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THE EFFECTS OF EARLY COSMIC REIONIZATION ON THE SUBSTRUCTURE PROBLEM IN GALACTIC HALOS

HAJIME SUSA
Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshimaku, 171 Tokyo, Japan; susa@rikkyo.ac.jp
AND
MASAYUKI UMEMURA
Center for Computational Sciences, University of Tsukuba, Ten-nodai, 1-1-1 Tsukuba, Ibaraki 305-8577, Japan; umemura@rccp.tsukuba.ac.jp
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ABSTRACT

Recent observations of the cosmic microwave background by the *Wilkinson Microwave Anisotropy Probe* strongly suggest that the reionization of the universe took place quite early ($z \sim 17$). On the other hand, it has been pointed out that the cold dark matter cosmology suffers from a substructure problem in which more subgalactic halos are produced in the Local Group than dwarf galaxies. In this Letter, as a potential mechanism for solving this problem, we consider the feedback effects of early reionization on the formation of small-scale structures. For this purpose, we perform three-dimensional radiation hydrodynamic simulations, incorporating the radiative transfer for ionizing photons. As a result, it is found that the early reionization is devastating for low-mass systems with $M_{\rm vir} \lesssim 10^8\ M_\odot$ or $v_{\rm circ} \lesssim 20$ km s^{-1}, and almost all gas is photoevaporated in more than 95% of low-mass systems. Such a strong negative feedback on the formation of low-mass galaxies may solve the substructure problem and support the picture that Local Group dwarf galaxies are descendants of the more massive halos that experienced and survived tidal stripping.

Subject headings: galaxies: dwarf — galaxies: formation — hydrodynamics — molecular processes — radiative transfer

1. INTRODUCTION

It has been claimed that, compared to the dwarf galaxies observed in the Local Group, too many subgalactic halos are formed in a cold dark matter (CDM) universe (Klypin et al. 1999; Moore et al. 1999). One of the simplest ways to resolve this discrepancy is to exclude baryonic matter from small halos by the use of some feedback mechanisms. The mechanisms could be either the gas ejection due to the energy input by multiple supernova (SN) explosions (Dekel & Silk 1986; Yepes et al. 1997; Efstathiou 2000; Kay et al. 2002; Marri & White 2003; Wada & Venkatesan 2003; Ricotti & Ostriker 2004) or the photoevaporation by ultraviolet background (UVB) radiation (Umemura & Ikeuchi 1984; Bond et al. 1988; Efstathiou 1992; Babul & Rees 1992; Thoul & Weinberg 1996; Barkana & Loeb 1999; Kitayama & Ikeuchi 2000; Kitayama et al. 2000; Kitayama et al. 2001; Bullock et al. 2000; Somerville 2002; Benson et al. 2002; Ricotti et al. 2002; Susa & Umemura 2004). As for the former process, Wada & Venkatesan (2003) recently performed high-resolution hydrodynamic simulations and concluded that 1000 SNe are required in order to disrupt a galaxy with $M \sim 10^8\ M_\odot$ at $z \sim 10$, while only 100 SNe in the halo would trigger the recollapse of the whole system. These results show that SN explosions are not always destructive to the formation of low-mass galaxies, although it depends on the initial mass function of stars (e.g., Ricotti & Ostriker 2004). On the other hand, the previous studies on the UVB feedback have shown that the photoevaporation by UVB is dependent on the virial mass. As long as systems are more massive than $\approx 10^8\ M_\odot$, the photoevaporation by the UVB is not effective because deep potential wells can retain the ionized gas. However, at smaller mass scales, the feedback by the UVB is expected to play a very important role. Recently, using *Wilkinson Microwave Anisotropy Probe* (*WMAP*) Kogut et al. (2003) suggested that the universe was reionized in a rather early epoch ($z \sim 17$). If this is the case, the UVB feedback could be quite effective for low-mass systems, since density fluctuations are photoheated before they collapse to form stars.

