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The First Galaxies: Assembly of Disks and Prospects for Direct Detection

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The *James Webb Space Telescope* (*JWST*) will enable observations of galaxies at redshifts $z \gtrsim 10$ and hence allow to test our current understanding of structure formation at very early times. Previous work has shown that the very first galaxies inside halos with virial temperatures $T_{\rm vir} \lesssim 10^4$ K and masses $M_{\rm vir} \lesssim 10^8$ $M_{\odot}$ at $z \gtrsim 10$ are probably too faint, by at least one order of magnitude, to be detected even in deep exposures with *JWST*. The light collected with *JWST* may therefore be dominated by radiation from galaxies inside ten times more massive halos. We use cosmological zoomed smoothed particle hydrodynamics simulations to investigate the assembly of such galaxies and assess their observability with *JWST*. We compare two simulations that are identical except for the inclusion of non-equilibrium H/D chemistry and radiative cooling by molecular hydrogen. In both simulations a large fraction of the halo gas settles in two nested, extended gas disks which surround a compact massive gas core. We post-process the simulated galaxies by combining idealized models for star formation with stellar population synthesis models to estimate the luminosities in nebular recombination lines as well as in the ultraviolet continuum. We demonstrate that *JWST* will be able to constrain the nature of the stellar populations in galaxies such as simulated here based on the detection of the He1640 recombination line. With a field of view of ~ 10 arcmin^2, *JWST* may find up to hundreds of star-bursting galaxies similar to those simulated here in future deep exposures of the $z \gtrsim 10$ universe.

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1. Introduction

The combination of upcoming observations with the *James Webb Space Telescope* (*JWST*) with supercomputer simulations of the first galaxies and reionization will transform our knowledge of structure formation in the universe. Most of the numerical effort in early galaxy formation has concentrated on investigating the properties of the very first building blocks of galaxy assembly, minihalos and dwarf galaxies with virial temperatures $\lesssim 10^4$ K, corresponding to halo masses $\lesssim 10^8$ $M_\odot$ at $z \gtrsim 10$ (e.g., [1]; [2]; [3]; [4]; [5]). A key result emerging from the existing work is that the luminosities of these very low-mass objects are, unless magnified by gravitational lensing, too low, by at least one order of magnitude, to be detected in even very deep exposures with *JWST* (e.g., [6]). The light collected in future observations with the *JWST* may thus be dominated by emission from dwarf galaxies inside halos that are about ten times more massive, $M_{\rm vir} \sim 10^9$ $M_\odot$.

Our goal is to extend and complement existing numerical work on the first galaxies by investigating the role played by galaxies inside halos with masses $M_{\rm vir} \gtrsim 10^9$ $M_\odot$, at times before and during the epoch of reionization, when these galaxies were assembling, to the present day, when these galaxies may be found in the Local Group as fossil probes of the beginnings of galaxy formation (e.g., [8]; [9]). Here, we report our first steps towards achieving this goal by studying the assembly of dwarf galaxies in halos reaching virial masses $M_{\rm vir} \approx 10^9$ $M_\odot$ at $z = 10$ using cosmological smoothed particle hydrodynamics simulations. We combine our simulations with idealized models for star formation to assess the detectability of the first galaxies with *JWST*.

This work is described in more detail in [10].

2. Simulations

We use a modified version of the N-body/TreePM Smoothed Particle Hydrodynamics (SPH) code GADGET ([11]) to perform a set of cosmological hydrodynamical simulations. The simulations are initialized at $z = 127$ assuming ΛCDM cosmological parameters $\Omega_{\rm m} = 0.258, \Omega_{\rm b} = 0.0441, \Omega_\Lambda = 0.742, \sigma_8 = 0.796, n_{\rm s} = 0.963$, and $h = 0.719$ ([12]).

We utilize a zoomed simulation technique (e.g., [13]) to zoom into a parent large-scale cosmological simulation with box size $L = 3.125$ h^{-1} Mpc comoving. This allows us to study the gravitational and hydrodynamical assembly of a galaxy in a halo with virial mass $M_{\rm vir} \approx 10^9$ $M_\odot$ at $z = 10$ at high resolution corresponding to gas (dark matter) particle masses $m_{\rm g} = 484$ $M_\odot$ ($m_{\rm DM} = 2350$ $M_\odot$). The simulations are run with the gravitational forces softened on a scale 0.1 h^{-1} kpc comoving. We follow the non-equilibrium chemistry and cooling of H_2, D, HD, D^+, H^+, H, D, and He, and we include H^- and H_2^+ assuming their equilibrium abundances ([14]; [5]).

