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THE DUAL ORIGIN OF STELLAR HALOS

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ABSTRACT

We investigate the formation of the stellar halos of four simulated disk galaxies using high-resolution, cosmological SPH + *N*-body simulations. These simulations include a self-consistent treatment of all the major physical processes involved in galaxy formation. The simulated galaxies presented here each have a total mass of $\sim 10^{12}\ M_{\odot}$, but span a range of merger histories. These simulations allow us to study the competing importance of in situ star formation (stars formed in the primary galaxy) and accretion of stars from subhalos in the building of stellar halos in a ΛCDM universe. All four simulated galaxies are surrounded by a stellar halo, whose inner regions ($r < 20$ kpc) contain both accreted stars, and an in situ stellar population. The outer regions of the galaxies' halos were assembled through pure accretion and disruption of satellites. Most of the in situ halo stars formed at high redshift out of smoothly accreted cold gas in the inner 1 kpc of the galaxies' potential wells, possibly as part of their primordial disks. These stars were displaced from their central locations into the halos through a succession of major mergers. We find that the two galaxies with recently quiescent merger histories have a higher fraction of in situ stars (∼20%–50%) in their inner halos than the two galaxies with many recent mergers (∼5%–10% in situ fraction). Observational studies concentrating on stellar populations in the inner halo of the Milky Way will be the most affected by the presence of in situ stars with halo kinematics, as we find that their existence in the inner few tens of kpc is a generic feature of galaxy formation.

Key words: Galaxy: formation – Galaxy: halo – galaxies: formation – galaxies: halos – methods: *N*-body simulations

Online-only material: color figures

1. INTRODUCTION

Accreted stellar halos are a natural consequence of galaxy formation in a Λcold dark matter (ΛCDM) universe in which the smallest structures collapse first and galaxy formation is thought to proceed bottom-up (e.g., White & Rees 1978; Searle & Zinn 1978). Halos, composed of both dark and baryonic matter, grow by merging with other halos. While the gas from mergers and accretions loses its energy through cooling and settles into a disk, the accreted stars and dark matter form a halo around the galaxy. Galactic stellar halos are thus predicted to be built from multiple accretion events starting from the first structures to collapse in the universe.

It is for this reason that much work has focused on using kinematically identified halo stars to look for fossil records of the galaxy's accretion history. The possibility remains, however, that stars formed within the potential well of a galaxy can become displaced from the inner-most regions into a kinematic stellar halo. In order to draw conclusions about the accretion history of a galaxy based on halo stars, one must know how abundant such in situ stars are in the halo, and how they may dilute the signatures of accretions and mergers.

Owing to the low surface brightness of halos, the only presently well-studied stellar halos are those of the Milky Way and M31. Current observational studies of the Milky Way's halo find strong evidence that its outer regions ($r \geqslant 20$ kpc) were at least partially assembled through accretion events. Numerous stellar streams believed to have originated from small accreted galaxies have been observed in the Milky Way's outer halo (e.g., Newberg et al. 2002; Yanny et al. 2003; Belokurov et al. 2006; Grillmair 2009). Multiple wraps of stars believed to have been tidally removed from the Sagittarius dSph (Ibata et al. 1994; Majewski et al. 2003) highlight the process of disrupting satellites in the Milky Way's potential, and serve as strong evidence of hierarchical merging. Bell et al. (2008) have found, using F and G turnoff stars in the Sloan Digital Sky Survey (SDSS), that the distribution of halo stars is highly structured, and the outer halo is consistent with being formed almost entirely from accreted subhalos. M31's stellar halo is observed to contain possibly even more substructure and streams than what is observed around the Milky Way (e.g., Ibata et al. 2001, 2007; Gilbert et al. 2007), suggesting its recent merger history may have been more active. Despite the plethora of streams observed around the Milky Way and M31, both the fraction of halo that is accreted and the number of distinct accretion events leading to the observed substructure are unclear.

Although the nearby halo of our Galaxy has been studied more extensively than the outer halo, in some ways its properties are less well understood. This is due in part to the short dynamical timescales close to the disk, where accreted stars would no longer betray their origin through spatial structures. It is in these inner several tens of kpc of the halo that one might expect dissipative processes to contribute to the overall stellar population. Observational evidence of the contribution of accretion to the inner halo is slowly growing. Helmi et al. (1999) have detected two streams in the solar neighborhood by studying the angular momentum of stellar orbits. Morrison et al. (2009) have also recently shown that the angular momentum distribution of a sample of stars with a median height above the Galactic plane of 2 kpc does not seem to be smooth, possibly indicative of an accretion origin. A hybrid theory in which the Milky Way was assembled through a combination of hierarchical accretions and dissipative processes has been used by some to understand properties of field halo stars (e.g., Norris 1994; Carollo et al. 2007). Chiba & Beers (2000), using a large set of halo stars selected with no kinematic bias, find a vertical gradient in the mean rotation of metal poor stars, a signature of dissipational processes. Ibata et al. (2007), using number count maps, have shown that a large fraction of the halo of M31 appears to be rather smooth. The authors interpret these observations to suggest that some of the halos of M31 may have formed through dissipative processes. However, the degree to which dissipation is important in the formation of stellar halos, or one of their components, remains uncertain.

Simulations have also been extensively used to investigate the formation of galactic halos. The work of Bullock & Johnston (2005) combines dark matter only *N*-body simulations with semi-analytic models to study the buildup of stellar halos via accretions alone. Their work has been highly successful in explaining the discrepant chemical abundances of Milky Way satellite galaxies and field halo stars (Font et al. 2006a, 2006b; Johnston et al. 2008). While this powerful and efficient tool is particularly suited to better understand progenitors and signatures of accretion events, it cannot tell us about the possible relative importance of dissipative processes in the assembly of a galactic halo. Brook et al. (2003) have used *N*-body + SPH to simulate the formation of disk galaxies in a self-consistent way, following the evolution of dark matter, gas and star formation. They find that recently accreted satellites contribute stars to the halo which can be distinguished from an early-formed halo through phase-space information. Abadi et al. (2006), using a set of fully cosmological simulations, find that in situ stars dominate the inner 20 kpc of their galaxies, while accreted stars make up the majority of the outer regions. While the Abadi work distinguishes between the accreted and in situ populations in their galaxies, the work does not investigate the possible importance of in situ stars in simulated stellar halos.

