ADAPTIVE SMOOTHED PARTICLE HYDRODYNAMICS AND THE SIMULATION OF LARGE-SCALE STRUCTURE FORMATION [1]

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Abstract

We have developed an improved version of Smoothed Particle Hydrodynamics (SPH) – Adaptive SPH (ASPH) – for cosmological gas dynamical simulations. We have applied our ASPH method to three models – Hot, Cold, and Mixed Hot-and-Cold Dark Matter (HDM, CDM, and MDM) – to simulate large-scale structure formation in 2D. We have analyzed these simulations to determine how the ratio of gas to total density in each differs from that of their universal mean values – the density bias – as a function of the degree of overdensity of the matter. All three models show a tendency for the gas density to be anti-biased (i.e. gas mass fraction less than its mean value) in regions of highest overdensity, while positively biased in regions of moderate overdensity. This anti-bias trend may cause models like these with $\Omega = 1$ and with Ω_{baryon} limited by standard Big Bang nucleosynthesis to be inconsistent with previous X-ray and optical determinations of the baryonic mass fraction in rich clusters. The CDM model also shows positive bias in the underdense regions.

1. Introduction

Most current theories explain galaxy and large-scale structure formation as the result of the growth of primordial density fluctuations by gravitational instability. The study of theoretical models by comparison of observational data with the results of large-scale N-body simulations of such fluctuation growth in a gas of collisionless particles has been very fruitful in constraining the models and in driving the accumulation of more and better data. Recently, however, it has been realized that gas dynamical effects must be simulated as well, to help reconcile the models with existing observations, to allow comparisons with a broader range of observables, such as X-ray emission from shock-heated gas or the Sunyaev-Zel'dovich effect, and to make the models fully self-consistent. As one example, gas dynamical effects can "bias"

the distributions of gas and galaxy mass in space relative to each other and to the total mass distribution, including dark matter. We must study the coupling of gravitational and gas dynamical effects in order to learn what the bias is. In what follows, we focus on this density bias in three models: HDM, MDM, and CDM.

2. Adaptive Smoothed Particle Hydrodynamics (ASPH)

We have developed a new version of the SPH method, called Adaptive SPH, with substantially improved numerical resolving power and treatment of shocks compared to the original method.[4,6,7,8] Standard SPH[5] suffers from two limitations which are particularly acute in simulations of cosmological structure formation by the gravitational growth of density fluctuations, as follows: (1) the smoothing is isotropic, while gravitational collapse leads to highly anisotropic volume changes, and (2) supersonic collapse leads to strong shocks, requiring that artificial viscosity be introduced, but this results in widespread, spurious viscous heating of gas far from the shocks. ASPH solves these problems by: (1) introducing an anisotropic smoothing tensor and kernel which adjust dynamically to follow anisotropic volume changes and vorticity, and (2) using this to track shocks by predicting the occurence of caustics and, thereby, to limit artificial viscous heating to those particles actually encountering a shock.

3. 2D, Cosmological Hydro Simulations Using ASPH/PM: HDM, CDM, and MDM Universes

We apply our ASPH method in 2D to simulate the growth of large-scale structure in a universe dominated by either HDM, CDM, or MDM, with initial density fluctuations given by Gaussian random noise based upon a Harrison-Zel'dovich primordial power spectrum ($n = 1$), with amplitude fixed by the COBE satellite detection of Cosmic Microwave Background anisotropy and power spectra appropriate to each model. The 2D power spectrum is the same as in 3D, but multiplied by $2k$, where k is the wavenumber — i.e. equal rms $\delta\rho/\rho$ in 2D and 3D for equal fluctuation scale length. We couple our ASPH method to a standard Particle Mesh (PM) gravity solver in 2D.[10] We take $h = 0.5$, $\Omega_{tot} = 1$, $\Omega_{DM} = 0.9375$, $\Omega_B = 0.0625$, $\Omega_{HDM} = \Omega_{CDM}$ for the MDM case, and two simulations per model, of different resolutions (except CDM, with only one), as follows. The total particle number $N_{particles} = 256 \times 256 = 65,536$ (low resolution; LR) or $512 \times 512 = 262,144$ (high resolution; HR), of which 1/16 are gas, so that $N_{gas} = 64 \times 64 = 4,096$ (LR) or $128 \times 128 = 16,384$ (HR) particles, with initial positions perturbed away from a uniform square lattice in a simulation box of side $L_{box} = 200\,\mathrm{Mpc}$ with 512×512 (LR) or 1024×1024 (HR) PM cells and periodic boundary conditions, at initial redshift $z_i = 24$. The initial density fluctuations are represented as the superposition of plane wave perturbations with random phases including all wavevectors which satisfy periodic boundary conditions with dimensionless wavenumber $k = L_{box}/\lambda$ in the range $1 \leq k \leq k_{\max}$, $k_{\max} = 32$ (LR) or 64 (HR). We use the same set of modes with the same randomly generated phases but different amplitudes for all three models. Radiative cooling is neglected.

