THE SPATIAL DISTRIBUTION OF THE GALACTIC FIRST STARS I: HIGH-RESOLUTION N-BODY APPROACH

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ABSTRACT

We study the spatial distribution of Galactic metal-free stars by combining an extremely high-resolution ($7.8 \times 10^7 M_\odot$ per particle) Cold Dark Matter N-body simulation of the Milky-Way with a semi-analytic model of metal enrichment. This approach allows us to resolve halos with virial temperatures down to the $10^4 K$ atomic cooling limit, and it is sufficiently flexible to make a number of robust conclusions, despite the extremely uncertain properties of the first stars. Galactic metal-free stars are formed over a large redshift range, which peaks at $z \approx 10$, but continues down to $z \approx 5$, contributing stars at wide range of Galactocentric radii. Stars containing only metals generated by primordial stars are similarly widespread. Neither changing the efficiency of metal dispersal by two orders of magnitude, nor drastically changing the approximations in our semi-analytical model can affect these result. Thus, if they have sufficiently long lifetimes, a significant number of stars formed in initially primordial star clusters should be found in the nearby Galactic halo regardless of the specifics of metal-free star formation. Observations of metal abundances in Galactic halo stars should be taken as directly constraining the properties of primordial stars, and the lack of metal-free halo stars today should be taken as strongly suggesting a $0.8 M_\odot$ lower limit on the primordial initial mass function.

Subject headings: Galaxy:formation – Galaxy:evolution – stars:abundances – cosmology:theory

1. INTRODUCTION

Metals are made in stars, but stars need not to have metals. While the early universe was an efficient source of helium, primordial nucleosynthesis was halted before it was able to produce elements heavier than lithium. Thus the first stellar generation of Population III (PopIII) stars condensed from a gas that was free of carbon, silicon, iron, or any of the other heavy elements that are prominent today.

Indeed, to date not a single star has been observed that does not contain metals. Instead stellar nucleosynthetic products are everywhere. The lowest metallicity galaxies known are enriched to $\sim 0.02 Z_\odot$ (Searle & Sargent 1972); the lowest-density regions of the intergalactic medium (IGM) appear to be enriched out to the highest redshifts probed (Schaye et al. 2003; Pettini et al. 2003; Aracil et al. 2004); and extensive searches for metal-poor halo stars have failed to uncover any PopIII candidates beyond a handful of stars with extremely low abundances of elements heavier than magnesium (Christlieb et al. 2002; Cayrel et al. 2004). Interpretation of these stellar abundances is especially complicated by the fact that searches for metal-poor stars are targeted at the Galactic halo, where dust extinction is minimal and crowding is not a serious concern. These analyses have provided a number intriguing constraints on the enrichment history of the halo (Freeman & Bland-Hawthorn 2002; Beers & Christlieb 2005), including detailed measurements of the metallicity distribution function from $[\text{Fe/H}] \sim -5$ to $[\text{Fe/H}] \sim -1$ (e.g. Ryan & Norris 1991; Beers et al. 1992; Barklem et al. 2005), a detection of a shift in iron peak ratios below $[\text{Fe/H}] \sim -3$ (McWilliam et al. 1995; Carretta et al. 2002; Cayrel et al. 2004, Cohen et al. 2004), and the presence of extremely heavy element deficient stars in which $\text{[C/Fe]} > 2.0$ (Christlieb et al. 2002; Frebel et al. 2005). While these and other observations have provided the basis for several theoretical analyses of the first stars (e.g. Hernandez & Ferrara 2001; Scannapieco, & Broadhurst 2001; Oey 2002; Schneider et al. 2003; Tumlinson 2006), these are subject to substantial uncertainties due to the unknown spatial distribution of such objects.

In fact, it is still unclear how the observed population of halo stars is related to PopIII star formation. Indeed, White & Springel (2000) used high-resolution cosmological simulations to show that the oldest stars are naturally strongly concentrated towards the center of the Galaxy, but stars that form in the full population of $T_{\text{vir}} \approx 10^4$ K halos are widely distributed. More recently, Diemand, Madau, & Moore (2005) used a resimulation technique to track the positions of particles contained in the protogalactic halos collapsing from very rare $3.0\sigma$ and $3.5\sigma$ perturbations (where $\sigma^2$ is the variance of linear fluctuations on the scale of the objects). Associating PopIII stars with $3.0\sigma$ perturbations, they found that the density of such objects in the Galactic halo at the radius of the solar orbit is three orders of magnitude lower than in the bulge. Associating PopIII stars with $3.5\sigma$ per-
turbations led to even more extreme results, decreasing the number of first stars at the solar orbital radius by almost another order of magnitude. Similarly, Karlsson (2006) was able to reproduce a “metallicity desert” between \([\text{Fe}/\text{H}] = -5 \text{ and } -4\) by associating metal-free star formation with only the very earliest forming stars.

Yet this association of metal-free stars with the highest density regions is likely to be misleading. As shown in Scannapieco, Schneider, & Ferrara (2003, hereafter SSF03; see also Schneider et al. 2006) cosmological enrichment was a local process, which occurred in different regions over an extended redshift range. Thus while the peak of PopIII star formation is likely to have occurred at \(z \approx 10\), such stars should have continued to form at much lower redshifts. Furthermore, in these models metal free stars do not form in perturbations of a given \(\sigma\), but rather within \(10^{-18} \mathcal{M}_\odot - 10^9 \mathcal{M}_\odot\) objects, which are just large enough to cool within a Hubble time, but small enough that they are not clustered near areas of previous star formation.

This spread in \(\sigma\) and formation redshift raises the prospect that the remnants of metal-free protogalactic clouds would have indeed ended up in the halo. This would mean that the absence of observed metal-free objects might require the first stars to form with an initial mass function (IMF) biased to stars with lifetimes shorter than a Hubble time, and perhaps even biased to masses \(\geq 100 \mathcal{M}_\odot\) as suggested by a number of recent theoretical studies (e.g. Nakamura & Umemura 1998; Abel, Bryan, & Norman 2000; Bromm et al. 2001; Schneider et al. 2002; Ripamonti et al. 2002; Tan & McKee 2004). Furthermore, it would mean that some of the stars with unusual yields found in the halo of our galaxy are indeed providing us with direct information about the yields of PopIII stars.