Very recently, Kravtsov et al. (2004) analyzed the dynamical history of small substructure halos with a present mass of $\lesssim 10^8$–$10^9\ M_\odot$ using a cosmological simulation. They found that 10% of small halos originate in considerably larger systems with $\gtrsim 10^9\ M_\odot$ that survived the tidal stripping. They suggest that the Galactic satellites are descendants of relatively massive systems that formed at higher redshifts and did not significantly suffer from the UVB. This argument is plausible if systems with $\gtrsim 10^9\ M_\odot$ are impervious, even to early reionization, and if star formation in low-mass systems is completely suppressed.

Kitayama et al. (2001) have investigated the UVB feedback using a one-dimensional radiation hydrodynamic simulation for halos that collapse at $z \lesssim 10$ and found that the central parts cannot cool down to form stars if the virial temperature is less than 10^4 K and if $I_{21} \gtrsim 10^{-2}$, where I_{21} is the intensity at the Lyman limit in units of 10^{-21} ergs s^{-1} cm^{-1} Hz^{-1} sr^{-1}. Dijkstra et al. (2004) extended this work to higher redshifts by using one-dimensional hydrodynamic calculations and found that gas is not photoevaporated in halos with circular velocities of 10–20 km s^{-1} at $z > 10$. But, in the hierarchical structure formation of a CDM universe, three-dimensional time-dependent self-shielding is significant for the UVB feedback, as shown by Susa & Umemura (2004). In particular, such radiative transfer effects are likely to be essential, when the reionization proceeds at higher redshifts (in higher density intergalactic matter).

In this Letter, we perform three-dimensional radiation hydrodynamic simulations by solving the radiative transfer for ionizing photons, and we attempt to elucidate the feedback effects of early reionization on the formation of subgalactic systems. In § 2, the method of numerical simulation is briefly described, and the assumption for the ionizing radiation intensity is provided. In § 3, we present the numerical results for UVB feedback and also make a convergence check of the results. Section 4 is devoted to discussion of the substructure problem.

2. NUMERICAL METHOD

The details of the numerical method are given in Susa & Umemura (2004). Here, we briefly describe the model and method for the simulations. The hydrodynamics are calculated by using the smoothed particle hydrodynamics (SPH) method. We use the version of SPH by Umemura (1993), with the modification by Steinmetz & Müller (1993), and we also adopt the particle resizing formalism of Thacker et al. (2000). The gravitational force is calculated by a special-purpose processor for gravity, GRAPE-6 (Makino 2002). In order to access the GRAPE boards, we utilize the Heterogeneous Multi-Computer System (HMCS; Boku et al. 2002), which allows us to use GRAPE in parallel processors (such as PC clusters).

The softening length for gravity is set to be 20 pc for SPH and CDM particles. This value is based on the convergence test shown in § 3. The nonequilibrium chemistry and radiative cooling for primordial gas are included with the code developed by Susa & Kitayama (2000), in which H_2 cooling and reaction rates are taken from Galli & Palla (1998). To solve the radiative transfer in an SPH scheme, we employ the method proposed by Kessel-Deynet & Burkert (2000), which utilizes the neighbor lists of SPH particles to evaluate the optical depth from a certain source to an SPH particle.

To generate UVB radiation, we use a single ionizing source that is located very far from the simulated region, and we control the UV intensity by specifying the incident flux to the simulation box. We assume that the history of the UV intensity allowed for the early reionization inferred by *WMAP*. Since the recombination timescale is shorter than the Hubble expansion time at $z \gtrsim 10$ (Peebles 1968), ionizing photons should be continuously supplied in order to retain the ionization. The requisite UV intensity is given by equating the recombination rate to the ionization rate:

$$I_{\nu_{\rm L}} = \frac{n_0(1+z)^3 k_{\rm rec} h_{\rm P}(\alpha+3)}{4\pi\sigma_{\nu_{\rm L}}} \frac{(1-y_{\rm H\,I})^2}{y_{\rm H\,I}}, \qquad (1)$$

