Formation of Dwarf Galaxies in Reionized Universe with Heterogeneous Multi-computer System

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Abstract. HMCS (Heterogeneous Multi-Computer System) is a very powerful and ideal computational environment for large scale computational astrophysics simulations including multiple physical phenomena. In this system, general purpose and special purpose parallel processing systems are involved to realize very high performance computation. We have constructed a system with MPP and PC-cluster as general purpose side and GRAPE-6 gravity engine as special purpose side.
We perform 3D radiation smoothed-particle-hydrodynamics (RSPH) simulations on the formation and the photoevaporation of subgalactic objects ($M \sim 10^8 - 10^9 M_\odot$). We confirm the suppression of the formation of small galaxies after the reionization. We also find that the galaxies that undergo violent photoevaporation process, still retain certain amount of stars, which are formed at small scale high density peaks. These cooled components merge with each other when the dark matter halo of the whole system is formed. It is also found these low mass galaxies should have large mass-to-light ratio, and these systems could be the progenitor of dwarf spheroidal galaxies in Local Group.

1 Introduction

Galaxy formation is one of the important issues on computational astrophysics. In this field, we are especially interested into the formation of dwarf galaxies in reionized universe which requires very heavy simulations under multiple physical phenomena. The main part of the simulation consists of two elements: SPH (smoothed particle hydrodynamics) and N-body gravity calculation. We have developed a parallel code for the first half on both massively parallel processor and Linux PC clusters. The latter half is extremely heavy because it requires $O(N^2)$ computation. For this part, we introduced a special purpose processor GRAPE-6[1] which provides 1 TFLOPS peak performance with only a single board. We have developed a combined system with these two parts, named

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HMCS (Heterogeneous Multi-Computer System)[2]. In this paper, we describe the simulation result of the formation of dwarf galaxies on HMCS as well as the brief introduction of HMCS itself.

2 Formation of Low Mass Galaxies and Ultraviolet Background Radiation Field

According to the standard theory of cosmology, first galaxies are small ($M \sim 10^6 - 10^8 M_\odot$[1]), and are formed when the universe is a hundred million years old. These first generation galaxies start to reionize the universe due to the ultraviolet radiation field emitted from the massive stars in them. These emitted ultraviolet photons built up the ultraviolet background radiation field. In fact, recent observations strongly suggest that the universe is highly ionized after the age of the universe ($t_{\rm H}$) is approximately 3×10^8 years [5]. On the other hand, these small galaxies are so tiny that they cannot afford to keep the ionized hot gas in their gravitational potential, because of the gas pressure. Thus, if the background ultraviolet photons penetrate and heat up the galaxy, the gas component escapes from the potential of the host galaxy. This mechanism is always called as *photoevaporation*. In order to evaluate the effects in realistic clumpy forming galaxies, we perform numerical simulations on the formation of small galaxies under the ultraviolet background radiation field. The code includes the effects of radiation transfer of ionizing photons, chemical reaction network, radiative cooling, star formation, gravity, dark matter particles and smoothed particle hydrodynamics (SPH). This type of simulation with radiative transfer on the formation of small galaxies have never been done before, because of the complexity and high cost of radiation transfer. We utilize the newly developed parallel processing platform Heterogeneous Multi-Computer System [2,7] to realize the present numerical simulation which includes various type of physical phenomena.

3 Heterogeneous Multi-computer System

HMCS (Heterogeneous Multi-Computer System) [2] is a paradigm combining heterogeneous parallel processing systems to solve multi-physical or multi-scale problems which cannot be solved ordinary single system architecture such as general purpose MPPs or clusters. In HMCS, basically, two or more high performance parallel processing systems are connected by wide-bandwidth parallel commodity network such as parallel link of Fast- or Gigabit-Ethernet. We have developed a prototype system of HMCS for astrophysics introducing special purpose gravity engine GRAPE-6[1]. GRAPE-6 is developed at University of Tokyo, and we made a cluster with eight boards of GRAPE-6 in a collaborative work with the originators of GRAPE-6[2].

Fig. 1 shows the conceptual overview of our HMCS prototype. As general purpose machines (GPMs hereafter), we are using CP-PACS[4] MPP system

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[1] $M_\odot$ denotes the mass of Sun.

