly with minimal tuning of the models. This relation appears in Figure 1 where a selected group of LG dwarfs is plotted in the style of Caldwell (1999). Survivors and polluted fossils are marked in gray type; true fossils are italicized. Mean metallicities are taken from Mateo (1998), except for And V (Zucker et
al. 2004) and Ursa Major (Willman et al. 2005). Absolute V-band magnitudes for $z = 0$ are obtained by interpolation of the tabulated isochrones for 1/50 and 1/200 solar metallicity from Girardi et al. (2002) and applied individually to stars that reside in the final halo at $z_{\text{end}}$. The points mark the theoretical calculations for $M_h = 10^9, 10^8, 5 \times 10^7, 2 \times 10^7, 10^7 M_\odot$, from left to right; the models are not intended to perfectly match the survivor and polluted fossils that have experiences recent star formation (in gray). Within each constant-mass sequence, the time-averaged star formation parameter $\epsilon_s = 1 - 3 \times 10^{-10}$ and $z_{\text{end}} = 6 - 10$. An increase in $\epsilon_s$ or decrease in $z_{\text{end}}$ moves points up and to the left in the constant-mass sequences. For the same $\epsilon_s$ and $z_{\text{end}}$ combination, the variation in mass traces out a line of the same slope as the observed trend. We can therefore interpret the observed $L - Z$ relation as a variation in mass with scatter introduced by small variations in the star formation histories of individual objects. This concordance was achieved with minimal tuning; it was necessary to vary only $\epsilon_s$ with the same mean and in the same range found in Paper I to match the Galactic halo metallicity distribution. I conclude that the simple description of LG dwarf satellites as fossils from before reionization is accurate and that a more complicated model is unnecessary.

The second result of this study is the strong correlation between total star formation efficiency, $f_*$, and mean metallicity of the resulting dwarf galaxy for thousands of model halos (Figure 2). Because metallicity and efficiency are effectively mass-normalized quantities, this correlation is insensitive to halo mass. Only at the lowest mass plotted here ($M_h = 10^7 M_\odot$) does the relation depart to slightly higher efficiency for a given metallicity, with increased scatter. This relation can now be used to determine the star formation efficiency of Local Group “fossil” dwarfs.

Estimates in $f_*$ in the LG fossil dwarfs are obtained by varying the assumed total halo mass, $M_h$, and time averaged star formation parameter, $\epsilon_s$, to obtain best fits to the observed $M_V$ and $\langle [Fe/H] \rangle$, assuming the errors in these quantities tabulated by Mateo (1998). The optimization is done with a Monte Carlo Markov chain maximum likelihood estimator so that confidence intervals are also obtained. Figure 4 shows the results for total star formation efficiency $f_*$ compared with $T_{\text{vir}}$ derived from fits to the observed L-Z relation. For the model “true fossils”, $f_*$ ranges from 2 – 8%, while the best-fitting halo masses clearly indicate that these galaxies lie in the regime of cosmological “minihalos” at high redshift. There is also tentative evidence for a positive correlation of $f_*$ with $T_{\text{vir}}$, at 90% significance; a linear best fit is shown in the dotted line. These results assume a fixed $z_{\text{end}} = 6$, but there are no substantial changes to the individual values or trend if $z_{\text{end}} = 10$. The width of the model metallicity distribution function (MDF) does vary with $z_{\text{end}}$: shorter total star formation times (higher $z_{\text{end}}$) yield narrower distributions. Halos that form stars until $z = 6$ have broader distributions than those that had their star formation truncated earlier, but the existing observations of $\sigma([Fe/H])$ are too imprecise to use this as a sensitive indicator of the duration of their bursts. Constraints on models of the detailed star formation and feedback mechanisms in these objects would benefit from the more sensitive and precise observations of MDF and relative chemical abundances that future large telescopes could provide.

