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The reionization times of z=0 galaxies

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Abstract. We study the inhomogeneity of the reionization process by comparing the reionization times of z = 0 galaxies as a function of their mass. For this purpose, we combine the results of the CODA-I AMR radiative hydrodynamics simulation of the Reionization with the halo merger trees of a pure dark matter tree-code z = 0 simulation evolved from the same set of initial conditions. We find that galaxies with $M(z = 0) > 10^{11} M_\odot$ are reionized earlier than the whole Universe, with e.g. MW-like haloes reionized between 100 and 300 million years before the diffuse IGM. Lighter galaxies reionized as late as the global volume, probably from external radiation.

Keywords. galaxies: high-redshift, methods: numerical

1. Introduction

Reionization is often defined with a single number, the reionization redshift. The transition however is known to be inhomogeneous and proceeds in an inside-out manner : primordial galaxies in dense regions are ionized first whereas the diffuse IGM, distant from these sources, is reionized the latest as the HII regions overlap. As a consequence, current z = 0 galaxies did not experience the rise of the UV field at the same time and not in the same conditions. For instance galaxies can experience short-lived transitions originating from external fronts created by powerful neighbors galaxies or clusters progenitors. Alternatively, other objects are slowly self-reionized by their own stellar populations. Since the photoheating induced by the rising UV field is expected to suppress star formation in low mass halos, this inhomogeneity should be reflected in the ages of old stellar populations of dwarf galaxies (such as the one studied by e.g. Brown *et al.*(2014)) or in their spatial distribution (see e.g. Ocvirk & Aubert(2011)).

In the current work, we aim at presenting quantitative predictions on the diversity of reionization pasts of z = 0 galaxies, using cosmological simulations. For this purpose we combined results from a z = 0 pure dark matter simulation that provides the buildup history of today's galaxies with a new radiative hydrodynamics simulation of the Reionization that provides the reionization context of these objects. Because they share the same set of initial conditions, z = 0 halos from one simulation can be connected to their reionization histories from another simulation.

In the next sections, first we briefly describe our methodology and second, we present the first results.

2. Methdology

In order to investigate the reionization times of z = 0 galaxies we combine two simulations that used the same set of initial conditions: these initial conditions assumed a WMAP 5 cosmology in a $(91\ \mathrm{Mpc})^3$ comoving volume sampled with 2048^3 particles and cells.

- CODA I-DM is a pure dark matter Gadget Simulation (Springel(2005)), run until z = 0. Dark matter halos were identified using a FOF algorithm and merger trees were produced to retrieve the buildup history of all z = 0 galaxies. 20 millions halos were available at z = 0 with a minimal mass of $10^8 M_\odot$.
- CODA I-AMR is a radiative hydrodynamics simulation produced with the EMMA code (Aubert *et al.*(2015)). Adaptive mesh refinement was used to ensure a 500 pc (proper) resolution. Standard star formation and feedback recipes were used and radiative transfer was modeled using the M1 approximation coupled to an out-of-equilibrium hydrogen chemistry solver. It provides a good agreement of cosmic star formation, reionization histories and CMB optical depth with observational constraints. The reionization history is modeled until z = 6, providing *reionization maps*, i.e. the spatial distributions of redshifts (or time) each cell of the simulation crosses a 0.5 ionized fraction threshold.

From this combined set of data, we were able to assign reionization times to z = 0 halos using two different definitions. First we were able to track the position at $z > 6$ in the CODA I-AMR reionization maps of the most massive progenitor of each z = 0 halo from the CODA I-DM simulation . We define a *progenitor-based* reionization time as the first time this progenitor is located in a cell that has already been reionized. Second, we applied the same procedure but to all the particles that belong to a z = 0 halo from the CODA I-DM simulation: for each particle we were able to define a reionization time as the first time it belongs to a cell that has already been reionized. We then define a *particle-based* reionization time of a z = 0 halo as the average of its individual particles reionization times.

Progenitor-based estimates are set by collapsed matter and structures already in place at high z : they are biased toward early reionization times, because the first sources are likely to appear in these progenitors. However they require progenitors to exist at $z > 6$ and $z = 0$ low mass halos ($10^8 - 10^9 M_\odot$) are under-represented in statistics that use this definition. Particle-based estimates are not sensitive to this bias, however the contribution of more diffuse matter, maybe not even within halos at $z > 6$ but in the IGM, tend to promote lower reionization redshifts as they come from regions more distant from the first sources.

3. Results

Fig. 1 presents the reionization times of z = 0 halos using both types of reionization times estimates. First we consider progenitor-based estimates : clearly galaxies reionize earlier than the global volume when they are massive enough ($M(z = 0) > 10^{11} M_\odot$). This is not surprising since the first sources appear in the first high-z structures that will eventually end up in the current most-massive objects. In this range of masses, the more massive a galaxy, the earliest its progenitor experienced the reionization. A Milky-Way like object with $M(z = 0) \sim 10^{12} M_\odot$ was typically reionized at $z \sim 13$, 400 million years before the global volume. Note that the scatter can be quite important with e.g. ±150 million years percentile scatter at the same mass.