We analyze two simulations, *Z4* and *Z4NOMOL*, that differ only in the treatment of the chemistry and cooling of the primordial gas. In simulation *Z4*, gas cools by collisional ionization and excitation, the emission of free-free and recombination radiation, Compton cooling off the CMB, and emission of radiation by molecular hydrogen. Simulation *Z4NOMOL* is identical to simulation *Z4* except that the formation of molecular hydrogen is suppressed, as would be the case in the presence of a strong photo-dissociating Lyman-Werner radiation background (e.g., [15]). Gas in simulation *Z4NOMOL* therefore cools only via atomic processes, which are inefficient in cooling primordial gas below $\approx 10^4$ K.

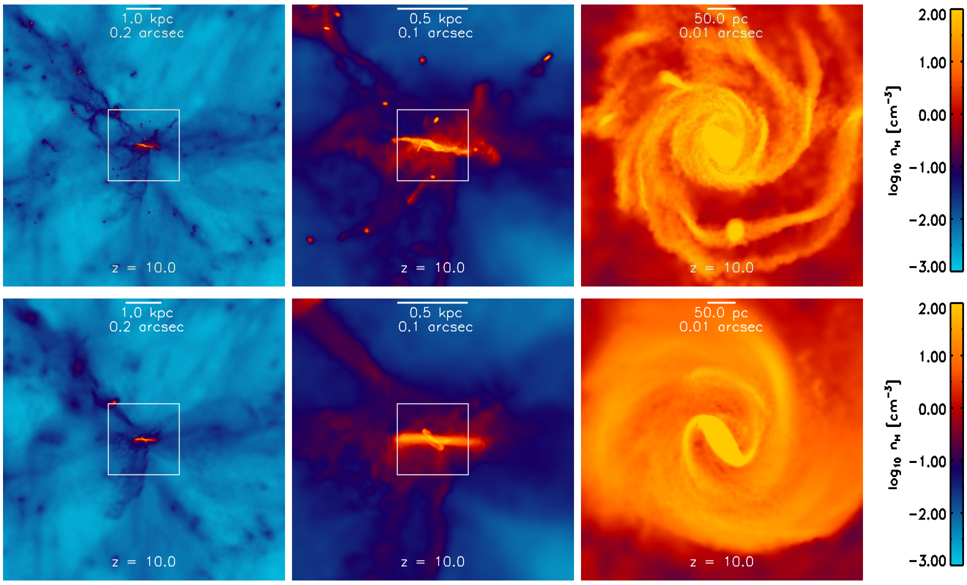

Figure 1: Gas densities at $z = 10$ in simulation *Z4* (top) and in simulation *Z4NOMOL* (bottom) in which molecular hydrogen cooling was suppressed. Individual panels show cubical slices through the simulation centered on the most bound halo particle. The left panels present edge-on views of the disks and encompass a volume slightly larger than the virial region with radius $r_{\rm vir} \approx 3.1$ kpc. The middle panels are zooms into the cubical regions marked in the left panels. The right panels are zooms into the cubical region marked in the middle panels and are reoriented such that the outer disk is seen face on. The spirals do not show signs of fragmentation; the gas clump in simulation *Z4* seen in the bottom of the face-on view of the disk (top right panel) is a gas-rich subhalo in projection.

3. The First Disks

An interesting outcome of our simulations is the collapse of gas into two extended rotationally supported disks. Figure 1 shows the baryonic structure of the simulated halos at the final simulation time, for both simulation *Z4* and simulation *Z4NOMOL* in which molecular hydrogen formation was suppressed. The disks, which are tilted with respect to each other, surround a compact ($\lesssim$ 10 pc), massive ($\approx 5 \times 10^7$ $M_\odot$) gas core. The presence of the core helps stabilizing the disks against fragmentation ([16]). It constitutes a prime site for the formation of a nuclear stellar cluster and/or a massive black hole (e.g., [20]).

When and how the first galaxy-scale disks were formed is currently not well understood. Extended disks are found in large-scale hydrodynamical cosmological simulations and in cosmological simulations of individual massive halos or halos at low redshifts (e.g., [17]; [18]; [19]). Cosmological simulations of high-redshift low-mass ($\lesssim 10^8$ $M_\odot$) halos, however, have not yielded such disks (e.g., [3]; [13]; [20]). The gas dynamics inside these halos is dominated by turbulent motions instead. This morphological bimodality suggests that mass is an important factor in determining whether a given halo may host an extended disk.

