Galaxy Evolution with Adaptive Mesh Refinement

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Abstract. To numerically model the evolution of galaxies very high resolution simulations are indispensable because of non-linear couplings between pc and Mpc scales. We present a method to interpolate particle data onto an Eulerian adaptive mesh. This allows us to study galaxy mergers and evolution using the cosmological adaptive mesh refinement (AMR) code *enzo*[1] [2]. This pipeline also makes it straightforward to compare smooth particle hydrodynamics (SPH) simulations with AMR simulations of the same physical system. We present the evolution of a stable disk galaxy and test whether the same system moving at 220 km/s across the grid show the same physical evolution and find satisfactory results. We also show calculations that follow the formation of a gas rich low mass disk including star formation and feedback. These early tests are encouraging and demonstrate that *enzo* is well suited for studying galaxy evolution as has been shown previously by Tasker and Bryan [3].

Keywords: Galaxy Formation, Galaxy Evolution, Numerical Method
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INTRODUCTION

One of the most fundamental challenges in structure formation theory is understanding the evolution of galaxies. Modeling galaxy evolution with computers requires very high resolution simulations, as it consists of numerous micro-processes occurring on a wide range of distance scales: from pc (star forming regions) to Mpc (distance between the galaxies). We also have to incorporate multiphase gas physics and stellar feedback to fully model the evolution of galaxies.

We present a method of using AMR simulations to study galaxy mergers and their evolution. A cosmological Eulerian AMR hydrodynamics simulation code *enzo* is used to demonstrate the formation and evolution of galaxies. The conversion pipeline from particle data to an adaptive mesh and details of the simulation technique are discussed in the next section. In the following section we walk through the first results of our calculations, and in the discussion we describe the potential of our method and future works.

PIPELINE AND METHODOLOGY

Conversion Pipeline

We built up a pipeline which converts galactic N-body particle data of GalactICS[4] to an SPH dataset for Gadget[5], and then to an adaptive mesh for *enzo*. This pipeline, illustrated in Figure 1, inherently facilitates a comparison test between SPH and AMR simulations of the same physical system.

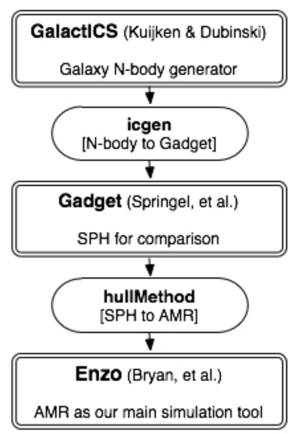

FIGURE 1. The pipeline for dataset conversion

GalactICS to Gadget converter *icgen* can generate gas particles in disk and halo by splitting collisionless particles of N-body data. Because the fraction of dark matter particles in N-body data are transformed to halo SPH particles with the same velocity dispersion, they will virialize to the desired virial temperature automatically.

Gadget to *enzo* converter *hullMethod* employs IDL function *qhull* (Delaunay triangulation) and *qgrid3* (linear interpolation) to reconstruct the density map using particle dataset. It uses an oct-tree structure to grid particle data onto an adaptively refined mesh. This conversion routine is similar to Delaunay tessellation field estimator (DTFE) method[6] except the fact that we use the density value at each particles' position precalculated by Gadget's density estimator.

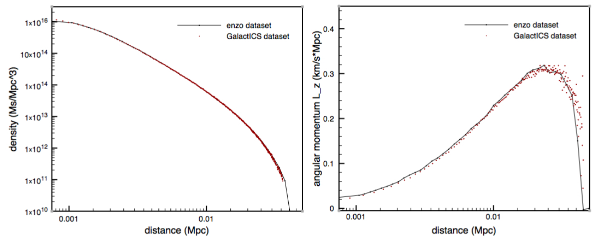

FIGURE 2. Comparison of radial profiles before and after the data conversion pipeline: gas radial density (left) and mass weighted gas angular momentum L_z (right) calculated in GalactICS/icgen (dots) and in *enzo* (solid line)

