THE REIONIZATION OF GALACTIC SATELLITE POPULATIONS

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ABSTRACT

We use high-resolution simulations of the formation of the local group, post-processed by a radiative transfer code for UV photons, to investigate the reionization of the satellite populations of an isolated Milky Way–M31 galaxy pair in a variety of scenarios. We use an improved version of ATON which includes a simple recipe for radiative feedback. In our baseline models, reionization is initiated by low-mass, radiatively regulated halos at high redshift, until more massive halos appear, which then dominate and complete the reionization process. We investigate the relation between reionization history and present-day positions of the satellite population. We find that the average reionization redshift (z_r) of satellites is higher near galaxy centers (MW and M31). This is due to the inside out reionization patterns imprinted by massive halos within the progenitor during the epoch of reionization, which end up forming the center of the galaxy. Due to incomplete dynamical mixing during galaxy assembly, these early patterns survive to present day, resulting in a clear radial gradient in the average satellite reionization redshift, up to the virial radius of MW and M31 and beyond. In the lowest emissivity scenario, the outer satellites are reionized about 180 Myr later than the inner satellites. This delay decreases with increasing source model emissivity, or in the case of external reionization by Virgo or M31, because reionization occurs faster overall and becomes spatially quasi-uniform at the highest emissivity.

Key words: cosmology: theory – galaxies: formation – galaxies: high-redshift – intergalactic medium – methods: numerical – radiative transfer

Online-only material: color figures

1. INTRODUCTION

In the last decade, the epoch of reionization (hereinafter EoR) has received increasing attention. Most observational works now seem to converge on reionization beginning as early as z = 15 (Kogut et al. 2003) and finishing around z = 6 (Fan et al. 2006), in apparent agreement with theoretical predictions (Haardt & Madau 2011). The EoR also affects the way galaxies form: it has been suggested that the rising metagalactic UV radiation field is responsible for photo-evaporating the gas of low-mass galaxies (Gnedin 2000; Hoeft et al. 2006; Benitez-Llambay et al. 2014), shutting down or delaying their star formation in the first billion years of the universe. This process could provide a credible solution to the “missing satellites problem” (Klypin et al. 1999; Moore et al. 1999) by inhibiting star formation in low-mass galaxies at early times (Bullock et al. 2000; Benson et al. 2002a, 2002b, 2003). In this framework, a number of simple semi-analytical models (hereinafter SAMs) have been shown to reproduce well the satellite population of the Milky Way (hereinafter MW), such as Koposov et al. (2009), Muñoz et al. (2009), Busha et al. (2010), Macciò et al. (2010), Li et al. (2010), and Font et al. (2011). They suggest that the ultra-faint dwarf galaxies (hereinafter UFDs) discovered by the Sloan Digital Sky Survey (Martin et al. 2004; Willman & et al. 2005; Zucker et al. 2006; Belokurov & et al. 2007; Irwin & et al. 2007; Walsh et al. 2007) are effectively reionization fossils, living in sub-halos of about 10^6–10^9 M_☉. More recently, Ocvirk & Aubert (2011, 2012) showed that the structure of the UV background during reionization has a strong impact on the properties of the satellite population of galaxies. In particular, they showed that an internally driven reionization led to significant changes in the radial distribution of satellites. It is therefore of prime importance to determine how central, or, on the contrary, how uniform, the UV field is within a MW progenitor during reionization in a realistic setting. This is what the authors set out to determine in Ocvirk et al. (2013; hereinafter Paper I). Due to the adequate spatial resolution of their radiative transfer (hereinafter RT) simulation (∆x = 21 h^{-1} kpc), they were able to investigate the development and propagation of the ionization fronts (hereinafter I-front) within a typical Milky Way galaxy progenitor. They found that the process is patchy and dominated by a few (one to four) major regions expanding, percolating, and finally filling the whole volume of the progenitor. The amount of structure in the process depends on the ionizing sources emissivity, and the patchiest reionization is obtained for the lowest emissivity. Within this picture, it becomes clear that the reionization redshift of a satellite depends on its position within the galaxy progenitor. In particular, a future satellite that is close to the most massive halo of the MW progenitor is likely to reionize earlier than its more distant counterparts. Therefore, it is reasonable to expect that the properties of the satellites will be correlated with their position at reionization. In this paper, we ask the following questions. Do these correlations survive down to present times? Should we expect the satellite properties to be correlated in some way with their z = 0 distance to the MW’s center, for instance? From reionization to present times, the MW progenitor undergoes 12.7 Gyr of dynamical evolution, sometimes violent, thereby blurring the dynamical memory of the system. This process is expected to also blur or smother

5 Here the progenitor is defined as the volume containing all the particles that end up within 300 kpc of the MW center at z = 0, as in Ocvirk et al. (2013). Therefore, any MW satellite progenitor is already contained in the MW progenitor at high z.
any correlation between satellite properties and their position. However, evolving gravitational collisionless systems are known to retain some form of memory of their past configuration due to Liouville’s theorem (Binney & Tremaine 1987). This kind of memory in gravitationally driven evolution is widely acknowledged and described at cosmological scales (Crocce & Scoccimarro 2006) and intergalactic scales (Zaroubi et al. 1996; Aubert et al. 2004; Knebe et al. 2008; Libeskind et al. 2012). At galactic scales this memory is at the basis of galactic archaeology (Helmi & White 1999). Therefore, it is possible that some correlation between reionization history and position within the MW survives today? In this paper, we aim to answer this question by analyzing simulations of the reionization of the local group in terms of the relation between a satellite’s reionization history and its position within the MW halo at z = 0. Moreover, the present study brings an important improvement in our radiative transfer scheme, which now includes a simple recipe for radiative feedback, in the spirit of Iliev et al. (2007). The paper is organized as follows: first we describe the simulation used and radiative transfer postprocessing technique (Section 2). We then proceed to our results (Section 3), and discuss them (Section 4), before presenting our conclusions.

