Probing the epoch of reionization with Milky Way satellites

Joseph A. Muñoz,† Piero Madau,2 Abraham Loeb1 and Jürg Diemand2†

1Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS 10, Cambridge, MA 02138, USA
2Department of Astronomy & Astrophysics, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA

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ABSTRACT
While the connection between high-redshift star formation and the local Universe has recently been used to understand the observed population of faint dwarf galaxies in the Milky Way (MW) halo, we explore how well these nearby objects can probe the epoch of first light. We construct a detailed, physically motivated model for the MW satellites based on the state-of-the-art Via Lactea II dark-matter simulations. Our model incorporates molecular hydrogen (H₂) cooling in low-mass systems and inhomogeneous photoheating feedback during the internal reionization of our own Galaxy. We find that the existence of MW satellites fainter than $M_V \approx -5$ is strong evidence for H₂ cooling in low-mass haloes, while satellites with $-5 > M_V > -9$ were affected by hydrogen cooling and photoheating feedback. The age of stars in very low-luminosity systems and the minimum luminosity of these satellites are key predictions of our model. Most of the stars populating the brightest MW satellites could have formed after the epoch of reionization. Our models also predict a significantly larger dispersion in $M_{300}$ values than observed and a number of luminous satellites with $M_{300}$ as low as $10^6 M_\odot$.

Key words: galaxies: dwarf – cosmology: theory – early Universe.

1 INTRODUCTION
According to the standard cold dark matter (CDM) paradigm of cosmic structure formation, massive objects such as the halo of our own Milky Way (MW) grow hierarchically with smaller subunits collapsing earlier and merging to form larger and larger systems over time. Computer simulations have long shown that this merging is incomplete and that the dense cores of such progenitors may survive today as gravitationally bound ‘subhaloes’ within their hosts (e.g. Moore et al. 1999). Recently, state-of-the-art simulations have revealed that present-day galaxy haloes are extremely lumpy, filled with tens of thousands of surviving substructures on all resolved mass scales (Diemand, Kuhlen & Madau 2007; Diemand et al. 2008; Springel et al. 2008). The predicted subhalo counts vastly exceed the number of known dwarf satellites of the MW, creating a ‘missing satellite problem’ whose solution within the ΛCDM framework may lie both in the luminosity bias that affects the observed satellite luminosity function (LF) (Koposov et al. 2008; Tollerud et al. 2008) as well as in the reduced star-forming efficiency predicted for small-mass, dwarf-sized substructure. It is widely accepted that cosmic reionization may offer a plausible mechanism for effectively inhibiting star formation in haloes that are not sufficiently massive to accrete warm intergalactic gas, and a number of studies have attempted to interpret the observed population of MW satellites using the process of early, external UV background feedback (Bullock, Kravtsov & Weinberg 2000; Benson et al. 2002; Somerville 2002; Kravtsov, Gnedin & Klypin 2004; Moore et al. 2006; Simon & Geha 2007; Strigari et al. 2007; Madau, Diemand & Kuhlen 2008a; Busha et al. 2009; Macciò et al. 2009b).

Lately, it has been suggested that a detailed quantitative resolution of the ‘missing satellite problem’ may require some ‘pre-reionization’ suppression mechanism to avoid producing too many faint Galactic dwarf spheriodals (dSphs). Using results from the Via Lactea II (VLII) simulation, Madau et al. (2008b) showed that thousands of surviving subhaloes in the halo of the MW today have progenitors massive enough for their gas to cool via excitation of H₂ and fragment prior to the reionization epoch, which they assumed occurred around $z \sim 10$. In addition, they found that star formation in these objects must have been extremely inefficient converting only a small fraction of their gas into stars or having a top-heavy initial mass function (IMF; e.g. Abel, Bryan & Norman 2002). Similar conclusions have been reached by Koposov et al. (2009).

Inspired by these results, we develop a detailed, astrophysically motivated model for the formation of dSphs. We consider a general scenario in which H₂ fragmentation can shut off before the suppression of atomic hydrogen cooling during reionization and include post-reionization star formation in the largest subhaloes. This work is unique in that it considers the possibility that the MW was self-reionized from the inside out, which further suppresses the...
amount of stars produced in progenitors with $M > 10^8 M_\odot$. This assumption is in agreement with observations that the mean-free-path of ionizing radiation through intervening Lyman-limit systems (LLSs) is much less, at $z > 7$, than the 20 Mpc distance between the Virgo Cluster and the MW (Faucher-Giguère et al. 2008). Using this physical model with the most recent observations of the ultra-faint MW satellites found in the Sloan Digital Sky Survey Data Release 5 (SDSS DR5) as a probe of both reionization and early star formation physics, differentiates our work from previous studies that focused on the properties of dSphs. In this work, we adopt subhalo catalogues from the one billion particle VLII simulation, which allow us to track the progenitors of surviving present-day MW substructure far up in the merger hierarchy than done before. The unprecedented mass resolution, combined with the fossil signatures of the reionization epoch in the Galactic halo, allows us to study gas cooling in the early Universe, star formation in the first generation of galaxies, and the baryonic building blocks of today’s galaxies.

This paper is organized as follows. In Section 2, we briefly describe the VLII simulation and develop our model. In Section 3, we compare the results with observations, examine which observables best constrain model components, and determine model parameters. Finally, we summarize our conclusions and discuss how they contribute to our understanding of reionization and high-redshift star formation in Section 4.

2 BASIC MODEL

The recently completed VLII simulation (Diemand et al. 2008) uses just over a billion dissipationless particles each weighting 4100 $M_\odot$ to simulate the formation of a $M_{200} = 1.9 \times 10^{12} M_\odot$ MW-sized halo in a Wilkinson Microwave Anisotropy Probe (WMAP) 3-yr cosmology (Spergel et al. 2007). It resolves 50,000 subhaloes today within the host’s $r_{200} = 402$ kpc (the radius enclosing an average density 200 times the mean matter value) and tracks the merger history of each subhalo that survives to the present epoch through 400 time slices between $z = 27.54$ and today. In this study, we analyse catalogues that, for each surviving subhalo, give the number of progenitors and their masses at a given redshift. The details of the progenitor determinations are given in Madau et al. (2008b). Progenitors are resolved down to masses of $10^5 M_\odot$, almost a factor of 200 better than the dissipationless simulation of the MW used by Gnedin & Kravtsov (2006). This extra resolution allows us to incorporate physical models involving H$_2$ cooling in very low-mass haloes at extremely high redshift.

