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The effects of early reionization on the formation of dwarf galaxies

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Abstract. We consider the feedback effects of the early reionization on the formation of small galaxies. For this purpose, we perform 3D radiation hydrodynamic simulations with incorporating the radiative transfer for ionizing photons. As a result, it is found that the early reionization is so devastating for low mass systems with $M_{\rm vir} \lesssim 10^8 M_\odot$ or $v_{\rm circ} \lesssim 20$km/s, and almost all gas is photo-evaporated in more than 95% of low mass systems. These results indicate that the low mass dwarf galaxies are not formed directly from isolated CDM density perturbations.

Keywords. radiative transfer,methods: numerical,galaxies: dwarf,formation

1. Introduction

According to the latest cosmology, first galactic systems have formed at $z \sim 10$–30, and the masses of the systems are as large as those of low mass dwarf galaxies, i.e. $10^6 M_\odot \lesssim M \lesssim 10^8 M_\odot$. Because of such early formation epoch, the remnants of these first galactic objects should have very old stellar populations, which are in fact found in all of the dwarf galaxies in Local Group. Therefore, first generation galaxies directly formed from CDM density fluctuations are expected to be the most plausible candidate of the progenitor of present dwarf galaxies observed in our neighborhood.

On the other hand, the results from WMAP satellite tell us that the universe was reionized at very early epoch. Because of the negative feedback effects of the ionizing radiation field in very early universe, formation of low mass galactic systems might have suppressed severely.

In order to assess the effects of reionization on the formation of such systems, we have to take into account the effects of radiative transfer of ionizing photons, otherwise, we overestimate the negative feedback effects.

In this contribution, we present the 3D radiation SPH simulation on the formation of such low mass systems, especially taking into account the effects of radiative transfer and early reionization.

2. Numerical Methods

The detail of numerical method is provided in Susa & Umemura(2004a). In this section, we briefly describe the simulations done in this work.

Hydrodynamics is calculated by Smoothed Particle Hydrodynamics (SPH) method. We use the version of SPH by Umemura(1993) with the modification according to Steinmetz & Müller(1993), and also we adopt the particle resizing formalism by Thacker *et al.* (2000). The gravitational force is calculated by a special purpose processor for gravity calculation, GRAPE-6 (Makino 2002). In order to access GRAPE boards, we utilize the Heterogeneous Multi-Computer System (HMCS) (Boku *et al.* 2002) which enables us to use GRAPE in parallel processors such as PC clusters.

The softening length for gravity is set to be 20pc for all SPH and CDM particles. This value is determined by the convergence test. The non-equilibrium chemistry and radiative cooling for primordial gas are calculated by the code developed by Susa & Kitayama (2000), where H_2 cooling and reaction rates are taken from Galli & Palla (1998). Radiation transfer equation for ionizing photons is solved based upon the method proposed by Kessel-Deynet & Burkert (2000), which utilizes the neighbor lists of SPH particles to assess the optical depth from a certain source to an SPH particle.

The "star formation" conditions employed in this work is basically the same as Susa & Umemura(2004a), except that $c_* = 1$ is adopted in this paper. The assumption of $c_* = 1$ allows the star formation at physically acceptable maximal rate, because no stars should not form faster than local free-fall time scale.

As for ionizing flux, we employ the UV intensity $I_{21} = 0.01$ for $z < 17$, that allows the early reionization of the universe inferred by *WMAP* (Susa & Umemura(2004b)).

3. Results & Discussion

The summary of the numerical runs is shown in Figure 1, where M is the mass of virialized halo and z_c is the collapse epoch. In order to distinguish the fate of baryonic component, we evaluate the final mass-to-light ratio (M/L) of the formed small galaxies by assuming $M_{\rm star}/L = 3$ for formed stars in solar units. Open circles denote $M/L > 100$ and filled circles $M/L < 100$. The dotted lines represent the collapse epoch of halos formed from $1\sigma, 2\sigma$ and 3σ CDM density fluctuations. Roughly 95% of fluctuations collapse after the epoch predicted by the 2σ line. Dashed lines denote the loci of constant circular velocities (5 km/s, 10km/s, 20km/s) of the collapsed halos.