In this paper, we use four high-resolution cosmological SPH + *N*-body simulations to investigate the origin of stellar halos. These self-consistent simulations permit the study of the competing importance of in situ star formation and accretion from subhalos in the formation of stellar halos in a ΛCDM universe. Furthermore, the supernova feedback and cosmic UV background implemented in our simulated galaxies result in a luminous satellite population that is more similar to the Milky Way's than those in previous *N*-body+SPH studies. This improvement is essential to model realistic stellar halos. We quantify the degree to which the halos are accreted and note the effect of accretion histories on the overall formation of the stellar halos. While past numerical efforts have concentrated on the growth of stellar halos through pure accretion, we show that both accretion and in situ star formation contribute to the inner regions of stellar halos.

The paper is organized as follows. Section 2 describes the details of the simulations used, and the methods used to determine the origin of halo stars. In Section 3, we discuss the dual origin of the stellar halos of our simulated galaxies and investigate how the properties of the in situ and accreted populations in the stellar halos vary with merging history. Section 4 discusses possible numerical and resolution effects on the formation of the stellar halos in our simulations, as well as the effect of feedback on the accreted fraction. Section 5 discusses the connection to observational results and concludes.

2. SIMULATIONS

The high-resolution simulations used in this study were run to $z = 0$, as part of an ongoing simulation project. The two more massive galaxies (MW1hr, Gal1) are described in detail in Governato et al. (2007, hereafter G07), but have since been rerun at 8 times the mass resolution and twice the spatial resolution. The reader is referred to G07 for the full details of these simulations. The remaining two lower mass galaxies (H277, H285) are a continuation of these efforts. H277 is described in Brooks et al. (2009). We briefly summarize the salient features of these simulations here.

The halos used in this study were selected, based on their mass and merger history, from low-resolution, dark matter only simulations run with GASOLINE (Wadsley et al. 2004), using WMAP year 1 cosmology for MW1hr and Gal1, and WMAP year 3 cosmology for H277 and H285. Each halo was then resimulated at higher resolution using the volume renormalization technique (Katz & White 1993). This approach simulates only the region within a few virial radii at the highest resolution, while still simulating a large enough box to account for the effect the large-scale tidal field has on the angular momentum of the halo.

We concentrate a large part of this work on MW1hr, the highest resolution *N*-body + SPH simulation of a Milky Way mass galaxy run to $z = 0$ published to date. We single this simulation out for extensive study as it has a lower resolution counterpart run with the identical initial conditions, but 1/8 the mass resolution of MW1hr, as well as several runs completed with different treatments of feedback. The previous extensive study done on MW1hr (see G07) permits the numerical and resolution tests necessary for this work. MW1hr has 4.9 million particles (dark matter + gas + stars) within its virial radius, and a mass of $1.14 \times 10^{12}\ M_{\odot}$. We define the redshift of last major merger as the time at which a secondary galaxy, with a mass no less than 1/3 of MW1hr's mass, first enters the virial radius of MW1hr. This occurs at a redshift of 4, although the merger is not complete until $z \sim 2.5$. The merger history of MW1hr is thus similar to that of the Milky Way, which is thought to have experienced its last major merger at $z \sim 2.5$ (Hammer et al. 2007). The mass of star particles in this simulated run is $\sim 2.7 \times 10^4\ M_{\odot}$, high enough to resolve an infalling dwarf galaxy of stellar mass $10^9\ M_{\odot}$ with more than 10^4 star particles. A physically motivated recipe was used to describe star formation and supernovae feedback (Stinson et al. 2006), with a uniform UV background that turns on at $z = 9$, mimicking cosmic reionization (Haardt & Madau 1996). The properties of all the simulated galaxies used in this work are described in Table 1.

All dark matter halos and subhalos in the simulation are identified using AMIGA's Halo Finder[7] (AHF, Knebe et al. 2001). Each halo is identified using a minimum of 64 dark matter particle members, above which the halo mass function converges (G07, Reed et al. 2003). The properties of each simulation particle are output at $z = 6$, $z = 5$, $z = 4$, and

[7] AMIGA Halo Finder, available for download at http://www.aip.de/People/aknebe/AMIGA

Table 1
Properties of Simulated Galaxies

Run	$M_{\rm vir}$ ($M_\odot$)	$N_{\rm tot}$ at $z = 0$ Dark+Gas+Stars	$M^{\rm DM}_{\rm particle}$ ($M_\odot$)	$M^{*}_{\rm particle}$ ($M_\odot$)	$\epsilon^{\rm a}$ (kpc)
MW1hr	1.1×10^{12}	4.9×10^{6}	7.6×10^{5}	2.7×10^{4}	0.3
MW1med	1.1×10^{12}	6.1×10^{5}	6.1×10^{6}	2.2×10^{5}	0.3
Gal1	3.3×10^{12}	3.7×10^{6}	2.6×10^{6}	9.2×10^{4}	0.3
h277	7.4×10^{11}	2.3×10^{6}	1.2×10^{6}	4.6×10^{4}	0.35
h285	7.7×10^{11}	3.0×10^{6}	1.2×10^{6}	4.6×10^{4}	0.35

Notes. [a] Gravitational softening length.

every 320 Myr after until $z = 0$, for a total of 43 time steps output.

2.1. *Selection of Halo Stars*

Before we can study the mechanisms that builtup the stellar halos of our simulated galaxies, it is first necessary to identify the star particles which make up the galactic halos. In both our study and observational work, it is important that the stellar samples used to draw conclusions about halo properties and formation are not contaminated by a population of disk stars. Unless an observational sample only includes stars that reside several disk scale heights above a galaxy's mid-plane, the use of kinematic and metallicity information is necessary to obtain a clean sample of halo stars. Some observational works rely on samples of stars chosen based on a metallicity cut, where the calculated [Fe/H] is several tenths of dex below that of disk stars (for example, Beers et al. 2000; Chiba & Beers 2000). Other observational studies have used the proper motions of stars to isolate those with halo kinematics (Smith et al. 2009), while other works combine both metallcities and kinematics (Carollo et al. 2007; Morrison et al. 2009).