Our model for assigning stars and luminosities to MW subhaloes from the VLII catalogues involves carefully charting the state of cosmic hydrogen and a comparison of the cooling mass with the Jeans mass throughout cosmic time. We identify four epochs of star formation that can contribute to the stellar populations of MW dSphs: (1) stars can form at $z \sim 20$, well before reionization, in systems large enough for the cooling of molecular hydrogen; (2) H$_2$ cooling produces stars before reionization that are responsible for photoheating the intergalactic medium (IGM); (3) further cooling via H$_1$ from reionization to $z \sim 2$ produces stars in subhaloes large enough to hold on to their gas and (4) stars form in the last 10 Gyr from metal cooling. In the following sections, we describe the process of star formation in each of the above epochs following Barkana & Loeb (2001), and detail how we attach stellar populations to the simulation subhaloes. In incorporating this model, we use the set of best-fitting cosmological parameters from the WMAP 5-yr data release (Komatsu et al. 2009), which are fully consistent with the previous results from WMAP3.

2.1 Epoch of molecular hydrogen cooling

In the pristine early Universe beyond $z \sim 20$, cooling via H$_2$ is efficient in systems with total halo masses as low as $M_{200} \sim 5 \times 10^8 M_\odot$, while the Jeans mass is lower by an order of magnitude (Barkana & Loeb 2001). The resulting first stars create a background of Lyman–Werner photons, which both dissociates H$_2$ and acts as positive feedback to replenish it (Ricotti, Gnedin & Shull 2002a,b). Supernova explosions from these stars also begins to enrich the IGM with the small amount of heavy metals necessary for metal cooling.

Ultra-faint MW dwarf satellites are a natural and unavoidable consequence of H$_2$ cooling in the pre-reionization Universe (Ricotti & Gnedin 2005; Bovill & Ricotti 2009), and this mechanism can be responsible for the low observed metallicities of these objects (Salvadori & Ferrara 2009). We take advantage of the high mass resolution of VLII to trace the pre-reionization progenitors of these ultra-faint dwarfs, for the first time, down to an H$_2$ cooling mass as small as $10^7 M_\odot$ to make quantitative predictions about their abundance and observable properties.

Motivated by Madau et al. (2008b), where an extremely small star formation efficiency was invoked in $< 10^7 M_\odot$ objects at $z = 11$ to avoid overpopulating the faint end of the MW satellite LF, we allow for the possibility that H$_2$ cooling is suppressed earlier than H$_1$ cooling (Haiman, Rees & Loeb 1997; Haiman, Abel & Rees 2000). Earlier suppression could explain the very small efficiency of these small objects in a very natural way since the haloes able to cool via molecular hydrogen would be less numerous at early times. Whalen et al. (2008) have suggested that this suppression may occur around $z \sim 20$ and result from supernova feedback.

We assume a redshift, $z_{H_2}$, after which H$_2$ cooling is quenched, and a mass threshold for haloes, $M_{H_2}$, below which such cooling is inefficient. We consider the VLII redshift snapshots at $z = 17.9$ and $23.1$ as possible values for $z_{H_2}$ and extract from the halo catalogues all surviving MW subhaloes at $z = 0$ with progenitors above $M_{H_2}$ at $z_{H_2}$. We further assume that a fraction $f_0 = \Delta_m / \Omega_m$ $\sim 0.16$ of the total mass in each progenitor is in gas. Due to the metal-poor state of the primordial gas, the first generation of Population III stars has a top-heavy IMF and does not survive to the present day. Rather, the deaths of these stars seed the gas with traces of metals and spawn a new, metal-cooled stellar population with a Salpeter IMF. While these metal-cooled stars are the ones with local relics seen today, the system initially must have satisfied the conditions for H$_2$ cooling. We assume that, through this process, a fraction $f_{H_2}$ of the initial gas is converted into stars with a Salpeter IMF; this factor accounts for any gas that may have been expelled by supernovae. The low-mass stellar population will survive to the present day with a visual luminosity of $M_V = 6.7^1$ per solar mass of initial stars (Bruzual & Charlot 2003; Madau et al. 2008b).

\footnote{1 We set a minimum stellar mass of 0.1 $M_\odot$ for the Salpeter IMF. However, in principle, the cosmic microwave background creates a temperature floor to any cooling process that may in turn determine the minimum mass of stars at high redshifts (Bromm & Loeb 2003; Bromm & Larson 2004). In our discussion, we implicitly assume that stars at this lower limit would survive to the present day (or equivalently that this limit is below ~1 $M_\odot$). In this regime, the luminosity per unit mass is not very sensitive to the value of the low-mass cut-off of the Salpeter mass function.}
subhalo, we sum up the stars contributed by each progenitor at $z_{\text{rh}}$. We assume that these stars are quickly incorporated into the centre of the forming subhalo so that they are not stripped during subsequent mergers or tidal encounters with the MW.

2.2 Atomic hydrogen cooling before reionization

Next, we discuss the formation of stars in subhaloes from H I cooling prior to the photoheating of the IGM at reionization. This cooling process is very efficient only in gas with temperatures above $T_{\text{c}} = 10^4$ K. Before the IGM photoheats to approximately $T_{\text{c}}$, this temperature requirement limits H I cooling to haloes whose virial temperatures exceed $T_{\text{c}}$ or, equivalently, to those with halo masses above $M_d = 10^6 M_\odot (1 + z)^{-1.5} $ (Barkana & Loeb 2001). Stars formed in this way are responsible for producing the $N_{\text{clump}}$ photons required on average to reionize each atom of H I in the Universe. This happens when the collapse fraction of haloes with $M > M_d$ exceeds a critical threshold (Barkana & Loeb 2004). Thus, the condition for the average reionization redshift of the Universe, $z_{\text{rei}}$, is

$$N_{\text{clump}} \Omega_b \rho_{\text{crit}} = N_p f_{\text{H1}} f_b \int_{M_d}^{\infty} dM' M' \frac{dn}{dM'} (M', z_{\text{rei}}),$$