In this paper we combine an extremely high-resolution N-body simulation of the formation of the Milky-Way with a semi-analytical model of metal enrichment that closely parallels that discussed in SSF03. While we plan to conduct a careful comparison of this approach with a more direct chemodynamical model of the Milky-Way in a companion publication (Brook et al. in prep.), the dark-matter based model described here nevertheless has a number of distinct advantages. Although gas cooling is essential to reproduce the spatial distribution of late-forming metal-rich Galactic disk stars, the spatial distribution of low-metallicity stars in the bulge and halo can be approximated from an N-body point of view. Such stars were formed at early times in star clusters contained in much smaller dark matter halos, and they subsequently evolved as collisionless particles. Thus by carefully tagging N-body particles directly in progenitor halos as star-particles, we can use them to infer the positions of the earliest stellar populations. This approach allows us to work at a mass resolution \((7.8 \times 10^7 \mathcal{M}_\odot)\) per dark-matter particle that is currently impossible in gas simulations of the Milky-Way, which means that we can capture the formation of all halos within which efficient star-formation is expected to occur.

Our semi-analytic model of metal enrichment, on the other hand, gives us the flexibility to use this simulation to study a wide range of models for the properties of the first stars. As the typical mass of such stars remains uncertain within at least two orders of magnitude, the metal and kinetic energy output from SNe arising from PopIII stars remains completely unknown. This uncertainty is further compounded by the possibility that metal-free stars in the \(\approx 200 \mathcal{M}_\odot\) mass range may have given rise to tremendously powerful pair-production supernovae (e.g. Heger & Woosley 2002), with kinetic energies up to \(10^{53}\) ergs per event. While exploring this full range of possibilities by direct simulations is extremely computationally expensive, our technique allows us to carry out this parameter study in a few minutes, leading to a number of robust conclusions despite the large uncertainties involved.

The structure of this work is as follows. In §2 we describe our simulations and semi-analytical model. In §3 we apply our model to consider the distribution of the first and second stars in a wide range of cosmological scenarios. Conclusions are given in §4.

2. Method

To identify the location of PopIII stars in our galaxy, we combine a high-resolution N-body simulation of the formation of a Milky-Way size galaxy with a semi-analytical model of metal enrichment. In §2.1 we describe our simulation in detail, as well as the method we use to extract gravitationally bound halos. In section §2.2, we describe our semi-analytical model and discuss how it is used to construct the expected positions for stars forming from gas that is initially primordial, which we label as “the first stars,” and stars forming from gas that is initially enriched by only primordial stars, which we label as “the second stars.”

2.1. Simulation and Identification of Halos

Throughout our study we assume a Cold Dark Matter model with parameters \(\hbar = 0.71, \Omega_0 h^2 = 0.135, \Omega_A = 1 - \Omega_0, \Omega_b h^2 = 0.0224, \sigma_8 = 0.9, \text{ and } n = 1\), where \(h\) is the Hubble constant in units of 100 \(\text{km/s/Mpc}\), \(\Omega_0\), \(\Omega_A\), and \(\Omega_b\) are the total matter, vacuum, and baryonic densities in units of the critical density, \(\sigma_8^2\) is the variance of linear fluctuations on the \(8h^{-1}\text{Mpc}\) scale, and \(n\) is the “tilt” of the primordial power spectrum (e.g. Spergel et al. 2003). Our N-body simulation is carried out with the GCD+ code (Kawata & Gibson 2003a), and it uses a multi-resolution technique (Kawata & Gibson 2003b) to achieve high-resolution in the regions of interest, while the outer regions exerting tidal forces are handled with lower resolution.

The initial conditions for these simulations at \(z = 56\) are constructed using the public software GRAFIC2 (Bertschinger 2001). The low-resolution region is a \(20h^{-1}\text{ Mpc}\) diameter sphere selected from a low-resolution cosmological simulation, for which an isolated boundary condition is applied. The highest resolution region is a sphere with a radius four times the virial radius of the system at \(z = 0\). In this region, the Dark Matter (DM) particle mass and softening length of are \(M_{\text{vir}} = 7.8 \times 10^5 \mathcal{M}_\odot\) and \(r_{\text{vir}} = 540\) pc, respectively. The system consists about \(10^6\) particles within the virial radius. The virial mass and radius of the system at \(z = 0\) are \(M_{\text{vir}} = 7.7 \times 10^{11} \mathcal{M}_\odot\) and \(r_{\text{vir}} = 239\) kpc, which are roughly consistent with the estimated mass \(M_{\text{vir}} = 1.0 \times 10^{12} \mathcal{M}_\odot\) and virial radius \(r_{\text{vir}} = 258\) kpc of the Milky Way (Klypin, Zhao, &
of dissociating photons is 1994) to generate a total of 2001; see also Schaerer 2002; Venkatesan, Tumlinson, & Rees 2001; see also Schaerer 2002; Venkatesan, Tumlinson, & Rees 2001; see also Schaerer 2002; Venkatesan, Tumlinson, & Rees 2001; see also Schaerer 2002; Venkatesan, Tumlinson, & Rees 2001; see also Schaerer 2002; Venkatesan, Tumlinson, & Shull 2003) and the stars live 30 Myrs (Fagotto et al. 1994) to generate a total of \(10^{62}\) dissociating photons per star. In the 200 \(M_\odot\) case the dissociating rate is \(\approx 2 \times 10^{49}\) s\(^{-1}\), but the lifetime is only 2 Myrs, resulting in a total of \(10^{63}\) such photons per star. Combining these values with the \(3 \times 10^{-4}\) mean cosmological fraction of \(H_2\) (e.g. Yoshida et al. 2003), we can estimate the typical radius of a region dissociated by a primordial star as \(r_{\text{diss}} = 200\Delta^{-1/3}\) comoving kpc in the 10 \(M_\odot\) case and \(r_{\text{diss}} = 450\Delta^{-1/3}\) comoving kpc in the 200 \(M_\odot\) case, where \(\Delta = \rho/\bar{\rho}\) is the mean overdensity of the dissociated region.

Using a low-resolution simulation including gas physics and star formation, we confirm that this initial condition will lead to a disk galaxy. A closer comparison between our results here and a lower-resolution gas-dynamical model will be presented in a future publication (Brook et al. in prep.). While gas physics is essential to reproduce the spatial distribution of disk stars, an N-body approach is appropriate for the halo and bulge populations on which we are focused here. Such stars should initially form in much smaller gas disks condensing in neighboring halos, and later interact as collisionless particles. Thus by carefully tagging N-body particles directly in progenitor halos as star-particles, we can use them to infer the positions of the first and second stars in our final galaxy.