2. METHODOLOGY

The methodology of this study is similar to Paper I, but features an improved radiative transfer scheme, accounting for radiative feedback suppressing star formation in low-mass halos.

2.1. The CLUES Simulation

The simulation used in this work was performed in the framework of the CLUES project (Gottlöber et al. 2010). It was run using standard Lambda cold dark matter initial conditions assuming a WMAP3 cosmology (Spergel et al. 2007), i.e., Ωm = ΩΛ = 0.24, Ωb = 0.042, Ωχ = 0.76. A power spectrum with a normalization of σ8 = 0.73 and a n = 0.95 slope was used. The PMTree-SPH MPI code GADGET2 (Springel 2005) was used to simulate the evolution of a cosmological box with a side length of 64 h−1 Mpc. Within this box, a model Local Group that closely resembles the real Local Group was identified using a 10243 particle run (see Libeskind et al. 2010). This Local Group was then re-sampled with 64 times higher-mass resolution in a region of 2 h−1 Mpc about its center giving an equivalent resolution of 40963 particles, i.e., a mass resolution of mdm = 2.1 × 105 h−1 M⊙ for the dark matter and mgas = 4.42 × 104 h−1 M⊙ for the gas particles. For further details, we refer the reader to Gottlöber et al. (2010). The feedback and star formation prescriptions of Springel & Hernquist (2003) were used. Outputs are written on average every 30 Myr. The simulation starts at z = 50. As it runs, dark matter and gas collapse into sheets and filaments, extending between halos, in the spirit of Iliev et al. (2007). More details are given in Section 2.2.4. By design, self-shielding is also accounted for and results in a later reionization of sourceless high-density regions, such as mini-halos or the cold gas filaments.

2.2. Radiative Post-processing

2.2.1. ATON

ATON is a post-processing code that relies on a moment-based description of the radiative transfer equations and tracks the out-of-equilibrium ionizations and cooling processes involving atomic hydrogen (Aubert & Teyssier 2008). Radiative quantities (energy density, flux, and pressure) are described on a fixed grid and evolved according to an explicit scheme under the constraint of a Courant–Friedrich–Lewy condition (hereafter CFL). The simulations presented in this work used a mono-frequency treatment of the radiation with a typical frequency of 20.27 eV for 50,000 K blackbody spectrum. Because of the high resolution of the CLUES simulation, we do not make any correction for the clumping, as was done for the largest boxes of Aubert & Teyssier (2010). ATON has been ported on multi-GPU architecture, where each GPU handles a Cartesian sub-domain and communications are dealt using the MPI protocol (Aubert & Teyssier 2010). By achieving an x80 acceleration factor compared to CPUs, the CFL condition is satisfied at high resolution within short wallclock computing times. As a consequence, no reduced speed of light approximation is necessary and it may be of great importance for the timing arguments of the local reionization discussed hereafter. Along the course of this work, simulations were run on segments of 8–64 GPUs on the Titan and Curie machines of the CCRT/CEA supercomputing facility, with typically 160,000 radiative timesteps performed in 37 hr.

The postprocessing approximation has potentially important consequences on our results, as discussed, for instance, in Baek et al. (2009) and Frank et al. (2012). While the temperature of the gas is consistently followed by ATON, the gas density is “frozen” to that given by the smoothed particle hydrodynamics (SPH) simulation snapshots. This means that our scheme does not allow for photo-evaporation, however, we do include a simple recipe for the effect of photo-heating of the baryons in halos, resulting in suppression of star formation in low-mass halos, in the spirit of Iliev et al. (2007). More details are given in Section 2.2.4. By design, self-shielding is also accounted for and results in a later reionization of sourceless high-density regions, such as mini-halos or the cold gas filaments.

2.2.2. Field Setup

The gas density field is projected onto a 5123 grid of 11 comoving h−1 Mpc side. The center of the grid is the barycenter of all the particles which end up within 300 h−1 kpc of the MW at z = 0. This setup gives us a spatial resolution of Δx = 21 h−1 kpc. The sources are projected on the same grid. As explained in Section 2.1, the CLUES simulation uses a zoom technique, with a high- and low-resolution domains. The high-resolution (hereafter HR) domain contains the objects of interest (MW and M31), and is described with dark matter, gas, and star particles. At 5123 resolution, all grid cells contain at least one of properties of galaxy formation at high resolution (Forero-Romero et al. 2011; Knebe et al. 2011a, 2011b; Libeskind et al. 2011a, 2011b). Besides being a well-studied simulation, the advantage of this data set for the present study is twofold. First of all, it produces a fairly realistic local group at z = 0: the MW and M31 are in the correct range of masses and separation. Second, its mass resolution in the zoomed region allows us to resolve the 107 h−1 M⊙ halos. This is of crucial importance in reionization studies since they are the most numerous sources of UV photons.
gas particle in the HR region in the highest redshift snapshot ($z = 19.5$). On the other hand, the low-resolution (hereafter LR) domain does not have any SPH particle. Therefore, we set the gas density in the low-resolution domain to $\rho_{LR} = 10^{-2} \rho_C$, where $\rho_C$ is the critical density of the universe. The LR region does not contain any stars either. Photons reaching the HR/LR boundary region just leave the local group and quickly reach the edges of the computational box. There, we use transmissive boundary conditions, i.e., light just exits the box.

### 2.2.3. Ionizing Sources

Our model is based on dark matter halo catalogues produced using the Amiga halo finder\(^7\) (Gill et al. 2004; Knollmann & Knebe 2009). We keep only the halos that have 100% of their mass in high-resolution dark matter particles. Dwarf galaxies of the early universe are subject to a wide range of feedback processes beyond photo-evaporation by a UV background. Although our code does not allow for live self-regulation of the sources, we tried to account for the influence of at least some of the relevant feedback processes. We use a constant $f_{esc} = 0.2$, which is among values allowed by recent studies on the UV continuum escape fraction of high-$z$ galaxies (Wise & Cen 2009; Razoumov & Sommer-Larsen 2010; Yajima et al. 2011; Wise et al. 2014). We neglect any possible AGN-phase of our emitters. Such sources could already be in place in rare massive proto-clusters during reionization (Dubois et al. 2011, 2012), and contribute to the cosmic budget of ionizing photons (Haardt & Madau 2011), but they are beyond the scope of the present study. The properties of our source models are summarized in Table 1.