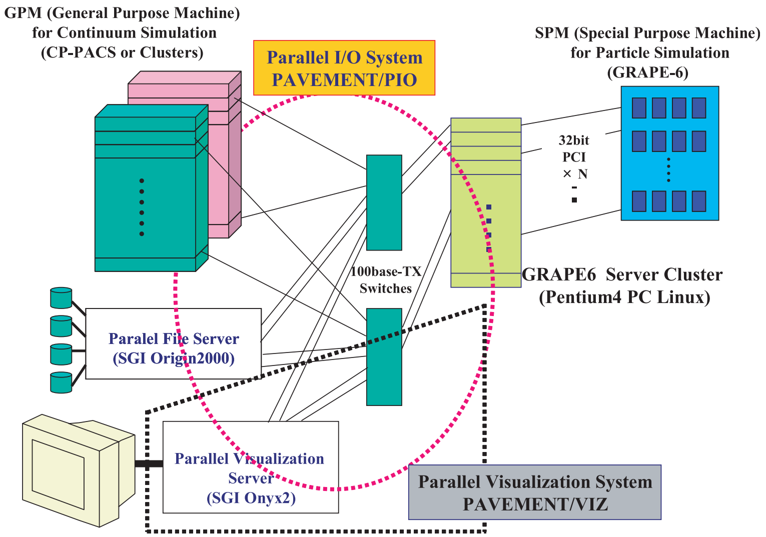

Fig. 1. HMCS overview

with 2048 processors (peak performance = 614 GFLOPS) or commodity-base Pentium Xeon PC-cluster with 37 nodes (74 processors, peak performance = 414 GFLOPS). Eight boards of GRAPE-6 (peak performance = 8TFLOPS) are connected to a small PC-cluster with Pentium4 operated by Linux. Each node of this PC-cluster is connected to a GRAPE-6 board via 32-bit PCI. A parallelized management program written in MPI is provided to control multiple GRAPE-6 boards performing a large scale particle calculation in parallel.

We have designed the system to allow multiple GPMs share a cluster of GRAPE-6 in time-sharing manner. Thus, this GRAPE-6 cluster, named HMCS Server Cluster, works as a server system to provide gravity calculation service, and all GPMs work as client machines. GPMs communicate with HMCS Server Cluster via serial or parallel Ethernet links according to the load of calculation, i.e. the number of particles to be processed. This network with parallel Ethernet links is controlled by user-level middleware named PIO[3] which provides high bandwidth communication with trunk of parallel Ethernet links on TCP/IP level.

Each GRAPE-6 board consists of 32 ASICs for N-body calculation and provides 1 TFLOPS of peak performance on gravity calculation. HMCS Server Cluster operates with MPI-based management program for 1) parallel data exchanging with GPMs through PIO, 2) time-sharing controlling of multiple requests of gravity calculation by multiple GPMs and 3) coordinating parallel gravity calculation on all GRAPE-6 boards. The server program is well designed to maximize the utilization ratio of GRAPE-6 regardless the communication speed between any of GPMs and the server[8].

In HMCS prototype, we can distribute multiple series of simulations with various initial conditions to multiple GPMs surrounding HMCS Server Cluster.

For relatively small scale problems where the number of particles is less than 50,000, one or two GRAPE-6 boards are involved to minimize the overhead for parallel processing among multiple boards. For larger problems, 4 to 8 GRAPE-6 boards are involved. Currently, this distribution control is performed manually with system configuration setting, however we are now developing the automatic load distribution and balancing system to optimize the utilization ratio of eight GRAPE-6 boards.

4 Algorithm and Execution on HMCS

HMCS is an ideal platform for computational astrophysics problems which require both continuum and particle simulations in the target system. In the simulation of dwarf galaxies, there are multiple physical phenomena to be simulated such as hydrodynamics, chemical process and gravity and so on. We simulate all these elements except gravity calculation on GPM while HMCS Server Cluster performs gravity calculation with GRAPE-6.

The basic algorithm of 3D RSPH with gravity on HMCS is as follows.

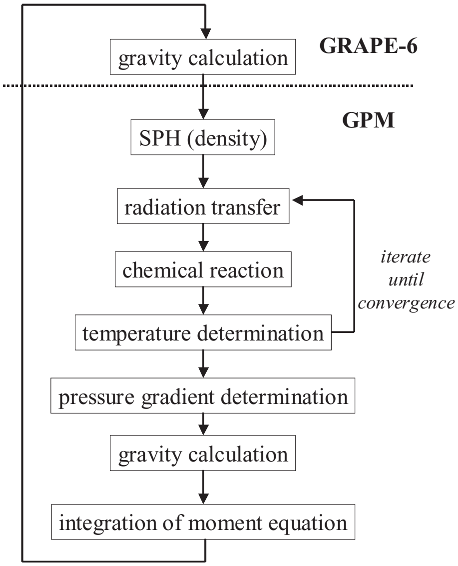

Fig. 2. Basic algorithm and workload of 3D RSPH with gravity

1. Initialize all physical conditions of particles such as mass, location and velocity, and the field such as density, temperature, the amount of chemical seeds, etc.
2. Transfer the particle data from GPM to GRAPE-6, and evaluate the self gravity.
3. Calculate the density, pressure and gradient of pressure with SPH.