Open symbols $(M/L > 100)$ should be regarded as "failed" halos, because the maximal M/L in Local Group dSphs is roughly 100 (van den Bergh(1999), Mateo (1998), Hirashita, Takeuchi & Tamura(1998)). It is noted, however, the specific choice of the critical mass-to-light ratio of 100 is not so important, since the gradient of M/L on $z_c - M$ plane is quite steep.

From these results, it is clear that most of the baryonic component in the halos formed from relatively low density peaks $(\delta\rho/\rho \lesssim 2\sigma)$ is blown away by the thermal pressure of photo-heated gas. On the other hand, in the halos at high density peaks $(\delta\rho/\rho \gtrsim 2\sigma)$, gas components are efficiently converted to stars, avoiding the complete photo-evaporation caused by the reionization of the universe. Since the assumed star formation time scale (local free-fall time) is the shortest among the physically acceptable estimates, the mass of luminous matter in the halos should be regarded as maximal one. In other words, the obtained mass-to-light ratios of galaxies designate the lower limits. Therefore, the area in which the galaxies are "failed" in Figure 1 can be underestimated. If we adopt more realistic star formation scheme, the "failed" region would extend to higher redshift. However, it should be also noted that the gas in the halos with circular velocity $\gtrsim$20kms^{-1} does not evaporate even when it is photo-heated to $\sim 10^4$K, since the gravitational potential is deep enough to retain the ionized gas. Thus, it is concluded that, in more than 95% of the halos with $v_{\rm circ} \lesssim$20kms^{-1}, the galaxy formation is prohibited due to the early reionization feedback.

These results indicate that if we accept early reionization at $z > 17$, it is quite difficult for low mass dwarf galaxies to form $(M \lesssim 10^8 M_\odot$, especially dSphs) directly from isolated

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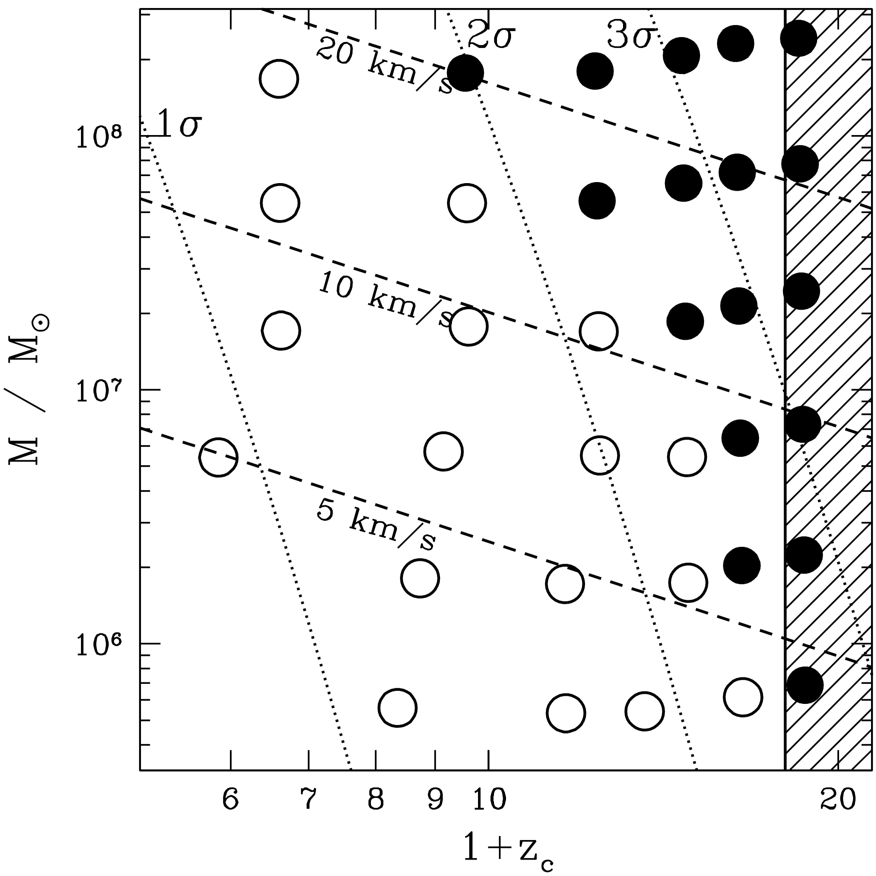

Figure 1. Summary of numerical runs are shown on collapse epoch v.s. virialized mass plane. Filled circles denote the runs in which the stars are formed effectively, and significant amount of baryonic matter remain in the halo potential($M/L < 100$). Open circles denote the runs in which almost all of the baryonic matters are lost($M/L > 100$). Dashed lines denote the loci of constant circular velocities (5 km/s, 10km/s, 20km/s) of the collapsed clouds, and the dotted lines denote the collapse epoch of CDM density perturbations whose amplitudes are 1σ, 2σ and 3σ. Hatched region in the right of the panel shows the pre-reionization era.