We use the full simulation information to identify the most complete and uncontaminated set of halo stars possible. We have chosen to define our halo sample using the full three-dimensional phase-space information available for all stars in the simulations. Rather than implementing a specific spatial cut, this approach allows us to study the detailed origin of all stars belonging to a halo. If we had instead chosen to define the stellar halo of each simulated galaxy as the population of stars with distances greater than ∼2 scale heights above the galactic disk, the trends we report in the following sections would be unchanged. However, our results then would not have been applicable to the many detailed observational studies of the Milky Way's halo that are focused on stars within $d < 5$ kpc. In a future paper, we will investigate the possible observational consequences of this predicted origin.

A kinematic analysis of the star particles in each galaxy was done to decompose them into disk, bulge, and halo kinematic components. To decompose the disk from the spheroid, we first align the angular momentum vector of the disk with the z-axis. This is done in order to place the disk in the x–y plane. We then calculate the angular momentum of each star in the x–y plane, J_z, as well as the momentum of the corotating circular orbit with similar orbital energy, $J_{\rm circ}$. In this definition, stars with circular orbits in the plane of the disk will have $J_z/J_{\rm circ} \sim 1$. Disk stars are selected with a cut of $J_z/J_{\rm circ} \geqslant 0.8$, which is equivalent to an eccentricity cut of $e < 0.2$. This condition matches the eccentricities observed of disk stars in the Milky Way (Nordström et al. 2004).

Once the disk population has been identified, we define a sphere centered on each galaxy, with a radius equal to that of the disk. For stars within this inner sphere, the spheroid (halo + bulge) of each galaxy is defined using a cut in $J_z/J_{\rm circ}$ such that the net rotation of the spheroidal population equals zero. The spheroidal component of the galaxy is further decomposed into halo and bulge because a break in the mass density profile is observed. Stars whose total energy is calculated to be low, and hence are tightly bound to the galaxy, are classified as part of the bulge. All other stars are placed in the halo category. The energy cut between the halo and bulge is set in order to make a two-component fit of the mass profile with bulge stars within the "break" and halo stars outside the "break." Bulge contamination is not a concern because the energy cut also ensures that stars which reside close to the center of the galaxy, and are classified as belonging to the halo, have orbits which take them far from a classical bulge. Moreover, observational studies that rely on kinematics to select halo stars would have associated our halo stars with a halo, not bulge, component. We show in Section 3 that the stellar populations we associate with the halo extend out to regions far beyond what would be considered a bulge. Stars which reside beyond the inner sphere defined by the disk's radius are all classified as halo stars, regardless of their kinematics. We have verified that the halo population has a rotational velocity with a Gaussian distribution.

The $J_z/J_{\rm circ}$ cuts described above leave a set of stars whose kinematics do not make either the disk or spheroid cuts. These stars are dominated by thick disk and pseudobulge stars. We note that using kinematic information for decomposing galactic components unavoidably leads to some slight overlap in populations.

For the remainder of the paper, we use the term "halo stars" to refer to stars identified using this kinematic definition. There is no bias for our selected halo in situ stars to be prograde in any galaxy. This indicates that we have not mistakenly classified a significant number of disk stars (in particular thick disk stars) as halo stars in our analysis.

2.2. *Halo Star Origin*

We trace each star particle located within the main galaxy at $z = 0$ back in time. We identify at each time step the dark matter (DM) halo to which each particle belonged using AHF. Stars are considered bound to a DM halo if they are identified as being a member of that halo for two consecutive time steps. We follow the particles' histories back to $z = 6$, as well as follow the gas particles from which stars have formed. This procedure results in four different classifications for stars' origin: accreted, in situ, ambiguous, and other. These classifications are described in the following sections.

2.2.1. *Accreted Versus In Situ*

We use these stellar histories to distinguish between stars that were accreted and those that formed "in situ." Accreted stars formed inside of halos other than the primary dark matter halo, but through accretion and merging have become unbound to their progenitor and now belong to the primary halo. In situ stars formed from gas particles bound to the primary. These stars formed within the primary potential well and will be referred to as the "in situ" sample. In Section 3.1, we show that while these in situ stars reside in the halo at $z = 0$, they formed near the center of the galaxies' potential wells, as part of their primordial disks. The gas particle progenitors of these in situ stars ended up in the primary halo from both smooth gas accretion, particularly in cold flows (Brooks et al. 2009), and subhalos that underwent gas stripping as they merged with the primary. All galaxies

Table 2
Stellar Halo Origins

Run	Total Halo: Mass ($M_\odot$)	Accreted: Fraction (%) Mass ($M_\odot$)	In Situ: Fraction (%) Mass ($M_\odot$)	Ambiguous: Fraction[a] Mass ($M_\odot$)	"Other" Stars:[b] Mass ($M_\odot$)
MW1hr		70	21	9	
	6.22×10^9	3.8×10^9	1.14×10^9	4.99×10^8	7.8×10^8
MW1med		66	25	9	
	5.24×10^9	3.23×10^9	1.21×10^9	4.42×10^8	3.57×10^8
MW1thermal[c]		85	12	3	
	9.74×10^9	7.96×10^9	1.19×10^9	2.17×10^8	3.6×10^8
Gal1		85	12	3	
	3.39×10^{10}	2.84×10^{10}	4.17×10^9	1.06×10^9	4.04×10^8
H277		32	58	10	
	9.03×10^9	2.7×10^9	4.85×10^9	7.89×10^8	6.9×10^8
H285		87	7	6	
	2.93×10^{10}	2.2×10^{10}	1.71×10^9	1.56×10^9	3.9×10^9

Notes.
[a] The origin of these stars is ambiguous due to the finite time resolution of the simulation, as described in Section 2.2.2.
[b] These stars are excluded from the analysis of this paper, as discussed in Section 2.2.3.
[c] MW1thermal was run with the same mass resolution as MW1med, but with a different supernova feedback recipe. This is discussed further in detail in Section 4.1.

are traced back far enough in redshift, to $z = 6$, that we can accurately determine the star formation history of the vast majority ($> 98\%$) of halo stars. Approximately 1% of the stars in these simulations formed before $z = 6$, and as such we cannot determine their formation origin. We can thus accurately distinguish the accreted stars from the in situ stars for the vast majority of particles in each simulated run.