where $dn/dM$ is the comoving mass function of haloes, $N_p$ is the number of ionizing photons produced per baryon in stars, $f_{\text{H1}}$ is the fraction of gas turned into stars by H I cooling, and $\rho_{\text{crit}}$ is the critical density of the Universe today. Here, $\Omega_b \rho_{\text{crit}}$ represents the total comoving mass density of baryons in the Universe to be reionized, not just those in underdense or mean-density regions. Therefore, the standard factor $f_{\text{esc}}$, the fraction of ionizing photons that escape into the IGM, does not appear on the right-hand side of equation (1). Using the Sheth & Tormen (1999) mass function for haloes, we can solve for the combination $Q = N_p f_{\text{H1}} / N_{\text{clump}}$ given any value of $z_{\text{rei}}$. For $z_{\text{rei}} = 11$, approximately the best-fitting WMAP5 value of the mean reionization redshift, we find $Q \approx 100$.

After reionization, the IGM is rapidly photoheated to $\sim 10^4$ K. Haloes with masses less than the filtering mass, $M_f$, can no longer hold on to their gas or accrete new baryonic material (Gnedin 2000). While Koposov et al. (2009) adopted the expression of Gnedin (2000) for the remaining gas available for star formation, Busha et al. (2009) correctly pointed out that only cold gas can actually form stars. The situation is made worse by infalling gas whose temperature increases by an extra order of magnitude during collapse. Thus, after reionization, only gaseous haloes with virial temperatures above $T_\text{c}$ can cool via H I to form additional stars (see Section 2.3).

As in Section 2.1, we compile a list of surviving MW subhaloes at $z = 0$ and all of their progenitors with $M > M_d$ at $z_{\text{rei}}$ and assign to each a stellar mass $M_\star$ and a luminosity (today, after more than 13 Gyr of cosmic time) of $M_\star = 6.7$ per solar mass of stars distributed with a Salpeter IMF. Our choice of IMF constrains $N_p = 4000$ (Bromm, Kurucz & Loeb 2001). As before, we assume that partial tidal stripping of their hosts at later times does not remove these deeply embedded stars. Present-day subhaloes with $M > M_d$ progenitors at $z_{\text{rei}}$ as well as earlier progenitors at $z_{\text{rh}}$ with $M > M_{\text{bh}}$, as outlined in Section 2.1, have contributions to their stellar populations from both epochs.

We now consider two alternatives for the reionization history of the MW galaxy-forming region (MWgfr) that affect the calculation of $M_\star$. Alvarez et al. (2009) suggest that the MW was most likely ionized externally by radiation from the Virgo Cluster. However, they do not include the effect of intervening LLSS, which absorb external UV photons and may allow the MWgfr to reionize from the inside out instead. Here, we consider and present results for both scenarios.

If the MWgfr was reionized externally by the Virgo Cluster, we would expect the ionization front to cross the region very quickly. In this case, we can assume that the region reionized promptly at $z_{\text{rei}}$, and consider the subhalo progenitors at that redshift. The mass in stars formed by each subhalo progenitor at $z_{\text{rei}}$ is the same as that assumed by Madau et al. (2008b),

$$M_\star = f_{\text{H1,ex}} f_b M_{\text{halo}},$$

where the subscript ‘ex’ denotes the assumption of external reionization. Considering only stars that formed through the H I cooling of gas before $z = 11$ and assuming a Salpeter IMF, Madau et al. (2008b) found that a star formation efficiency of $f_{\text{H1}} \approx 0.02$ for progenitors with $M_{\text{halo}} > 7 \times 10^7 M_\odot$ would reproduce the observed satellite LF.

On the other hand, if the MWgfr was ionized internally, different parts of it would have reached the critical collapse fraction of H I-cooling haloes necessary for reionization at different times due to their respective overdensities (Barkana & Loeb 2004). Thus, there should be fluctuations in the redshift of reionization within the MW itself about the mean at $z_{\text{rei}}$, an effect that has not been considered in the literature. Each subhalo progenitor will photoionize and reheat its own gas content at the time it has produced $N_{\text{clump}}$ ionizing photons per hydrogen atom. This condition is met when

$$M_\star = \frac{N_{\text{clump}} g(\delta)}{N_p (1 - f_{\text{esc}})} f_b M_{\text{halo}} = \frac{f_{\text{H1}} g(\delta)}{Q (1 - f_{\text{esc}})} f_b M_{\text{halo}},$$

where $g(\delta)$ gives the ratio of $N_{\text{clump}}$ in the overdense progenitor to the average $N_{\text{clump}}$ in the Universe. The factor $Q (1 - f_{\text{esc}})$ selects only those photons that do not escape from the overdense progenitor and can be used to photoionize it. Equation (3) tells us how much stellar mass to assign a progenitor of mass $M_{\text{halo}}$. Each progenitor, A, has its own $M > M_d$ progenitors, B, that form stars at redshift $z_{\text{rei}} > z_{\text{rei}}$; before system A collapses at $z_{\text{rei}}$. Baryonic material from the region that formed the A progenitor not converted into stars at $z_{\text{rei}}$ is photoionized before it can be incorporated into A at $z_{\text{rei}}$ and cannot form stars unless progenitor A eventually reaches a mass of $M_\star$, the mass corresponding to a virial temperature of $T_\text{c}$ or a circular velocity of $V_\circ = 52$ km s$^{-1}$. However, we expect most of the gas in B progenitors with $M > M_d$ at $z_{\text{rei}}$ to form stars.