Based on these results I conclude that minihalos contribute significantly to the reionization of the IGM at $z > 6$. However, we cannot be sure that the minihalos we see today as fossil dwarf galaxies in the LG are typical of minihalos that formed in this region of space, or that the LG population is representative of the minihalo population as a whole. Such a concern could be answered by detailed examination of dwarf galaxies outside the Local Group, but this task is probably too challenging for observations in the near future. Future theoretical work should attempt a full chemo-dynamical treatment of the Local Group to help assess the bias of the LG dwarfs in mass or metallicity, which may change their place in the scheme of reionization.

Total masses inferred from the L-Z relation in the process of constructing Figure 3 are compared to their dynamically estimated masses in Figure 4 where the best-fit $M_h$ is plotted against the measured $M_{\text{vir}}$ for the nine fossils with rotation-curve mass estimates (Mateo 1998). The models generally best match the observed L-Z relation for masses similar to the dynamical estimates (a 1:1 ratio is marked with the dashed line). Thus it does not seem necessary to invoke significant mass loss from the “true fossils” to explain any of their observed properties, except in a few cases. By this measure, Sculptor, Antlia, and And VI appear to have lost significant mass in this interval. This apparent mass loss, compared with other galaxies, can be taken as a prediction of the models presented here that may be testable by more detailed examination of their stellar populations.

The merger-tree models keep individual account of all supernova-forming stars, so the distribution of stellar metallicities is known exactly at all times. The models specify the fraction of ionizing photons produced by stars of different metallicities. Figure 5 shows the fraction of ionizing photons from metal-free stars, $F_{Z=0}$, plotted against the total ionizing photon budget per baryon in the final halo ($N_\gamma \approx f_\gamma z_{\text{end}} \geq 1000$ for the $\tau_{\text{es}} \gtrsim 0.1$ models of TVS04) for four of the five IMF test cases of Tumlinson (2006). For $z_{\text{end}} = 6$ (open circles), the mean $F_{Z=0}$ is $\approx 5\%$ for IMFs A and D. Results for IMF B are similar to case A and are not shown in the figure. Cases C and E are more top-heavy and give $F_{Z=0} \approx 0.5$ with a long tail to high $F_{Z=0}$. Paper I showed that cases A, B, and D, provided the best overall fit to the data on Galactic chemical evolution, while cases C and E generally over-produce very massive stars that are inconsistent with the abundance data. If $z_{\text{end}} = 15$ (open squares), the relative contribution of metal-free stars is larger, $F_{Z=0} \approx 0.1 - 0.5$ for cases A and D, but here stars are formed for a shorter total time and so have reduced $N_\gamma \sim 200$. As reionization models typically require $N_\gamma \gtrsim 1000$ from minihalos (TVS04, HH03) to achieve $\tau_{\text{es}} \gtrsim 0.1$, it seems that a successful model cannot reproduce the WMAP $\tau_{\text{es}}$ and also have metal-free stars as the primarily agents of reionization. If the minihalos that survive are typical of those that formed during the epoch of reionization, it appears that metal-free stars started but could not have completed this critical transition in the state of matter in the IGM.
4. CONCLUSIONS

Based on halo-merger-tree chemical evolution models of Local Group “fossil” dwarfs, I conclude that:

1. Models of small dark matter halos forming stars during reionization accurately reproduce the observed luminosity-metallicity relation for LG dwarf galaxies with the same model parameters that also match the Galactic stellar halo.

2. The strong correlation between mean metallicity and total star formation efficiency in “true fossils” implies total star formation efficiency \( f_\ast = 2 - 8\% \) for halos with mass \( M_h = 10^7 - 10^8 \, M_\odot \), or \( T_{\text{vir}} = 2000 - 7000 \, \text{K} \) at \( z = 6 - 15 \).

4. By tracking chemical enrichment inside these small halos, the models also specify that metal-free stars contribute approximately 5 - 10 \% of the total ionizing photon budget from minihalos to \( z = 6 \). Thus metal-free stars probably did not provide the majority of ionizing photons to the IGM.