As in Paper I, we consider that all halos with a virial temperature $T_{vir} < 10^4$ K are unable to form stars due to the Lyman–Werner background dissociating $H_2$, the only coolant of pristine hydrogen gas at these masses (Barkana & Loeb 2001; Ahn et al. 2009). More details are given in Paper I. In essence, we consider only halos with $T_{vir} > 10^4$ K as UV sources.

We assign an instantaneous star formation rate to each halo, assuming $\text{SFR} \propto M$. However, since the total emissivity of a given halo depends on its mass the star formation efficiency times the emissivity times the escape fraction and is therefore degenerate with respect to the last three parameters, it suffices to set the global emissivity of our models.

We also re-use two models of Paper I: SPH and H44 (SPH and H44 SNfb in Table 1) in order to investigate the impact of an alternative source modeling (see Section 3.1.2) and a case of external reionization of the MW by M31 (see Section 4.1).

A summary of the properties of our models is given in Table 1. The emissivities are given in photons s$^{-1}$ per h$^{-1}$ $M_{\odot}$ of dark matter halo and per h$^{-1}$ $M_{\odot}$ of young stars (<30 Myr). While this duration is larger than the typical 10 Myr used for the lifetime of massive, UV-bright stars, it is imposed by the temporal spacing between two snapshots of the SPH simulation which produced the star particles. This is equivalent to smoothing the star formation history of the simulation over 30 Myr, and this is not likely to affect our results.

The adopted emissivities give reionization redshifts for the local group galaxies progenitors between 8 and 13, i.e., well within the range allowed by observations (Fan et al. 2006) and large-scale simulations such as Alvarez et al. (2009).

### 2.2.4. Simple Radiative Feedback

In a fully coupled radiative-hydrodynamics simulation, the gas field reacts to the photo-heating, and can result in the dispersion of low-mass gas structures (Shapiro et al. 2004; Iliev et al. 2005, 2009). This should induce a form of self-regulation of star formation and therefore emissivity by shutting off sources in the ionized low-mass halos, as shown in Iliev et al. (2007). Even though a small number of coupled galaxy formation codes have recently been built (Petkova & Springel 2011; Rosdahl & Blaizot 2012; Finlator et al. 2011; Wise & Abel 2011), at the moment no application to the formation of the local group in a zoom simulation such as the CLUES data set we use here has been performed, mainly because of the very large computational cost involved.

In order to account for this effect in our semi-analytical model, we divide our sources into two classes:

1. **Low-mass, radiatively regulated halos.** These are massive enough not to be suppressed by Lyman–Werner background, i.e., they are atomically cooling halos ($T_{vir} > 10^4$ K), but are still sensitive to photo-heating. Using coupled radiative-hydrodynamical numerical simulations, Pawlik et al. (2013) showed that above $10^9 M_{\odot}$, a

| Model | Source | Criterion | Rad. Feedb. | Emissivity (photons s$^{-1}$ per h$^{-1}$ $M_{\odot}$) | $M_{\text{MW}}$ | $M_{\text{M31}}$ | $\Delta_{0.0}^{0.9}$ | $\Delta$ (Myr) |
|-------|--------|-----------|-------------|-----------------------------------------------|-----------|-----------|-----------------|-------------|
| H1e43 UVfb | $T_{vir} > 10^4$ K | Yes | $4.1 \times 10^{44}$ | 8 | 8.1 | 2.9 | 2.81 | 267 | 252 |
| H7e43 UVfb | $T_{vir} > 10^4$ K | Yes | $6.8 \times 10^{44}$ | 10.5 | 10.7 | 2.48 | 2.42 | 126 | 120 |
| H7e43 NOfb | $T_{vir} > 10^4$ K | No | | 11 | 11.2 | 2.25 | 2.28 | 103 | 101 |
| H7e44 UV fb | $T_{vir} > 10^4$ K | Yes | $6.8 \times 10^{44}$ | 13.1 | 13.3 | 3.27 | 2.14 | 98 | 66 |
| SPH | ... | No | $6.3 \times 10^{44}$ | 9 | 9.4 | 2.72 | 2.34 | 202 | 159 |
| H44 SNfb | $M > 10^9 h^{-1} M_{\odot}$ | No | $4.08 \times 10^{44}$ | 9.1 | 9.7 | 0.55 | 0.32 | 43 | 22 |

Notes. Column 2 gives the criterions of the source models, used to mimic Lyman–Werner and supernova feedback. Column 3 takes the value “yes” for models with radiatively regulated star formation, and “no” otherwise. Column 4 gives the halo emissivity per solar mass of dark matter halo, except for the SPH model where the emissivity is given per mass of young stars (<30 Myr, i.e., the duration between two snapshots of the SPH simulation), hence the * superscript. In all cases, the emissivity is given after accounting for an escape fraction $f_{esc} = 0.2$. Column 5 gives the reionization redshift of the MW and M31 progenitors for each model, i.e., the time when the mass-weighted ionized fraction of the progenitor reaches 0.5. Column 6 gives the duration of the progenitors’ reionization as the time spent to increase the mass-weighted ionized fraction ($x^m$) from 0.1 to 0.9. Column 7 gives this duration in megayears. The first four models are our baseline models, and the fifth is taken from Paper I.

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\(^7\) http://popia.ft.uam.es/AHF
proto-galaxy is able to self-shield and is dense enough that it is no longer affected by radiative feedback. We use this value as the upper mass of the low-mass, radiatively regulated halos class. These halos are UV sources only when the ionized fraction of their cell is smaller than \(x_{\text{I,UV}} = 0.5\). In this “neutral” state, they will form stars at some prescribed rate, which will live for 10 Myr. As a result, they undergo radiatively driven cycles of star formation (photo-heating, suppressed star formation, cooling + recombination, star formation) and therefore can turn on and off several times through the course of the simulation. This results in the oscillations seen in Figure 1.