4. Determine the time step from the velocity and force.
5. Vary the size of SPH particles.
6. Iterate the calculation of radiation, chemical reaction and energy equation of SPH until they converge, with optional adjustment of time step if necessary.
7. Integral the movement of particles according to SPH dynamic equation.
8. Iterate from Step 2 to 7 for required time length.

In each time step, HMCS Server Cluster (GRAPE-6) and GPM communicate to exchange particle data and acceleration. In this algorithm, most of computation time is spent by GPM. Even if the order of computation for gravity calculation is $O(N^2)$ for N particles, RSPH calculation part is much heavier than gravity part for $N \sim 50,000$. In such cases, GRAPE-6 is mostly idle, therefore we can share HMCS Server Cluster with multiple GPMs in time-sharing manner to perform multiple cases of simulation simultaneously.

5 Simulations and Results

We have performed several runs with two different total masses and various formation epochs of galaxies. The detailed of applied method and algorithm are shown in [7]. In this paper, results from four runs with parameters listed in Table 1 are shown. Projected positions of gas particles, star particles and dark matter particles in model A1 are plotted in Fig. 3. The left three panels represent the epoch prior to the reionization. At this epoch, gas particles are cold ($T < 10^4$K) and almost trace the distribution of dark matter particles. Stellar particles are not formed yet. After the reionization (middle three panels), the low density regions are heated up to $T \lesssim 10^4$K, while the high density peaks are self-shielded to the ultraviolet background radiation field. In the self-shielded dense clumps, stars are formed from cooled clouds. Finally (right three panels), the gas components are blown away due to the photoevaporation. The clumps of the star particles merge with each other, and form a spheroidal system. On the other hand, such as in case B2, the gas is not blown away, and most of the gas and stars settle onto the gravitational potential of dark matter particles, because the gravitational force is strong enough to keep the hot ionized gas with $T \simeq 10^4$K.

Table 1. Model parameters

Model ID	Formation epoch $z_{\rm c}$	Total mass $M_{\rm tot}$
A1	1.5	$2 \times 10^8 M_\odot$
A2	1.5	$2 \times 10^9 M_\odot$
B1	6	$2 \times 10^8 M_\odot$
B2	6	$2 \times 10^9 M_\odot$

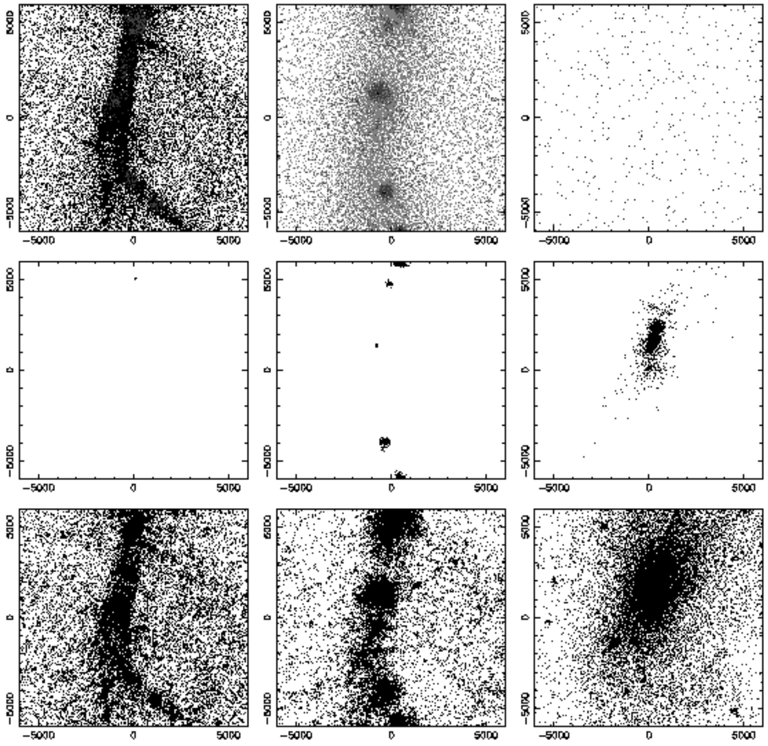

Fig. 3. Projected positions of SPH particles (upper panels), numerically formed star particles (middle) and dark matter particles (bottom panels) are plotted at three different epochs (left:$z = 8.958$, middle:$z = 5.755$ and right:$z = 1.361$) for model A1. Remark that larger redshift represents the earlier epoch. The color of the gas particles represents the gas temperature (red:$T \geq 10^4$K, green:$10^3\text{K} \leq T \leq 10^4$K, blue:$T \leq 10^3$K). The box size is 6 kpc × 6 kpc