Accounting for the inside-out morphology of the MWgfr reionization provides a natural explanation for the low values of $f_{\text{H1,ex}}$ found by several studies (Madau et al. 2008b; Busha et al. 2009; Koposov et al. 2009), which assumed a single value for the reionization redshift of the entire MWgfr. Since stellar mass is a linear function of halo mass in both equations (2) and (3), both morphologies fit the same observed LF when

$$f_{\text{H1,ex}} = \frac{f_{\text{H1}} g(\delta)}{Q (1 - f_{\text{esc}})}.$$

If $f_{\text{H1}} g(\delta)/(1 - f_{\text{esc}})$ is of order unity at $z_{\text{rei}} = 11$, we find that $f_{\text{H1,ex}} \approx 0.01$. We can understand this physically by considering how, at the redshift of star formation suppression, a lower efficiency is equivalent to a smaller amount of matter in collapsed objects (smaller $M_{\text{halo}}$ in equation 2) in terms of calculating how much stellar mass is produced. We see from this that, for a given average redshift of reionization in the MWgfr, the inside-out and outside-in morphologies fit the LF equally well but result in different interpretations of the fitting parameters.
2.3 Star formation after reionization

We assume that cosmic reionization and the photoheating of the MWgfr complete rapidly after $z_{\text{re}}$. Subsequently, only haloes that have accumulated a mass of $M_z > 1$ are able to hold on to their gas long enough for it to form further stars via H$_2$ cooling. We assume that this star formation is quenched when the subhalo begins to interact with the MW host. The merger histories of each surviving MW subhalo at $z = 0$ show only eight subhaloes that achieved a maximum circular velocity greater than $V_z$ at some point in their histories. We determine the redshift at which the maximum circular velocity reaches its peak. The subsequent reduction is due to tidal interactions during infall into the MW host with both neighbouring dwarfs and the host itself (Kravtsov et al. 2004) that we assume coincide with the quenching of star formation through ram pressure. In agreement with Klypin et al. (2009), we find that this mass loss typically occurs around $z = 2-4$ (in five of our eight subhaloes) but can happen as early as $z = 8$ and as late as $z = 1.6$.

We add an additional mass of $f_s f_{\text{max}}$ worth of stars minus the mass of any stars formed in either of the first two epochs to each subhalo whose peak circular velocity exceeds $V_z$. Here, $f_s$ is an efficiency parameter for star formation during this epoch that takes into account how much of the hot gas is cooled to form stars and how much of the gas mass is removed during infall. $M_{\text{max}}$ is the virial mass corresponding to the maximum value of the circular velocity for each subhalo. We calculate the age of these new stars from the redshift at which the subhalo attains its maximum circular velocity and use this age to calculate the luminosity of each solar mass of stars from Bruzual & Charlot (2003).

2.4 Recent star formation

The final episode of star formation that we include in our model occurs in the last 10 Gyr since $z = 1.6$. Since we are interested primarily in the physics of the early Universe, we do not attempt to develop here a detailed model for the production of these stars but presume that metal cooling is involved and use the observations of Orban et al. (2008) to add additional young stars in a stochastic way.

For each of the classical, pre-SDSS MW satellite, Orban et al. (2008) have measured $f_{\text{DG}}$, the fraction of stellar mass produced in the last 10 Gyr, and $\tau$, the mass-averaged stellar age. They find that the metallicities of the ultra-faint, SDSS satellites are so low that no star formation is expected for these in the last 10 Gyr. As we will show, subhaloes that achieve a maximum circular velocity of at least $V_z$ are associated only with the classical MW satellites studied by Orban et al. (2008), while stars that formed prior to reionization populate both the classical and SDSS dSphs. Therefore, we set $f_{\text{DG}} = 0$ for subhalo progenitors that only formed stars before reionization to be consistent with these metallicity observations. However, setting this constraint only for progenitors with $H_2$-induced cooling does not significantly change our results.

The cumulative probability distribution of $f_{\text{DG}}$ is approximately linear with a linear fit reaching unity at $f_{\text{DG}} = 0.89$ (Orban et al. 2008). Thus, for each subhalo with stars that formed after reionization, as outlined above, we select a value for $f_{\text{DG}}$ at random from a flat probability distribution within the interval [0.00, 0.89]. The mass of stars produced since $z = 1.6$ is, therefore, given by $f_{\text{DG}}/(1 - f_{\text{DG}})$ times the mass of stars produced from the mechanisms outlined in the previous three sections.

If we pretend that all of the stars formed in the MW satellites prior to $z = 1.6$ have an age of 14 Gyr, we can use the measured values of $f_{\text{DG}}$ and $\tau$ to estimate the mass-weighted average age of those stars formed in the last 10 Gyr. We find that the stars that formed after $z = 1.6$ in each satellite have ages between 1 Gyr and 8 Gyr with an average around 5 Gyr. Since the luminosity per solar mass of a stellar population does not vary much in this age range (Bruzual & Charlot 2003), we assume a fixed age of 5 Gyr for the recent stars formed in each of our subhaloes. Bruzual & Charlot (2003) give the luminosity of a stellar population with this age as $M_V = 5.8$ per solar mass.

3 COMPARISON WITH OBSERVATIONS

We are now at a position to compare the properties of the luminous subhaloes in our model with observations of MW dwarf satellites. These include values for Segue II, the newest MW satellite discovered in the SDSS data (Belokurov et al. 2009), but exclude Leo T which, at a distance of 417 kpc from the Sun, is outside the virial radius of the VLII simulation. The simulation abundance calculations represent mean values about which there is Poisson scatter. However, for clarity in the plots, we instead assign Poisson errors on the observational data as if the observed count was the mean value. We ignore the variations that would be expected in different cosmological realizations of the MW, and leave this analysis to future work.

In Section 3.1, we first outline the observational biases of our observed sample of satellites and describe how we apply a similar bias to the simulated population to account for the completeness of the sample. We then proceed to compare the simulated and observed luminosity functions of satellites in Section 3.2, and investigate how this important observable constrains our model. Finally, we consider how well our model reproduces other observables in Section 3.3 such as the radial distribution of satellites within the MW halo, the mass of a satellite within 300 pc of its centre, and a satellite’s mass-to-light ratio.

3.1 Observational completeness

Our sample includes two sets of MW satellites: those discovered prior to SDSS and the ultra-faint sample found in the SDSS DR5. However, the observational biases for the two samples are not the same. Not only is the SDSS sample complete only to a given surface brightness threshold, but the SDSS footprint only covers 20 per cent of the sky. Rather than apply corrections to the observed distribution functions of satellites to account for the total population as in Tollerud et al. (2008), we follow Madau et al. (2008b) in adjusting our simulated population to represent those objects that would be detected by SDSS.