2.2.2. Ambiguous Origin Due to Time Resolution

Our simulations also contain stars whose formation origin is unclear due to the limited number of time steps output for each simulation. For example, if a gas particle spawns a star particle at approximately the same time that it first becomes bound to the primary, it is uncertain whether that star formed in the primary or in its original subhalo. Such stars are referred to as "ambiguous" in the reminder of the paper. These stars comprise less than 10% of all the kinematically identified halo stars in all of the simulations (see Table 2).

2.2.3. "Other" Stars in the Simulation

To ensure that the in situ stars are a robust feature of these simulations, we now investigate whether this population of halo stars were formed preferentially near the density and/or temperature thresholds for star formation, where spurious star formation may occur due to numerical effects. The spatial resolution of these simulations is ~300 pc, much coarser than the scales on which star formation occurs in real galaxies. It is therefore necessary to use a prescription for star formation that captures globally the observed trends in galaxies. The prescription used here for star formation enforces a local gas density greater than 0.1 cm^{-3} and a temperature colder than 30,000 K at which stars form.[8] If a gas particle matches these criteria, there is some probability that it will form a star particle. This probability is scaled to match the observed Kennicutt–Schmidt law for star formation (see Stinson et al. 2006 for further details).

We found that in situ stars that formed at a look back time of 10 Gyr or more did not form near the density and temperature cutoffs. They formed under the same conditions as stars with similar ages in the disk of the galaxy. However, in situ halo stars in the simulation younger than 10 Gyr old formed at preferentially lower densities and higher temperatures than their young disk counterparts, near the implemented cutoff for density threshold. While we have no reason to believe these late forming in situ stars are a numerical artifact, changing our prescription for star formation would possibly affect whether or not these in situ stars had formed at all in the simulation. Maller & Bullock (2004) have shown that accounting for hot halo gas instabilities may be important in understanding the total baryonic mass of a galaxy. These authors show that the fragmentation of the hot halo gas results in hot low density gas which does not cool, and is able to survive in the halo of a galaxy. This might explain the young in situ stars in our simulation that formed from a low density hot gas. To be maximally conservative on our prediction of the extent to which in situ stars compose the halo, we have not included in situ stars that formed within the last 10 Gyr in any of the following analysis. The broad conclusions of this paper are not affected by whether or not we choose to ignore these intermediate and young in situ stars. We refer to these stars as "other" for the reminder of the paper, and only consider in situ stars formed more than 10 Gyr ago when discussing "in situ" stars. The total mass contributed by other and in situ stars to each simulated galaxy is listed in Table 2.

3. DUAL ORIGIN FOR STELLAR HALOS: A GENERIC FEATURE OF GALAXIES

The presence of both in situ and accreted stars is a generic feature of the kinematically defined halos of all four simulated

[8] This temperature floor is due to our adopted cooling curve, which assumes primordial abundances without metals, does not yet include molecular cooling, and thus cannot extrapolate below ~10,000 K. It is assumed that dense gas at this temperature will continue to rapidly cool.

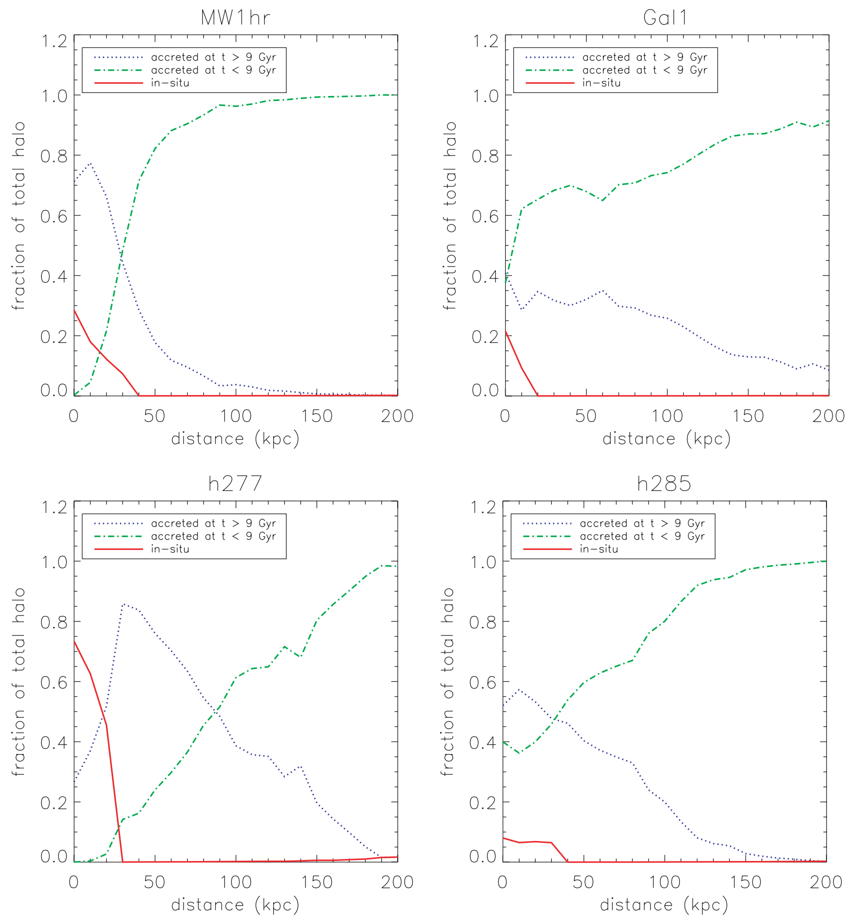

Figure 1. Relative contribution of accreted and in situ stars to the stellar halos of the simulated galaxies. Accreted stars are separated by the time at which the stars first became bound to the primary halo. The blue dotted line and the green dash-dot line show the accreted stars which became bound to the primary galaxy more than 9 Gyr ago and less than 9 Gyr ago, respectively, while the red solid line shows the in situ stars. Stars whose origins are unknown, as described in Section 2.2, were omitted in this figure, and their fractional contribution ignored.