In Fig. 4(a), time evolution of the fraction of stars and gas particles within 5 kpc[2] are plotted for four runs. For models A1 and A2, which correspond the models with later formation epoch (i.e. low $z_{\rm c}$), significant amount of gas are lost from galaxy. On the other hand, for models B1 and B2 (earlier formation epoch), most of the gas and stellar components do not escape from the galaxy. Gas particles are converted to star particles more efficiently than the previous case, because the gas clumps are formed prior to the reionization epoch (i.e. when the intensity of UV radiation field is weak), and they are easily self-shielded. Once the gas are converted to star particles, thermal pressure of the ionized gas does not disrupt the system.

These results also infer the large mass-to-light ratio (ratio of luminosity and total mass) for models A1 and A2, because gas are lost by photoevaporation while the dark matter particles are not affected by radiation. The observation of

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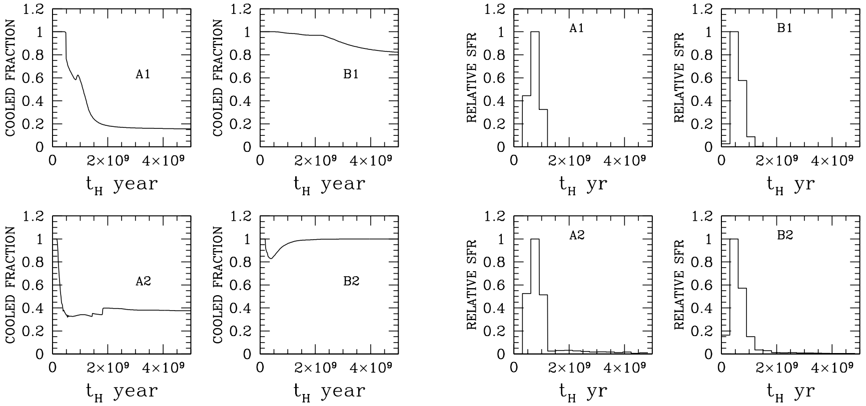
[2] kpc = 3.08×10^{21} cm

Local Group dwarf spheroidal galaxies[3] tells that those faint galaxies have very large mass-to-light ratio [6], which is similar to our results in models A1 and A2.

In Figure 4(b) relative star formation histories are plotted. We find a clear feature for all models: star formation rates[4] sharply drop at $t_{\rm H} = 1-2{\rm Gyr}$, which is the direct consequence of the photoevaporation of the gas. It is interesting to point out that this star formation history is again similar to that of dwarf galaxies in Local Group [6].



(a) Cooled fraction

(b) Star formation history

Fig. 4. (a) Time evolution of the fraction of cooled baryonic components are plotted for four runs. Horizontal axes denote the cosmological time, and vertical axes represent the fractions of the baryonic components (i.e. SPH particles and star particles) within 5kpc from the center of gravity. Left two panels represent the cases with $z_{\rm c} = 1.5$ (Model A1 and A2). Right two panels denote the cases with $z_{\rm c} = 6$ (Model B1 and B2). (b) Star formation history of four runs are plotted. Vertical axis denotes the star formation rate (mass of the formed stars per unit time) normalized by the peak value. Left two panels represent the cases with $z_{\rm c} = 1.5$ (Model A1 and A2). Right two panels denote the cases with $z_{\rm c} = 6$ (Model B1 and B2)

6 Conclusion

We performed 3D radiation hydrodynamical simulations on the formation of low mass objects with four set of parameters on HMCS prototype system with general purpose PC-clusters and special purpose cluster with GRAPE-6 gravity engine. Through these product runs, we confirmed that HMCS is an ideal and powerful tool for real applications of computational astrophysics. The suppression of the formation of low mass objects at later epoch is confirmed. It is also

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[3] Small galaxies in our neighbourhood.

[4] Mass of the formed stars per unit time.

found that the low mass galaxies formed at low redshift should have very large mass-to-light ratio and characteristic star formation history. Observational counter part of these systems might be the spheroidal components of Local Group dwarf galaxies.

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