CONNECTING REIONIZATION TO THE LOCAL UNIVERSE

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ABSTRACT

We present results of combined N-body and three-dimensional reionization calculations to determine the relationship between reionization history and local environment in a volume of 1 Gpc $^{-1}$ across and a resolution of about 1 Mpc. We achieve this by applying three-dimensional simulations of reionization, based on the extended Press-Schechter formalism, to the same initial conditions as the N-body simulations. We resolve about $2 \times 10^6$ halos of mass greater than $\sim 10^{12} M_\odot$ at $z = 0$, and determine the relationship between halo mass and reionization epoch for galaxies and clusters. For our fiducial reionization model, in which reionization begins at $z \sim 15$ and ends by $z \sim 6$, we find a strong bias for cluster-size halos to be in the regions that reionized first, at redshifts $10 < z < 15$. Consequently, material in clusters was reionized within relatively small regions, on the order of a few Mpc, implying that all clusters in our calculation were reionized by their own progenitors. Milky Way mass halos were on average reionized later and by larger regions, with a distribution most similar to the global one, indicating that low-mass halos are nearly uncorrelated with reionization when only halo mass is taken as a prior. On average, most halos with mass less than $10^{13} M_\odot$ were reionized internally, while almost all halos with masses greater than $10^{14} M_\odot$ were reionized by their own progenitors. We briefly discuss the implications of this work in light of the "missing satellites" problem and how this new approach may be extended further.

Key words: cosmology: theory – galaxies: formation – intergalactic medium

1. INTRODUCTION

The universe we observe at $z = 0$ must bear the marks of reionization. Reionization began when the first stars polluted the intergalactic medium and created individual H ii regions (Alvarez et al. 2006; Abel et al. 2007; Yoshida et al. 2007; Wise & Abel 2008). As the first galaxies grew in abundance, the H ii regions became longer lived, eventually containing perhaps tens of thousands of dwarf galaxies, growing and merging until they overlapped, marking the end of reionization (Shapiro & Giroux 1987; Miralda-Escudé et al. 2000; Gnedin 2000a; Sokasian et al. 2001; Nakamoto et al. 2001; Ciardi et al. 2003; Furlanetto et al. 2004; Iliev et al. 2006; Zahn et al. 2007; Trac & Cen 2007). Observations of high-redshift quasars imply that this process was complete by redshift $z \sim 6$ (Becker et al. 2001; Fan et al. 2002; White et al. 2003; Willott et al. 2007), while large-angle polarization measurements of the cosmic microwave background constrain the duration of reionization (Spergel et al. 2003; Komatsu et al. 2009).

During this time, the temperature of the intergalactic medium increased from a few to tens of thousands of degrees, dramatically changing the evolution of gas as it responded to the highly dynamic underlying dark matter potential.

Low-mass halos in ionized regions are less able to cool, collapse, and form stars than those in neutral regions, due to the increase in the cosmological Jeans mass when gas is ionized and photoheated, sometimes called “Jeans mass filtering” (e.g., Shapiro et al. 1994, 2004; Thoul & Weinberg 1996; Gnedin 2000b; Dijkstra et al. 2004; Okamoto et al. 2008). This suppression of structure is one of the fundamental ways that reionization can leave its imprint on subsequent structure formation, even up until the present day.

Correlating reionization with the present-day environment may be the key to the so-called “missing satellite problem” (Weinmann et al. 2007). Many more satellite halos are predicted to form in the cold dark matter theory of structure formation (CDM) than are actually observed as galaxies (Klypin et al. 1999; Moore et al. 1999). The leading explanation—an alternative to more exotic possibilities such as modifying dark matter or the amplitude of small-scale primordial density fluctuations—is that the UV background maintains the intergalactic gas in a photoheated state, preventing it from falling into the shallow potential wells of the progenitors of the satellite halos (e.g., Bullock et al. 2000; Benson et al. 2002). For example, one might expect that regions that were reionized earlier will have fewer luminous satellites than regions that were ionized later. However, biased regions, which are rich in early low-mass galaxy formation, would have reionized first. The latter effect implies that early reionization would lead to more satellite galaxies, while the former implies just the opposite. Detailed three-dimensional models are necessary in order to disentangle these competing effects and quantify their dependence on the inevitable assumptions that must be made when modeling reionization on such large scales.