The simulation data is output every 0.11 Gyr, and at each output, we use a friend-of-friends group finder (FOF, Davis et al. 1985) to identify the virialized DM halos. We apply a standard approach with a linking parameter of \(b = 0.2\) and threshold number of particles of 50, and we explore the results of varying this parameter below. We then construct a merger tree, associating the halos at different time steps. In particular, we search for the halo at each time step \(t\) that contains the largest number of the member particles of a given halo at the previous time step, \(t - 1\). We define the virial mass and radius for each halo, taking into account the density necessary to cool effectively to approximately 10\(^4\) K for star formation in halos at all redshifts. In our 200 \(M_\odot\) case this mass is \(\approx 2 \times 10^{47}\) ergs (Heger & Woosley 2002). Thus less than 1% of the universe is likely to have been enriched by this earliest generation of stars, and this only in the very densest regions. Rather the majority of primordial enrichment is should have occurred in larger objects with \(T_{\text{vir}} \geq 10^4\) K.

In this case, (sometimes referred to as Population II.5; e.g. Grieve & Bromm 2006) efficient atomic-line cooling establishes a dense locally-stable disk within which non-equilibrium free electrons catalyze \(H_2\). Unlike in less massive halos, \(H_2\) formation in these objects is largely impervious to feedback from external UV fields, due to the high densities achieved by atomic cooling (Oh & Haiman 2002). As discussed in SSF03, regions of late primordial star formation may have already been detected as a subgroup of high-redshift Lyman-alpha emitters, although distinguishing them from Population II/I stars is extremely difficult (Dawson et al. 2004).

In this study then, we adopt a fixed threshold of \(T_{\text{vir}} \geq 10^4\) K for star formation in halos at all redshifts. In our cosmology, and for the high redshifts relevant for the formation of primordial objects, this corresponds to a minimum mass of

\[
M_{\text{min}} \equiv 3.0 \times 10^9(1 + z)^{-3/2} M_\odot.
\]

While at high-redshift this mass can be over four orders of magnitude smaller than the final virial mass of the Galaxy, our high-resolution simulation nevertheless makes it possible to trace these objects. This means that at redshifts below 17, all the halos relevant to our study will contain at least 50 particles and be well-identified by our FOF group finder. However, at the very earliest redshifts \(\geq 17\) such halos will only be marginally resolved.

### 2.2. Identification of First and Second Objects
Having constructed the history of dark matter halos as a function of redshift, our next step is to use this to identify two types of objects: i) halos that collapse out of primordial gas, which we identify as Population III objects containing “the first stars,” and ii) halos that collapse from gas that has been enriched purely by material ejected from the Population III objects, which we identify as second-generation objects containing “the second stars.” While we vary the IMF of the first stars over a wide range of possibilities, we assume that the second stars form with an IMF similar to that seen today, although they are likely to display peculiar enrichment patterns.

It is important to make clear that our model is not able to say anything about the progression of star formation and self-enrichment within a particular halo (see e.g. Susa & Umemura 2006). Rather, our labels purely reflect the properties of the most metal-poor stars formed in any given region. Thus it is entirely possible that some fraction of the stars forming in halos that collapse from primordial gas will nevertheless contain metals that were inherited from other stars forming in the same temporarily-extended burst. For our purposes here then, stars formed in such self-enriched primordial star clusters are included in the distribution of “the first stars.” Similarly we exclude all halos that are direct descendents of first objects from our list of second generation objects, as these would exist cospatially with stars that were truly primordial.

These definitions are intended to extract the most information possible from our modeling approach. For observers, anywhere labeled first stars would be a good place to search for metal-free stars, if they are sufficiently long-lived to survive until today. Similarly, both regions labeled first stars and second stars in our method would be a good places to search for stars enriched purely by the products of metal-free stars. From a theoretical point of view, the spatial distribution of first stars in our models should be directly comparable to the spatial distribution of metal-free stars in future detailed gas simulations, while the spatial distribution of both first and second stars should be comparable to the spatial distribution of PopIII-enriched stars in such simulations. These definitions are important to keep in mind when interpreting our results, as emphasized below.

As the distribution of both these populations of stars is primarily dependent on the highly-uncertain properties of Population III objects, our goal is to develop a simple model of metal dispersal that allows us explore a large range of possibilities in a straightforward way. Following our approach in SSF03, we adopt a model of outflows as spherical shells expanding into the Hubble flow (Ostriker & McKee 1988; Tegmark, Silk & Evrard 1993), for both PopIII and PopII/I objects. These shells are assumed to be driven only by their internal hot gas pressure and decelerated by inertia due to accreting material and gravitational drag while escaping from the host. In this case there are two relevant evolutionary equations: one that describes the change in the velocity of the bubble,

\[ \frac{\dot{R}_b}{\rho R_s} = \frac{3P_b}{\rho R_s} \frac{3}{R_s} (\dot{R}_s - H R_s)^2 - \Omega_M \frac{H^2 R_s}{2}, \]

where the terms on the right hand side correspond to internal pressure, accumulation of material from the surrounding medium, and gravitational drag, respectively, and a second equation that describes the evolution of the internal energy of the bubble,

\[ \dot{E}_b = L(t) - 4\pi R_b^2 \dot{R}_b \rho_b, \]

where the terms on the right hand side correspond to energy input from the supernovae and the \( PdV \) work done by the interior gas. In these equations the overdots represent time derivatives, the subscripts \( s \) and \( b \) indicate shell and bubble quantities respectively, \( R_s \) is physical radius of the shell, \( E_b \) is the internal energy of the hot bubble gas, \( P_b \) is the pressure of this gas, and \( \rho_b \) is the mean IGM background density. Here we assume adiabatic expansion with an index \( \gamma = 5/3 \) such that \( P_b = E_b/2\pi R_s^2 \).

The evolution of each such bubble is completely determined by the mechanical luminosity evolution assigned, \( L(t) \). Again for simplicity, we take both PopIII and PopII/I objects to undergo a starburst phase of \( t_{SN} = 5 \times 10^7 \) years, but with different prescriptions for the total energy input into the wind. We approximately account for the gravitational potential of the host galaxy by subtracting the value of \( GM^2\langle \Omega_b/\Omega_M \rangle/r_{vir} \) from the total wind energy, where \( M \) is the total mass (dark + baryonic) of the object and \( r_{vir} \) is its virial radius. Approximating the collapse overdensity by a constant value of 178, the overdensity associated with a virialized cosmological object, then gives a mechanical luminosity of

\[ L(t) = 160L_\odot \left[ f_{III,II} f_{w} E_{kin}^{III,II} N^{III,II} \right. \\
\left. -5 \times 10^{-12} (M_b h \Omega_M/\Omega_b)^{2/3} (1 + z_c) \right] M_b \Theta(t_{SN} - t), \]

where \( f_s \) is the fraction of gas converted into stars, \( f_w \) is the fraction of the SN kinetic energy that is channeled into the galaxy outflow, \( E_{kin} \) in the kinetic energy per supernova, \( N \) is the number of supernovae per M\(_\odot\) of stars, \( M_b \) is the baryonic mass of the galaxy in units of solar mass, \( z_c \) is the collapse redshift of the object, and \( \Theta \) is the Heaviside step function. Note the precise value of \( t_{SN} \) is not important as long as it short relative to the \( \approx 500 \) Myr Hubble time at the redshift in which we are most interested. However, the value of the prefactor in front of \( E_{kin} \) in eq. (3) is defined by this choice. Halving \( t_{SN} \), for example would require for us to double this factor but have only a very weak effect on the time that the bubbles reach their neighbors, and hence on the final distribution of first and second stars. Note also that the gravitational drag is only important in objects with total masses \( \gtrsim 10^{13}(1 + z)^{-3/2}M_\odot \), and thus has only a minor impact on our results here.