where $I_{\nu_{\rm L}}$ denotes the intensity at the Lyman limit; $k_{\rm rec}$, $\sigma_{\nu_{\rm L}}$, and $h_{\rm P}$ represent the recombination coefficient, the ionization cross section at the Lyman limit, and the Planck constant, respectively; n_0 is the present-day baryon density; α is the spectral index of UV radiation; and $y_{\rm H\,I}$ is the fraction of neutral hydrogen. If $y_{\rm H\,I} = 0.1$ at $z \simeq 15$, $I_{21} \simeq 10^{-3}$ is required. This should be regarded as the minimal prerequisite for two reasons. First, this estimate is provided for optically thin media. In actual ionization history, the radiative transfer effect is definitely important (Nakamoto et al. 2001). Second, in an inhomogeneous universe, local density enhancements increase the recombination rate significantly. Taking these two reasons into account, we assume $I_{21} = 0.01$ for $5 < z < 17$ with a sharp decrease at $z > 17$ as $I_{21} \propto \exp[3(17-z)]$. Also, some models with $I_{21} = 1$ are simulated to investigate the dependence on I_{21}.

The "star formation" condition adopted in this Letter is basically the same as that in Susa & Umemura (2004), except that $c_* = 1$ is assumed here; $c_* = 1$ means the star formation at the maximal feasible rate, because no stars can form in a timescale shorter than the local free-fall time. Here, we do not include the internal feedback effects by stellar UV radiation or by SN explosions.

We assume $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_{\rm baryon}h^2 = 0.02$, and $h = 0.7$, as the background cosmology. Following the density fluctuations in this cosmology, the initial distributions of particles are set up. The mass of the virialized dark halo is in the range of $10^6\ M_\odot \lesssim M_{\rm vir} \lesssim 10^8\ M_\odot$, and the collapse epoch is $5 \lesssim z_c \lesssim 20$. We use 2^{15} SPH particles and 2^{15} dark matter particles for a run.

3. RESULTS

The numerical results are summarized in Figure 1. The left panel shows the fraction of the final mass in the stellar component to the initial baryon mass as a function of the collapse epoch z_c and $M_{\rm vir}$, while the right panel is the final fraction of gas. In both panels, the fraction is depicted by different symbols. The dotted lines represent the collapse epoch of halos formed from 1 σ, 2 σ, and 3 σ CDM density fluctuations. Roughly 95% of fluctuations collapse after the epoch predicted by the 2 σ line. The dashed lines denote the constant circular velocities, which are defined by $v_{\rm circ} \equiv (GM_{\rm vir}/r_{\rm vir})^{1/2}$ with the virial radius $r_{\rm vir}$ determined by z_c and $M_{\rm vir}$.

In Figure 1, we see that if $M_{\rm vir} \gtrsim 10^8\ M_\odot$ and $v_{\rm circ} \gtrsim 20$ km s^{-1}, almost all baryons are transformed into stars, leaving little gas. It is noted that a considerable fraction of baryonic matter forms stars even after the reionization ($z_c < z_{\rm reion} = 17$). On the other hand, if $v_{\rm circ} \lesssim 20$ km s^{-1}, $f_{\rm star}$ steeply decreases with decreasing circular velocities. Also, $f_{\rm gas}$ becomes quite small, as seen in the right panel. This reflects the effect of photoevaporation by the UVB. The dependence of photoevaporation on $M_{\rm vir}$ and z_c is understood by the self-shielding and by the gravitational potential. The self-shielding against the UVB becomes prominent if the local density exceeds the threshold density as

$$n_{\rm shield} = 1.4 \times 10^{-2}\ {\rm cm}^{-3} \left(\frac{M_{\rm baryon}}{10^8\ M_\odot}\right)^{-1/5} \left(\frac{I_{21}}{\alpha}\right)^{3/5} \qquad (2)$$

(Tajiri & Umemura 1998). This means that the self-shielding is more effective if the system is larger or if it collapses at higher redshifts. The gas envelope that is not shielded from the UVB is photoheated to $\lesssim 10^4$ K and is blown out by the enhanced thermal pressure, unless the gravitational potential is deep enough to retain the ionized gas (i.e., $v_{\rm circ} \gtrsim 20$ km s^{-1}). Hence, the photoevaporation is quite devastating for fluctuations with lower masses and later collapse epochs. Intriguingly, a steep transition of $f_{\rm star}$ for $v_{\rm circ} \lesssim 20$ km s^{-1} coincidentally lies on a line of nearly constant σ; i.e., $\delta\rho/\rho \approx 2\ \sigma$. This means that in more than 95% of the halos with $v_{\rm circ} \lesssim 20$ km s^{-1}, the star formation is strongly suppressed by early reionization.