The observational completeness of the SDSS DR5 was modelled by Klypin et al. (2008) and Tollerud et al. (2008) by defining the maximum radius at which a satellite of a given visual magnitude would be observed. This radial threshold is given by

$$r_{\text{max}} = \left(\frac{3}{4\pi f_{\text{DR5}}}\right)^{1/3} 10^{(-0.6 M_V - 5.23)/3} \text{ Mpc},$$

where $f_{\text{DR5}} = 0.194$ is the fraction of the sky covered by DR5. We exclude each subhalo in our simulation with a distance beyond this threshold for its particular luminosity. Moreover, when plotting the luminosity and radial distribution functions of satellites in Section 3.2 and Section 3.3, we correct these distribution by an additional factor of $f_{\text{DR5}}$. The observed distributions are also corrected so that each classical MW satellite contributes only $f_{\text{DR5}}$ to the total abundance, while each SDSS satellite contributes fully.

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However, all observed satellites contribute equally when calculating the fractional Poisson errors in the distribution functions.

### 3.2 The luminosity function

First, we would like to compare our simulated LF of MW satellites to the observed distribution and explore the importance of this observable for constraining model parameters.

The observed and simulated LFs are shown in Fig. 1. We present multiple theoretical curves, each of which includes additional layers of the model to demonstrate the relationship between the model and the predictions. For example, taking into account only subhaloes that reach a maximum circular velocity of at least $V_s$ at some point in their histories (see Sections 2.3 and 2.4) with $f_5 = 0.02$ roughly reproduces the LF of pre-SDSS satellites. Recent, high-metallicity star formation in the last 10 Gyr introduces some stochasticity in the theoretical LF, but the fluctuations are smaller than the observed errors. However, this limited model fails to account for observed satellites dimmer than $M_V \approx -9$. The addition of star formation in progenitors with $M > M_*$ before reionization at $z_{rei} = 11.2$ extends the agreement between the theoretical and observed LFs down to $M_V \approx -6$ when we assume $f_4 H_{ex} = 0.02$ in an external reionization model or $N_{clump} g(\delta)/(1 - f_{esc}) \approx 30$ in an inside-out model. Additionally, the inclusion of pre-reionization stars lowers the post-reionization efficiency to $f_5 = 0.01$.

However, it is only with the inclusion of stars in low-mass molecular hydrogen cooling systems that the model output reproduces observations of ultra-faint satellites. This element of our model and its ability to explain and be constrained by the data is a major new development in this work that distinguishes it from other studies in the literature. In Fig. 1, we assumed $z_{HI} = 23.1$ and $M_{HI} = 10^9 M_\odot$ with $f_{HI} = 0.4$. The model not only gives the correct abundance of satellites brighter than the faintest known object, Segue 1, it also provides an explanation for why no fainter objects have been found. To produce stars, our model requires a subhalo to have at least one progenitor with mass above the cooling mass for molecular hydrogen. The fewest stars are produced when the subhalo has exactly one of these progenitors that is just above $M_{HI}$. In this case, the mass in stars is $M_* = f_{HI} f_5 M_{HI} \approx 6600 M_\odot$, and the luminosity today is $M_V > -2.8$. The existence of a satellite as dim as Segue 1 is within the uncertainty of our approximations. While a precise measurement of the lower limit on the luminosity of MW satellites in the future will provide a tighter constraint on early star formation, our model implies that the exact value cannot be significantly below what has already been observed.

We emphasize this intriguing result that star formation from different time periods, before the suppression of H$_2$ cooling and before and after reionization, is required to fit the theoretical LF to the data at the faint, middle and bright ends, respectively. Although some objects do have stars from multiple epochs, they are typically dominated by the processes in a single part of the model. This helps to prevent degeneracy among all of our different parameters and allows us to learn about star formation parameters in each stage almost independently of the others.

So far, we have produced results by fixing $z_{HI} = 23.1$ and $z_{rei} = 11.2$ and varying the efficiencies and mass thresholds to obtain agreement. However, by allowing for different values of the suppression redshifts, we can arrive at new sets of parameters that allow the model to fit the observed LF.

Figure 2 compares the simulated LFs with reionization fixed at three consecutive VLII slices for which progenitor analysis is available: $z_{rei} = 7.77$, 9.14 and 11.2. For each of these redshifts, we find $Q = 28$, 46, and 130. We have fixed $z_{HI} = 23.1$ and $M_{HI} = 10^9 M_\odot$ but varied $N_{clump} = N_{H\text{I}} f_{HI} / Q$ and $f_{HI}$ to find the values resulting in the closest fit to the data. For convenience, we define $N_{clump} \equiv N_{clump} g(\delta)/(1 - f_{esc})$ and $f_{HI} \equiv f_{HI} g(\delta)/(1 - f_{esc})$. Our sets of fit parameters, then, are $(z_{rei}, N_{clump}, f_{HI}, f_4 H_{ex}) = \{(7.77, 7, 0.05, < 0.001), (9, 14, 17, 0.2, 0.1), (11.2, 30, 1, 0.4)\}$; the values of $f_{HI} H_{ex}$ for an external reionization scenario can be calculated from equation (4).

At earlier times, less mass in the Universe is in collapsed objects above the cooling mass. This results in a monotonically increasing value of $Q$ with $z_{rei}$ since each baryon in these objects must ionize a larger number of hydrogen atoms. This requires the Universe to be less clumpy for fixed $f_{HI}$. However, the reduction in the mass contained in each present-day subhalo’s progenitors at $z_{rei}$ increases requires larger values of $f_{HI}$ to produce the same observed stellar mass today. This effect produces global reionization more efficiently and allows increased clumping. Since $f_{HI}$ increases faster with $z_{rei}$ than does $Q$, the net result is an increasing $N_{clump}$.

Because later reionization allows for star formation in more objects near the cooling threshold before H I cooling is suppressed, star formation in molecular hydrogen cooling haloes at earlier redshifts is allowed to be less efficient to produce roughly similar LFs.
This is responsible for the reduced values of $f_{\text{HI}}$ that we for lower $z_{\text{rei}}$. The value $f_{\text{HI}} < 0.001$ effectively means that the contribution of stars in molecular hydrogen cooling systems before $z_{\text{rei}}$ to the luminosity of MW satellites is negligible; this results in an absence of satellites with luminosities fainter than $M_V \approx -5$.