The only difference in the wind evolution of PopIII and PopII/I arises from the product, \( f_{III,II} f_{w} E_{kin}^{III,II} N^{III,II} \), which, again following SSF03, we define as the "energy input per unit gas mass" \( E_{g}^{III,II} \), which we express below in units of 10\(^{53}\)erg M\(_\odot^{-1}\).

To determine this value in the PopII/I case, we take \( f_{w} \) to be 0.1, which gives good agreement with the observed high-redshift star formation rates and abundances of metals measured in quasar absorption line systems (Thacker, Scannapieco, & Davis 2002; Scannapieco, Ferrara, & Madau 2002). Also in this case, we constrain \( f_w \) by combining the overall efficiency of 30% derived
for the $2 \times 10^8 M_\odot$ object simulated by Mori, Ferrara, & Madau (2002) with the mass scaling derived in Ferrara, Pettini & Shchekinov (2000), which was obtained by determining the fraction of starburst sites that can produce a blow-out in a galaxy of a given mass. This gives $f_w(M) = 0.3 \delta_B(M)/\delta_B(M = 2 \times 10^8 M_\odot)$ where

$$\delta_B(M) = \begin{cases} 
1.0 & 0 \leq \hat{N}_t \leq 1 \\
1.0 - 0.165 \ln(\hat{N}_t) & 1 \leq \hat{N}_t \leq 100 \\
[1.0 - 0.165 \ln(100)] \frac{100}{\hat{N}_t} & 100 \leq \hat{N}_t 
\end{cases}, \tag{5}
$$

and $\hat{N}_t \equiv 1.7 \times 10^{-7} (\Omega_b/\Omega_M) M/M_\odot$ is a dimensionless parameter that increases linearly with the overall number of SNe produced in a starburst, divided by the star formation efficiency, $f_{\text{SFE}}$.

In the PopIII case, on the other hand, there are no direct constraints on either $f_{\text{SFE}}^\text{PopIII}$ or the wind efficiency. For these objects we allow these parameters to be free, varying $t_{\text{SFE}}$ over a large range as discussed below. Finally, when outflows slow down to the point that they are no longer supersonic, our approximations break down, and the shell is likely to be fragmented by random motions. At this point we let the bubble expand with the Hubble flow. These prescriptions then give us a complete model of $R_{\text{III,II}}(M, z, z')$, the comoving radius of an outflow at a redshift $z'$ associated with a PopIII or PopII/I halo of mass $M$ collapsing at a redshift $z$.

Our goal is then to tag halos that form outside of all expanding shells as first stars objects, and to tag halos that form within PopIII outflows as second-stars objects. In our fiducial model we assume that in each such halo stars form with the same radial profile as the dark matter, although we also vary this assumption in §2.2. As we are concerned only with whether a halo is contained within any such wind from a neighbor or direct progenitor, we need not worry about the possibility of double counting by identifying the same collapsed object at multiple outputs. Rather to determine if a halo forming at a redshift $z'$ has been enriched, we can safely compute $R_{\text{III,II}}(M, z, z')$ for each and every object forming with $z > z'$ and determine if any of them has overtaken the lower-redshift object. In this case the impact of a given halo on its neighbors as well as its direct descendants will be determined by the maximum $R_{\text{III,II}}(M(z), z, z')$ computed at any $z > z'$, while all other smaller shells will have no impact on the calculation.

While this picture neglects the precise density and infall structure around each forming object, we are able to quantify the errors arising from this approximation by adopting two methods for computing the distance between two objects. Note however that as the outflows we are most concerned with occur at very high redshift, the nonlinear evolution of structure will not be as severe an issue as it is for lower-redshift winds.

One method of computing distances, which we shall refer to as “Eulerian,” allows each wind to move along with the center of mass of its central halo. This means that as we move between each output we compute the most likely daughter halo associated with each higher redshift outflow and re-center it around the position of this object. This takes advantage of the nonlinear motions computed in the simulation, but is likely to overestimate the impact of winds as it does not take into account the impact of infall around collapsing structures.

A second method of computing distances, which we shall refer to as “Lagrangian,” works completely in the reference frame in which the position of each halo is computed as the center of the mass of the original $z = 55.7$ positions of the particles it contains. While this approach neglects much of the nonlinear information available from the simulation, it is neverthelless likely to represent a more fair comparison as: i.) our thin-shell solution, which assumes expansion in the Hubble flow, is essentially already working in this coordinate system; ii.) enrichment should be more closely dependent on the column depth between the source and recipient halos than on their physical separation. Furthermore this approach most directly parallels that of our previous analytical models (SSF03), and thus we adopt it as our fiducial method in the results presented below.

### 3. RESULTS

In this section we summarize our results for a wide range of parameters choices and assumptions, the details of which is described in detail below. For reference purposes, the specifics of each of these runs is summarized in Table 1.

#### 3.1. Fiducial Modeling

In Figure 11 we show the star formation rate in first and second stars as a function of redshift, for a wide range of feedback efficiencies and for both Lagrangian and Eulerian distances, corresponding to runs 2L-4L and 2E-4E in Table 1 respectively. When computing the star formation rate, we consider only stars that end up gravitationally bound to our final galaxy, so as to exclude objects formed near the boundary of the simulation volume. In all cases we assume $f_{\text{SFE}} = f_{\text{SFE}}^\text{PopIII} = 0.1$ such that 10% of the gas mass in each PopIII halo is converted into stars. Note that while this value is consistent with the observed star formation rate of normal stars at lower redshifts (e.g. Scannapieco, Ferrara, & Madau 02), it is certainly possible that metal-free star formation was less efficient and that a lower value such as $f_{\text{SFE}}^\text{PopIII} = 0.01$ is appropriate in the PopIII case. While this normalization will remain a primary uncertainty in our investigation, it