2. High-mass, self-shielding star forming halos. These objects are massive enough \((>10^9 \, M_\odot)\) to keep forming stars even when their cell is completely ionized. We know from high-resolution simulations such as Pawlik et al. (2013) that such halos are able to self-shield, but we do not have the spatial resolution in our RT simulation to resolve the shielded region. Therefore, we consider that such massive halos will continue forming stars even if the RT cell in which they reside is completely ionized. Therefore, these halos are UV-bright throughout the simulation.

The basic behavior of this model is illustrated in Figure 1 for a H7e43 UVfb model. For this example only, a 256\(^3\) grid was used instead of 512\(^3\), but the basic behavior is identical to the higher-resolution 512\(^3\) runs of the rest of the paper. In this example, the box reionizes at \(z \sim 6\). The left panel shows the number of ionizing sources. The blue line shows the number of active low-mass halos. At high redshift, it is close to the total number of halos (low and high masses), but radiative self-regulation suppresses a fraction of the low-mass halos, giving rise to the oscillations. The volume-filling fraction of these halos and their Stromgren spheres increases rapidly with decreasing redshift, and at \(z \sim 12\), some of them start to overlap, leading to an increasing offset between the maximum of emitting low-mass halos and the total number of halos (i.e., a smaller and smaller fraction of the low-mass halos is a source). This becomes even more marked by \(z \sim 10\), where the first high-mass halos, immune to radiative feedback, start to appear. Their Stromgren spheres rapidly expand, suppressing star formation in nearby low-mass halos until the latter are almost totally shut down. The high-mass sources finally outnumber the low-mass sources at \(z \sim 6\). However, due to their high mass and therefore larger photon output (and considering a constant \(f_{\text{esc}}\) for all halo masses), they outshine the low-mass halos as early as \(z \sim 7\), as shown by the middle panel of Figure 1. This evolution is similar to that reported in Iliev et al. (2007) and Wise et al. (2014), where low-mass galaxies are responsible for initiating reionization at high redshift, but are gradually radiatively suppressed by the more massive halos insensitive to the UV background which finally outshine them. However, since they appear earlier, the cumulated photon output of the low-mass halos through cosmic history is actually comparable to that of the massive halos at the time of overlap, although the universe is kept ionized by the high-mass halos afterward. The time at which the cumulated photon output of the two classes of halos are equal actually depends on source emissivity. The suppression of low-mass sources reduces the overall emission of UV photons through cosmic time. As a result, models with UV feedback (“yes” in Column 3 of Table 1) should reionize slower than models without UV feedback. This is confirmed, for instance, by the reionization timings (Columns 5–7 of Table 1) of model H7e43 UVfb versus model H7e43 NOfb (same emissivity but without feedback, therefore more sources active at any given time). In the former, the MW reionizes at \(z = 10.5\), while in the latter, it reionizes at \(z = 11\). The same holds for M31.

3. RESULTS

In this section, we check the good behavior of our RT scheme with radiative feedback using classical Eulerian reionization maps. Then we introduce the Lagrangian reionization map technique, using dark matter halos as tracers. We then turn to computing the reionization histories of the satellite populations of MW and M31 and show that they also depend on satellite positions.

In general, the Eulerian reionization maps we obtain, shown in Figure 2, are rather similar to those of Paper I, however, with slightly more small-scale structures at a given emissivity. For instance, the low-emissivity scenario H1e43 UVfb has much more small-scale structures than the low-emissivity scenario of Paper I. In particular, there are a number of small early-reionized bubbles (100–200 \(h^{-1} \, \text{kpc}\)) across at some distance from the main patches of each progenitor, as well as outside of the progenitors. These are produced by small self-regulated...
halos in low-density intergalactic medium (IGM): they turn on, ionize their neighborhood, and self-suppress, therefore turning off. However, the density of the IGM in these regions is too low for the gas to recombine and a unique episode of star formation in these low-mass halos is enough to produce these small patches in the map. The H7e43 UVfb and H7e43 NOfb allow us to illustrate the impact of the feedback recipe on the reionization map: again, the maps are very similar, except that the model with UV feedback reionizes slightly later, and has more small scale structures. This is not surprising: feedback reduces overall emissivity, and Paper I showed that reducing emissivity leads to later reionization and more small-scale structures. Moreover, the H4e44 UVfb model, with the highest emissivity, also shows the smallest degree of small-scale structures, in agreement with Paper I. This validates our understanding of the behavior of our model with feedback. Finally, we see that the addition of UV feedback does not change the basic conclusions of Paper I, which is that the MW and M31 appear to reionize in isolation within the emissivities considered here.

3.1. Lagrangian Reionization Maps

3.1.1. Dark Matter Halos and Particles as Tracers

In order to investigate the evolution and the possible survival of the structures seen in the reionization maps during the progenitor’s collapse and galaxy assembly, we build Lagrangian
reionization maps. Contrary to the Eulerian reionization maps, which are grid-based, Lagrangian reionization maps use the dark matter halos or particles of the simulation as tracers. In each snapshot, we assign to the particles the $x_{\text{ion}}$ of the cell in which the particle resides. This yields for each particle a reionization history, from which we define a reionization redshift for each particle as the last redshift where $x_{\text{ion}} < 0.5$. Since we are interested in understanding the impact of patchy reionization on the satellite population, we select halos with a mass between $10^7$–$10^9 h^{-1} M_\odot$ at $z = 0$, i.e., the mass range expected for ultra-faint dwarfs halos (Ocvirk & Aubert 2011). This low-mass satellite population is supposed to be the most sensitive to photo-heating. More massive satellites, such as Large Magellanic Cloud or Small Magellanic Cloud, are not affected by reionization since they are still forming stars today. This is why we restrict ourselves to the low-mass satellite population. Note that we only consider the surviving satellites at $z = 0$ and not the disrupted ones. We compute reionization redshift of a $z = 0$ dark matter halo as the average reionization redshift of its core dark matter particles ($< 0.1 R_{\text{vir}}$), so as to minimize contamination by background particles. We can then produce Lagrangian reionization maps at any redshift. The main novelty of such maps is that they account by construction for the dynamical evolution of the system down to the epoch of interest. In particular, unlike Eulerian reionization maps, they allow us to investigate the structure of the reionization history of the MW at $z = 0$.

