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Assembly of the first disk galaxies under radiative feedback from the first stars

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Abstract. The first galaxies are thought to have reionized the universe in the first billion year after the Big Bang. However, the properties of these galaxies are currently poorly understood. Here we investigate how Lyman-Werner dissociating and ionizing radiation from the first stars affects the assembly of the first galaxies in zoomed cosmological radiation-hydrodynamical simulations. We focus on a galaxy assembling inside a halo that reaches a mass of $\sim 10^9$ $M_\odot$ at $z = 10$. Photodissociation and photoionization impede gas accretion and suppress star formation in the minihalo progenitor, thus exerting a strong negative feedback on the initial phase of galaxy assembly. The radiative feedback also leads to a significant reduction in the central dark matter densities of the minihalo. 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 is therefore a robust outcome of our simulations. Dwarf galaxies such as simulated here will be probed in observations with the upcoming James Webb Space Telescope.

Key words. cosmology: theory – galaxies: formation – galaxies: high-redshift – stars: formation – hydrodynamics – radiative transfer

1. Introduction

The ionizing radiation emitted by the first galaxies is thought to have transformed the cold and neutral cosmic gas that was present shortly after the Big Bang into the hot and ionized plasma that we observe in the intergalactic medium today. Research into this transformation - the epoch of reionization - is crucial for understanding the formation and evolution of galaxies, including our own galaxy, the Milky Way (e.g., Robertson et al. 2010; Barkana & Loeb 2001). Little is currently known about reionization, but a new generation of telescopes, perhaps most prominently featuring the James Webb Space Telescope (JWST), is about to unravel the astrophysics at these early times. Comparisons of the upcoming observations with simulations of the first galaxies and reionization will offer a unique opportunity to test and extend our models of structure formation in the epoch of first light.

A key question driving research in the field concerns the nature of the galaxies that reionized the universe. Current zoomed cosmological simulations provide us with an ab ini-

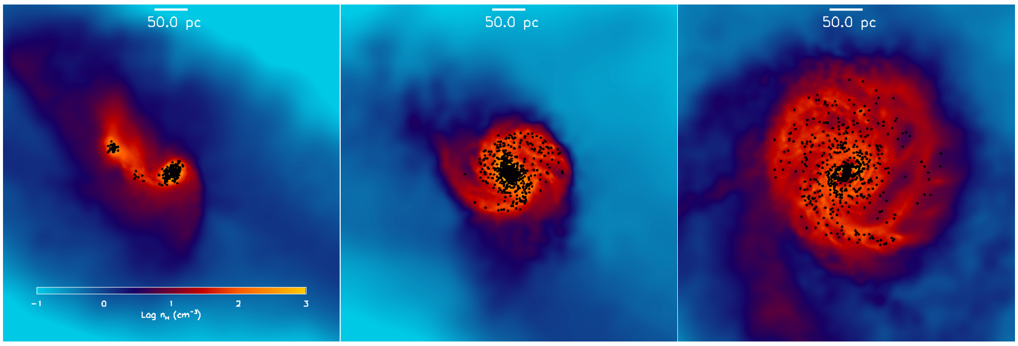

Fig. 1. Snapshots at $z = 14.5, 13$, and 11 (from left to right) of the gas densities in a simulation of a dwarf galaxy that reaches a halo mass of $\sim 10^9$ M$_\odot$ at $z = 10$. This simulation accounted for the photodissociation and ionization of the primordial gas by the radiation emitted by the first stars, whose location is marked by black dots. The prominent galactic disk is shown face-on.

tio theoretical picture of the formation of the first galaxies inside halos with masses up to about 100 million solar masses at $z > 10$, which includes the so-called minihalos and the first atomically cooling galaxies (e.g., Bromm & Yoshida 2011). This is an extraordinary achievement, but such masses are still about an order of magnitude short of the lowest mass scale expected to be probed by JWST (unless the galaxies are gravitationally lensed; e.g., Zackrisson et al. 2012). Thus, most of the stellar light collected by JWST from $z > 10$ is expected to originate from dwarf galaxies in halos with masses near a billion solar masses (e.g., Johnson et al. 2009; Pawlik et al. 2011). Such galaxies are currently poorly understood.

Motivated by the exciting prospects for observations with the upcoming JWST, we have previously presented zoomed cosmological simulations of dwarf galaxies that reach halo masses $\sim 10^9$ M$_\odot$ at $z = 10$ (Pawlik et al. 2011). An interesting outcome of these simulations is the collapse of the halo gas in a galactic disk, raising the question of the emergence of the first disk galaxies. However, our work ignored the feedback from star formation, which may impact the morphology of low-mass galaxies. Here we report results from a new set of zoomed cosmological simulations of the assembly of disks in dwarf galaxies at redshifts $z > 10$ that account for the radiative feedback from the first stars.