In this Letter, we present our first calculations to address the correlation between reionization and local environment. We take a novel approach, combining N-body simulations with a “seminumerical” algorithm (Zahn et al. 2007; Mesinger & Furlanetto 2007) for calculating the reionization history for the simulation, allowing us to achieve a higher dynamic range in resolving the scales of reionization than has been possible until now. We then report on the statistical correlations between halo properties and their reionization epoch and environment. We present our hybrid N-body/seminumerical method in Section 2, our results in Section 3, and end with a discussion in Section 4. Throughout, we assume a flat universe with $\Omega_\Lambda = 0.25$, $\sigma_8 = 0.8$, $n_s = 1$, $\Omega_b = 0.04$, and $h = 0.7$.

2. MODEL

Our hybrid approach consists of two steps. First, we run an N-body simulation of structure formation to determine the positions and masses of halos at $z = 0$. We then calculate the reionization history of the same volume in order to determine the reionization epoch of each halo.
2.1. N-body Dark Matter Simulations

For our cosmological $N$-body simulations, we used the code GADGET-2 (Springel 2005). We simulated a periodic box 1 Gpc $h^{-1}$ on a side with 1120$^3$ $N$-body particles. We did not include any gas dynamics, a reasonable choice given that we are interested only in the global properties of the dark matter halos, not the internal properties of the baryonic component. We used a comoving softening length of 25 kpc, sufficient to resolve the formation of halos of mass $\sim 10^{12} M_\odot$. At $z = 0$, we use a friends-of-friends halo finder with a linking length of 0.2 mean interparticle spacings to identify the halos.

2.2. Seminumerical Reionization

Our model is based on the analytical formalism first introduced by Furlanetto et al. (2004) and later extended to three-dimensional realizations by Zahn et al. (2007). Its main assumption is that a region is fully ionized if its collapse fraction, defined as the fraction of matter present in halos above some minimum mass $M_{\text{min}}$, is greater than some threshold,

$$\zeta f_{\text{coll}} > 1.$$  \hspace{1cm} (1)

This corresponds, for example, to the assumption that $\zeta f_{\text{coll}}$ ionizing photons are released per atom per unit time. If recombinations are neglected, then Equation (1) results by ensuring the time-integrated number of ionizing photons released is greater than the number of the atoms. Another interpretation of the efficiency factor $\zeta$ is that each halo produces a spherical ionized region around it, the size of which is directly proportional to its mass. Thus, all the recombination, and radiative transfer physics is absorbed into our choice of $\zeta$. For example, $\zeta = (f_{\text{esc}} f_s N_{\gamma}/b)/(1 + n_{\text{rec}})$, where $f_{\text{esc}}$ is the escape fraction of ionizing photons from each halo, $f_s$ is the fraction of matter converted to stars within a halo, $N_{\gamma}/b$ is the number of ionizing photons produced in stars per hydrogen atom, and $n_{\text{rec}}$ is the average number of recombinations per hydrogen atom during reionization (Furlanetto et al. 2004).

To apply this criterion for “self-ionization” to an actual three-dimensional linear density field, we use the following relation for the collapsed fraction within a spherical region of mass $m$ and density contrast $\delta$ (Lacey & Cole 1993),

$$f_{\text{coll}} = \text{erfc} \left[ \frac{\delta_m(z) - \delta_0}{\sqrt{2}\sigma^2(M_{\text{min}})} \right],$$ \hspace{1cm} (2)

where $\sigma^2(m)$ is the mass variance over the scale $m$, $\delta_m(z)$ is the critical density for collapse, and $M_{\text{min}}$ is the minimum mass of halos to be counted in the collapsed fraction, i.e., the minimum mass of a halo capable of producing a significant amount of photoionizing radiation. Note that the time dependence of the density field has been taken into account in the critical density for collapse, $\delta_m(z) = \delta_{m,0}/D(z)$, where $D(z)$ is the linear growth factor, so that $\delta(m)$ and $\delta_0$ are constant in time. As shown by Furlanetto et al. (2004), this results in a time- and scale-dependent “barrier” around each point

$$\delta_m \geq \delta_m(z) - \frac{\sqrt{2}}{\sqrt{2}[\sigma^2(m_{\text{min}}) - \sigma^2(m)]^{1/2}}\text{erf}^{-1}(1 - \zeta^{-1}).$$ \hspace{1cm} (3)

The mean density within a sphere around a given point, $\delta_m$, must be greater than this barrier, $\delta_m(z)$, in order for that point to be ionized by that region. A given point is considered to be ionized when the condition in Equation (3) is met for any smoothing scale $m$, so that

$$z_{\text{reion}} = \text{MAX}_m \left[ D_0 \left( \delta_m + \sqrt{2} \text{erf}^{-1}(1 - \zeta) \times \left[ \sigma^2(m_{\text{min}}) - \sigma^2(m) \right] \right) - 1 \right]^{-1},$$ \hspace{1cm} (4)

where $\text{MAX}_m$ indicates the maximum value over all smoothing scales $m$.

