The Shape of the First Collapsed Objects

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In the early seventies, there was a conjecture (based on the Zel'dovich approximate solution) that the first collapse of a self-gravitating dustlike medium (appropriate approximation for nonbaryonic dark matter) results in the formation of a "pancake" object that is a thin surface. Recent works cast doubt on the Zel'dovich conjecture, suggesting that the first collapse might be pointlike or filamentlike rather than pancakelike. Our N-body simulations show first pancake collapse. We can reject with 97% confidence the Bayesian prior that the other kinds of collapse are more or equally probable.

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In the evolution of gravitational clustering in the expanding universe, it has gradually been recognized that the first collapse is usually anisotropic. This has important consequences for the formation of all objects by gravity, including gas clouds, stars, galaxies, and superclusters. It may be visible today only in superclusters, which are just collapsing now.

The known exact solution obtained for the spherically symmetric, nonrotating, pressure-free case (e.g., [1]) predicts two types of collapse from rest. If the initial density is monotonically decreasing then the first collapse is pointlike toward the origin. However, if the initial density is nonmonotonic then the first collapse is shell-like. Considering a uniform, nonrotating, pressure-free spheroid, Lin, Mestel, and Shu [2] found that it collapses toward either a disk or a spindle depending on whether it is oblate or prolate at the initial time.

Zel'dovich [3] proposed an approximation for a generic initial perturbation which predicts that the first collapsed objects have a pancakelike shape. Gurevich and Zybin [4] revisited the issue and concluded that the nondissipative gravitational collapse of a generic perturbation results in the formation of a stationary dynamical structure with a pointlike singularity at its core $\rho \propto r^{-24/13}$. Recently, Bertschinger [5] and Bertschinger and Jain [6] proposed a purely local gravitational instability solution based on general relativity which implied that prolate collapse to filaments comes first. Kofman and Pogosyan [7] and Bertschinger and Hamilton [8] showed that this solution had neglected certain terms of the same order as others included in it which may be justified in ultrarelativistic cases, but not in the Newtonian limit. The difference between the collapse in dustlike matter in Newtonian and ultrarelativistic cases was stressed by Zel'dovich and Novikov [9]; see also Matarrese, Pantano, and Saez [10]. This provides a renewed justification for the neo-Newtonian approach generally used for studying low-amplitude cosmological perturbations inside the horizon.

However, as noted by Bertschinger and Hamilton [8] it does not resolve the question of whether pancakes or filaments form first. Although the Zel'dovich [3] approximation (ZA) predicts pancakes, this approximation is not exact in three dimensions. It is known, for example, that collapse in nonlinear gravitational clustering simulations proceeds faster than ZA predicts. It is therefore important to determine whether the quasi-two-dimensional structures predicted by ZA really occur.

One should distinguish between the two statements we might make: (1) The first collapse is always pancakelike. (2) The first collapse is usually pancakelike but could be filamentlike in some cases. In this paper, we present evidence for the second (weaker) statement based on numerical simulations. The initial conditions we set up are of a generic type, which means that a smooth small arbitrary perturbation does not change qualitatively the type of initial condition in any sense.

We examined an ensemble of five N-body simulations on a 128^3 particle-mesh gravitational clustering code with periodic boundary conditions and random Gaussian initial perturbations. At very low amplitudes, the ZA we used and the Eulerian linear perturbation theory of the growing mode are essentially indistinguishable. We also stress that using shot noise with a dying mode component [11] or a logarithmic distribution of modes [12] has not made noticeable differences. Further details on simulation methods can be found in [13]. The initial conditions corresponding to the growing mode were constructed in four realizations with initial fluctuations of wave number 1 through $\sqrt{3}$ in units of the fundamental mode of the box. Thus, the minimum wavelength present in initial conditions is 74 mesh units. A smaller upper bound on wave number would cause alignment with coordinate axes. An additional simulation with initial wave number range 1 through 3 was performed as a check (simulation 1 in Table I). We found nothing special in this case. All simulations were started with rms density fluctuation $\sigma \sim 0.03-0.04$ in order to allow time (an expansion factor of ~ 17) for transients to die out and the full growing mode including nonlinear effects to establish itself. Two simulations (2 and 4), as a check, started with half the initial amplitude and ran for twice the expansion factor.