While all three considered values of $z_{\text{rei}}$ produced similar totals for the number of observed MW satellites, the LF slope between $-5 > M_V > -9$ seems to favour earlier reionization around $z_{\text{rei}} = 11$.

We also considered the effect of varying $z_{\text{HI}}$ and examined two VLII slices at $z = 17.9$ and 23.1. We fixed the reionization parameters to be those best fit for $z_{\text{rei}} = 11.2$, but varied $M_{\text{HI}}$ and $f_{\text{HI}}$ to find the best agreement with the LF data. Fig. 3 shows the resulting LFs and compares them with observations. The model with parameters set at $(z_{\text{HI}}, M_{\text{HI}}/M_\odot, f_{\text{HI}}) = (23.1, 10^5, 0.4)$ produces almost identical results as that with $(17.9, 10^4, 0.04)$. Allowing more time for stars to form before the suppression of H$_2$ cooling is compensated for by a larger cooling mass threshold and a smaller star formation efficiency. The minimum cooling masses for the redshifts we considered are around the minimum masses typically assumed in simulations of feedback from the first stars (Whalen et al. 2008).

### 3.3 Radial distribution, $M_{200}$ and $M/L$

Given the degeneracies of various degrees that we have seen in the LF for some sets of model parameters, we attempt to use the other observables to learn more about the early Universe. Fig. 4 shows the radial distribution throughout the MW of the observed and simulated satellites for different pairs of fixed $(z_{\text{rei}}, z_{\text{HI}})$ with other model parameters optimized to produce the best agreement with LF data. We find that all of the $z_{\text{HI}} = 23.1$ models are fairly consistent with the radial data deviating non-negligibly only for satellites in the range $50 < r/\text{kpc} < 100$ of the MW centre. The $(z_{\text{rei}}, z_{\text{HI}}) = (11.2, 23.1)$ prediction for the radial distribution rises more sharply than expected for $r < 100\text{kpc}$, but the statistical strength of this deviation is by no means overwhelming.

We further explored whether these parameter sets were distinguishable in the distribution function of the maximum circular velocity of the subhaloes. This property is difficult to measure observationally from the velocity dispersion of real satellites at
a given radius from the centre of the object. However, no significant difference was found among the distributions for model parameters that also fit the LF data.

In addition to considering distribution functions, we would also like to test for agreement between our model and observations of specific satellite properties. The mass enclosed within 300 pc, $M_{300}$, as a function of luminosity has been studied using both observational (Mateo 1998; Gilmore et al. 2007; Strigari et al. 2008) and theoretical (Li et al. 2008; Koposov et al. 2009; Macciò, Kang & Moore 2009a) approaches that hinted at a characteristic mass scale for MW satellites of about $10^7 M_\odot$. Both the relatively constant value of $M_{300}$ and the extreme observed mass-to-light ratios of the faintest satellites are properties of the population that we would like our model to reproduce, however, we keep in mind that both $M_{300}$ and the total mass from which mass-to-light ratios are calculated are difficult to determine observationally.

In Fig. 5, we present measurements of $M_{300}$ for MW satellites from Strigari et al. (2008) and compare them with the output from our ($z_{\text{rei}}, z_{\text{H}_2} = (11.2, 23.1)$) model with $M_{300}$ measured directly from the simulation. Red squares show values of $M_{300}$ measured, for each subhalo, at the time when the evolution in its maximum circular velocity has reached its peak and assuming an NFW profile. The short-dashed blue, solid black, dotted green and long-dashed lines represent power-law fits of the $M_{300} - L_V$ relation respectively from observations, directly from the simulation, assuming NFW profiles for simulated subhaloes today, and assuming NFW profiles for the subhaloes when their maximum circular velocities peak.

While our model predicts a fairly constant $M_{300}$ as a function of luminosity (a variation of about an order of magnitude over six decades in luminosity), there is still some disagreement at low luminosities where we find a lower average $M_{300}$ and greater scatter than observed. We find that values of $M_{300}$ measured directly from the simulation match very well with those obtained assuming, for each satellite, an NFW profile (Navarro, Frenk & White 1997) fit to its simulated maximum circular velocity and the radius at which this maximum is reached. A power-law fit to the resulting scatter plot of $M_{300}$ versus $L_V$, of the form $M_{300} = \beta L_V^{\alpha}$ yields $\alpha = 0.22$ for both the simulated and NFW values of $M_{300}$. This is much steeper than the value of $\alpha = 0.05$ for the Strigari et al. (2008) measured values of $M_{300}$ with the up-to-date values of $L_V$.

Assuming that the NFW profile is a good fit for all subhaloes at all times, we also calculated $M_{300}$ for each subhalo at the redshift when the evolution in its maximum circular velocity reaches its peak. The difference between peak and present values should give us an idea of how much tidal stripping changes the mass estimates. Macciò et al. (2009a) recently suggested that tidal stripping would result in a flattening of the $M_{300} - L_V$ relation. However, our results show a further steepening as more low-luminosity subhaloes lose a significant amount of their mass than do high luminosity ones. We find $\alpha = 0.15$ for the early values of $M_{300}$. While it is true that large, low-concentration systems lose more total mass to tidal stripping than smaller ones do, they are actually denser and more robust to stripping at a fixed radius. Additionally, if the smaller subhaloes are also initially fainter, they must be deeper in the inner halo to be detected (i.e. have smaller $r_{\text{max}}$) where tidal effects are stronger, while larger, brighter haloes can be detected even at large radii where tides are weak.

Of course, an NFW profile is not always a good fit for all subhaloes at all times. For example, if the peak in the maximum circular velocity is reached during a merger, one can get a rather large radius as well, which results in a low concentration and low $M_{300}$.
The actual mass distribution during a merger is quite different from NFW, and the true \( M_{\text{vir}} \) would be higher. This explains why a few of the subhaloes plotted in Fig. 5 appear to gain mass from the peak until today. However, if we were able to plot the true, larger values of \( M_{\text{vir}} \) at the time of the peak circular velocity for all subhaloes, it would only show a greater steepening between the epoch when the peak is reached and today.