For less massive objects $M(z = 0) < 10^{11} M_\odot$, reionization times become consistent with the average volume value or even slightly later : these light objects are probably reionized by external radiation as they are inefficient in producing internal sources at $z > 6$. The small lag in reionization times (compared to the global value) measured for these dense and collapsed objects would be the consequence of their greater resistance to the ionizing radiation compared to the more diffuse IGM. For the lightest objects, a dip in reionization times can be seen : since such $M(z = 0) \sim 10^8 M_\odot$ objects must have $z > 6$ progenitors to be included in the statistics, they could be peculiar objects that

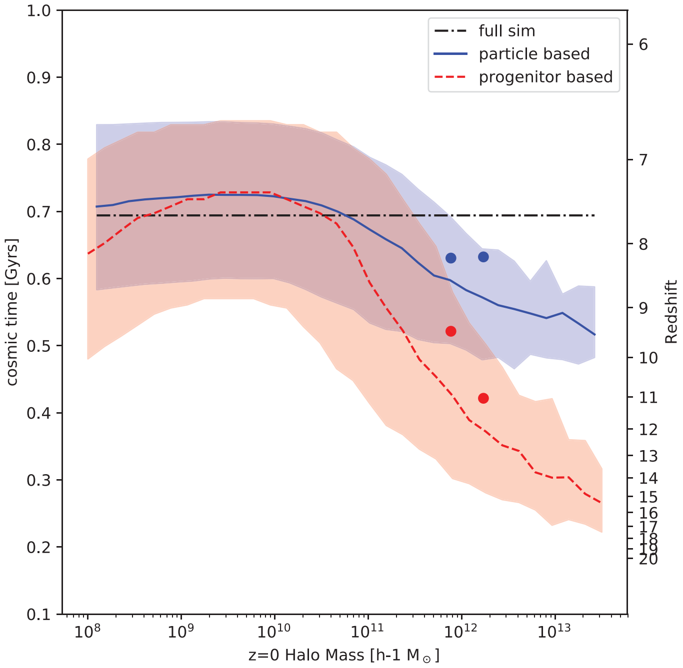

Figure 1. Reionization times of z = 0 haloes using two kinds of estimator (see text for details). The dashed horizontal lines stands for the volume averaged reionization time of the simulation. Dots stand for the reionization times of the Milky Way ($7.7\times10^{11}M_\odot$) and M31($1.7\times10^{12}M_\odot$).

were more massive in the past (allowing them to have identified progenitors during the reionization) and thus having reionization times representative of more massive objects.

We now consider *particle-based* estimates and similar trends can be seen. Massive objects tend to reionize earlier than the global volume whereas lighter halos have reionization times consistent with the global one. However reionization times of massive halos tend to have greater values (thus corresponding to lower reionization redshifts) compared to the previous estimator : since all the material that end up in the halo at z = 0 is considered, the influence of diffuse matter accreted at later times from the IGM is more important. Such material, more distant from the first sources has lower reionization redshifts, pulling reionization times estimates closer to the global value. It should be noted also, that all halos can be included in this statistics (since no requirement on existing progenitor exists) and the dip in reionization times for the lightest halos is significantly reduced.

Finally, Fig. 1 also shows the reionization times of the Milky Way and M31 analogs present in the simulations : the set of CLUES initial conditions (Gottloeber *et al.*(2010)) used here were chosen to include such a pair of galaxies with realistic masses in the proper large-scale environment. Using the progenitor-based reionization time estimates, we measure that M31 reionized earlier than the Milky-Way, as expected since the former is heavier. However both galaxies are on the late side of the distribution of reionization times, probably a reflection of their specific buildup history or environment. Using the particle-based estimates, both objects share similar reionization times : it's not surprising since these two galaxies are close to each other and accreted diffuse particles from the same environment, with similar reionization times.

4. Perspectives

First results on the reionization times of galaxies were presented, obtained from the combination of a z = 0 halo catalog with a full-physics simulation of the Reionization. From there, we plan to investigate the durations of reionization by analyzing the distributions of reionization times within haloes. Furthermore, we already measured that the reionization times of z = 0 galaxies present a significant scatter and are likely to be related to the buildup histories of halos, their star formation histories and/or their environments. Investigations on these relations are also underway.

References

Aubert, D., Deparis, N., & Ocvirk, P. 2015, *MNRAS*, 454, 1012
Brown, T. M., Tumlinson, J., Geha, M., *et al.* 2014, *APJ*, 796, 91
Gottloeber, S., Hoffman, Y., & Yepes, G. 2010, ArXiv e-prints, arXiv:1005.2687
Ocvirk, P. & Aubert, D. 2011, *MNRAS*, 417, L93
Springel, V. 2005, *MNRAS*, 364, 1105