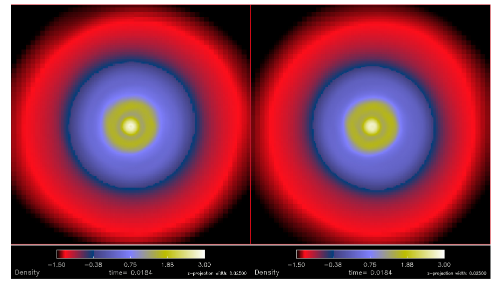

FIGURE 3. Face-on gas surface density of the stationary galaxy (left) and the moving galaxy (right) after 1.36 Gyrs. The right one has moved by 0.31 Mpc. The width shown is 0.1 Mpc.

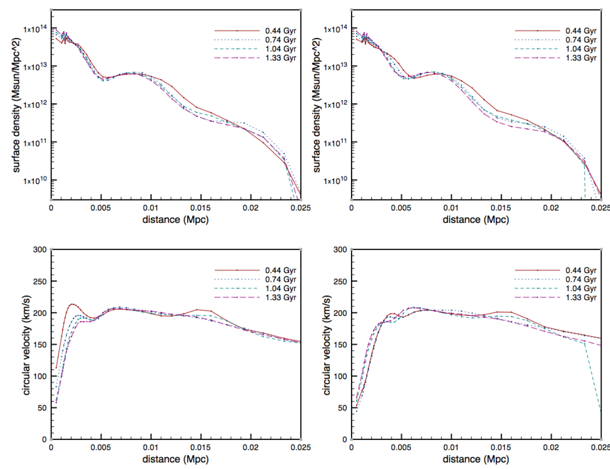

FIGURE 4. Comparison of galaxy profiles for the first 1.36 Gyrs: gas surface density (top) and gas circular velocity (bottom) for the stationary galaxy (left column) and the moving galaxy (right column).

Simulation Code

Our conversion pipeline now allows us to study galaxy mergers and their evolution with the cosmological simulation code *enzo*.

Enzo utilizes high-resolution Eulerian AMR techniques and can refine the grid adaptively up to a dynamic range of 10^{15}, which enables us to include all components of the galaxy at all scales. This technique has been successful in achieving well-resolved multi-phase gas dynamics as it resolves the phase boundary sharply. *Enzo* also contains all relevant physics previously discussed, such as star formation and stellar feedback from type II supernovae explosions.

FIRST RESULTS

Conversion from Particle Data to Adaptive Mesh

Using the particle data of a galactic sized halo with dark matter and gas, we examined the compatibility of the initial N-body dataset and the adaptive mesh we produced through our pipeline.

Figure 2 shows radial profiles calculated at two different places of the conversion process: at the start (GalactICS) and at the end (*enzo*). We can observe clear agreement between the two datasets confirming sufficient validity and functionality of our pipeline.

Galaxy Advection

Many research topics, such as high-resolution galaxy mergers with diffuse gas halos, would benefit from an AMR approach to galaxy simulations.

To check the translational invariance of the simulation code, we performed a simulation that compares two isolated galaxies: one is fixed in space and the other is moving at 220 km/s across the grid. Each has total mass of $3.16 \times 10^{11} M_{\odot}$ with 1.5% gas in disk and halo. It has 10^5 dark matter particles and 2.2×10^5 star particles, all of which are set up through the pipeline previously described. To draw a proper comparison, the background intergalactic medium of the moving galaxy also moves at 220 km/s. We use 3-dimensional ZEUS hydrodynamics algorithm in *enzo* while we assume adiabatic cooling and no star formation or feedback. The maximum resolution in this calculation is 120 pc.