This work is described in more detail in Pawlik et al. (2013).

2. Simulations

The simulations are run using a modified version of the SPH/TreePM galaxy formation code GADGET (last described in Springel 2005). The simulations are initialized at $z = 127$ in a box of size 3.125 h^{-1} comoving Mpc, which is hierarchically refined to achieve a baryonic particle mass of ~ 500 M$_\odot$. This enables us to follow the non-equilibrium chemistry and cooling of the primordial gas in halos reaching a mass $\sim 10^9$ M$_\odot$ at $z = 10$, and to track the emergence of dwarf galaxies starting from their birth inside a minihalo.

Star formation is implemented by stochastically converting gas particles into collisionless star particles at densities above $n_{\rm H} = 500$ cm^{-3}. We assume that the star-forming gas collapses in free fall and adopt a star formation efficiency of 1%, consistent with observations in the local universe. We use the Schaerer (2003) population synthesis models to compute the ionizing and Lyman-Werner luminosities of the star particles, assuming a Salpeter initial mass function in the range 50 – 500 M$_\odot$ and zero metallicity.

We compute the photodissociation of molecular hydrogen and hydrogen deuteride by the stellar Lyman-Werner radiation in the optically thin limit, and we apply a shielding correction to approximate radiative transfer effects (e.g., Wolcott-Green et al. 2011).

We use the radiative transfer code TRAPHIC (Pawlik & Schaye 2008; Pawlik & Schaye 2011) to follow the transport of the stellar ionizing radiation. TRAPHIC solves the time-dependent radiative transfer equation by tracing photon packets through the simulation box directly on the spatially adaptive set of SPH particles. Hence, the radiative transfer exploits the full dynamic range of the simulations. TRAPHIC further employs a directional merging of photon packets, which renders the computational cost of the radiative transfer independent of the number of radiation sources.

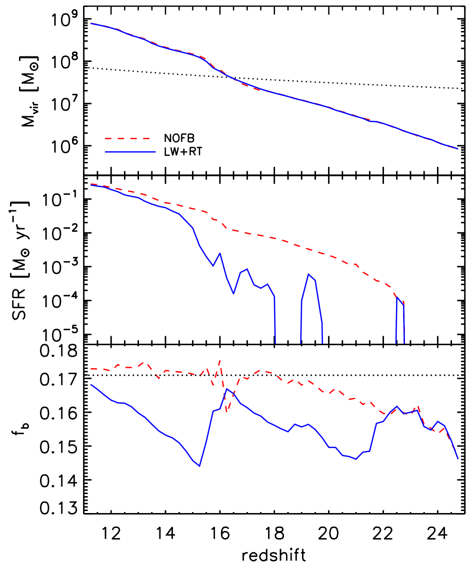

Fig. 2. Evolution of the virial mass, star formation rate, and baryon fraction in our simulation of a dwarf galaxy under the feedback from Lyman-Werner and ionizing radiation by the first stars (LW+RT; blue solid curves). For comparison, we also show the evolution of these quantities in a simulation in which the emission of radiation was suppressed (NOFB; red dashed curves). The black dotted curves show the virial mass corresponding to a virial temperature of 10^4 K, and the universal baryon fraction. The assembly of baryons is initially strongly affected by radiative feedback. Once the minihalo turns into an atomically cooling galaxy, the star formation rates become insensitive to the inclusion of radiation.

3. Results

Figure 1 shows characteristic stages of the assembly of the simulated dwarf galaxy. A major merger at redshift $z = 15$ channels gas in the halo center, leading to the formation of a small gaseous and stellar disk. Subsequently, starting at $z = 12$, a number of minor mergers continue to fuel the halo center with gas, leading to the formation of a second, more extended disk. The initial disk can still be visually and dynamically distinguished in the central region, but efficient transport of angular momentum has significantly reduced its size.

Figure 2 quantifies the formation history of the dwarf galaxy. The dark matter halo hosting the galaxy grows from a minihalo with mass $\sim 10^6$ $M_\odot$ at $z = 25$ into an atomic cooler with mass $\sim 5 \times 10^7$ $M_\odot$ at $z = 16$, and then evolves further into a dwarf galaxy with mass $\sim 10^9$ $M_\odot$ at $z = 11$.

The gas accreted by the minihalo condenses efficiently thanks to cooling by molecular hydrogen, leading to the first stellar burst at $z = 23$. Photoheating by the ionizing radiation emitted by this burst initiates a gaseous outflow that reduces the baryon fraction $f_b = M_b/M_{vir}$, where M_b is the mass in gas and stars, and temporarily shuts off star formation. However, a second burst of star formation is ignited already shortly later. Because the minihalo is now more massive, this second burst does not lead to as strong a decrease of the baryon fraction and is temporally more extended. Eventually, however, this burst is also shut off. Star formation sets in again just before the minihalo evolves into an atomic cooler and occurs at rates that quickly become insensitive to the inclusion of radiation.