### Table 1

| Model Name | $t_{\text{SFE}}$ | Distance Linking | Distribution of Stars | Minimum $T_{\text{vir}}$ |
|------------|-----------------|------------------|------------------------|-------------------------|
| 2L         | Lagrangian 0.2  | Follows DM       | 10^4 K                 | 10^4 K                  |
| 3L         | Lagrangian 0.2  | Follows DM       | 10^4 K                 | 10^4 K                  |
| 4L         | Lagrangian 0.2  | Follows DM       | 10^4 K                 | 10^4 K                  |
| 2E         | Eulerian 0.2    | Follows DM       | 10^4 K                 | 10^4 K                  |
| 3E         | Eulerian 0.2    | Follows DM       | 10^4 K                 | 10^4 K                  |
| 4E         | Eulerian 0.2    | Follows DM       | 10^4 K                 | 10^4 K                  |
| 2Lc        | Lagrangian 0.2  | Central 10%      | 10^4 K                 | 10^4 K                  |
| 3Lc        | Lagrangian 0.2  | Central 10%      | 10^4 K                 | 10^4 K                  |
| 4Lc        | Lagrangian 0.2  | Central 10%      | 10^4 K                 | 10^4 K                  |
| 2L15       | Lagrangian 0.15 | Follows DM       | 10^4 K                 | 10^4 K                  |
| 3L15       | Lagrangian 0.15 | Follows DM       | 10^4 K                 | 10^4 K                  |
| 4L15       | Lagrangian 0.15 | Follows DM       | 10^4 K                 | 10^4 K                  |
| 2LRe       | Lagrangian 0.2  | Central 10%      | 10^4 K/5×10^4 K        | 10^4 K/5×10^4 K         |
| 3LRe       | Lagrangian 0.2  | Central 10%      | 10^4 K/5×10^4 K        | 10^4 K/5×10^4 K         |
| 4LRe       | Lagrangian 0.2  | Central 10%      | 10^4 K/5×10^4 K        | 10^4 K/5×10^4 K         |
can be easily accounted for by rescaling our final results, and does not affect the overall trends on which we are primarily focused.

In SSF03, we considered the range of physically possible $\xi_{E}^{III}$ values in detail. An upper bound is provided by the case in which the initial mass function (IMF) of primordial stars is biased to very high masses $>100 M_\odot$. While much of the stars in this mass range would have died forming black holes, progenitors with masses between 140 and 260$M_\odot$ end their lives in tremendously powerful pair-production supernovae. In these SNe, $e^+e^-$ pair creation softens the equation state at the end of central carbon burning, leading to rapid collapse, followed by explosive burning (e.g. Barkat, Rakavy, & Sack 1967; Ober, El Eid, & Fricke 1983; Bond, Arnett, Carr 1984; Heger & Woosley 2002). The more massive the star, the higher the temperature at bounce and the heavier the elements that are produced by nuclear fusion. In all cases, the star is completely disrupted and the ejection energies ($\approx3-100 \times 10^{51}$ ergs) are enormous. In this case, choosing a narrow Gaussian IMF centered at 200 $M_\odot$, taking a 10% star formation efficiency, and fixing $f_w \approx 0.5$ places a generous upper limit of $\xi_{E}^{III} = 10^{-2}$, corresponding to the strongest feedback model in Fig. 1.

Note that while this extreme model is useful to set an upper limit on feedback, widespread enrichment from stars with such an IMF is inconsistent with the observed abundance patterns of metal poor stars owing to the absence of pair-instability yields in the data (Umeda & Nomoto 2003; Tumlinson, Venktesan, & Shull 2004).

A lower limit on $\xi_{E}^{III}$, on the other hand, is computed by assuming that such stars form with a typical Salpeter IMF, $f_w^{III} \approx 0.1$ and $f_w \approx 0.1$, which gives $\xi_{E}^{III} \approx 10^{-4}$. Not only does this model take metal ejection from PopIII to be somewhat less efficient than from PopII/I objects, but as shown in SSF03, even less efficient models of PopIII metal ejection are so weak that a large primordial star formation rate is predicted to this day. Thus the weakest, $\xi_{E}^{III} = 10^{-4}$, model shown in Figure 1 can be taken to represent a conservative estimate of the minimum efficiency with which metals from PopIII objects were mixed into their surroundings.

This large range of efficiencies of PopIII objects is what forces us to adopt a semi-analytical model of winds in the first place. Yet, as shown in Figure 1, robust general conclusions can be drawn despite these uncertainties. Firstly, the primordial objects that predated the Milky-Way were formed over an extremely large range of redshifts, mirroring the overall cosmological PopIII distribution (see SSF03). Furthermore, for all $\xi_{E}^{III}$ values, and in both the Eulerian and Lagrangian models, appreciable PopIII star formation continues down to a relatively low redshift of $z \approx 5$. In fact, excluding the most extreme models, PopIII formation continues at a substantial rate down to $z \approx 3$.

While increasing the efficiency of feedback has the impact of moving the PopIII star formation to higher redshifts, the overall $z \approx 10$ peak and $\Delta z \approx 5$ width of the epoch of PopIII formation are surprisingly constant among models. Instead, the distribution of second stars is much more sensitive to these uncertainties, ranging from an extended burst in the $\xi_{E}^{III} = 10^{-2}$ case, to a weak high-redshift burst in the $\xi_{E}^{III} = 10^{-4}$ case.

Again, we stress that these second stars are the stars forming in halos that have been initially pre-enriched by PopIII neighbors, and that a significant population of Pop-III enriched stars are also likely to exist in “first stars” halos forming of initially primordial gas. Finally, comparing the Eulerian and Lagrangian models, we find, as expected, that Eulerian distances lead to somewhat more efficient metal dispersal, although this is likely to be somewhat of an overestimate. Nevertheless the differences between these two models are relatively mild for all choices of $\xi_{E}^{III}$, giving us further confidence in the approximations involved in our semi-analytic approach.
Fig. 2.— Distributions of first and second stars (3rd and 4th columns) in a a 200 proper kpc³ region, at various redshifts, in model 2L, a Lagrangian model with $E_{III}^{III} = 10^{-2}$. For comparison, the 1st and 2nd columns show all the particles and all the particles within halos with masses above $M_{\text{min}}$ in equation (1), respectively. In the 1st and 2nd columns, to avoid confusion, we only plot 1/10 of the whole sample.
Fig. 3.— Distributions of first and second stars at $z = 0$ in our fiducial, Lagrangian models. From top to bottom, the rows correspond to the central 100 kpc region in the $E^{III} = 10^{-2}$ model, the central 100 kpc in the $E^{III} = 10^{-4}$ model, the central 10 kpc in the $E^{III} = 10^{-2}$ model, and the central 10 kpc in the $E^{III} = 10^{-4}$ model. In interpreting this figure, it is important to note that we are explicitly ignoring mass loss due to stellar evolution.
but now on the outer regions of the progenitor galaxy, because they are not yet affected by the bubbles from the first stars that formed preferentially in the central region. As seen in the star formation rate plot, Figure 1 the formation of the first and second stars is complete around \( z = 3 \), at which time the full region is enriched with metals. Also at this redshift, first and second stars start to be accreted into the assembling Galactic halo. This assembly is almost complete by \( z = 1 \), and thus the distribution at this redshift is similar to that at \( z = 0 \), although at \( z = 0 \) the stars are more smoothly distributed.