(A color version of this figure is available in the online journal.)

galaxies. Each simulated stellar halo was found to be composed of a purely accreted outer halo, and an inner halo where both accreted and in situ populations reside. This is illustrated by Figure 1. The red solid lines in this figure show the fractional contribution of in situ stars to the stellar halos as a function of distance. The blue dotted lines and green dash-dot lines show the same for stars accreted to the halo at lookback times of more and less than 9 Gyr, respectively. This figure shows that all four stellar halos have an in situ component that primarily resides within their inner ∼20 kpc, and that the accreted component of each stellar halo extends to more than 100 kpc from the center of each galaxy. The outermost regions of the stellar halos of all four simulated galaxies are dominated by stars accreted within the last 9 Gyr. The central location of all four in situ populations shows that their presence is most relevant for observational studies that are limited to the inner halo of the Milky Way. Table 2 lists the fractional contribution, as well as the total mass, of the in situ and accreted populations in each of the four simulated halos in our sample.

3.1. *In Situ Star Formation*

We go on to study in detail the formation properties of in situ stars in the halo of MW1hr. As explained in Section 2, we focus on this particular simulated halo because of the extensive numerical and resolution testing which it has undergone. We find that the in situ stars of Gal1, h277, and h285 formed and populated their stellar halos by the same qualitative process described below for MW1hr.

In order to understand where the in situ stars in the halo of MW1hr originated, we studied the gas particles that formed this stellar population. The vast majority of the gas progenitors were brought into the primary galaxy in smooth gas flows. Fewer than 2% of the in situ stars were formed from gas stripped from accreted subhalos. Cold gas flow was found to also be the dominant contributor to the disk stars of MW1hr (Brooks et al. 2009).

To investigate how in situ stars came to form part of the stellar halo of MW1hr, we first study the locations at which these stars formed relative to the center of the galaxy. Figure 2 shows the radial distribution of in situ stars at the time of their formation relative to the center of the primary (black solid line). This shows that in situ stars form near the very center of MW1hr's potential well.

Approximately 70% of the in situ stars were formed by $z \sim 3$. Between $2 < z < 3$, MW1hr experienced at least three significant mergers with mass ratios $\frac{M_{\rm MW1hr}}{M_{\rm subhalo}} < 10$, defined at the time of virial radius crossing. Substantial mergers disrupt the orbits of stars in both the primary and merging galaxies. As two galaxies of approximately equal mass collide, their potentials change rapidly, causing the energies of their stars to change as

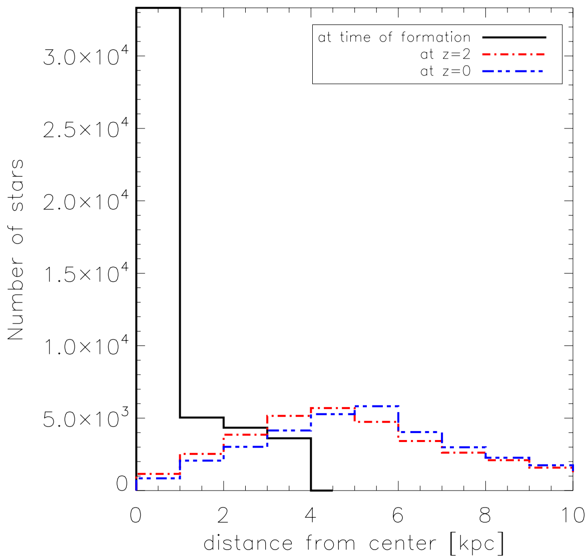

Figure 2. Radial distribution of MW1hr's in situ halo stars at the time of their formation (black solid line), at $z = 2$ (red dotted line), and at present day (blue dashed line), relative to the center of MW1hr.

(A color version of this figure is available in the online journal.)

well. The violent relaxation process will cause some stars to gain energy, and alter their initial orbits. We find that by $z = 2$ (red dotted line in Figure 2), the distribution of in situ stars is no longer sharply peaked at the inner 1 kpc of the galaxy, but is instead peaked at 5 kpc from the galactic center. This transformation from centrally located orbits to halo orbits was most likely due to the major mergers which MW1hr experienced between $2 < z < 3$. After $z = 2$, MW1hr does not undergo any more mergers with such small mass ratios, and so we expect that the radial distribution of in situ stars will not change. Indeed, we find that their distribution at the present day (blue dashed line in Figure 2) is very similar to that at $z = 2$.

The origin of the halo in situ stars in cold gas flows and their formation in the innermost regions of MW1hr's potential well all highlight that this population of stars formed in a rapid inflow and collapse of gas that also formed the disk of MW1hr, but were displaced through merger events into the halo. The process by which these in situ stars formed is reflected in that their relative importance in each stellar halo rises toward the center of each simulated galaxy.

3.2. Comparing The Accreted Halos With Other Works

Much work has been done recently with dark matter only *N*-body simulations coupled with semi-analytic models to study the growth of Milky Way-like galactic halos via pure accretion of stars. In this section, we compare results from such numerical studies with our findings for MW1hr's accreted halo. We focus here on MW1hr, as it was chosen to have a total mass and merger history similar to that of the Milky Way (Governato et al. 2007), making it a good candidate to compare with previous works which have also focused on simulating Milky Way-like stellar halos. We find that the accreted halo of MW1hr displays properties which are typical in comparison with other numerical studies.

As shown in the top-left panel of Figure 1, accreted stars dominate the halo of MW1hr at all radii. While the innermost 20 kpc of the halo contains both accreted and in situ stars, the halo beyond this is highly dominated by accretion. The earliest accreted stars, which became bound to the primary halo of MW1hr at a lookback time of ∼9 Gyr or more, dominate the accreted population of the halo out to 30 kpc from the center. In the halo's outer regions, however, the majority of stars were accreted more recently.

