Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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Masclet: a new multidimensional AMR cosmological code

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Abstract. A new cosmological multidimensional hydrodynamic and N-body code based on an Adaptive Mesh Refinement scheme is described and tested. The hydro part is based on modern *high-resolution shock-capturing* techniques, whereas the N-body approach is based on a Particle Mesh method. The code has been specifically designed for cosmological applications.

1. Introduction

Numerical simulations are crucial tools in theoretical cosmology. The gaseous component – baryons – is also a crucial ingredient in cosmological structures. Therefore, realistic simulations aimed to understand structure formation require hydrodynamical simulations able to describe the evolution of baryons. Two general approaches can be mentioned in order to broadly classify the numerical techniques used to evolve the gaseous component: Lagrangian (SPH) and Eulerian. Among the Eulerian schemes, techniques based on Riemann solvers have been specially successful (Ryu et al. 1993; Quilis, Ibáñez & Sáez 1994; Bryan, Norman, Stone, Cen & Ostriker 1995; Gheller, Pantano & Moscardini 1998 and others). Due to their Eulerian character these techniques are constrained by a poor spatial resolution. We present a new numerical code which combines the best of both, Lagrangian and Eulerian, approaches. The basic idea is to improve the numerical resolution by implementing a scheme known as Adaptive Mesh Refinement (AMR) described originally by Berger & Oliger (1984) and Berger & Colella (1989). In order to do this, we use an Eulerian approach as the ones described above but being able to gain resolution – spatial and temporal – by refining the original grid. The AMR schemes have shown as extremely powerful in many fields related with fluid dynamics. In cosmology, in the recent past, AMR implementations have been designed by Bryan & Norman (1997), Kravtsov, Klypin & Hoffman (2002) and Teyssier (2002).

2. Basic numerical procedure

Our basic hydro solver is based on a particular implementation of the HRSC (high resolution shock-capturing) methods. Its main ingredients are the following: i) It is written in *conservation form*, ii) *the reconstruction procedure* allows the method to gain resolution by reconstructing through interpolations the distribution of the quantities within the numerical cell, iii) a *Riemann solver* to compute the numerical fluxes across cell interfaces, and iv) a third order Runge-Kutta which preserves the TVD properties of the scheme. This implementation is able to handle shocks, discontinuities and strong gradients in the integrated quantities, and it has excellent conservation properties.

The dark matter is treated as a collisionless system of particles. In our code we solved these equations by using a Lax-Wendroff scheme which is second order. In order to recover the continuous density field for dark matter component, we use a triangular shaped cloud (TSC) scheme at each time step.

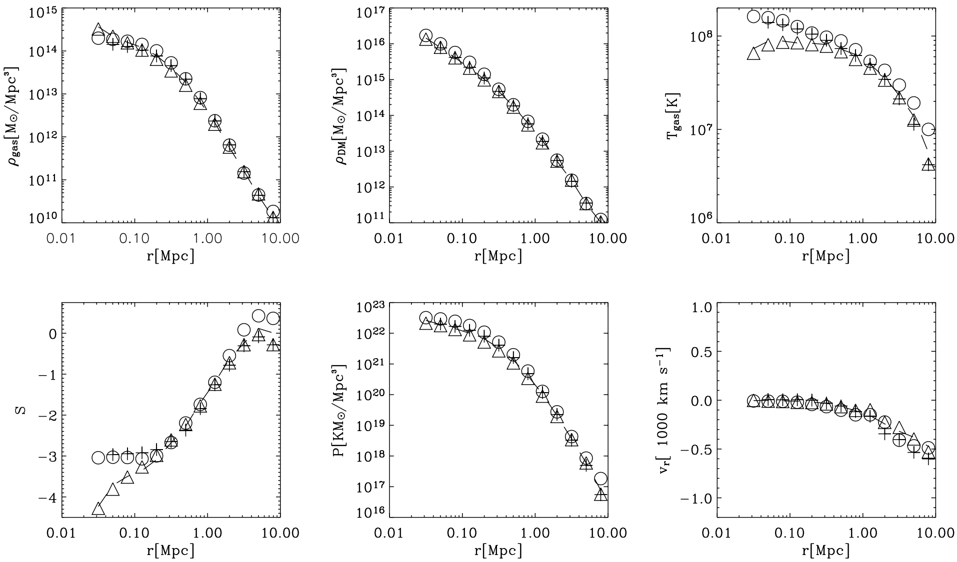

Figure 1. Radial profiles of the Santa Barbara cluster. Dashed lines stands for the average results of all the simulations displayed in the original paper by Frenk et al. (1999). Triangles and crosses show the results of simulations carried out by Jenkins (SPH) and Bryan (SAMR), respectively. Open circles display our results.

3. The Adaptive Mesh Refinement strategy

The fundamental idea behind the AMR strategy is to overcome the lack of resolution associated with the Eulerian description on a fix grid. The basic idea is simple. Regions in the original computational domain, are picked up according to some criteria. These new computational domains which we call *child grids* or *patches*, are remapped with a higher number of cells and therefore with better resolution. The value of the different quantities defined on the child grids are obtained by interpolating from the *parent grid*. Once the child grids are built, they can be evolved as an independent computational domain by using the same methods used for a fix grid. Although conceptually simple, there are severe technical complications related to the communication among the different patches and the boundary problems at different levels. Our implementation of the AMR schemes follows the one described in Berger & Colella (1989).

4. Cosmological simulation: the Santa Barbara cluster

The best test we can think of for a cosmological code in a realistic setting is to compare with the results presented in Frenk et al. (1999). In this reference, authors performed adiabatic simulations of a galaxy cluster with several codes. The initial conditions were generated in order to obtain a galaxy cluster $\sim 10^{15} M_{\odot}$ located at the center of a computational box of 64 Mpc side length. The coarse grid (l=0) has 64^3 cells. The first refinement (l=1) is fixed covering the central 32 Mpc. Higher refinements are carried out according to a local density criterion. In figure 1 radial profiles for gas density, dark matter density, temperature, entropy ($S = \ln[T\rho_{gas}^{-(\gamma-1)}]$), pressure, and gas radial velocity are shown, respectively. The profiles have been computed by averaging the quantities in spherical shells of 0.2 dex logarithmic width. The inner radius of the first shells is 10 kpc and the outer radius of the last one is 10 Mpc. Every panel displays the average results

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of all simulations (dashed line), results from Jenkins and Pearce simulation using Hydra SPH (triangles), and the simulation of Bryan and Norman using the SAMR Eulerian code (crosses). Open circles stand for the results of our simulation. Our results show very good agreement with the general trends shown by the average results of all simulations. There is a special good match with the profiles from Bryan' SAMR code.

Results using AMR simulations – with resolution comparable to those of SPH – showed substantial differences in quantities like temperature and entropy with respect to SPH results. This is an important conclusion – confirmed by our simulations – which points out crucial differences between the SPH and the Eulerian methods when describing the physics of structure formation.

The AMR like codes as the one presented in this paper will be crucial tools in the future of Numerical Cosmology. They combine successfully the best properties of previous traditional approaches: i.e. excellent spatial resolution as the SPH techniques, and an accurate description of the hydrodynamics of the problem (shock and discontinuities handling, void regions, accurate thermodynamics, turbulence, and some others) inherited from the Eulerian codes based on Riemann solvers.

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