In Figure 3 we show the \( z = 0 \) spatial distribution of the first and second stars in closer detail, contrasting two extreme models with strong \( \xi_{III} = 10^{-2} \) and weak \( \xi_{III} = 10^{-4} \) feedback. From this figure, we see that for all choices of \( \xi_{III} \), the first or second stars are not confined to the center of the Galaxy. Rather, this plots shows a widespread distribution that is punctuated by dense concentrations of stars associated with satellite galaxies, as seen most clearly in the 100 kpc panels. Furthermore, comparing the satellite distributions between the two models shows that as one moves from the strongest to the weakest feedback models, a large number of the satellite second-generation objects switch over to the first-generation population. This is because these objects were only enriched by primordial stars, thus a large number of them form from primordial gas if the winds from PopIII stars are weakened. The more isolated the satellite galaxy, the more likely it is to contain primordial stars even in strong feedback models.

Focusing on the central 10 kpc of our simulation, which is more representative of the Galaxy itself, we see that the distribution of first and second stars, while peaked towards the center, nevertheless contains many stars at large radii. Again this is true even in the most extreme feedback models, and it represents the single most important finding of our investigation. If they have sufficiently long lifetimes, a significant number of stars formed in initially primordial star clusters should be found in the Galactic halo, regardless of the specifics of PopIII star formation.

To quantify this statement further, in Figure 4 we plot the radial mass density of first and second stars, as compared to the dark matter distribution in our simulation. Again, in computing these masses, we assume that 10% of the gas mass in each halo is converted into stars and we intentionally make no attempt to account for mass loss due to the evolution of these stars. Furthermore, we plot only out to 250 kpc, which is 1/4 the size of the high-resolution region.

Here we see that the density profiles of first and second stars are similar to the total dark matter density profile, although the second stars have a slightly shallower slope. As a result, the density of first stars at the center is 100 times higher than at the 8 kpc orbital radius of the sun. However, the important number for developing observational strategies is the relative density of such stars with respect to field stars. While this is not directly computed in our simulation, the lower panels of Figure 4 show the local mass density of stars normalized by the local density of dark matter.

Amazingly, the mass fraction contained in the first stars varies only very weakly with radius. Moving from 1 to 100 kpc in the \( \xi_{III} = 10^{-4} \) model, for example, the fraction of the mass in first stars decreases only by a factor \( \approx 4 \). Furthermore, increasing the efficiency of PopIII winds to \( \xi_{III} = 10^{-2} \) has the effect of decreasing the fraction of first stars without strongly affecting their radial distribution. Note that in the inner region, the overall stellar density is expected to be higher than dark matter density (e.g. Widrow & Dubinski 2005), that is the density of spheroidal stellar component of the Milky Way decreases with the radius more quickly than the dark matter component. Therefore, the fraction of the first stars compared with the field stars should be somewhat higher at large radii than what Figure 4 predicts. This raises the possibility that the overall fraction of first stars may even be higher in the halo than in the bulge!

These results have a number of immediate implications. First, as stars enriched only by primordial stars (which trace the overall distribution of both first and second stars in our study) are found throughout the Galactic halo, measured abundances of metal-poor stars in the Galactic halo should be taken as directly constraining the properties of primordial objects. Furthermore since only a slightly larger fraction of stars in the Galactic bulge are primordial, there is no compelling theoretical reason that observations should have to focus in this extremely difficult region. Instead the lack of metal-free stars observed in the halo is likely to imply a real lower mass limit in the metal free IMF of at least \( 0.8M_\odot \), the mass of a low-metallicity star with a lifetime comparable to the Hubble time (Fagotto et al. 1994). In fact the \( \sim 10^{-6} M_\odot \) pc\(^{-3} \) value for PopIII stars in the solar neighborhood we compute is so high as compared to the observed stellar mass density of \( 5 \times 10^{-6} M_\odot \) pc\(^{-3} \) (Preston, Shectman, & Beers 1991) that several primordial \( 0.8M_\odot \) stars would
White & Springel (2000) also estimated the history of stars are very strongly concentrated near the Galactic center, and that their relative number density drops by at least a factor of 30 as we move towards 8 kpc. In the lower left panel of this figure, we plot the normalized radial mass density of first stars with formation redshifts above 10. This shows that essentially all of the earliest forming first stars are located near the Galactic center, to a spatial distribution closely following the overall dark matter distribution. Our more detailed modeling shows that metal free star formation displays elements of both these scenarios. Primordial stars form in the smallest halos that can cool efficiently, while always high, nevertheless drop off strongly as a function of radius.

Finally, the upper right panel of Figure 5 shows the average formation redshift of second stars in our simulation. Again we remind the reader that these are the stars that contain metal from primordial stars but are not formed in the same star clusters. These stars display a similar radial trend as the first stars, but shifted to somewhat lower formation redshifts. In this case, the majority of these stars in the solar neighborhood are formed at redshifts below 8, as shown in the lower right panel of this figure.

3.2. Model Tests and Refinements

As our results in Figs. 3 and 4 have a number of wide-reaching implications, it is important to understand to what degree they are dependent on our assumptions. The primary simplification in our model is our use of a Lagrangian coordinate system combined with a bubble model that assumes expansion into the Hubble flow. To assess this approximation, we show in Figure 6 the results of a calculation that replaces the initial coordinates with "Eulerian positions" that re-center each bubble from output, as described in §2.2. As this approach combines the large bubble radii computed in the absence of infall, with the small separation computed by account-
ing for the proper motions of halos, it can be taken as providing a lower limit on the distribution of first stars.

Thus, it is not surprising that the densities of first stars in these models are lower than their Lagrangian counterparts. Yet, in no cases are these differences dramatic. Instead, the radial distributions in the $E^\text{III} = 10^{-3}$ (model E3 in Table 1) and $10^{-4}$ (model E4) cases in Figure 4 show only a slightly lower overall normalization and a marginally steeper radial trend than seen in the Lagrangian case. The $E^\text{III} = 10^{-2}$ model also shows an overall radial trend that is very similar to that in Fig. 4, although it contains a gap from 5-20 kpc with a factor of $\approx 2$ deficit in stars. Thus, even in this most extreme of any of our models, the Galactic halo contains a substantial number of the remnants of PopIII objects.