The accretion history of MW1hr's stellar halo agrees well with the numerical study of Helmi et al. (2003). These authors found that ∼90% of stars are in place in the inner 10 kpc of a Milky Way-like halo 10 Gyr ago, while the mass growth of the outer regions is more continuous. The work of Font et al. (2006a) also found that nearly 80% of the stars in the inner 20 kpc of simulated halos were in place at a lookback time of 9 Gyr. Font et al. (2006b) have shown in their numerical work that the inner regions of halos are typically assembled from a few satellites with stellar masses $M_\star \sim 10^9\,M_\odot$. In MW1hr, the majority (75% by mass in stars) of the accreted mass in the inner 50 kpc originated in two subhalos, each with total mass $\sim 2.5 \times 10^{10}\,M_\odot$.

The accreted stars which reside in the halos of Gal1 and H285 differ significantly from those found in the stellar halo of MW1hr. Unlike the accreted population of MW1hr, the majority of the accreted stars in the halos of Gal1 and H285 became bound to their respective stellar halo more recently, as shown in Figure 1. This is likely due to the fact that both Gal1 and H285 have had a more active recent merger history, as described in the following section. The accreted stellar halo of H277 was assembled at similar times to that of MW1hr, although the accreted population of this stellar halo contributes far less to the overall mass of the halo in comparison to MW1hr.

3.3. Possible Role of Merger History

Despite the universal presence of both in situ and accreted halo stars in all of the simulations, the relative contributions of these dual components vary widely among the four stellar halos. The fractional contributions of these stellar populations to the simulated stellar halos, as well as their total masses, are summarized in Table 2. The fraction of accreted halo stars ranges from ∼30% to 85%, while the fraction of in situ halo stars ranges from less than 10% to more than 50%. The high and low ends of these ranges do not sum to 100% because of the small presence of the ambiguous stars. Although the fractional contribution of in situ stars covers a wide range, the total mass of these stars in all four simulations is substantial. The mass of in situ stars in both the stellar halos of H277 and Gal1 is $\sim 4 \times 10^9\,M_\odot$ and $\sim 1 \times 10^9\,M_\odot$ for MW1hr and H285.

All four of these simulated galaxies have similar total masses; however, they span a range of merger histories. Three of the galaxies, MW1hr, H277, and H285 each host a stellar disk with a mass of $\sim 2 \times 10^{10}\,M_\odot$, while the mass of Gal1's stellar disk is $\sim 6 \times 10^{10}\,M_\odot$. The total halo mass of H277 and MW1hr is $6–9 \times 10^9\,M_\odot$, and $\sim 3 \times 10^{10}\,M_\odot$ for Gal1 and H285. The bulge-to-disk ratio (B/D) of each simulated galaxy was obtained using a two-component Sersic + exponential fit to the one-dimensional radial profile of the *I*-band surface brightness maps made with the SUNRISE software package (Jonsson et al 2006). The B/Ds for MW1hr, Gal1, H277, and H285 are 0.37, 0.66, 0.29, and 1.2, respectively (A. M. Brooks et al. 2009, in preparation). What role might merger history play in the range of accreted/in situ fractions observed in these four simulations? There is not an obvious trend between epoch of last major merger and either in situ fraction or average assembly time of the accreted component; Gal1 and MW1 had their last 3:1 merger at $z \sim 4$ and H277 and H285 at $z \sim 2.5$. However, there appears to

Table 3
Low z Mergers in Simulated Galaxies

Run	Mass Ratio (10:50)	Mass Ratio (50:200)
MW1hr	2	5
Gal1	2	10
H277	1	2
H285	7	8

Notes. The number of merged satellites within the given mass ratio for each simulated galaxy ($M_{\rm primary}/M_{\rm satellite}$) at times more recent than a redshift of 2.

be a possible trend with the galaxies' recent merger histories. Figure 1 illustrates one manifestation of this. The accreted stellar halo components of MW1 and H277, the two galaxies with the highest in situ fraction, were largely assembled more than 9 Gyr ago, with the innermost regions of these halos containing very few stars accreted in the last 9 Gyr. However, Gal1 and H285, which contain few in situ halo stars, have accreted stellar halos that, on average, were assembled much more recently at all radii, with at least 30% accreted within the last 9 Gyr. It is important to recall that we have defined accretion time as the time at which a star becomes unbound from its subhalo, and bound to the primary dark matter halo, which is a different, and invariably later time than when the subhalo entered the primary's virial radius.

In order to more explicitly study the merger histories of the simulated galaxies, we traced the total number of luminous satellites that enter the virial radius at different redshifts. In particular, we are interested in those satellites whose masses are in the range $10 < M_{\rm primary}/M_{\rm satellite} < 200$ at the time of merging, as these are expected to be the building blocks of the accreted component of stellar halos (Bullock & Johnston 2005). Table 3 shows the number of such merged satellites at redshifts smaller than $z = 2$. The stellar halos of Gal1 and H285, the two galaxies with more recently assembled stellar halos, have continued to accrete a large number of satellites after $z = 2$. The masses of these galaxies' accreted stellar halos are comparatively large ($> 10^{10}\, M_\odot$), overwhelming the population of halo in situ stars. In contrast, MW1hr and H277, whose stellar halos were found to have assembled at more ancient times, have had a more quiet recent merger history. These galaxies merged with fewer satellites in the studied mass and redshift range, and have the less massive accreted halos. Both MW1hr and H277 have halos which host a comparatively larger in situ population than Gal1 and H285.

4. NUMERICAL AND RESOLUTION STUDIES

Owing to a dual origin, the detailed properties of a stellar halo are a function of both (1) the properties of the primary galaxy itself, and (2) the properties of the protogalaxies that merged to form its accreted component. Accurate modeling of a galaxy's stellar halo thus requires an accurate treatment of the formation and evolution of that galaxy over a wide dynamical range. In this section, we discuss the effects of feedback, as well as numerical and resolution effects, on the overall formation of stellar halos in our simulated galaxies.