4. Results: The Density Bias

We focus here on our simulation results at $z = 0$ for the density bias of the gas relative to the total matter distribution. Since these large-scale simulations neglect radiative cooling, we are, in effect, simulating the intergalactic medium and the dark matter, not the galaxies. We define the gas density bias parameter, as follows:

$$B \equiv \frac{\rho_{IGM}/\rho_{tot}}{\langle\rho_{IGM}\rangle/\langle\rho_{tot}\rangle} = \Omega_B^{-1}\frac{\rho_{IGM}}{\rho_{tot}}\,, \tag{1}$$

where $\langle\ \rangle$ refers to the universal mean value, and $\rho_{tot} = \rho_{IGM} + \rho_{DM}$. The values of ρ_{IGM} are given at the locations of gas particles directly by their ASPH values. The values of ρ_{DM} at these same locations are calculated by smoothing the density of the DM mass points by performing a "gather" calculation as in standard SPH, by centering an isotropic Gaussian interpolation kernel on each gas particle location, with a width, or smoothing length h, adjusted so as to keep the number of DM particles within a distance $3h$ of the gas particle equal to the mean number within a distance $6\Delta x$, where Δx is the initial mean DM particle spacing.

The positions of gas particles at $z = 0$ are shown in Figure 1. We also zoom in on the richest "cluster" in the HDM simulation to display DM particle positions. The bias parameter B for each gas particle is plotted against the total overdensity $\Delta_{tot} \equiv \rho_{tot}/\langle\rho_{tot}\rangle$ in Figure 2. The value of B averaged over all particles of the same total overdensity is plotted against overdensity in Figure 3.

Our results indicate that the gas density in all three models is "anti-biased" (i.e. $B < 1$) at the highest total overdensities ($\Delta_{tot} > 10^2$). At moderate overdensities ($1 < \Delta_{tot} \leq 10$), there is positive bias (i.e. $B > 1$), on average, although at every value of Δ_{tot} there are mass points with a broad range of B, encompassing both bias and anti-bias. For the HDM model, at least, the prevalence of nearly 1D, planar pancakes as a generic feature (seen edge-on as lines in Figure 1) may explain how moderate and intermediate total overdensities tend to be biased and anti-biased, respectively. Detailed, 1D calculations of pancakes[9] show that interpenetrating counterstreams of infalling and outflowing HDM occupy nearly the same volume as the planar layer of shocked gas, but with gas just inside the shocks anti-biased while gas nearer to the pancake central plane is biased. To the extent that MDM and CDM models also exhibit pancakes, this explanation applies in part for them as well. The highest overdensities ($\Delta_{tot} > 10^2$) occur primarily at the *intersections* of multiple pancakes, however, where clusters presumably form, and there the simple description for single pancakes does not apply.

The greatest distinction amongst the three models occurs in the underdense regions ($0 < \Delta_{tot} < 1$). For the HDM model, the underdense regions are mostly unbiased ($B \cong 1$), as expected since these are the regions outside of pancakes and caustics and their intersections. In such regions, the gas is cold and adiabatic and moves as if nearly pressure-free, its acceleration dominated by the same gravitational force as felt by the HDM. For the CDM model, however, the underdense regions contain bias, antibias, and no bias, with the average trend toward *positive* bias. This may result from the fact that fluctuations on small scales, including those inside large-scale voids, become nonlinear, driving the biasing pattern inside the voids toward that which reflects the presence of small-scale pancakes superimposed on the large-scale underdensity. For the MDM model, the results are intermediate between those for HDM and CDM, with the underdense regions almost unbiased.