On the other hand, much larger differences between our Eulerian and Lagrangian models are visible in the distribution of second stars. These stars are substantially more centrally-concentrated in the Eulerian models, and in the $E^\text{III} = 10^{-4}$ case this difference is so severe that very few second stars are located in the Galactic halo. This represents the largest uncertainty in our approach, and thus for the limited case of a weak-feedback model, we are unable to draw any clear conclusions as to the halo distribution of second stars.

The differences between the Lagrangian and Eulerian approaches are further investigated in Figure 7 which shows the spatial distribution of first and second stars in both models. Here we see the same overall trends as in the radial profiles. In the strong feedback case, first and second stars are more concentrated than in the Eulerian approach, although in both models significant numbers of these stars are found in the halo and in satellite galaxies. In the weak feedback case, on the other hand, the differences in the first-star distribution are minor, but the lack of second stars in the Galactic halo in the Eulerian model is considerable. Finally, apart from the difference in radial trends, the detailed distribution of satellites containing PopIII stars differ somewhat between each of these approaches. Although in general, there are fewer PopIII satellites in the Eulerian cases, there are also occasionally PopIII satellites in these models without Lagrangian counterparts.

A second important issue is our association of stars with the overall distribution of dark matter in each halo. In reality, the gas in a given object will condense into a rotationally-supported disk whose radius is substantially smaller that its dark matter virial radius. Furthermore, due to the increased impact of tidal effects on the most loosely bound particles, it is possible that stars forming in such disks may end up distributed significantly differently at $z = 0$ than their associated dark matter.

To account for this possibility, we repeated our Lagrangian model, but now only associating stars with the inner 10% of the dark matter particles in first and second-generation objects, while leaving the number of stars formed in each halo fixed. The resulting radial distributions and spatial profiles are shown in Figures 5 and 6 respectively. Here we see that while limiting the number of particles associated with stars leads to larger statistical fluctuations, the distribution of first and second stars otherwise remains the same as in our fiducial modeling. Carrying out the same exercise in the Eulerian case yields similar agreement, and thus our results do not seem to be affected by differences in tides across halos.

Another important parameter in our analysis is our choice of $b = 0.2$ linking length when identifying halos. To test the dependence of our results on this choice, we generated new lists using a much smaller 0.15 length, which associates halos with objects almost twice as dense as in the standard picture. In Figure 10 we show the results of this calculation in the Lagrangian case (models 2L15-4L15).

From the left panels of this figure, we see that while adopting this more stringent criteria reduces the number of PopIII stars somewhat, this effect is no stronger than a factor of $\approx 2$. Furthermore, the overall radial profiles in the $b = 0.15$ case are very similar, if not flatter than in the fiducial model, indicating that the choice of linking length has no impact on our conclusions about the radial distribution of first stars. On the other hand, changing $b$ results in a substantial increase the number of second-stars within 8 kpc as shown in the right panels. This can be traced to the presence of a large object at $z = 11$, which was identified as a single large halo in the $b = 0.2$ case, but split into several smaller objects in the $b = 0.15$ case. While in the fiducial case, this large object was a...
Fig. 8.— Radial profile of first and second stars at $z = 0$ in our Lagrangian models, but now only associating stars with the mass in the central 10% of each halo. Panels are as in Figs. 4 and 6, while the lines represent models 2Lc (solid), 3Lc (dashed), and 4Lc (dot-dashed). In all cases, the radial profiles are consistent with those in our fiducial approach, shown in Fig. 4.

Fig. 9.— Comparison of the $z = 0$ distribution of first and second stars between our fiducial models and Lagrangian models in which stars are associated with the mass in the inner 10% of each halo. Consistent with Fig. 5 there are no strong difference between these two approaches.

Fig. 10.— Radial profile of first and second stars at $z = 0$ in Lagrangian models with a 0.15 choice of linking length. Panels are as in figure 4 and 6 and the lines represent models 2L15 (solid), 3L15 (dashed), and 4L15 (dot-dashed). For the first stars, the radial profiles are consistent with those in our fiducial, $b = 0.2$ approach, shown in Fig. 4. However, choosing $b = 0.15$ results in more second-stars being identified within $\approx 8$ kpc, which is primarily due to a large high-redshift object that is split into several sub-halos with this smaller choice of linking length.

direct descendent of a first stars halo, and thus excluded from the second-stars count. In the 0.15 case, most of the mass in this object was tagged as neighboring halos, and was added to the second-stars count. While this difference is consistent with our approach to counting first and second stars, it nevertheless illustrates some of the ambiguities involved in distinguishing stars that are formed in gas initially enriched by primordial stars, from stars that are formed within purely self-enriched primordial gas. Note however, that at Galactocentric radii $\gtrsim 8$ kpc, the overall distributions of second stars are similar between the models with different choices of linking length.

Another concern is the possibility that our models are assigning first and second stars to all halos that collapse in primordial areas or areas enriched only by primordial stars. However, a one-to-one association between dark matter halos and Milky-Way satellites leads to a large excess with respect to their observed numbers, which is commonly referred to as the missing satellite problem (e.g. Moore et al. 1999). Although ram pressure stripping before star formation (e.g. Scannapieco, Ferrara, & Broadhurst 2002) tidal stripping after star formation (e.g. Kravstov, Gnedin, & Klypin 2004) and other issues are important in resolving this issue, the largest source of suppression of dwarf galaxy formation is the increase in IGM thermal pressure following reionization (e.g. Bullock, Kravstov, & Weinberg 2000). While reionization will clearly have the largest effect on the very latest forming stars, rather that the objects in which we are most concerned here, the relatively large number of satellites seen in plots such as Figs. 2 and 3 indicates that our results may nevertheless suffer from such a excess of Galactic satellites.

Recently Benson et al. (2002), have shown that incorporating the increase in IGM pressure associated with reionization into semi-analytical models of galaxy for-
Fig. 11.— Comparison between the spatial distribution of stars in models with a fixed minimum virial temperature (2Lc and 4Lc), and models with a gradually increasing threshold associated with reionization (2LRc and 4LRc). While incorporating reionization leads to a far smaller number of first and second satellites, the overall distribution of such stars remains widespread.

Fig. 12.— Radial profile of first and second stars at \( z = 0 \) in Lagrangian models that include reionization. Panels are as in Figures 4 and 6, and the lines represent models 2LRc (solid), 3LRc (dashed), and 4LRc (dot-dashed). Increasing the filtering scale from \( 10^4 \) K at \( z = 9 \) to \( 5 \times 10^4 \) K below the final overlap redshift of \( z = 7 \) has only a weak effect on our results.