4.1. The Effect of Feedback on the Simulated Galaxies

The four simulated galaxies used in this study have sizes, ages, and metallicities that match those observed at low redshift. G07 and Governato et al. (2009) showed that disk galaxies naturally form in a cosmological context in simulations such as those studied here, and have sizes that place them on the I-band Tully–Fisher relation (TF, e.g., Giovanelli et al. 1997; McGaugh 2005; Geha et al. 2006). Brooks et al. (2007) used a set of GASOLINE simulations (including MW1) to show that galaxies with total $z = 0$ halo masses in the range $3.4 \times 10^9\, M_\odot < M_\star < 1.1 \times 10^{12}\, M_\odot$ have (O/H) abundances that match both those measured by Tremonti et al. (2004) for more than 53,000 SDSS galaxies locally and those measured by Erb et al. (2006) at $z = 2$. Maiolino et al. (2008) demonstrated that galaxies simulated with GASOLINE (including the progenitors of H277 and H285) are also a good match to the observed mass–metallicity relationship at $z = 3$.

The success of these simulations in matching the observed mass–metallicity relationship at varying redshifts (Brooks et al. 2007; Maiolino et al. 2008) demonstrates that these simulations have made substantial progress in overcoming the historic "overcooling problem" (e.g., Mayer et al. 2008). Gas in simulations has traditionally cooled rapidly, forming stars quickly and early, and thus producing a mass–metallicity relation that is too enriched at a given stellar mass, particularly at high z. In the simulations examined here, supernova energy is deposited into the interstellar medium mimicking the blast wave phase of a supernova (following the Sedov–Taylor solution, details in Stinson et al. 2006). Cooling is turned off for gas particles within the supernova blast wave radius for a period of time after the supernova event. Supernova feedback regulates star formation efficiency as a function of halo mass, resulting in the mass–metallicity relationship described above. This regulation of star formation also leads to realistic trends in gas fractions, with our lowest mass galaxies being the most gas-rich (Brooks et al. 2007), and reproducing the observed incidence rate and column densities of damped Lyα systems at $z = 3$ (Pontzen et al. 2008).

Feedback, with its role in regulating star formation, will also affect the luminosity function of galaxies in a simulation, which will, in turn, effect the properties of the accreted stellar halo. For example, if the simulated dwarfs have too many stars relative to dwarf galaxies in the real universe, then we may overestimate the relative importance of accreted versus in situ stars in the halos. We therefore compare the luminosity function of satellites within the virial radius of our two medium resolution galaxies, MW1med and MW1thermal. We use these two simulated runs because they have the same mass resolution, but different implemented feedback mechanisms. MW1med adopts the blast wave model discussed above, and used for all of the high-resolution runs studied here. In MW1thermal, supernova energy was deposited as thermal energy to the surrounding gas particles, but cooling is not turned off in these particles. These gas particles will then quickly radiate away the deposited energy, and this simulation will suffer from the overcooling problem.

Using the age and metallicity of each stellar particle in a satellite, we calculated the absolute V-band magnitudes of the $z = 0$ satellites of MW1med and MW1thermal using the stellar population models of Starburst99 (Leitherer et al. 1999; Vázquez & Leitherer 2005). Figure 3 shows the luminosity function of the satellites in MW1med and MW1thermal, as well as the observed luminosity function of Milky Way dwarfs, from Grebel et al. (2003). The satellites of MW1med are similar in total number and luminosity to the Milky Way's, except at the bright end of the luminosity function. The satellites of MW1thermal, however, are too numerous at all luminosities. The discrepancy between the luminosity function of MW1med

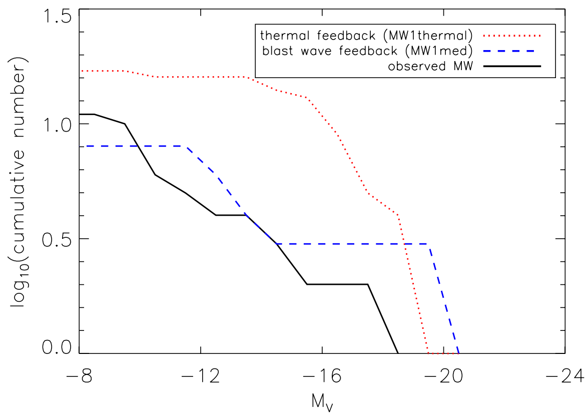

Figure 3. Luminosity function of satellites for two simulated runs with different feedback prescriptions, as well as the observed luminosity function of the Milky Way's dwarfs, from Grebel et al. (2003).

(A color version of this figure is available in the online journal.)

and MW1thermal is due to the overcooling problem typical of simulations with thermal feedback, which causes satellites to form which are highly centrally concentrated and contain too many stars. Because the MW1thermal run produces over-luminous dwarf galaxies, we expect that its halo will be more dominated by accreted stars than the halo of MW1med. As shown by Table 2, which lists the accreted and in situ fractions of both of these galaxies, the halo of the MW1thermal has $\sim$20% more accreted stars in its halo relative to in situ stars than MW1med (85% versus 66%) and $< 1/2$ of the fraction of in situ stars (12% versus 25%). While the total mass of in situ halo stars is about the same for both simulated runs ($1.2 \times 10^9\ M_\odot$), the total mass of accreted stars in the thermal run is $8 \times 10^9\ M_\odot$ and only $3.2 \times 10^9\ M_\odot$ in the run with blast wave feedback.

In summary, several features of the simulations we analyze here contribute to bringing the number of luminous satellite galaxies into good agreement with those observed around the MW. Our uniform UV background unbinds baryons from simulated halos with total masses below $\sim 10^9\ M_\odot$, creating "dark" halos and bringing down the number of luminous satellite galaxies. Our supernova feedback scheme helps to significantly reduce the number of stars produced in the remaining low-mass satellite galaxies. However, because our satellites are still slightly too bright (i.e., have too many stars), our accreted fractions are an upper limit. This only serves to increase the potential relative contribution of in situ stars in the inner halos of galaxies.