In the present simulation, star formation is assumed to proceed in local free-fall time. This leads to the physically maximal star formation rate. Hence, the stellar fraction obtained in a halo should be regarded as a maximal one. If the star formation proceeds for a longer timescale, baryon gas in a halo with $v_{\rm circ} \lesssim 20$ km s^{-1} could be almost completely photoevaporated after the reionization. On the other hand, fluctuations with $v_{\rm circ} \gtrsim 20$ km s^{-1} are likely to be impervious to the photoevaporation since the gravitational potential is deep enough to retain the ionized gas.

To examine the dependence of the results on the assumed UVB intensity (I_{21}), we also perform several runs with $I_{21} = 1$. In this case, a steep transition of $f_{\rm star}$ is slightly shifted to higher σ as $\delta\rho/\rho \approx 2.5\ \sigma$. Thus, it turns out that the results are not strongly dependent on the UVB intensity. Such insensi-

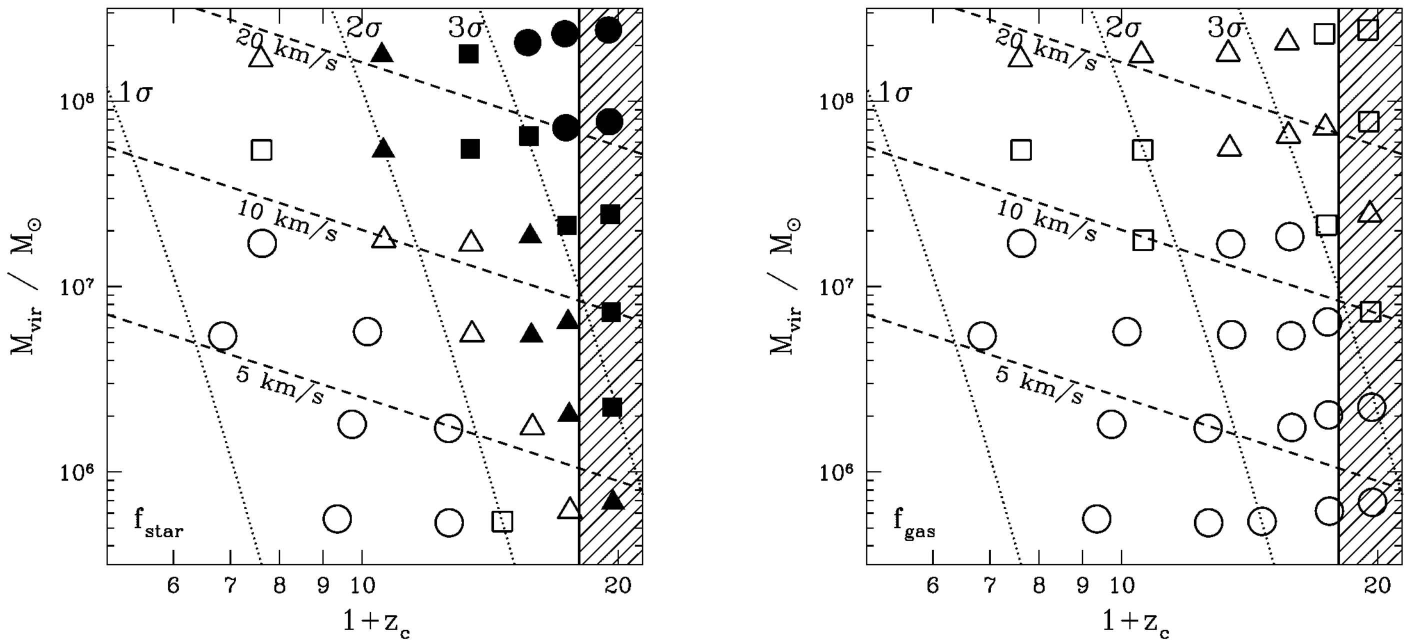

FIG. 1.—Summary of numerical runs shown as a function of the collapse epoch z_c and the virialized halo mass M_{vir}. The left panel shows the fraction of the final mass in the stellar component to the initial baryon mass, while the right panel is the final fraction of gas. In both panels, the fraction f is depicted by different symbols: $f > 0.9$ (*filled circles*), $0.5 < f < 0.9$ (*filled squares*), $0.1 < f < 0.5$ (*filled triangles*), $0.01 < f < 0.1$ (*open triangles*), $10^{-3} < f < 0.01$ (*open squares*), and $f < 10^{-3}$ (*open circles*). The dotted lines represent the collapse epoch of halos formed from 1 σ, 2 σ, and 3 σ CDM density fluctuations. The dashed lines denote the constant circular velocities of 5, 10, and 20 km s^{-1}.

tiveness may be understood as the weak dependence of the self-shielding on the UV intensity, as seen in equation (2).

Finally, to check the numerical effects, we analyze the convergence of the runs by changing the mass resolution and softening length. In Figure 2, the left panel shows the final stellar fraction (f_{star}) in runs with $M_{vir} = 6 \times 10^7\ M_\odot$ and $z_c \simeq 10$, while the right panel shows f_{star} in runs with $M_{vir} = 6 \times 10^6\ M_\odot$ and $z_c \simeq 15$. These runs are at the transition region of f_{star} in Figure 1. The horizontal axis in Figure 2 represents the softening length ϵ for gravity. The four different curves correspond to the different numbers of particles used in the simulations. We can see that f_{star} almost converges, if $N_{SPH} \gtrsim 2^{15}$ and if $\epsilon \lesssim 10$–20 pc.