3.1.2. Radial Reionization Maps

We computed the reionization redshifts of the $z = 0$ surviving dark matter halos of the MW and M31 for our four baseline models. We then investigate the relation between the halo positions at $z = 0$ and their reionization redshifts ($z_{\text{r}}$) and reionization times ($t_{\text{r}}$, with the Big Bang as origin $t_{\text{r}} = 0$), by means of the $z_{\text{r}}$—distance to the MW center distribution shown in Figure 3.

Figure 3. Distribution of the reionization redshifts of the MW satellite halos as a function of position at $z = 0$. The color codes the relative number of satellites in each cell, with each radial bin normalized by a fit to the number of satellites per bin. For instance, the darkest inner cells contain only one satellite each. The red solid line shows the average satellite $z_{\text{r}}$ for each radial bin, and the black thin dashed lines the dispersion of $z_{\text{r}}$. The red dotted line shows the linear fit to the average, with parameters given in Table 2. (A color version of this figure is available in the online journal.)
**Impact of emissivity.** Increasing emissivity reduces the dispersion of \( z_t \) and \( t_1 \), and, more importantly, flattens the radial \( t_1 \) gradient, and shows a quick comparison between the H1e43 UVfb, H7e43UVfb, and H4e44 UVfb models. At high emissivity, reionization happens faster, therefore reducing the delay between reionization of the outer and inner progenitors. This then translates to a smaller delay between inner and outer MW sub-halos. The slopes for our baseline models vary from 123 Myr dex\(^{-1}\) at low emissivity down to 36 Myr dex\(^{-1}\) at high emissivity, as shown in Table 2. However, due to the logarithmic evolution of redshift as a function of time, the slope in \( z_t \) remains relatively constant for all baseline models, and is always close to 1 dex\(^{-1}\).

**Impact of UV feedback.** The \( t_1 \) gradient of the H7e43 UVfb model is slightly steeper than that of the H7e43 NOfb model. However, the latter also features a slightly higher overall emissivity due to the lack of UV feedback. Therefore, it is very likely that the difference in slopes between these two models are just emissivity-driven. This shows that the gradient found is not a consequence of some peculiar topology of reionization resulting from our implementation of radiative feedback.

**Galaxy to galaxy variations.** We show the radial Lagrangian reionization maps centered on M31 in Figure 4 for our four baseline models. They are very similar to the maps centered on the MW, and the same comments as for Figure 3 hold. The reionization history of the satellites of M31 is correlated with their \( z = 0 \) position as well, with a very similar gradient slope. The average reionization redshift curves (solid line) for MW and M31 are well within 1σ of each other. It is remarkable that for both galaxies, the radial profiles of \( z_t \) at \( z = 0 \) are so similar for all massive galaxies which undergo internal reionization. However, the underlying Gadget-2 simulation from which we take the gas distribution and halo catalogs also features star formation, spawning star particles, which we can thus use as UV sources if young enough. In principle, stars form in halos, so we expect that at least the location of sources will be the same as with the halo model. However, there may still be a number of significant differences between the two source models.
1. Supernova hydrodynamical feedback is best accounted for in the SPH formalism used, while our baseline models only include radiative feedback of young stars. Explicitly accounting for the effect of supernova explosions in our halo model would only reduce the overall star formation efficiency, which is degenerate with respect to other parameters such as specific emissivity and escape fraction. Besides, the H44 SNfb model uses a very strong prescription for supernova feedback, allowing only massive halos to be sources, while low-mass halos will form no stars at all.

2. The star formation rate of halos in the SPH simulation are sporadic and complex, at variance from our simple halo model where it is simply proportional to halo mass.

3. The baseline halo models include radiative feedback, meaning low-mass halos can be shut down by remote, more massive halos, as far as several hundreds of kiloparsecs. This will not happen with the SPH star model, where supernova feedback will be purely internal and local.

In order to investigate the impact of these differences, we repeated our experiments using the SPH star particles as sources instead of the halo models. The reionization map for the SPH model was shown in Paper I, where we noted very few differences with the halo models of similarly tuned emissivity, which did not include radiative feedback. Again, we note that the SPH star model reionization map is very similar to that of our baseline models. In terms of timing and structure, it is intermediate between the H1e43 UVfb and H7e43 UVfb models. This also holds for the $z_r$ gradients, as shown in Figure 5 and Table 2. Therefore, our main result is robust to a change of source model: there is a clear radial gradient in $z_r$ at $z = 0$ and its slope is correlated with the duration of the reionization process of galaxy progenitor, which is set by the emissivity of the sources.

3.1.3. Temporal Evolution of the Gradient

In order to gain insight into the origin of the $z_r$ gradient, we now turn to the investigation of its temporal evolution. Unfortunately, only the most massive sub-halos at $z = 0$ can be tracked up to $z = 6$ and beyond. This severely limits our ability to study the temporal evolution of the gradient. A useful
alternative is to simply compute Lagrangian reionization maps for all the dark matter particles in the high-resolution region of the simulation. While this is not the same as tracking the halo themselves, we will see that this is still very instructive. We compute radial Lagrangian reionization maps for the H1e43 UVfβ model at three epochs from just after reionization, $z \sim 5$, to 0, i.e., the only difference between these three maps is the positions of the particles at these three redshifts. The center of the MW progenitor ($R = 0$) is defined as the center of the main branch halo at all redshifts (Klimentowski et al. 2010; Sríswat et al. 2013).