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TABLE I. Information on the objects in the five simulations.

Simulation	Thickness (mesh units)	Width (mesh units)	Length (mesh units)
1	0.1	3.5	8
2	0.5	5	16
3	0.6	32	37
4	0.8	7.5	48
5	0.8	17	37

We follow Zel'dovich and define the first collapsed objects as the regions where the first shell crossing occurs. Formally, this definition does not assume that the particles that have undergone shell crossing form a gravitationally bound object, though it is likely at the later stages. We stopped the simulations after the *first* shell crossings. Our time steps are very strictly constrained so that the *fastest* particle could travel 0.4 mesh unit in a single time step. All particles were tagged which had local shell crossing (as determined by whether the local volume element had gone negative). Thousands of particles typically shell crossed for the first time in a single step. It is worth stressing that the particles in question show the regions between caustics and do not represent well the density distribution. They were all highly anisotropic and resembled surfaces rather than lines. One was ribbonlike but still essentially very flat. We will illustrate this with multiple pictures from one simulation; other simulations look similar.

Figure 1 shows three orientations of a typical surface (5 in Table I) viewed along the three eigenvectors of the initial deformation tensor toward the middle of the surface. Figures 1(a) and 1(b) suggest finite thickness ($\sim 1-6$) but this is because the surface is curved (bowl-like). In Fig. 2 we show two cross sections of this surface to indicate its thinness. Figure 1(c) shows the pancake region face on. The reader should not be misled by the little rows of particles which are the usual result of the standard "quiet start" with particles on a slightly deformed cubic lattice.

Figure 2(a) shows a cross section perpendicular to the z axis, and Fig. 2(b) shows a cross section perpendicular to the y axis. Both cross sections are very thin. They suggest that the real thickness of the region (asymptotically equal to the distance between caustics) is of the order of 1 mesh unit, while the diameters [size in y and z directions as seen in Fig. 1(a)] are about 37 and 17 mesh units. From this we conclude that the shape of the region is pancakelike with approximate ratios 1:17:37, rather than filamentlike. We looked closely at many more additional thin slices and concluded that the actual maximum thickness was always <0.8, in agreement with the time step constraint. The other dimensions were much larger, as can easily be seen.

Catastrophe theory suggests that the diameters of a pancake grow as $\sim(t - t_c)^{1/2}$ and its thickness (definedas the distance between caustics) as $\sim(t - t_c)^{3/2}$; therefore, the ratio of the thickness to the diameter is proportional to $\sim(t - t_c)$ at small $t - t_c$ (here t_c is the time of the formation of the first singularity) [14]. Also, the diameters are not equal in a generic case. In our simulation we plot Figs. 1 and 2 after a small but finite time from the first local crossing (the first "singularity" to the accuracy of the simulation) and therefore expect the small but finite thickness of the pancake.