Fig. 3 shows that in the absence of radiative feedback, the dark matter density profile of the simulated galaxy is approximately singular isothermal at all redshifts. On the other hand, the radiative feedback on the distribution of baryons leads to a change in the gravitational potential of the gas and, in turn, in the gravitational pull on the dark matter, which therefore remains less centrally concentrated.

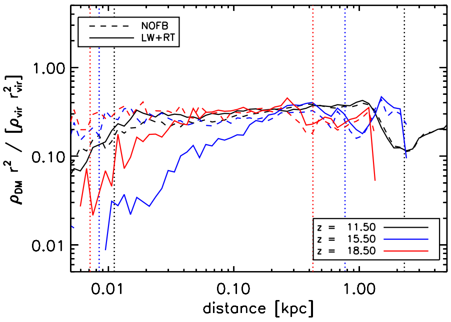

Fig. 3. Dark matter density profiles of the dwarf galaxy in simulations with (LW+RT; solid) and without (NOFB; dashed) the radiative feedback from the first stars, at three characteristic redshifts indicated by the color in the legend. The profiles are normalized by dividing by a singular isothermal profile to reduce the dynamic range. The dotted lines on the left mark the gravitational softening radius, and the dotted lines on the right mark the virial radius at each of the redshifts. The redistribution of the gas by the feedback from Lyman-Werner and ionizing radiation implies a suppression in the central dark matter densities in the minihalo progenitor.

Previous works have demonstrated the ability of supernova explosions to lower the central dark matter densities in dwarf galaxies with masses $\sim 10^9$ M$_\odot$ at $z < 10$ (e.g., Mashchenko et al. 2008). Here we have shown that photodissociation and photoheating can have a qualitatively similar effect on the dark matter distribution in high-redshift minihalos (see also, Ricotti 2003; Wise & Abel 2008). In our case, radiative feedback generates a dark matter profile that is well approximated by an Navarro et al. (1997) profile with concentration parameter $c \sim 2$.

Photoheating creates diffuse cavities in the dense disk gas, leaving behind a complex disk morphology. Overall, however, the disk remains robust against the inclusion of radiation. This is consistent with the fact that at the time of disk formation, the galaxy has already evolved into an atomically cooling object. Its gravitational potential is thus deep enough to confine the photoheated gas.

At the final redshift, the star formation rates reach ~ 0.2 M$_\odot$ yr^{-1}, consistent with results from other works (e.g., Ricotti et al. 2008; Wise et al. 2012). Galaxies with such low star formation rates will be among the faintest galaxies JWST will detect (e.g., Pawlik et al. 2011).

4. Conclusions and outlook

We have presented simulations of a dwarf galaxy that reaches a halo mass of $\sim 10^9$ M$_\odot$ at $z = 10$. Our simulations show that the assembly of a galactic disk in the dwarf halo is a feature robust against the radiative feedback from the first stars.

We have ignored the feedback from supernovae, which may affect the morphologies of dwarf galaxies even more massive than investigated here. The metal enrichment that accompanies the supernovae will transform the nature of the stellar populations, lowering the number of ionizing photons emitted per baryon (e.g., Bromm 2013). Supernova feedback will thus also affect the fraction of the ionizing photons that escapes the galaxies and is available to reionize the intergalactic medium (e.g., Wise & Cen 2009). We plan to address these and other issues in future work.

A great opportunity for advancing our understanding of galaxy formation lies in the upcoming observation of the 21 cm signal from neutral hydrogen in the early universe with, e.g., LOFAR and MWA (e.g., Zaroubi 2013). These observations will constrain the properties of the first galaxies by measuring their impact on reionization. The interpretation of the 21 cm signal will depend heavily on the use of cosmological radiative transfer simulations of reionization. The first such simulations have become feasible in the last decade thanks to advances in numerical techniques and the availability of supercomputers. However, simulating reionization remains a computationally demanding task (e.g., Trac & Gnedin 2011). The principle challenge is to follow reionization in large representative volumes of the universe while resolving the formation of the galaxies driving it.

Treating this vast a range in scales requires spatially adaptive simulation techniques. While such techniques are routinely employed in modern cosmological hydrodynamical simulations, most accurate radiative transfer methods have not yet arrived at this level of algorithmical sophistication. Moreover, most radiative transfer methods require a computational cost that increases linearly with the number of sources, which greatly exacerbates the numerical challenge.

The radiative transfer code TRAPHIC (Pawlik & Schaye 2008; Raičević et al. 2014) enables the spatially adaptive transport of photons and has a computational cost independent of the number of sources, making it a tool of choice for simulating reionization. We are in the progress of applying TRAPHIC in large-scale radiation-hydrodynamical simulations of galaxy formation in the early universe and the reionization of the intergalactic medium.

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