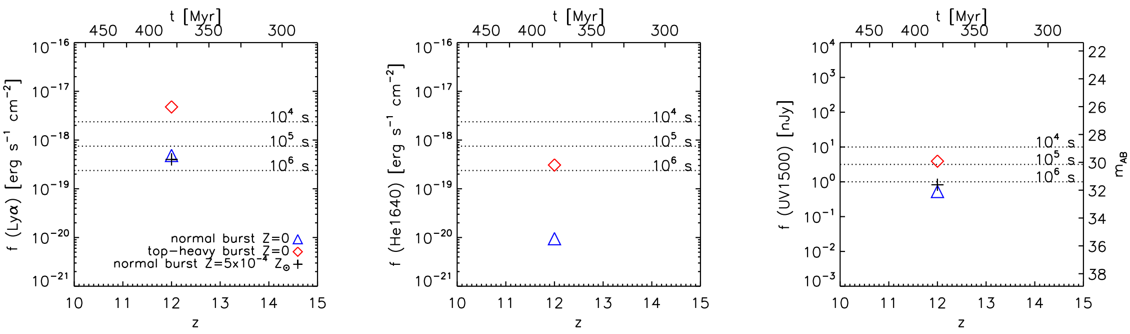

Figure 2: Observed fluxes in the Lyα (left) and He1640 (middle) recombination lines and observed flux densities of the combined stellar and nebular UV1500 continuum (right) of starbursts with stellar mass $M_\star = 10^6$ M$_\odot$, and IMFs and metallicities as indicated in the legend. The low-metallicity burst predicts He1640 line fluxes too low to fall inside the plot range. The results scale linearly with the fraction of stellar ionizing photons assumed to be absorbed by the interstellar gas, $(1 - f_{\rm esc}) = 1$. Dotted lines show the sensitivity limits for observations with *JWST*, assuming exposures of 10^4, 10^5, and 10^6 s (top to bottom) and S/N=10 ([21]; http://www.stsci.edu/jwst/science/data_simulation_resources/sensitivity). With exposures $t_{\rm exp} \lesssim 10^6$ s, *JWST* will allow to distinguish between metal-free starbursts with top-heavy IMF and metal-free or metal-enriched starbursts with normal IMF based on the detection of the He1640 line.

4. Detection with the *James Webb Space Telescope*

A key science goal of the upcoming *JWST* is the detection of light from the first galaxies ([21]). Here we estimate the signal expected from the first galaxies based on our simulations of galaxies with halo masses $M_{\rm vir} \approx 10^9$ M$_\odot$ at $z \gtrsim 10$ and investigate their detectability with the instruments aboard *JWST*. We focus on the Lyα ($\lambda_{\rm e} = 1216$ Å) and He1640 ($\lambda_{\rm e} = 1640$ Å) recombination lines which will be detected with *JWST's* NIRSpec at a spectral resolution $R \sim 1000$, and on the UV1500 ($\lambda_{\rm e} = 1500$ Å) continuum which will be imaged with *JWST's* NIRCam.

We assume that a stellar population forms at $z = 12$ in an instantaneous burst with stellar mass $M_\star = 10^6\ {\rm M}_\odot \left(\frac{f_\star}{0.1}\right)\left(\frac{f_{\rm cool}}{0.01}\right)\left(\frac{M_{\rm vir}}{10^9\ {\rm M}_\odot}\right)$, where $f_{\rm cool}$ is a conversion factor that determines the amount of gas mass available for starbursts inside halos with virial masses $M_{\rm vir}$, and $f_\star$ is the star formation efficiency, i.e., the fraction of the available gas mass that is turned into stars. Setting $f_{\rm cool} = 0.01$, this scenario is motivated by the rapid accretion of large gas masses ($M_{\rm g} \gtrsim 10^7$ M$_\odot$) onto the central core observed in our simulations of halos with virial masses $M_{\rm vir} \approx 10^9$ M$_\odot$ at around $z \approx 12$ ([10]). The adopted conversion factor $f_{\rm cool} = 0.01$ between the gas mass available for star formation and the halo virial mass is consistent with gas collapse fractions in previous simulations of the first galaxies (e.g., [3]; [20]). We choose a star formation efficiency $f_\star = 0.1$ expected for the initial bursts (e.g, [7]; [6]).

Following [22], we use case B recombination theory to relate the ionizing luminosities of the stellar population with specific age, mass, and metallicity to the nebular luminosities of the surrounding gas, assuming that all ionizing photons are absorbed, i.e., that the fraction of ionizing photons escaping the galaxy, $f_{\rm esc}$, is zero. We explore three representative starburst scenarios (see [10] for details): a zero-metallicity starburst with top-heavy initial mass function (IMF), a zero-metallicity starburst with normal IMF, and a low-metallicity starburst with normal IMF.