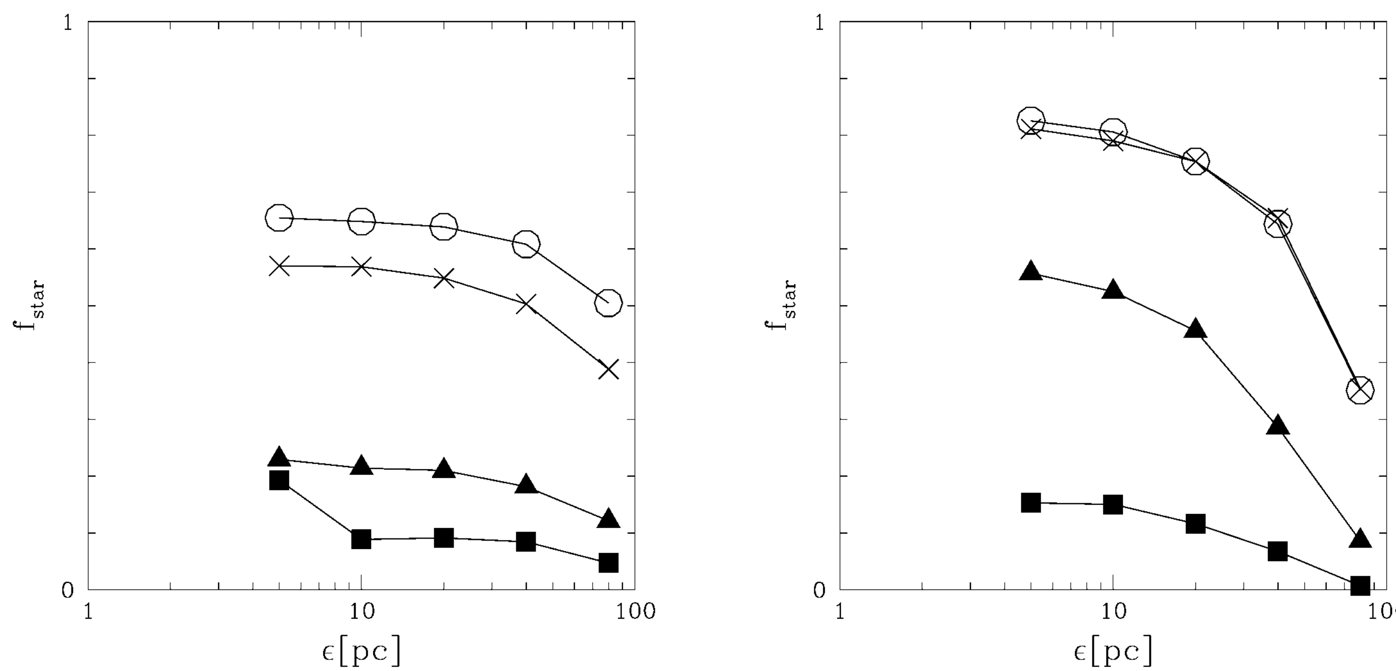

FIG. 2.—Convergence check of the numerical simulations. The left panel shows the convergence of runs with $M_{vir} = 6 \times 10^7\ M_\odot$ and $z_c \simeq 10$, and the right panel shows the convergence of runs with $M_{vir} = 6 \times 10^6\ M_\odot$ and $z_c \simeq 15$. In both panels, the vertical axis represents the final stellar mass fraction, and the horizontal axis represents the softening length of the gravitational force. The four different curves correspond to the different numbers of particles: $N_{SPH} = 2^{17}$ (*circles*), $N_{SPH} = 2^{15}$ (*crosses*), $N_{SPH} = 2^{14}$ (*triangles*), and $N_{SPH} = 2^{13}$ (*squares*).

Thus, the present simulation with $\epsilon = 20$ pc and $N_{SPH} = 2^{15}$ ($= N_{DM}$) is unlikely to suffer from numerical effects.

4. DISCUSSION

The present numerical simulations predict strong negative feedback on the formation of dwarf galaxies with $v_{circ} \lesssim 20$ km s^{-1}. Based on f_{star}, we can make a rough estimation of the mass-to-light ratios (M/L) for fully formed galaxies. If we assume $M_{star}/L = 3$ for stars in solar units, $f_{star} = 0.01$ corresponds to $M_{vir}/L = 2.6 \times 10^3$, and $f_{star} = 0.1$ to $M_{vir}/L = 2.6 \times 10^2$. But these values cannot be compared directly with the observed M/L of satellite galaxies because quite a large fraction (typically more than 90%) of the dark matter