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Assembly of the First Disk Galaxies under Radiative Feedback from Pop III Stars

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Abstract. We investigate how radiative feedback from the first stars affects the assembly of the first dwarf galaxies. We perform cosmological zoomed smoothed particle hydrodynamics simulations of a galaxy assembling inside a halo reaching a virial mass $\sim 10^9 M_\odot$ at $z = 10$. The simulations follow the non-equilibrium chemistry and cooling of primordial gas and the subsequent conversion of the cool dense gas into massive metal-free stars. To quantify the radiative feedback, we compare a simulation in which stars emit both molecular hydrogen dissociating and hydrogen ionizing radiation with a simulation in which stars do not emit radiation but remain dark. Photodissociation and photoionization exert a strong negative feedback on the assembly of the galaxy inside the minihalo progenitor, impeding gas condensation and suppressing star formation. The radiative feedback on the gas implies a suppression of the central dark matter densities in the minihalo by factors of up to a few, which is a significant deviation from the singular isothermal density profile characterizing the dark matter distribution in the absence of radiative feedback. The properties of the galaxy become insensitive to the inclusion of radiation once the minihalo turns into an atomic cooler. The formation of a rotationally supported extended disk inside the atomically cooling galaxy therefore is a robust outcome of our simulations. Our simulations make predictions for observations with the upcoming *James Webb Space Telescope*.

Keywords: cosmology: theory – galaxies: formation – galaxies: high-redshift – radiative transfer

PACS: 98.62.Ai, 98.58.Hf, 98.56.Wm, 98.52.Wz, 97.20.Wt, 95.30.Jx, 95.30.Lz

SIMULATIONS

The simulations are performed with a customized version of the smoothed particle hydrodynamics code GADGET (1; 2). We start from the same cosmological initial conditions used to set up simulation Z4 in [3], to which we refer the reader for details. Zooming in a large cosmological box to resolve a halo that reaches a mass of $\sim 10^9 M_\odot$ at $z = 10$, we track the non-equilibrium chemistry and cooling of the primordial gas (4; 5). Gas particles above a threshold density $n_H = 500 \text{ cm}^{-3}$ are converted into star particles, at a rate determined by the dynamical time at the threshold density, and assuming a star formation efficiency consistent with observations of the nearby universe (6).

To investigate the radiative feedback from the stars, we compare two simulations. In the first simulation (hereafter reference simulation, *LW+RT*), star particles are interpreted as clusters of metal-free massive stars (so-called Pop III stars; e.g., 7) and emit both dissociating radiation in the Lyman-Werner (LW) band and hydrogen ionizing radiation (8). Photodissociation rates are computed by summing the contributions to the LW intensity from individual star particles in the optically thin limit (e.g., 9), adding a LW background with evolving intensity consistent with previous works (e.g., 10), and applying a self-shielding correction (11). Photoionization rates are computed by following the radiative transfer of ionizing photons from star particles using TRAPHIC (12; 13).

The second simulation is identical to the first simulation, but the emission of radiation is disabled and the intensity of the LW background is set to zero (hereafter no-feedback simulation, *NOFB*). In this simulation, stars hence cannot exert radiative feedback.

RESULTS

Figure 1 shows the formation history of the dwarf galaxy. The dark matter halo hosting the galaxy evolves from a minihalo with virial mass $M_{\text{vir}} \sim 10^6 M_{\odot}$ at $z \approx 25$ into an atomic cooler with mass $\approx 5 \times 10^7 M_{\odot}$ at $z \approx 16$, and then further into a dwarf galaxy with mass $\sim 10^9 M_{\odot}$ at the final simulation redshift, $z = 11$ (left top). The gas accreted by the minihalo cools and condenses efficiently by radiative de-excitation of rovibrationally excited molecular hydrogen, and a first stellar burst is ignited at $z \approx 23$ (left middle).