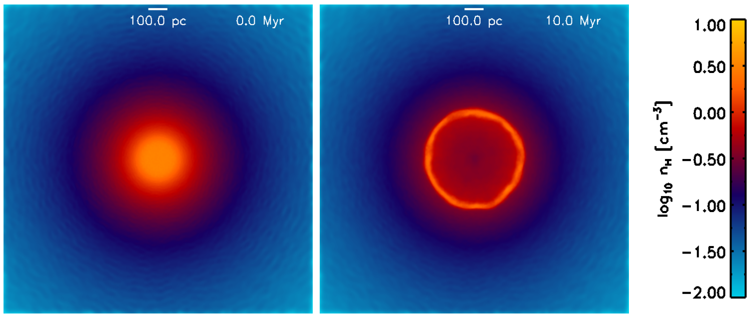

Figure 3: Photoevaporation of a centrally condensed gas clump by a central ionizing source. The panels show the gas densities in a slice centered on the source at times $t = 0$ (left) and 10 Myr (right) after the onset of stellar emission. The simulation was performed using the radiative transfer code TRAPHIC ([29]; [30]). The small deviations from sphericity are due to unavoidable impurities in the setup of the initial particle positions. The results are in very good agreement with the numerical reference solutions presented in [28].

To investigate the detectability with *JWST* we assume that the stellar bursts are spatially and spectrally unresolved. We translate the line luminosities $L_{\rm line}$ into observed line fluxes[1] $f_{\rm line}$ using $f_{\rm line} = L_{\rm line}/[4\pi d_L^2(z)]$, where $d_L(z)$ is the luminosity distance to the starburst at redshift $z = 12$. We translate the UV continuum luminosities L_ν into observed flux densities f_ν using $f_\nu = L_\nu(1+z)/[4\pi d_L(z)^2]$. Figure 2 shows our results. In deep exposures of its field of view of ~ 10 arcmin^2, *JWST* may detect tens to hundreds of starbursts such as described here (for details see [10]).

Note that Lyα radiation from galaxies at redshifts $z \gtrsim 10$ may be strongly absorbed because the reionization of the universe was probably only accomplished at much lower redshifts (e.g., [23]). On the other hand, scattering off outflowing interstellar gas may help the Lyα radiation to escape (e.g., [24]), and galaxies may reside in an ionized bubble sufficiently large for Lyα photons to redshift away in the expanding universe (e.g., [25]). Hence, the Lyα line remains a powerful probe of high-redshift galaxy formation (e.g., [26]). However, since we do not treat radiative transfer effects here, the reported Lyα line fluxes must be considered upper limits.

5. Future Work

The most important challenges for future work concern effects related to feedback from star formation (for a review see, e.g., [27]). Key question we aim to address include the effects of photoheating from ionizing sources and the effects of supernova feedback on the assembly of the first galaxies. Figure 3 shows the effects of ionizing radiation from a central source on the structure of a centrally condensed sphere of gas with isothermal density profile, such as found in minihalos in high-redshift cosmological simulations. The simulation setup is identical to that of Test 6 in [28], except for the lower mass resolution (96^3 gas particles). The simulation was performed with the radiative transfer code TRAPHIC ([29]; [30]). This code is particularly well suited for our work because its computation time is independent of the number of ionizing sources, hence allowing radiation-hydrodynamical simulations of the first galaxies with complex star formation histories.

[1] Note that in [10] we instead quote line flux *densities*.

6. Summary

Motivated by the exciting prospect of the direct detection of stellar light from redshifts $z \gtrsim 10$ with the upcoming *JWST*, we investigated the assembly of the first dwarf galaxies using high-resolution cosmological zoomed smoothed particle hydrodynamics simulations of individual halos. Previous works suggest that galaxies inside halos with masses $M_{\rm vir} \lesssim 10^8$ M$_\odot$ at $z \gtrsim 10$ are likely too faint, by at least a factor of 10, to be observed in the proposed exposures with *JWST*. Hence, the light collected in future observations with *JWST* may come mostly from galaxies inside halos with masses $M_{\rm vir} \sim 10^9$ M$_\odot$.

We performed two simulations of such galaxies that were identical except for differences in the employed non-equilibrium primordial gas chemistry and cooling network. Our simulations show that the formation of extended gas disks is possible in halos with masses as low as $M_{\rm vir} \sim 10^9$ M$_\odot$ at redshifts as high as $z \gtrsim 10$. The simulations provide a useful reference for comparison with simulations that include star formation and feedback that we will present in future works.

We have post-processed the simulated galaxies using idealized models for star formation and for the strength of the associated recombination and UV continuum radiation, and we have estimated the observability of the first dwarf galaxies with *JWST*. We showed that *JWST* will have the sensitivity to detect these galaxies and to constrain the nature of star formation inside them. With a field of view of ~ 10 arcmin^2, *JWST* may find tens to hundreds of star-bursting galaxies similar to those investigated here in future deep exposures of the distant universe.

Acknowledgments

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