halos of satellites can be tidally stripped, as shown by Kravtsov et al. (2004). Thus, the eventual M/L of satellites is likely to decrease by a factor of 10; e.g., $M/L = 2.6 \times 10^2$ for $f_{star} = 0.01$. Local Group dwarf galaxies (dwarf spheroidal and dwarf irregular galaxies) exhibit a wide range of M/L, from a few up to ≈100 (van den Bergh 1999; Mateo 1998; Hirashita et al. 1998). Hence, the formed galaxies with $f_{star} \gtrsim 0.01$ may account for the Local Group dwarf galaxies. The present simulation predicts that only a few percent of fluctuations result in $f_{star} \gtrsim 0.01$, if $v_{circ} \lesssim 20$ km s^{-1}. If the star formation rate is lower, the probability is reduced further. Hence, such intrinsically low-mass halos may be too few to account for all the Galactic satellites.

One possibility for reconciling this discrepancy could be found in the model suggested by Kravtsov et al. (2004). They found that 10% of small halos originate in considerably larger systems with $\gtrsim 10^9\ M_\odot$ that survived the tidal stripping, and they suggest that the Galactic satellites are descendants of relatively massive systems that formed at higher redshifts. In our simulation, systems larger than $10^8\ M_\odot$ are not subject to the UVB feedback. Thus, their model seems likely to account for the number of Local Group dwarf galaxies.

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