The ionizing radiation emitted by this burst heats the gas in the minihalo, increasing the gas pressure. This generates a gaseous outflow, temporarily reducing the baryon fraction $f_{\text{bar}} = M_{\text{bar}}/M_{\text{vir}}$, where M_{bar} is the mass in baryons inside the virial radius, and shutting off star formation. However, the gas cools and recondenses, and a second burst of star formation is ignited a few tens of Myr later. Because the minihalo is now more massive, this second burst does not lead to a strong decrease of the baryon fraction and continues for a longer time. Eventually, however, this burst is also shut off by the radiative feedback. Star formation continues just before the minihalo evolves into an atomic cooler, and it becomes insensitive to the inclusion of radiation shortly afterwards.

The radiative feedback on the baryon distribution affects also the distribution of the dark matter (Figure 1, right). In the no-feedback simulation, the dark matter density profile is approximately singular isothermal at all redshifts. In the reference simulation, on the other hand, the radiative feedback implies a significant change in the gravitational potential and, in turn, in the gravitational pull on the dark matter, which then remains less centrally concentrated. Previous works have demonstrated that supernova explosions may lower the central dark matter densities in dwarf galaxies with masses $\sim 10^9 M_{\odot}$ at $z < 10$ (e.g., 14). Our results show that radiative feedback can have a qualitatively similar effect on the dark matter distribution in high-redshift minihalos (see also, 15).

A major merger at redshift $z \approx 15$ channels gas in the halo center, leading to the formation of a small gaseous disk by $z = 13.5$. At $z \approx 12$, a sequence of minor mergers replenishes the halo center with gas, leading to the formation of a second, more extended gaseous disk. The second disk surrounds the first disk, and the two have orientations tilted with respect to each other. Figure 2 provides a face-on view of the disks in the reference (left) and no-feedback (right) simulation.

Photoheating creates hot low-density cavities in the otherwise cold and dense disk gas. These cavities remain, however, locally confined, and the disks remains relatively unaffected by photoheating. This insensitivity of the disk gas to photoheating is consistent with the fact that at the time of formation of the disks, i.e., at $z \approx 15$, the galaxy has already entered the atomic cooling regime. Hence, its gravitational potential is sufficiently deep to confine photoheated gas in its interior.

At the final redshift, the star formation rates in the reference and no-feedback simulations are similar, $\sim 0.2 M_{\odot} \text{ yr}^{-1}$. Galaxies with such low star formation rates will be among the faintest galaxies the *James Webb Space Telescope* may detect (e.g., 3; 16).

FIGURE 1. Assembly history of the dwarf galaxy. *Left:* evolution of virial mass, star formation rate, and baryon fraction (from top to bottom) in the reference simulation (*LW+RT*; red dashed), and in the no-feedback simulation (*NOFB*; black solid). The dotted curves show the virial mass corresponding to a virial temperature of 10^4 K (top), and the universal baryon fraction $\Omega_b/\Omega_m \approx 0.17$. *Right:* dark matter density profiles $\rho_{DM}(r)$ in the reference simulation (dashed), and in the no-feedback simulation (solid) at three different redshifts as indicated in the legend (bottom), and the ratio of the density profiles in the reference and no-feedback simulation at the three redshifts (top). The profiles are normalized by dividing by a singular isothermal profile to reduce the dynamic range. The left-hand dotted lines mark the gravitational softening radius, and the right-hand dotted lines mark the virial radius at each of the redshifts. The inclusion of radiation affects both the assembly of baryons inside the minihalo, reducing the star formation rates, and that of the dark matter minihalo, suppressing the central dark matter densities.

DISCUSSION

We have ignored the feedback from explosions of massive stars in supernovae (SNe). SN feedback may strongly affect both the distribution of baryons (e.g., 17) and the central dark matter densities (e.g., 14) inside dwarf galaxies. It may also strongly disturb the assembly of the first disks (e.g., 18; but see, e.g., 14). The metals expelled in SN explosions enrich the interstellar and intergalactic gas, triggering the transition from metal-free to metal-enriched stellar populations (e.g., 18). An investigation of these processes is left for future work.

FIGURE 2. Face-on view of the gas densities in the dwarf galaxy at the final simulation redshift $z = 11$, both in the reference simulation ($LW+RT$; left), and in the no-feedback simulation which did not include radiation ($NOFB$; right). The black dots mark the positions of recently formed star particles with ages less than 3 Myr. The formation of a rotationally supported extended disk in the atomically cooling halo is an outcome robust against the inclusion of LW and ionizing radiation.

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