The tension at low luminosities between our predictions and the measurements of Strigari et al. (2008) may well be explained by the difficulty in determining \( M_{\text{vir}} \) observationally. The tracer stars in many small systems do not extend past 100 pc and converting the mass within this radius to that inside 300 pc requires assumptions about the dark matter distribution (e.g. shape, orientation, density profile) and about the orbits of the stars. Additionally, interlopers and/or undifferentiated binary stars could systematically skew velocity dispersion measurements, especially in those satellites where the dispersion is small (\( \sim 5 \text{ km s}^{-1} \)). These errors could significantly inflate the mass of low-mass systems.

While the observed mass-to-light ratios are calculated from the mass within the stellar ‘tidal’ radius, theoretical values from the simulation are computed using the mass within the dark matter tidal radius of the subhalo. This means that the model predictions are upper limits on the observed values. This is the best we can do without modelling the radial distribution of the stars within subhaloes. The two definitions of mass-to-light ratio agree only in systems where the stars and the dark matter are truncated by tides at the same radius. Despite this difference, the model roughly reproduces the slope and amplitude of the relation between satellite mass-to-light ratio and visual luminosity. We do appear to produce extra faint haloes with ratios even larger than observed, which most likely is a result of the definitional difference between the observed and theoretical values.

These results show that our model not only produces the correct abundance of luminous subhaloes at each luminosity, but it also gives subhaloes with approximately the correct physical properties for their luminosity. That is, the simulated subhaloes that correspond to the brightest satellites or to the ultra-faint satellites in terms of their abundance have the same physical properties as the brightest or faintest satellites, respectively. Our faint objects do not, for example, have the physical properties, such as \( M_{\text{vir}} \) or mass-to-light ratio, of the brightest satellites. This consistency increases confidence in our model.

Unfortunately, the different sets of model parameters we have been considering produce the about same range of \( M_{\text{vir}} \), or mass-to-light ratio for a given luminosity. Of course, certain luminosities are under- or overpopulated by points in different models, but these differences are better represented as differences in the LF as we have described in Section 3.2. Therefore, these scatter plots are less useful for learning about reionization and star formation in the early Universe.

4 DISCUSSION AND CONCLUSIONS

In this paper, we have shown that a physical model for star formation applied to the subhaloes of a high-resolution galactic N-body simulation can, indeed, explain the full observed population of MW dwarf satellites. While Macciò et al. (2009b) reached similar conclusions, they were not able to reproduce the faint end of the LF because their model did not include molecular hydrogen cooling in haloes with masses below \( 10^9 \text{ M}_\odot \). Our inside-out model of the reionization of the MW galaxy-forming region (MWgfr) is characterized by the star formation efficiency \( f_{\text{esc}} \), cooling mass \( M_{\text{cool}} \), and suppression redshift \( z_{\text{sup}} \) of H\(_2\) cooling, the normalized efficiency of H\(_1\)-cooled stars \( f_{\text{H}_1} \), normalized IGM clumping \( N_{\text{clump}} \), the mean redshift of reionization \( z_{\text{rei}} \), and the star formation efficiency \( f_s \) of massive systems capable of H\(_1\) cooling after reionization. Here, \( N_{\text{clump}} \equiv N_{\text{clump}}(1 - f_{\text{H}_1}) \) and \( f_s \equiv f_{\text{H}_1} \). Our results are slightly at odds with recent measurements from the literature of \( M_{\text{vir}} \) for ultra-faint systems, but we anticipate that measurement uncertainties may have resulted in the difference (see Section 3.3).

In Section 3.2, we used our model to explore what the observed LF of MW satellites could tell us about the early universe and discovered that satellites of different luminosities give clues about star formation at different epochs.

(1) MW satellites with luminosities fainter than \( M_V \approx -5 \) can be explained by the inclusion of second-generation stars in low-mass haloes above a cooling threshold of \( M_{\text{H}_2} \sim 10^{6-8} \text{ M}_\odot \) that were initially able to cool via molecular hydrogen in the very early universe.

We took advantage of the VLII's high resolution to probe this process in very small systems and allowed for the possibility that a mechanism other than reionization was responsible for its suppression in the early universe. We have shown that our theoretical subhaloes illuminated in this way are very faint, metal poor (due to their very early creation), and have extreme mass-to-light ratios and the correct abundance to be responsible for the faintest population of satellites discovered in the SDSS DR5.

Using observations of these ultra-faint satellites to learn about the star formation process, we have found that molecular hydrogen cooling systems convert a fraction \( f_{\text{H}_2} \) of their initial gas into stars before star formation is suppressed very early in cosmic history at \( z_{\text{H}_2} \). While the observed LF could not distinguish between models with \( z_{\text{H}_2} \sim 23.1 \) and 17.9, the radial distribution of these objects somewhat favours earlier suppression. The best-fitting values of the cooling mass and star formation efficiency for each value of \( z_{\text{H}_2} \), assuming cosmic reionization at \( z_{\text{rei}} = 11.2 \), are \((z_{\text{H}_2}, M_{\text{H}_2}/\text{M}_\odot, f_s) = [(23.1, 10^7, 0.4), (17.9, 10^6, 0.04)]\). Only if \( z_{\text{rei}} < 8 \) is H\(_2\) cooling in low-mass systems required to reproduce the observed MW satellite LF. Confidence in our models increases when we note that our values of the cooling threshold are consistent with what has been already been assumed in simulations of the formation of the first stars (Whalen et al. 2008). Our results put further constrains on input parameters for these studies.

The physical difference between the two sets of \((z_{\text{H}_2}, M_{\text{H}_2}/\text{M}_\odot, f_s)\) values that we considered may not be stark. The fact that \( f_s \) increases for an earlier \( z_{\text{H}_2} \) may suggest a similarity with the inside-out reionization model of Section 2.2, where progenitors that reionized before the rest of the MWgfr have a star formation efficiency much greater than in an external reionization scenario. The similarities are intriguing, but we leave this problem to future work.

For either value of \( z_{\text{H}_2} \) that we considered, ultra-faint satellites are clearly the sites of the very first and oldest in the universe, and we agree that searches for these stars should be targeted there (Kirby et al. 2008; Frebel et al. 2009). While we do not expect stellar ages from future surveys precise enough to distinguish between formation at \( z = 20 \) and 8, the absence of any metal-poor stars older than 13 Gyr would represent a problem for our model.