4.2. *Resolution Effects on Star Formation*

Brooks et al. (2007) found that several thousand particles were required inside of the virial radius of a halo in order for the star formation history to converge. For the high-resolution simulations studied here, this convergence criterion is met in halos with total masses above a few $\times 10^9\ M_\odot$. For the medium resolution runs, the convergence limit is met in halos with total masses above $2 \times 10^{10}\ M_\odot$. Resolution testing has shown that poorly resolved halos have smaller total stellar masses than halos which are fully resolved. We therefore underestimate the contribution to the primary stellar halos from dwarf galaxies with total mass below this convergence limit. However, we find that dwarf galaxies less massive than $10^{10}\ M_\odot$ contribute less than 5% to the overall mass in accreted stars in the high-resolution stellar halos. Due to the resolution effects discussed above, this small fraction of accreted satellites will contribute even fewer stars at lower resolution than they would if they were fully resolved, decreasing their overall contribution to the accreted stellar halo of the medium resolution runs (MW1med and MW1thermal). This effect is minimal due to the tiny contribution of these halos. Our findings agree with the work of Bullock & Johnston (2005), who showed that satellites with total mass greater than $2 \times 10^{10}\ M_\odot$ contribute 75%–90% of the mass to the primary stellar halo.

Because the in situ stars are forming deep in the potential well of the high-resolution main halo, we do not expect their formation properties to vary with resolution because the star formation history of the main halo is fully resolved. In order to test this assumption, we compared the in situ formation in the high-resolution MW1hr run with the lower resolution MW1med run. We expect that if the formation of these stars was caused by a numerical resolution effect, then their fractional contribution to the simulated halos would change as the resolution at which the galaxy is simulated changed. We find, however, that at both resolutions, in situ stars make up a substantial fraction of the stellar halo of the Milky Way-massed galaxies. Table 2 shows that the overall in situ fractions of the stellar halos of MW1hr and MW1med are 21% and 25%, respectively. The 4% larger contribution of in situ stars to the stellar halo of MW1med is likely due to the slight underestimating of accreted stars in this medium resolution run, as described above.

5. DISCUSSION & CONCLUSIONS

In this paper, we have analyzed four SPH + *N*-body simulations of approximately $L^\star$ disk galaxies to investigate the formation of their stellar halos. We have shown that the inner halos of all four galaxies contain both stars accreted from merged satellites and in situ stars formed within the primary galaxy. While these results are theoretical, they are backed by recent observational studies of the stellar halos of the Milky Way and M31.

Observational work has shown that the properties of Milky Way halo stars exhibit signatures of a possible double population. Carollo et al. (2007) have found that a sample of local halo stars in the SDSS can be thought of as two distinct, but overlapping, components, with different spatial distributions, orbits and metallicities. They attribute, as others have, these different stellar properties to different formation mechanisms for the two halo components. They conclude that the inner halo may have formed dissipatively from the gas-rich merger of early sub-galactic halos, while the outer halo stars were accreted from subhalos which merged with the Milky Way's dark matter halo.

Observations of M31 have revealed that this giant spiral galaxy is also surrounded by a large extended stellar population. M31 has been shown to have a distinct stellar halo with a surface brightness profile similar to the Milky Way's, and a metallicity gradient with the inner regions of its halo ($R < 30$ kpc) more metal-rich than the outer regions (Guhathakurta et al. 2005; Kalirai et al. 2006). Using number count maps, Ibata et al. (2007) find a large metal-poor smooth component to the halo of M31, with a more metal-rich inner halo. These works highlight the possible signatures that M31's stellar halo may, like the Milky Way, have two underlying components, with different formation histories.

The results of such observational findings for the halos of the Milky Way and M31, however, have previously lacked counterparts in simulations as most of the numerical studies done to date on stellar halos have concentrated on their buildup through pure accretions. Our work begins to bridge the gap by studying self-consistent simulations where the contribution of in situ stars to the overall halo has been taken into account. Our main results are as follows.

1. In situ stars are a generic feature of kinematically defined stellar halos. These stars formed deep in the potential well of the primary galaxy and were later displaced to halo orbits as a result of mergers.
2. In situ stars reside primarily in the inner few tens of kpc of the galaxies' halos.
3. Stars accreted off satellites dominate the stellar halo at all radii for three of the four galaxies studied. The accreted stellar halo components were found to extend to out to a few hundred kpc.
4. The fractional contribution of in situ stars to the simulated galaxies' halos varies greatly, from 5% to 50%.
5. The two galaxies in our sample whose halos had the smallest contributions from in situ stars were also those with accreted halos that assembled less than 9 Gyr ago. This is likely because such galaxies have more active recent accretion histories, which lead to massive accreted halos. The large contribution of recently accreted stars overwhelms the underlying in situ populations in these halos. The other two galaxies in our sample, with large contributions from in situ stars, had a significant fraction of their accreted stars in place at times earlier than 9 Gyr ago. The relative importance of in situ stars in these halos is due to the recent quiet merger history of these galaxies, which have led to less massive accreted halos.
6. Different supernova feedbacks greatly impact the formation of simulated stellar halos. This underscores the necessity of carefully implementing feedback to produce a realistic satellite luminosity function, and hence to conduct realistic studies of halo formation.
7. The overall importance of in situ stars to the stellar halos found in this study is likely a lower limit. This is because (1) we have ignored a fraction of in situ stars for numerical reasons, and (2) the satellites of the simulated galaxies studied here are brighter than those observed in the Milky Way. The calculated contributions of accreted stars to the stellar halos are thus an upper limit.
8. The qualitative trends of our results are unchanged if we had instead used a spatially defined set of stellar halos.

Our results suggest that galaxies with more active recent mergers, like M31, may host halos where the relative importance of an in situ population is low. Galaxies, such as the Milky Way, with little evidence for recent merger events, on the other hand, may have a larger relative contribution from an in situ population in its inner regions, along with its accreted stars. However, a larger set of simulations with a wide range in merger histories is needed to fully understand the complex relationship between halo formation and mergers.

Vast observational resources are currently dedicated to the study of the Milky Way's and M31's halos. Spatial, kinematic and chemical abundance information of halo stars being collected and used to attempt to reconstruct the accretion and formation history of the galaxies. Our results highlight that such data sets, particularly those focused on local, and hence inner, halo stars, will contain a significant population of stars born in situ in the galaxies. These in situ stars may dilute the signatures of accretion history in observations. Given the short dynamical timescales in the inner halo, one may not expect to be able to discriminate these two populations using their kinematics alone. However, given the very different sites of their formation, the chemical abundances of in situ and accreted stars may be quite distinct. In a future paper, we will investigate possible ways to observationally disentangle the two halo populations.

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