Figures 3 and 4 depict gas surface density and gas circular velocity. These two galaxies show the same physical evolution and a very close resemblance of profiles. The moving galaxy simulation takes about 50% more calculation time than that of the stationary galaxy. Even though these model galaxies don't seem to be stable enough to maintain their initial profiles, this results from unrealistic physical conditions, such as adiabatic cooling, and should not affect our conclusion.

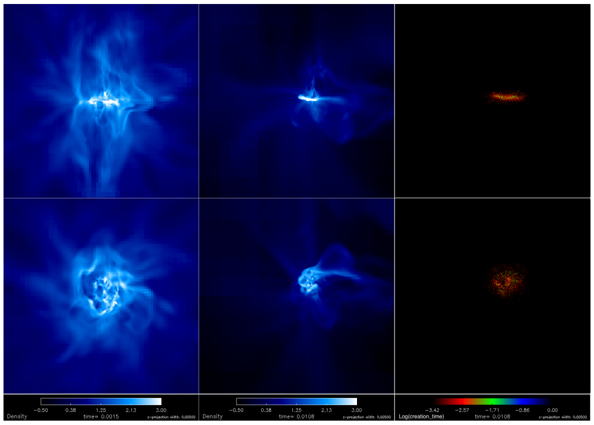

FIGURE 5. Gas surface density for galaxy formation simulation after 110 Myrs (left), 800 Myrs (middle) and stellar distribution after 800 Myrs (right) from edge-on view (top row) and face-on view (bottom row). The width shown is 20 kpc.

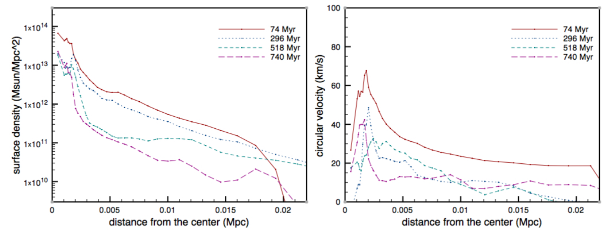

FIGURE 6. Galaxy profiles for the first 800 Myrs in galaxy formation simulation: gas surface density (left) and gas circular velocity (right).

Galaxy Formation

A high-resolution study of galaxy formation incorporating all components of the galaxy, star formation and supernova feedback can be feasible using our pipeline and AMR. The dark matter particle distribution generated in our pipeline can dynamically evolve in time.

We tested the collapse of a galactic sized halo of total mass = $2.01 \times 10^{10} M_{\odot}$ with 9.1% in gas. Here we apply the same velocity dispersion distribution to both dark matter and gas with spin parameter $\lambda \sim 0.06$. (See radial profiles in Figure 2.) We use 3-dimensional ZEUS hydrodynamics algorithm and assume equilibrium cooling, star formation, and supernova feedback.

As seen in Figure 5, displaying gas surface density and stellar distribution, a thin rotating gas rich disk has formed. Gas is continuously expelled from the disk into the halo via supernova feedback and falls back to the disk after a while. A stellar disk of $1.99 \times 10^{8} M_{\odot}$ also has formed for the first 800 Myrs. Figure 6 shows the evolution of gas surface density and gas circular velocity. During this calculation, we achieved the desired maximum resolution (3.8 pc) adequate to investigate star forming regions. We are now able to follow the galaxy evolution history further in time and look into other characteristics, such as the angular momentum distribution and the supernova-regulated star formation rate.

DISCUSSION

We established a conversion method that can properly interpolate particle data onto an Eulerian adaptive mesh. We tested the evolution of stable disk galaxy with *enzo* and found that our simulation code gives translationally invariant results. We also conducted a test that follows the formation of a gas rich low mass disk including star formation and feedback.

These early tests are encouraging and demonstrate that *enzo* is well suited for studying galaxy evolution as has been shown by Tasker and Bryan [3]. We are now poised to realize simulations of galaxy formation and mergers with AMR. We will analyze various types of galaxy simulations and explore more in parameter space.

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