The maps are shown in Figure 6. There is a clear flattening of the gradient with time. At $z = 5$, very little dynamical evolution has taken place. The gradient is very marked, especially in the 100–1000 $h^{-1}$ kpc range, and the reionization profile is still evocative of a Strömgren sphere (Barkana & Loeb 2001), although somewhat perturbed. The center has very few low $z_r$ particles. The dispersion in $z_r$ is smaller than at any other redshift. At $z = 1$ some mixing within the MW halo and merging of small structures has already taken place, and intermediate $z_r$ particles have managed to sink in, but the gradient is still rather steep and the dispersion is still smaller than on the $z = 0$ map. At $z = 0$, the average $z_r$ profile (thick black line) is much smoother. It has settled in its shallowest slope, which is comparable to the slope found for the satellites on the map of Figure 3. The similarity of the $z_r$—distance distribution between the dark matter particles and the halos suggests that the process giving rise to the inside out $z_r$ gradient is the same for both tracers.

Besides the gradient, the maps of Figure 6 also show a number of vertical structures (most distinctly at $z = 1$, but also present in the other two maps) tracing individual massive halos. These give rise to the bumps seen in the average $z_r$ profile. While the furthest one is M31 (beyond 1000 $h^{-1}$ kpc), the other smaller wiggles are produced by smaller objects, although massive enough to reionize internally. The $z = 1$ map features a structure at $\sim 200 h^{-1}$ kpc on the verge of merging with the main MW halo. It is no longer present in the $z = 0$ map, signifying the accretion of the object. We know from Paper I and Figure 2 that at least the MW, M31, and, to some extent, M33 reionize internally, in isolation, with our baseline models, along with a number of more remote, smaller regions. Therefore, the bumps in the average $z_r$ are the counterparts of the internally reionized patches seen in Figure 2. In contrast, halos experiencing external reionization will show up as vertically narrow structures. An example of such an occurrence is the region around $R = 10^5$–$10^7 h^{-1}$ kpc, $t_r \sim 0.825$ Gyr in the $z = 5$ map. This structure has been reionized at $z \sim 6.8$, and accreted on the largest progenitor at some time between $z = 6.8$–5, as we can see it is already quite extended radially, suggesting a strong tidal interaction. On the later maps, it has migrated inward and become more and more diffuse (we recall that in these maps, structures can only move horizontally).

As a conclusion, this section confirms our earlier interpretation: inside out reionization patterns around the brightest sources of the MW progenitor give rise to the $z_r$ gradients, which are well marked and very steep by the end of reionization. They are then flattened and blurred by the subsequent 12.7 Gyr of dynamical evolution. However, they are not completely washed out and survive to present times.

4. DISCUSSION

4.1. Impact of Massive Nearby Sources

An important caveat of our study is that we treat the MW–M31 pair as an isolated system: we do not account for the effect of the nearby galaxy cluster Virgo, which may have been a major source of UV photons during the EoR. Here we show that despite this simplification, our main conclusions hold. Using a larger, lower-resolution simulation of the local group formation, I11 showed that for a low-emissivity scenario (comparable to our H1e43 and H7e43 models), the MW–M31 system reionizes internally, i.e., its reionization is achieved before the I-front from Virgo reaches us. Therefore, for our H1e43 and H7e43 models, not accounting for Virgo is a reasonable approximation. However, in the high-emissivity scenario (corresponding to our H4e44 model), I11 showed that the MW–M31 system is reionized by Virgo. In this case, the reionization of the MW–M31 system is not inside out, but is driven externally by an I-front from Virgo which sweeps through the MW progenitor halo in less than 15 Myr (estimated from I11 figures), i.e., reionization of the MW is quasi-instantaneous. Therefore, no
Figure 6. Temporal evolution of the reionization redshift gradient of dark matter particles for the H1e43 UVfb model (lowest emissivity), centered on the MW. The title of each panel gives, along with the map center (here MW), the model used and the redshift chosen for the particles positions. Each radial bin is normalized by the number of particles in the bin. The thick red line shows the median \( z_r \) of the particles. The center of the MW progenitor (\( R = 0 \)) is defined as the center of the main branch halo at all redshifts. The reionization redshift gradient of the particles is steepest at high redshift, and becomes smoother with time. The horizontal ridges are artifacts due to an uneven timing of the RT postprocessing outputs. The distributions were smoothed by a Gaussian for readability.

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

\( z_r \) gradient should be found within the MW halo. Our results show that the high-emissivity scenario leads to an almost flat \( z_r \) gradient (the slope is three times smaller than the dispersion in \( z_r \)). We see that, based on the I11 results, including Virgo could actually make it even flatter. In order to confirm this expectation, we re-analyzed model H44 of Paper I (H44 SNfb in this work).

The interest of this model for the present study is that it provides us with a case of reionization by an external front: indeed, in this model, Paper I showed that the MW progenitor is reionized externally by M31, in a very short time (43 Myr). We computed \( z = 0 \) the sub-halo \( z_r - \)distance distribution for this model, centered on the MW, shown in Figure 7, and find the distribution is the flattest of all models. Therefore, our main conclusion remains unchanged: low emissivity yields a slow, inside out reionization history for the MW satellite population, whereas high emissivity leads to a fast, quasi-uniform reionization throughout the MW progenitor, resulting in a quasi-constant reionization redshift for the satellite population.