CDM density fluctuations, because 1) they are too small to retain the reionized gas, and 2) the evidence of star formation activity at $z \lesssim 5$ are found for these galaxies.

There are a few logical scenarios for the formation of such galaxies:

1. Reionization epoch is much later ($z \lesssim 10$). Thus, the radiative feedback is not important for the halos formed at $z \gtrsim 10$. However, even with such late reionization assumption, we need some other mechanism which can allow the star formation activity well after the reionization.

2. The circular velocities of dSphs are much larger as claimed by N-body simulations (Stoehr *et al.* 2002, Hayashi *et al.* 2003). If this is the case, photo-evaporation mechanism give the low mass limit of small galaxies ($M > 10^8 M_\odot$).

3. dSphs are embedded in tidally stripped halos, that is originally more massive (Kravtsov, Gnedin & Klypin 2004). Kravtsov *et al.* found that 10% of subgalactic halos

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were formed through the tidal stripping of rather massive halos ($M \sim 10^9 M_\odot$). They suggest that dSphs are formed in such halos, not from the small scale ($M \lesssim 10^8 M_\odot$) density perturbations imprinted in the very early universe. This suggestion could be consistent with the strong negative feedback effects of early reionization and the observed star formation history of dSphs.

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References

Boku, T., Makino, J., Susa, H., Umemura, M., Fukushige, T. & Ukawa, A. 2002, *IPSJ Transactions on High Performance Computing Systems* 41, 5
Galli D. & Palla F. 1998, *A&A* 335, 403
Hayashi, E., Navarro, J., Taylor, J.,Stadel, J. & Quinn, T. 2003, *ApJ* 584, 541
Hirashita, H., Takeuchi, T.T. & Tamura, N. 1998, *ApJL*, 504, L83
Kessel-Deynet, O. & Burkert, A. 2000, *MNRAS* 315, 713
Kravtsov,A., Gnedin,O. & Klypin, A., 2004, *astro-ph(0401088)*
Makino, J. 2002, *ASP Conf. Ser. 263: Stellar Collisions, Mergers and their Consequences*, 389
Mateo, M. 1998, *ARA&A* 36, 435
Steinmetz, M. & Müller, E. 1993, *A&A* 268, 391
Susa, H. & Kitayama, T. 2000, *MNRAS* 317, 175
Susa, H. & Umemura, M. 2004, *ApJ* 600, 1
Susa, H. & Umemura, M. 2004, *ApJ* 610, L5
Stoehr, F., White, S.D.M., Tormen, G. & Springel, V., 2002, *MNRAS* 335, 84
Thacker, J., Tittley, R., Pearce, R., Couchman, P. & Thomas, A. 2000, *MNRAS* 319, 619
Umemura, M. 1993, *ApJ* 406, 361
van den Bergh, S. 1999, *A&ARv* 9, 273

Discussion

Ferguson: How does the ionizing photon density from the dwarf galaxies in your model compare to the ionizing background you assumed at the start (from WMAP)?

Susa: In my model the intensity of ionizing photons is set high enough to reionize the universe at z $\approx$ 17. Because the radiation field is treated as external radiation field, the ionizing photons from the dwarfs are not included. At present we haven't compared the intensity from dwarfs with the assumed background intensity. But it might be possible.

Lin: If the background UV radiation is supplied by massive stars, its flux would be self-regulated. The evaporated gas may be episodically cooled to fall back to the minihalos of dwarf galaxies. Have you considered the case where individual dwarf ellipticals are not isolated but embedded in a much larger intergalactic medium complex?

Susa: If the source of ionizing radiation is massive stars, self-regulation might be possible. However, if the radiation is supplied by black holes or other mechanisms, self-regulation doesn't work. Concerning the last part of your question, the answer is no, I haven't.