The Hydrodynamics of Galaxy Formation on Kiloparsec Scales

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Two dimensional numerical simulations of Zeldovich pancake fragmentation in a dark matter dominated universe were carried out to study the hydrodynamical and gravitational effects on the formation of structures such as protogalaxies. Preliminary results were given in Yuan, Centrella and Norman (1991). Here we report a more exhaustive study to determine the sensitivity of protogalaxies to input parameters. The numerical code we used for the simulations combines the hydrodynamical code ZEUS-2D (Stone and Norman, 1992) which was modified to include the expansion of the universe and radiative cooling of the gas with a particle-mesh code which follows the motion of dark matter particles. The resulting hybrid code is able to handle highly nonuniform grids which we utilized to obtain a high resolution ($\ll$ 1 kpc) in the dense region of the pancake.

In a universe with 10% of its mass composed of hydrogen and helium of cosmic abundances and 90% of its mass in the form of dark matter, we set up a sinusoidal density perturbation of $\lambda = 10$ Mpc in the x1 direction and small density fluctuations in the x2 direction at z=50. The perturbation amplitude in the x1 direction is larger than the amplitudes of the fluctuations in the x2 direction so that the mass collapses in the x1 direction and a pancake forms at z=5.

We ran six runs of different resolutions and different amplitudes and types of initial density fluctuation in the x2 direction, and we find the following main results: (1) The gas density is about 10 times the dark matter density in the central region right after the pancake collapse at $z \approx 5$, but the gas and dark matter densities are about the same in the fragmented dense clump at $z \approx 0$. (2) The gas overdensity is larger than the dark matter overdensity only in the shocked region, so the gas is biased over the dark matter only on the scale of equal or smaller than the size the shocked region. (3) The coupling of the cooling and gravitational instabilities causes the fragmentation of the gas pancake at the early time, the dark matter follows the gas fragmentation because the mass of the gas dominates the central region. The gravity dominates at later times causing the *merging of the clumps. The scale of the initial fragmentation for all* the runs fall in the range given by the critical wavelength of the cold pancake λ_{max} which is due to the gravitational instability and the distance sound wave travels in the pancake fragmentation time λ_f in the strong cooling region. (4) The time for the completion of the fragmentation and the amount of the cooled gas depend sensitively on the amplitude but not the type of the initial density power spectra.

References

Stone, J. M. and Norman, M. L. 1992. Ap. J. Suppl., 80, 000.
Yuan, W., Centrella, J. and Norman, M. L. 1991. Ap. J. Lett., 376, L29.

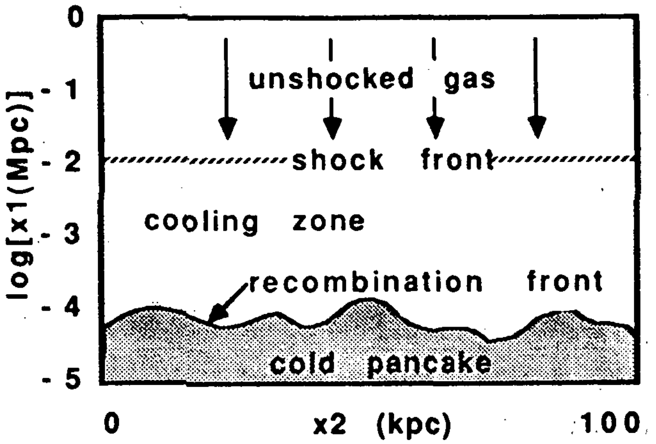

Fig. 1 Schematic of the pancake prior to fragmentation showing cold layer, cooling zone, and accretion shock.

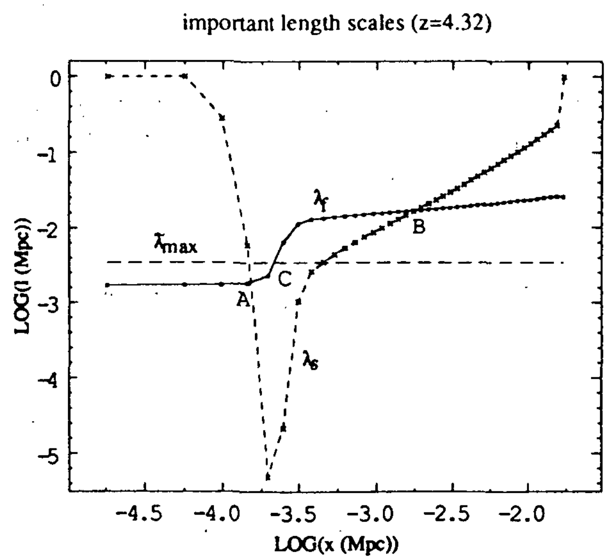

Fig. 2. The run of various length scales of interest as a function of x1: λ_f=fragmentation length in the cooling layer; λ_s=cooling length in the cooling layer; λ_{max}=wavelength of maximum perturbation growth due to gravitational instability in the cold pancake.