4.2. Impact on MW Satellites Studies

Our results suggest that the halos of isolated MW-like galaxies may have a stratified reionization history depending on the emissivity of the sources during the EoR. This is the result of an intrinsical inside out, fairly slow reionization coupled to some form of weak positional memory of the halos. This may have important consequences for the study of galactic satellites: it means that in the low-emissivity case, inner satellites at 10 kpc distance (or the disrupted remains thereof) could on average have been reionized up to 180 Myr earlier than the satellites of the outer halo, orbiting at \( \sim 300 \) kpc. If indeed reionization is responsible for suppressing star formation in low-mass satellites as widely discussed in the literature, then the...
delayed reionization of the outer halo could lead to differences in stellar content between the inner and outer satellites. On the contrary, in the high-emissivity scenarios, this delay is very small, and therefore the inner and outer satellites would be reionized at the same time. In this case, it would suppress star formation in the inner and outer satellites simultaneously, regardless of whether reionization is internally or externally driven (by Virgo or M31). Therefore, it seems that by measuring the age of the last generation of stars in a sample of outer and inner satellites, one could discriminate between the high- and low-emissivity scenarios. However, this requires measuring an age difference of the order of 100 Myr in a population older than 10 Gyr, which is extremely challenging even using Hubble Space Telescope color–magnitude diagrams and stellar population models in the spirit of Dolphin et al. (2005): the width of the oldest age bins in these star formation history reconstructions is typically 10 times larger than the 100 Myr difference we need to measure. However, while constrains on the local reionization scenario may be difficult to extract from individual satellites, the global properties of the satellite population may still hold important clues. For instance, in the low-emissivity case, we find a strong $z_\text{r}$ gradient, meaning that the outer satellites may have experienced a longer period of star formation than their more nearby counterparts. Therefore, at a given mass, they could be more luminous and be detected at larger distances. As a consequence, the radial distribution of the satellites could be more extended in the low-emissivity case than in the high-emissivity case. This recoups the result of Ocvirk & Aubert (2011), which showed, using simple semi-analytical modeling, that internal reionization, which is more likely at low emissivity than external reionization (I11), produced a more extended radial distribution of the satellites around the MW. The key feature for such a differentiation is the emissivity-dependent $z_\text{r}$ gradient at $z = 0$, which we confirm with a more realistic modeling in the present paper.

Therefore, it seems that low-mass MW satellites such as ultra-faint dwarfs hold important clues about the local reionization history, although understanding and modeling them will be a challenging but exciting task for years to come.

5. CONCLUSIONS

We have used high-resolution simulations of the formation and reionization of a MW–M31 galaxy pair to investigate the relation between reionization history and the present-day position of their satellite population. To do this, we have introduced the Lagrangian reionization map. It relies on determining a reionization redshift $z_\text{r}$ for each dark matter halo of the simulation. We then explored the relation between the distribution of $z_\text{r}$ and the distance to galactic center at $z = 0$, for four baseline reionization scenarios featuring various emissivities and feedback processes. In all cases we find that the average $z_\text{r}$ of satellites is higher near galaxy centers (MW and M31). This is due to the inside out reionization patterns imprinted by massive halos within the progenitor during the EoR, which end up forming the center of the galaxy. The reionization patterns are slowly flattened by the dynamical evolution of the proto-galaxy and the merging of many substructures. However, they are not totally washed out, and a clear radial gradient in the average satellites reionization redshift still exists today in the halo of our simulated MW and M31, and out to $400 h^{-1}$ kpc (571 kpc). In the lowest emissivity scenario, the reionization of the outer halo takes place about 180 Myr later than in the inner halo. This is a significant time span compared to the duration of the epoch of reionization itself, and could affect satellite properties by letting remote satellites form stars for longer periods of time or more efficiently than their nearby counterparts. The gradient flattens with increasing source emissivity, because reionization occurs faster overall, and becomes spatially quasi-uniform. However, the slope in $z_\text{r}$ remains remarkably constant in all baseline models, at about $−1$ dex$^{-1}$. We checked that our results are robust to changes in the source model by also using the stars spawned by the Gadget-2 simulation as sources rather than the dark matter halos. In the most luminous scenario, I11 suggests that UV photons from Virgo are expected to speed up drastically the reionization of the MW progenitor. This would likely make any radial $z_\text{r}$ profile even flatter than what we predict. We check this by analyzing a model in which the MW is externally reionized by M31 and effectively find a flat $z_\text{r}$ profile for the satellite population of the MW. On the other hand, the results of the two low-emissivity scenarios should not be affected by Virgo, since in this regime I11 shows that the local group reionizes internally. In all cases, the $z_\text{r}$ and $t_\text{r}$ gradients are well represented by a linear fit for which we give the parameters. We hope this will help to improve semi-analytical satellite population models (Muñoz et al. 2009; Busha et al. 2010; Macciò et al. 2010; Li et al. 2010; Font et al. 2011) by allowing authors to implement simply more realistic, position-dependent reionization histories.

As a conclusion, it seems that the population of low-mass satellites holds important clues about the local reionization history. However, deciphering these clues is currently very challenging, both from a theoretical and observational standpoint. A large amount of work remains to be done in order to improve the modeling of these systems, as well as to extend our knowledge of the MW and M31 satellite populations.

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8. [http://aramis.obspm.fr/LIDAU/Site_2/LIDAU_-_Welcome.html](http://aramis.obspm.fr/LIDAU/Site_2/LIDAU_-_Welcome.html)
REFERENCES