Our bias results for the CDM model agree qualitatively with those of recent simulations using the Eulerian, TVD method in 3D, of somewhat smaller spacial resolving power than ours in the densest regions.[3] We are encouraged to believe that bias results for the same model in 2D versus 3D should be qualitatively similar, therefore. Recent tree-code SPH simulations of the CDM model in 3D, which evolved the gas and dark matter dynamics in a single galaxy cluster, find bias within the cluster core which is positive and increasing toward the cluster center.[1] This differs from our antibias result and that of [3] for the highest total overdensities.

X-ray and optical observations of rich clusters indicate that $\rho_{IGM}/\rho_{tot} \sim 10h^{-1.5}\%$.[2] If $B = 1$, such empirical estimates imply that if $\Omega_B \leq \Omega_{B,max}^{BB} = 0.015h^{-2}$ as required by standard Big Bang nucleosynthesis (BBN) constraints, then the universe is open ($\Omega_{tot} < 1$), or else $\Omega_B > \Omega_{B,max}^{BB}$.[11] *Our bias results for the highest overdensity regions suggest that $B < 1$ in rich clusters for all three models, HDM, MDM, and CMD*, which would strengthen the inequalities in the conclusion above. This is consistent with the conclusion of [3] for CDM (but not with [1]). Our results suggest, in fact, that this antibias is generic to *all* such models involving adiabatic, Gaussian-random primordial density fluctuations in a DM-

dominated universe, indicating that either: (1) the models are incorrect, (2) the universe is open, (3) the baryonic content of the universe substantially exceeds the current BBN limit, or (4) the assumptions made in estimating the total mass and gas fraction in rich clusters from X-ray and optical data are flawed.

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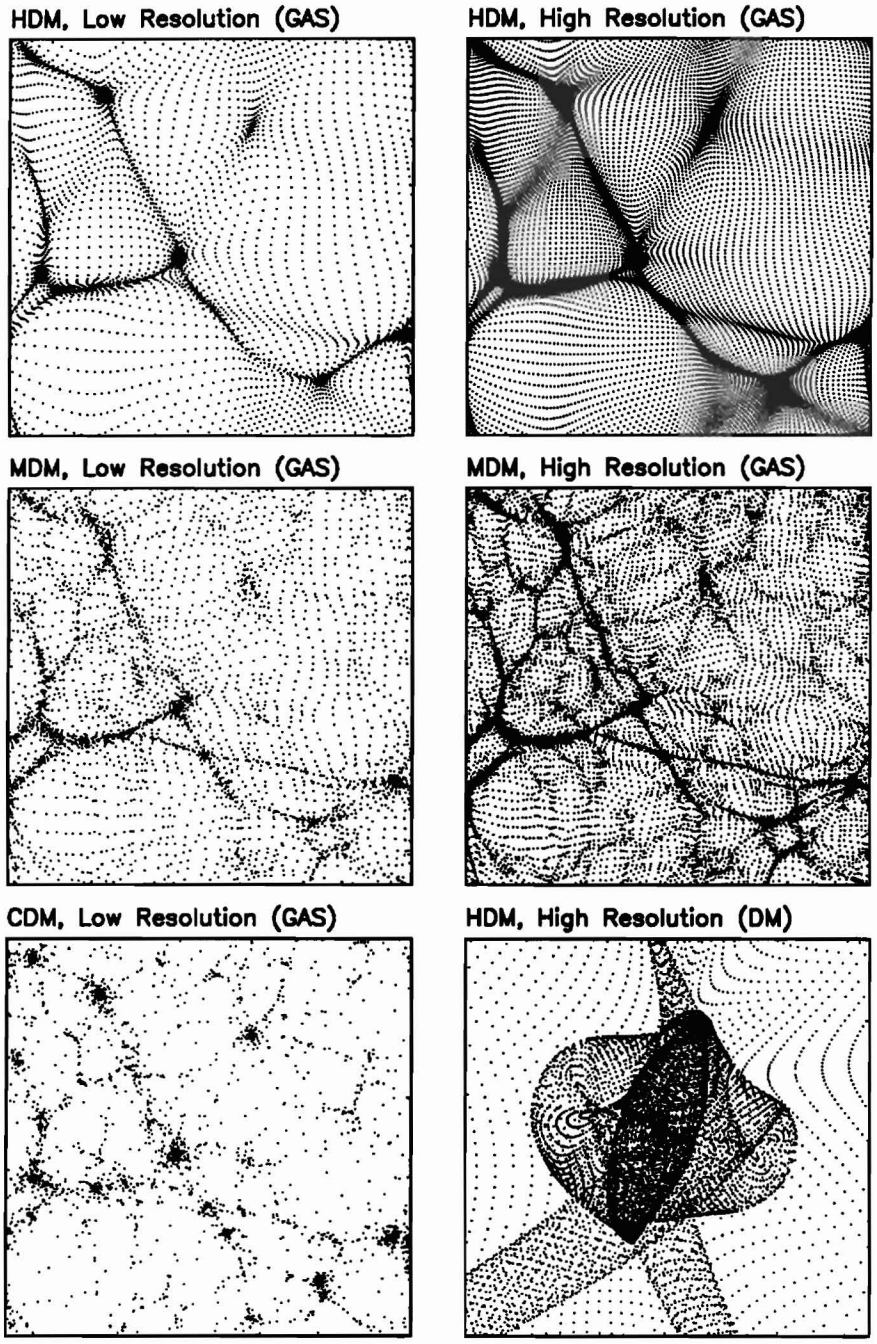