In practice, the outcome of this modeling is one value of $z_{\text{reion}}$ at each point on the grid, which characterizes the evolution of reionization over all time. The smoothing of the density field over all scales can be accomplished through a fast Fourier transform (FFT). We also store the radius at which each cell on the grid first crossed the barrier, and associate it with the characteristic size of the region containing the sources that ionized the gas within that cell.

Finally, to associate with each $z = 0$ halo a reionization epoch and $H$ $\tau$ region size, we assign each of them a value that corresponds to the cell in which its center of mass lies at present. Given that typical $H$ $\tau$ regions are tens of Mpc, the vast majority of halos in our volume would not have had the required sustained peculiar velocities in excess of $10^3$ km s$^{-1}$ for 10 Gyr to have moved out of such a region. We thus expect our results to be robust for most halos in the box, with the predictions being least accurate for the few halos that are just on the verge of falling into large galaxy clusters. Here, the reionization epochs could be overestimated, and $H$ $\tau$ region sizes underestimated. We set the parameters of the reionization model to have a minimum halo mass of $M_{\text{min}} = 10^8 M_\odot$ and an efficiency parameter $\zeta = 10$. These parameters are a reasonable choice and give results on the morphology of reionization consistent with a broad range of assumptions in more expensive radiative transfer calculations (e.g., McQuinn et al. 2007).

3. RESULTS

Figure 1 shows snapshots of the reionization calculation at four different times for a 1024$^3$ grid. Even on scales of 100 Mpc, reionization remains inhomogeneous, with the reionization redshift of regions as large as tens of Mpc varying between $z_r \sim 15$ and $z_r \sim 6$. Although regions that were reionized first are at the peaks of the underlying density field, there is not a one-to-one correspondence between the mass of the $z = 0$ halos and their reionization epochs, since the halo and reionization barrier shapes and amplitudes differ.

Figure 2 shows the distribution of halo reionization epochs for several ranges of halo mass. There is considerable spread in reionization redshifts in this model, ranging over 6 $< z_r < 15$. The most massive halos are biased toward higher values of $z_r$, peaking at $z_r \sim 10, 8$, and 7 for masses $M \sim 10^{15}, 10^{14}$, and $10^{13} M_\odot$. The distribution of the lowest mass halos, with masses $\sim 10^{12} M_\odot$, does not have a well-defined peak, but rather increases toward the lowest redshifts, peaking at the percolation epoch at $z \sim 6$. This indicates that these lowest mass halos are relatively unbiased with respect to the structure of reionization.

Figure 3 shows the 68% and 95% contours of the reionization redshift distribution for halos binned by their mass. The median value increases from $z_r \simeq 8$ for $M_h = 10^{12} M_\odot$ to $z_r \sim 12$ for $M_h = 10^{15} M_\odot$. The distributions have a long tail toward higher reionization values, which is more pronounced for higher-mass halos. Only $\sim 3\%$ of $10^{12} M_\odot$ halos have $z_r > 12$, while only $\sim 3\%$ of cluster scale halos have $z_r < 9$. Such a large spread in reionization epochs at all masses implies that other halo
properties, such as merger history and local matter density, may be important in setting the reionization epoch for a specific halo such as our own Milky Way. These results are in qualitative agreement with those of Weinmann et al. (2007), which were based on high-resolution N-body simulations coupled with radiative transfer (see their Figure 3).

The mass-dependent distributions of bubble sizes are shown in Figure 4. Lower mass halos largely form in regions with larger H II bubbles, since their sizes increase with time. Interestingly, all of the roughly 800 cluster-mass halos in our sample are associated with H II region sizes less than 30 Mpc. Only halos below about $10^{13} \, M_\odot$ have H II region sizes in excess of 100 Mpc, likely exceeding the mean free path for Lyman-limit systems and approaching (and potentially exceeding) the size of the box, 1 Gpc $h^{-1}$.