Ahn, K., Shapiro, P. R., Iliev, I. T., Mellema, G., & Pen, U.-L. 2009, ApJ, 695, 1430
Alvarez, M. A., Busha, M., Abel, T., & Wechsler, R. H. 2009, ApJ, 703, L167
Aubert, D., Pichon, C., & Colombi, S. 2004, MNRAS, 352, 376
Aubert, D., & Teyssier, R. 2008, MNRAS, 387, 295
Aubert, D., & Teyssier, R. 2010, ApJ, 724, 244
Baek, S., Di Matteo, P., Semelin, B., Combes, F., & Revaz, Y. 2009, A&A, 495, 389
Barkana, R., & Loeb, A. 2001, PhR, 349, 125
Belokurov, V., Zucker, D. B., Evans, N. W., et al. 2007, ApJ, 654, 897
Benitez-Llambay, A., Navarro, J. F., Abadi, M. G., et al. 2014, arXiv:1405.5540
Benson, A. J., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2003, MNRAS, 343, 679
Benson, A. J., Frenk, C. S., Lacey, C. G., Baugh, C. M., & Cole, S. 2002a, MNRAS, 333, 177
Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S. 2002b, MNRAS, 333, 156
Binney, J., & Tremaine, S. 1987, Galactic dynamics (Princeton, NJ: Princeton Univ. Press)
Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2000, ApJ, 539, 517
Busha, M. T., Alvarez, M. A., Wechsler, R. H., Abel, T., & Strigari, L. E. 2010, ApJ, 710, 408
Codis, S., Pichon, C., Devriendt, J., et al. 2012, MNRAS, 427, 3320
Crocce, M., & Scoccimarro, R. 2006, PhRvD, 73, 063520
Dolphin, A. E., Weisz, D. R., Skillman, E. D., & Holtzman, J. A. 2005, arXiv:astro-ph/0506340
Dubois, Y., Devriendt, J., Slyz, A., & Teyssier, R. 2012, MNRAS, 420, 2662
Dubois, Y., Pichon, C., Haehnelt, M., et al. 2011, MNRAS, 417, 1853
Fan, X., Strauss, M. A., Becker, R. H., et al. 2006, AJ, 132, 117
Finlator, K., Davé, R., & Özel, F. 2011, ApJ, 743, 169
Font, A. S., Benson, A. J., Bower, R. G., et al. 2011, MNRAS, 417, 1260
Forero-Romero, J. E., Hoffman, Y., Yepes, G., et al. 2011, MNRAS, 417, 1434
Frank, S., Rasera, Y., Vibert, D., et al. 2012, MNRAS, 420, 1731
Gill, S. P. D., Knebe, A., & Gibson, B. K. 2004, MNRAS, 351, 399
Gnedin, N. Y. 2000, ApJ, 542, 535
Gottlöber, S., Hoffman, Y., &Yepes, G. 2010, arXiv:1005.2687
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Haardt, F., & Madau, P. 2011, arXiv:1103.5226
Helmi, A., & White, S. D. M. 1999, MNRAS, 307, 495
Hoeft, M., Yepes, G., Gottlöber, S., & Springel, V. 2006, MNRAS, 371, 401
Hoffman, Y., Metuki, O., Yepes, G., et al. 2012, MNRAS, 425, 2049
Iliev, I. T., Mellema, G., Shapiro, P. R., & Pen, U.-L. 2007, MNRAS, 376, 534
Iliev, I. T., Shapiro, P. R., & Raga, A. C. 2005, MNRAS, 361, 405
Iliev, I. T., Whalen, D., Mellema, G., et al. 2009, MNRAS, 400, 1283
Irwin, M. J., Belokurov, V., Evans, N. W., et al. 2007, ApJL, 653, L11
Klementowski, J., Lokas, E. L., Knebe, A., et al., 2010, MNRAS, 402, 1899
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Knollmann, S. R., & Knebe, A. 2009, MNRAS, 390, 1326
Knebe, A., Libeskind, N. I., Doumler, T., et al. 2011a, MNRAS, 417, L56
Knebe, A., Libeskind, N. I., Knollmann, S. R., et al. 2011b, MNRAS, 412, 529
Knollmann, S. R., & Knebe, A. 2009, ApJS, 182, 608
Kogut, A., Spergel, D. N., Barnes, C., et al. 2003, ApJS, 148, 141
Koposov, S. E., Yoo, J., Rix, H., et al. 2009, ApJ, 696, 2179
Li, Y., De Lucia, G., & Helmi, A. 2010, MNRAS, 401, 2036
Libeskind, N. I., Hoffman, Y., Knebe, A., et al. 2012, MNRAS, 421, L137
Libeskind, N. I., Knebe, A., Hoffman, Y., Gottlöber, S., & Yepes, G. 2011a, MNRAS, 418, 336
Libeskind, N. I., Knebe, A., Hoffman, Y., et al. 2012b, MNRAS, 417, L93
Ocvirk, P., & Aubert, D. 2011, MNRAS, 417, L93
Ocvirk, P., & Aubert, D. 2012, in EPJ Web of Conferences, Vol. 19, Assembling the Puzzle of the Milky Way, ed. C. Reyle, A. Robin, & M. Schultheis (Les Ulis Cedex: EDP Sciences), 3005
Ocvirk, P., Aubert, D., Chardin, J., et al. 2013, ApJ, 777, 51
Ocvirk, P., Pichon, C., & Teyssier, R. 2008, MNRAS, 390, 1326
Pawlak, A. H., Milosavljević, M., & Bromm, V. 2013, ApJ, 767, 59
Petkova, M., & Springel, V. 2011a, MNRAS, 412, 935
Razoumov, A. O., & Sommer-Larsen, J. 2010, ApJ, 710, 1239
Rosdahl, J., & Blaizot, J. 2012, MNRAS, 423, 344
Shapiro, P. R., Iliev, I. T., & Raga, A. C. 2004, MNRAS, 348, 753
Spergel, D. N., Bean, R., doré, O., et al. 2007, ApJS, 170, 377
Springel, V. 2005, MNRAS, 364, 1105
Springel, V., & Hernquist, L. 2003, MNRAS, 339, 289
Stinson, G., & Jiang, J. 2012, MNRAS, 423, 310
Walsh, S. M., Jerjen, H., & Willman, B. 2007, ApJL, 662, L83
Willman, B., Dalcanton, J. J., Martinez-Delgado, D., et al. 2005, ApJ, 626, L85
Wise, J. H., & Abel, T. 2011, MNRAS, 414, 3458
Wise, J. H., & Cen, R. 2009, ApJ, 693, 984
Wise, J. H., & Chisari, F. 2014, MNRAS, 442, 2560
Yajima, H., & Nagamine, K. 2011, MNRAS, 412, 411
Zaroubi, S., Naim, A., & Hoffman, Y. 1996, ApJ, 457, 50
Zucker, D. B., Belokurov, V., Evans, N. W., et al. 2006, ApJL, 643, L103

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