Fig. 13.— The anisotropy parameter of the velocity dispersion, \( \beta \), as a function of radius, for all the particles (dotted), first star particles (solid), and second star particles (dashed).

From these plots, it is clear that incorporating such suppression leads to far fewer first and second satellites, moving from \( \approx 25 \) such objects with 100 kpc in our fiducial models, to less than 10 in the reionization models. Nevertheless, as shown in Figure 12 the overall radial profile of first and second stars are quite similar to our fiducial results. With metal-free stars (first stars), and stars that contain the products of metal-free stars (first + second stars) forming at all Galactocentric radii. Thus we do not expect the details of suppression of dwarf galaxy formation to have a strong effect on our conclusions.

Finally, we note that the cosmological parameters used in our model have recently been revised by the 3-year data release from the Wilkinson Microwave Anisotropy Probe experiment (Spergel et al. 2006). In general, we expect that the low \( \sigma_8 \) and \( n \) values implied by these measurements should strengthen our conclusions. Indeed, the reduced power on small scales leads to a delay in the onset of star formation and metal enrichment in our \( T_{\text{vir}} > 10^4 \) K halos. As a consequence, the first stars will form at more recent epochs than in our fiducial model, and are likely to give a larger contribution to the halo population.

3.3. Kinematics of First and Second Stars

Our simulation results offer not only the spatial distribution of first and second stars, but also their kinematics. In this section, we present the results of a representative Lagrangian model, model 2Lc. Figure 13 demonstrates the predicted radial profile of the anisotropy parameter, \( \beta \), of the velocity dispersions first and second star particles as compared to the overall distribution. Here, \( \beta = 1 - 0.5 \sigma_t^2/\sigma_r^2 \), where \( \sigma_r \) is the radial velocity dispersion and \( \sigma_t^2 = \sigma_\theta^2 + \sigma_\phi^2 \) is the tangential velocity dis-
The eccentricity, $e = (r_{\text{max}} - r_{\text{min}})/(r_{\text{max}} + r_{\text{min}})$, as a function of the radius at $z = 0$ for first (left panel) and second (center panel) star particles, contrasted with the full distribution (right panel). In all cases the line gives the average value as a function of radius.

The eccentricity is then defined as, $e = (r_{\text{max}} - r_{\text{min}})/(r_{\text{max}} + r_{\text{min}})$. This slightly exceeds the mean eccentricity $\langle e \rangle \approx 0.7$. This slightly exceeds the mean value of the overall distribution, which is roughly consistent with the observed value of $\langle e \rangle \approx 0.6$ (Chiba & Beers 2000).

4. CONCLUSIONS

Theoretical models of PopIII star formation have focused on their overall cosmological distribution, or their contribution to the global star formation history of the Galaxy. But $z = 0$ observations are not of this type. As PopIII stars would have been carrying out nuclear burning for roughly a Hubble time, they must be faint, low-mass stars that are only observable nearby, and in environments without significant dust extinction or crowding from higher-mass stars. For this reason searches for metal-poor stars have been targeted only in the halo of the Milky Way, with an emphasis on halo stars roughly in the solar neighborhood. This means that comparisons between theory and observations have been dependent on extremely uncertain extrapolations, drawn from measurements in a limited environment.

In this work, we have carried out the first theoretical investigation able to quantify the impact of this extrapolation. Our method relies upon two key ingredients. The first of these is an extremely high-resolution N-body simulation of the Milky Way, which is capable of reliably capturing the formation of objects down to the $10^4$ K atomic cooling limit. The second is a simple and flexible analytic model of metal-dispersal, which allows us to quickly identify regions of metal-free star formation, despite the enormous uncertainties in the properties of the first stars and supernovae.

Our results are robust and optimistic. Despite changing the efficiency of metal dispersal by two orders of magnitude, adopting different estimates for the distances between neighboring objects, and varying our assumptions as to the regions of star-formation within collapsed objects, local measurements place substantial constraints on PopIII star formation in all of our models. In particular we have found that:

1. Galactic PopIII star formation occurs over a range of redshifts, as metal pollution takes a substantial amount of time to affect all the Milky Way progenitors. While Galactic PopIII star formation is likely to have peaked at $z \approx 10$, it should have continued at appreciable values down to $z \approx 5$, paralleling the overall cosmological evolution.

2. The mass fraction of PopIII stars in the Galactic halo near the solar orbit is only slightly lower than it is in the bulge. Thus, if they have sufficiently long lifetimes, a significant number of stars formed in initially primordial star clusters should be found in the Galactic halo. This means that there is no compelling theoretical reason to motivate observational searches in more difficult environments, and present observations should be taken as directly constraining the properties of PopIII stars. This picture is also consistent with observational studies of the lithium-7 abundance of metal-poor stars, which suggests that a large fraction of the baryonic matter in the early halo may have been proceed by PopIII stars.

3. While our models are not able to quantify self-enrichment within individual star clusters in detail, we
expect that stars enriched purely by metal-free stars in the same cluster will exist cospatially with the “first stars” in our model. Furthermore, we are able to make statements about the distribution of “second stars” that do not form cospatially with PopIII stars, but rather form out of gas that is enriched by neighboring clusters of PopIII stars. In almost all of our models, the mass fraction of such stars in the Galactic halo is comparable to that of PopIII stars, although there are very few second stars in our weakest $E_{51} = 10^{-4}$, Eulerian case. Unless the efficiency of PopIII metal ejection was at the lower end of the allowed range, many of these stars should also be found nearby.

We find that the final distribution of first and second stars remains practically unchanged when we move from our fiducial model, which associates stars with all dark-matter particles in each first and second generation object, to a centrally-concentrated model, which associates stars with only the inner 10% of particles in each object. Thus we do not expect the spatial distribution of stars within each first and second generation object to affect their distribution today.

(5) Incorporating the effects of reionization leads to an overall smaller number of satellite galaxies containing stars with only the inner 10% of particles in each object, to a centrally-concentrated model, which associates stars with all dark-matter particles in each first and second generation object, to a centrally-concentrated model, which associates stars with only the inner 10% of particles in each object. Thus we do not expect the spatial distribution of stars within each first and second generation object to affect their distribution today.

While stars are the sources of all metals, metals need not be contained in every star. Furthermore, we have shown here that stars without metals need not to be located near the Galactic center. Rather observations of metal-poor halo stars are providing us with direct constraints on the properties of the first stars. Though primordial stars were formed in the distant past, some of our greatest clues to the process of primordial star formation are likely to come from our local Galactic neighborhood.

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