4. DISCUSSION

Using large-volume and high-resolution coupled simulations of reionization and halo formation, we have developed a new method for connecting the $z = 0$ distribution of halos to the reionization epoch. We have found that, when only their mass is known, galaxy scale halos are nearly uncorrelated with respect to reionization, with a distribution of H II region bubble sizes and reionization epochs that are roughly consistent with having a random spatial distribution. Higher mass halos, however, show a much stronger correlation, with none of the cluster scale objects having $z_r < 8$ or $R_{H\alpha} > 30$ Mpc.

An important distinction is between internal and external reionization. Figure 5 describes these two possibilities. In the external reionization case, the halo material was ionized by sources in a region with $R_{H\alpha} \gg R_{Lag}$, where $R_{Lag}$ is the comoving volume occupied by the mass of the halo at the cosmic mean density. In this case, most of the sources that ionized the material were not progenitors of the halo, and the ionization front swept over the halo’s progenitors quickly, leaving the halo with a relatively uniform reionization epoch. For internal reionization, $R_{H\alpha} \ll R_{Lag}$, and the halo’s reionization history is likely to be much more complex. In general, more massive halos were
predictions of our model. The peak at low masses can be attributed to the grid resolution, given by a radius $\sim 1$ Mpc. Increased resolution would reduce the effect, but on such small scales the role of recombinations and the stochasticity of the sources are likely to play an increasing role, effects we have not yet self-consistently included in these calculations. The distribution at scales larger than 1 Mpc are robust predictions of our model.

Our definition is somewhat different from previous definitions (e.g., Weinmann et al. 2007), but we believe our definition is best suited for the method used here. In our definition, halos are considered to be externally ionized if their Lagrangian radius, defined by $M_{\text{halo}} = 4\pi \rho R_{\text{Lag}}^3/3$, is smaller than their $H_{\text{II}}$ region radius. For galaxy scale objects, with Lagrangian radii of order 2 Mpc, it is clear from Figure 4 that most of these objects were externally ionized. Because our model does not resolve scales below about 1 Mpc, however, it is difficult to determine how few galaxies were internally ionized. More detailed modeling of the small-scale structure on galactic scales, while still retaining the large volume presented here, is therefore necessary. Our predictions for clusters are more robust. For these objects, with Lagrangian radii of order 20 Mpc, all but a tiny handful are internally ionized.

Our results have may important implications for galaxy formation, and in particular for the missing satellites problem. Because we find such a large spread in reionization epoch times, it is unlikely that Milky Way mass halos, more information, such as larger-scale environment and accretion history, will be necessary to determine the reionization epoch of our own halo, even after the global reionization history is well constrained. If the abundance of Galactic satellites is strongly dependent on the reionization epoch of the galaxy, our results indicate that Milky Way mass halos would have a large spread in the number of observable satellites. We explore this issue in a companion paper (Busha et al. 2009).

Our results also may have implications for the issue of galaxy “assembly bias,” the idea that galaxy clustering may be dependent on properties other than the mass of their host halos (Wechsler et al. 2006; Gao & White 2007; Croton et al. 2007). If the reionization epoch of halos at a given mass is correlated with halo formation time, and if the reionization epoch affects any aspects of the galaxy population, then assembly bias could be more important for such galaxies than it is for their host halos. Further study will be required to investigate such effects.

The approach we have presented here will serve as the foundation for such more detailed future studies that go beyond the fiducial model presented here, in which reionization begins at $z \sim 15$ and ends at $z \sim 6$. These studies will also investigate the statistical correlations between present-day structure and reionization, and will also incorporate detailed galaxy formation modeling. Such improvements will allow for an investigation of the detailed coupling between star formation histories and the local reionization history.

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Figure 4. $H_{\text{II}}$ region sizes at reionization for the same mass bins as Figure 2. The peak at low masses can be attributed to the grid resolution, given by a radius of $\sim 0.5$ Mpc. Increased resolution would reduce the effect, but on such small scales the role of recombinations and the stochasticity of the sources are likely to play an increasing role, effects we have not yet self-consistently included in these calculations. The distribution at scales larger than $\sim 1$ Mpc are robust predictions of our model.

Figure 5. Schematic diagram indicating the difference between external and internal reionization. $R_{\text{HII}}$ indicates the size of the reionizing bubble; $R_{\text{Lag}}$ indicates the Lagrangian radius of the halo.