Fig. 1. Gas particle positions at $z = 0$, except bottom right panel is a blow-up of DM particles in the subregion $0.39 \leq x \leq 0.45$, $0.42 \leq y \leq 0.48$ (in units $L_{box} = 1$) for HDM model (HR).

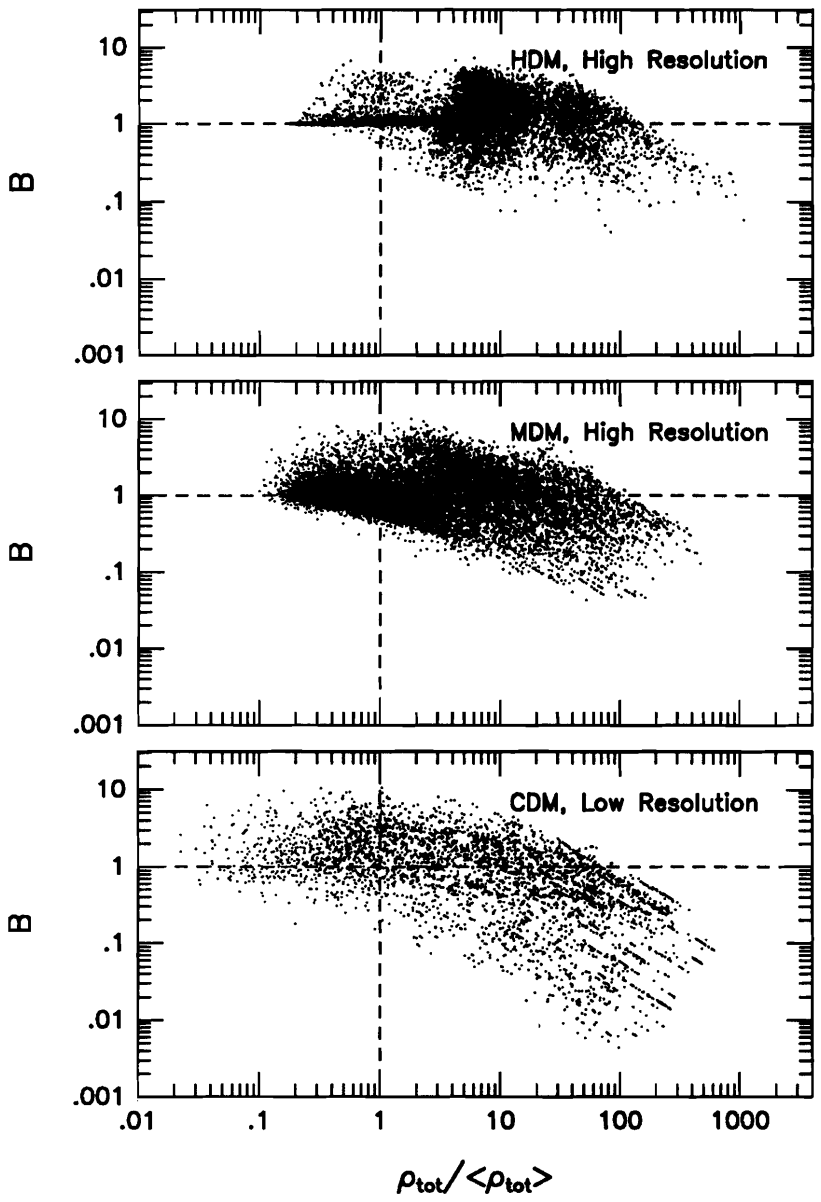