Another interesting prediction for the future is the cut-off that we find in the luminosity of MW satellites. We have shown that the molecular hydrogen cooling mass and the associated star formation efficiency sets a minimum luminosity for satellites that cannot be
significantly dimmer than what has already been observed. Interestingly, since the limit depends on the product $f_{HI} M_{HI}$, we find the same cut-off for both values of $z_{rei}$ considered. While our theoretical value is a bit brighter than that observed to date, the difference is within the uncertainties in our calculation. A precise measurement of this minimum luminosity in the future would be a useful test of our model, which would not be able to explain satellites much dimmer than Segue 1.

(2) The luminosity of satellites between $-5 > M_V > -9$ is dominated by stars produced through H\textsc{i} cooling of gas before the photoheating of the IGM at reionization.

We considered, for the first time, a model of reionization in the MWgfr with an inside-out morphology where dense progenitors more massive than the cooling mass, $M_c$, reionize before the rest of the region. This prescription is based in the potentially large optical depth of LLSs between the MW and the Virgo Cluster. We showed that this model explains the low star formation efficiency found in previous studies that assumed instantaneous, external reionization of the MWgfr, but both morphologies result in the same simulated observables.

We used the observed LF of satellites to probe $z_{rei}$, the mean reionization redshift of all regions within the MWgfr. Depending on the choice of morphology, this represents either the redshift at which the MWgfr is quickly ionized by the Virgo Cluster or, since the overdensity of the IGM is small, the mean reionization redshift of the Universe. However, if the MWgfr does self-ionize, then we can learn not only about the efficiency of star formation but also about the clumpiness of the IGM.

After analysing three possible values of $z_{rei}$ from VLII using the inside-out reionization prescription of Section 2.2, we found corresponding sets of model parameters that best fit the LF data: $(z_{rei}, N_{\text{clump}}, f_{HI}, f_{esc}) = [(7.77, 7, 0.05, < 0.001), (9.14, 17, 0.2, 0.1), (11.2, 30, 1, 0.4)]$; the values of $f_{HI}$, for an external reionization scenario can be calculated from equation (4).

We find that the data are most consistent with early reionization at $z_{rei} = 11.2$, consistent with the WMAP 5 central value, and very high values for the clumpiness of the IGM, star formation efficiency and escape fraction. This also implies a higher star formation efficiency in molecular hydrogen cooling systems at redshifts above $z \sim 20$ than for later reionization models. Our result also argues for early enrichment of the IGM (Furlanetto & Loeb 2003). Assuming consistency with WMAP results, simulations by Wise & Cen (2009) have found that, for a ‘normal’ (i.e. non-topheavy) IMF, the product $f_{HI} f_{esc}$, averaged over atomic cooling haloes with virial temperatures above 8000 K, to be 0.02 with $f_{esc} \sim 0.4$. This implies $g(\delta) \sim 12$ and that the cosmic IGM is relatively smooth with only a few recombination points per baryon and a couple photons required, on an average, to ionize each atom of hydrogen.

However, it remains possible that the discrepancy between the data and model predictions with later reionization results from a series of Poisson fluctuations or cosmic variance between VLII and the true MW history. In such a case, we are left with three possible points in parameter space. These points trace out a continuous path in the space of reionization parameters, but we were only able to probe discrete redshifts at which VLII slices have been analysed. However, any external information about one of these parameters fixes a single point that fits the data reasonably well. For example, evidence that stars formed in molecular hydrogen cooling haloes do not contribute to the luminosities of satellites today would argue for reionization around $z_{rei} \approx 8$.

Finally, we note that the entire MWgfr need not reionize in one particular way; the dense progenitors could begin to self-ionize with radiation from the Virgo Cluster completing reionization for the rest of the region at some later time. The results we obtained by assuming an inside-out morphology for the entire MWgfr are valid as long as the progenitors of the MW satellites completely reionize themselves. This is because the satellite data are only sensitive to what happens in these objects. In this case, $z_{rei}$ is the mean reionization redshift of the Universe, since it is the time from which the stellar mass produced by MW progenitors to reionize themselves early is calibrated.

(3) While stars formed before reionization do contribute somewhat to the luminosity of the brightest MW satellites ($M_V < -5$), this population of pre-SDSS objects can be explained by a combination of H\textsc{i} and metal-line cooling in the most massive subhaloes after reionization.

These satellites were represented in our model by VLII objects that have exceeded a maximum circular velocity of $V_5$ sometime in their histories. When we included the pre-reionization stars and Orban et al. (2008) results to determine the stellar mass formed in the last 10 Gyr, we determined that a fraction $f_s = 0.01$ of the photoheated gas retained by the largest subhaloes after reionization is converted into stars. The majority of the gas must be kept hot or at low density to prevent these objects from being brighter than observed.

While old stars may be found in these satellites, they are not prime candidates for finding the relics of the first stars.

Although we have produced some interesting results using MW satellite data to probe the early universe, the data will become sensitive to the parameters of even more complicated models if: (1) additional new satellites are discovered to improve the statistics of the sample; (2) the errors on the $M_{\text{gfr}}$ and the mass-to-light ratio of satellites are improved; (3) the degree of cosmic variance between different high-resolution MW simulations is understood and (4) new high-resolution simulations are developed to include baryons and feedback processes. Progress is already being made on some of these fronts. PanSTARRS (Kaiser et al. 2002), the Dark Energy Survey (Dark Energy Survey Collaboration 2005), SkyMapper (Keller 2007) and the Large Synoptic Survey Telescope (Ivezic et al. 2008) will intensively probe for satellites populating the galactic neighbourhood. Additionally, Ishiyama, Fujishige & Makino (2009) have compared subhalo populations for many different simulations of galactic haloes and found more scatter than anticipated by Springel et al. (2008) using a smaller sample, but their work has not yet resolved the progenitors that formed ultra-faint systems. Once developed, high-resolution cosmological simulations with baryons and feedback will test much more specific models of reionization and open an avenue for comparisons with new observables, in addition to those explored here, such as the half-light radius, which promises to hold interesting clues about the high-redshift formation physics of MW satellites. With these improvements, our basic methodology can be used in the future to further probe reionization and the process of star formation in the early universe.

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