I conclude that dwarf galaxies that form all their star early and survive into the present-day Local Group provide sensitive indicators of the star formation history of low-mass “minihalos” during the epoch of reionization. By comparison with the results of RG05, which stimulated this work, my results more accurately describe the present-day luminosity-metallicity relation and independently derive the total star formation efficiency and first-stars contribution to the ionizing budget. Conversely, these models lack the sophisticated treatment of radiative feedback and three-dimensional hydrodynamical evolution that simulations allow and do not account for possible biases in the surviving dwarf galaxy populations. The two approaches therefore complement each other and show how Local Group fossils provide potentially critical tests of competing scenarios for reionization. These results suggest that no reionization model should be considered successful unless it correctly incorporates the metallicity and age of old LG stellar populations into the history of this critical epoch. Because LG dwarf galaxies provide important information that is not available directly at high redshift, we may have as much to learn about reionization from \( z = 0 \), where we can study it residues, as at \( z = 6 \), where it ended.

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REFERENCES

Bromm, V., Coppi, P., & Larson, R. B. 2001, MNRAS, 328, 969
Bromm, V. & Larson, R. B. 2004, ARA&A, 42, 79
Bullock, J. S., Kravtsov, A., & Weinberg, D. 2001, ApJ, 539, 517
Cen, R. 2003, ApJ, 591, L5
Caldwell, N. 1999, AJ, 118, 1230
Girardi, L. 2002, A&A, 391, 195
Haiman, Z., & Holder, G. P. 2003, 595, 1 (HH03)
Mateo, M. L. 1998, ARA&A, 36, 435
Ricotti, M., & Gnedin, N. Y. 2005, ApJ, 629, 259
Santoro, F., & Shull, J. M. 2006, ApJ, in press

Schneider, R., Ferrara, A., Natarajan, P., & Omukai, K. 2002, ApJ, 589, 35
Somerville, R. S., & Kollatt, T. S. 1999, MNRAS, 305, 1
Tumlinson, J., Venkatesan, A., & Shull, J. M. 2004, ApJ, 612, 602 (TVS04)
Tumlinson, J. 2006, ApJ, in press (Paper I)
Venkatesan, A., Tumlinson, J., & Shull, J. M. 2003, ApJ, 584, 621
Willman, B., et al. 2005, AJ, 129, 2692
Zucker, D. B., et al. 2004, ApJ, 612, L121
Fig. 1.— Luminosity-metallicity ($L-Z$) relation for model dwarf galaxies on constant-mass sequences with $M_h = 10^9, 10^8, 5 \times 10^7, 2 \times 10^7, 10^7 \, M_\odot$ from left to right. The star formation parameter $\epsilon$ ranges from $1 - 3 \times 10^{-10} \, \text{yr}^{-1}$ from the bottom to top of the constant-mass sequences. The Ursa Major dwarf (Willman et al. 2005) has only a metallicity range.
Fig. 2.— The total star formation efficiency, $f_*$, in small halos of varying mass that cease forming stars at $z_{\text{end}} = 6$. The symbols are the same as in Figure 1. The correlation of $f_*$ with mean metallicity is strong and insensitive to $M_h$ and $z_{\text{end}}$. 
Fig. 3.— The total star formation efficiency $f_*$ for the LG true fossils, derived from maximum likelihood fits to the observed mean metallicity and luminosity. $T_{\text{vir}}$ is evaluated at $z = 6$ using the best-fitting halo mass, $M_h$, and assuming this is unchanged since $z = 6$. The error bars mark the $2\sigma$ (95%) confidence intervals derived from Markov chain searches of $(M_h, f_*)$ parameter space. The dotted line marks a tentative linear fit to $(\log T_{\text{vir}}, f_*)$. 
Fig. 4.— Comparison of total halo mass, $M_h$, inferred from halo merger tree models with dynamical masses, $M_{\text{tot}}$. Error bars show 2$\sigma$ (95%) confidence intervals.
Fig. 5.— Ionizing photon fraction from metal-free stars, $F_{Z=0}$, versus total ionizing photon production, $N_\gamma$, for four of the IMF test cases in Tumlinson (2006), e.g. IMF A has $m_c = 10 \, M_\odot$ and $\sigma_{IMF} = 1.0$. 