Fig. 2. Gas density bias B versus total overdensity Δ_{tot} for all gas particles.

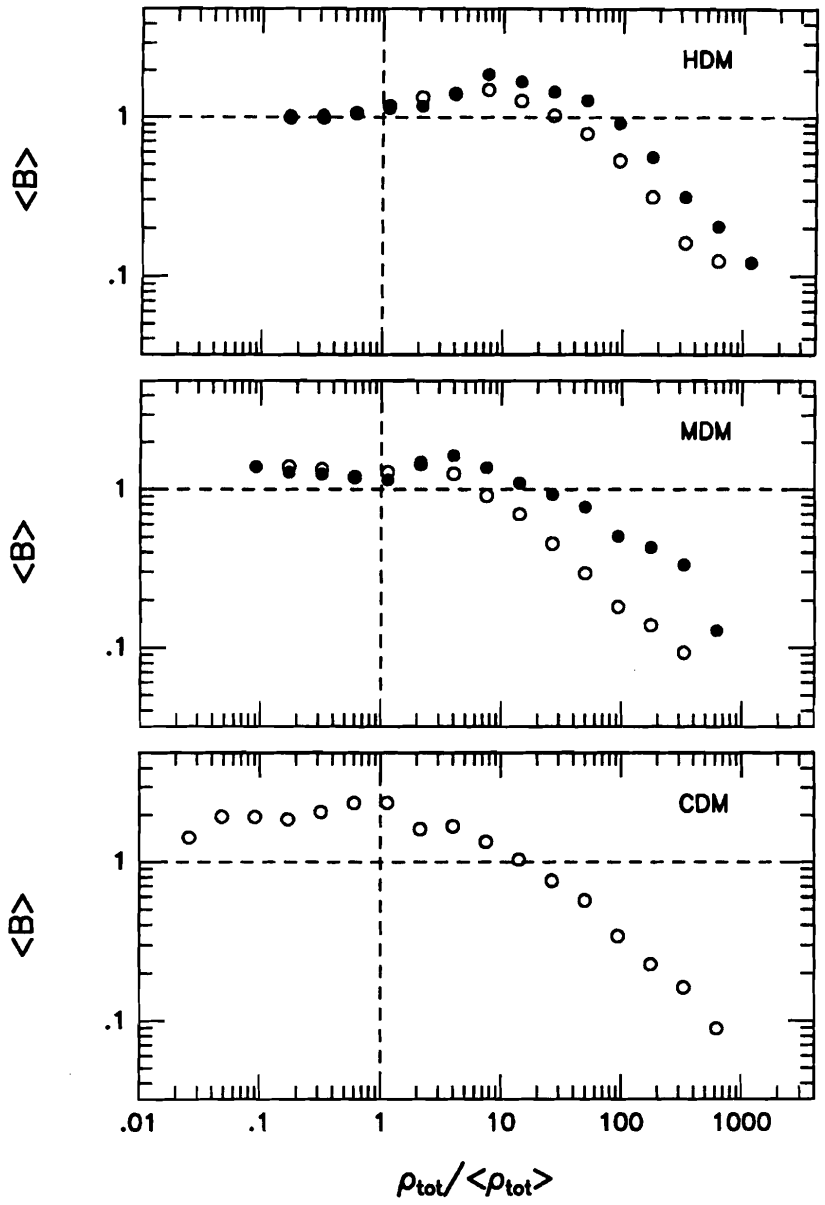

Fig. 3. Average density bias $\langle B \rangle$ (average of B-values for gas particles with the same Δ_{tot}) versus total overdensity (Open Circles = LR, Filled Circles = HR).