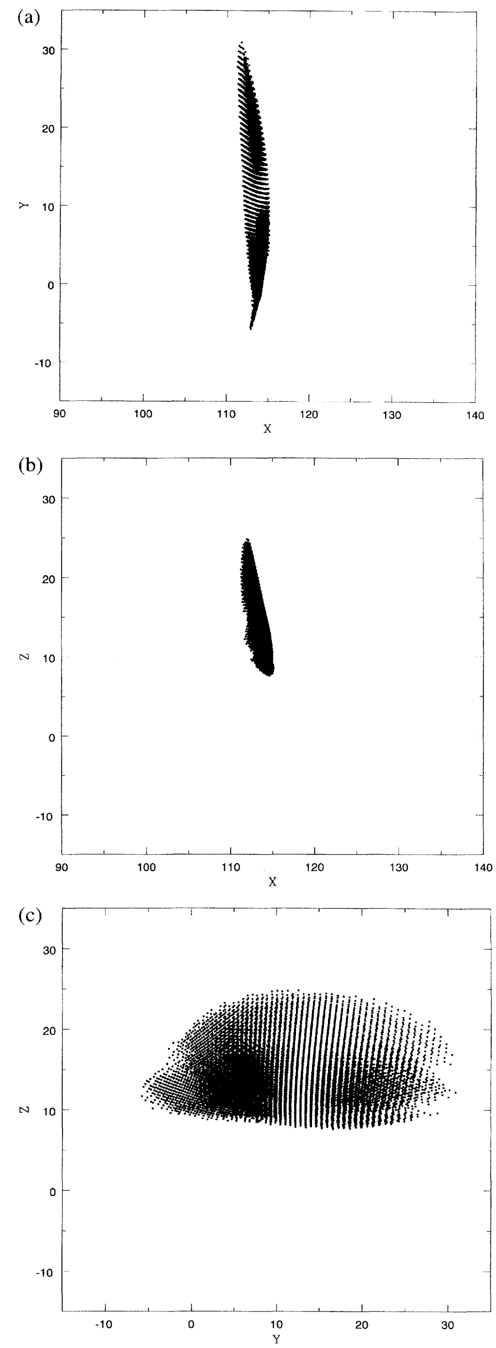

FIG. 1. Three projections of the collapsed points (past the singular stage) orthogonal to three principal axes of the initial deformation tensor.

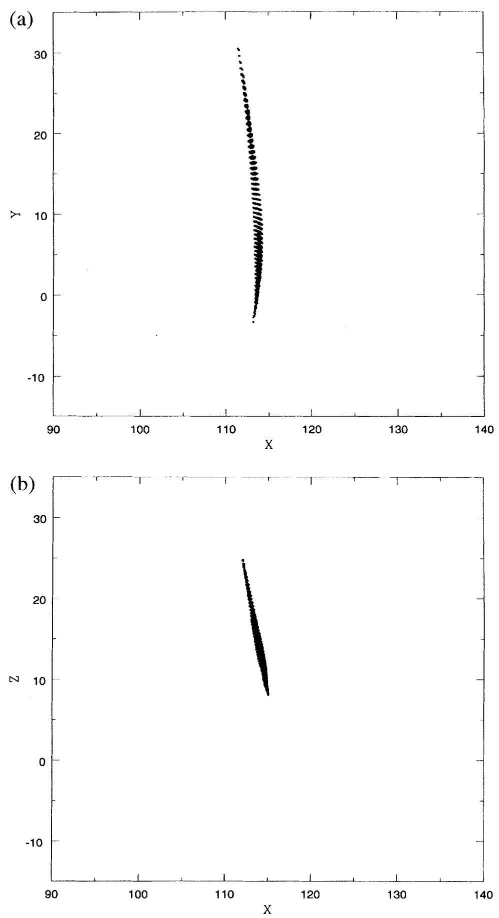

FIG. 2. Two thin slices (2 mesh units) approximately through the center of the pancake orthogonal to (a) z axis: $15 \leq z \leq 17$; (b) y axis: $10 \leq y \leq 12$.

In contrast to Fig. 2, Fig. 3 shows *all* particles in thin slices orthogonal to the principal axes of the initial deformation tensor at the largest eigenvalue. One can easily see the difference between the density distributions (Fig. 3) and the shape of the collapsed region (Fig. 2). All the statements about the shapes of the first collapsed regions derived from ZA refer to the shapes of collapsed regions (Figs. 1 and 2) which may be similar to but not the same as the density distributions (Fig. 3), especially in cases where the resolution is not sufficiently good.

Our simulations suggest that the first stage of collapse of a generic gravitational system is usually to a thin sheet as suggested by ZA. (Obviously we cannot say anything about the evolution of shapes between the last "uncollapsed" and the first "collapsed" stages, but we stress that our time steps are shorter relative to the characteristic formation time of the structures under consideration than any simulations to date.) Superclusters, now experiencing their first collapse, should include sheetlike structures. Filaments (another type of generic structure [14]) may be easier to see due to their higher density contrast and

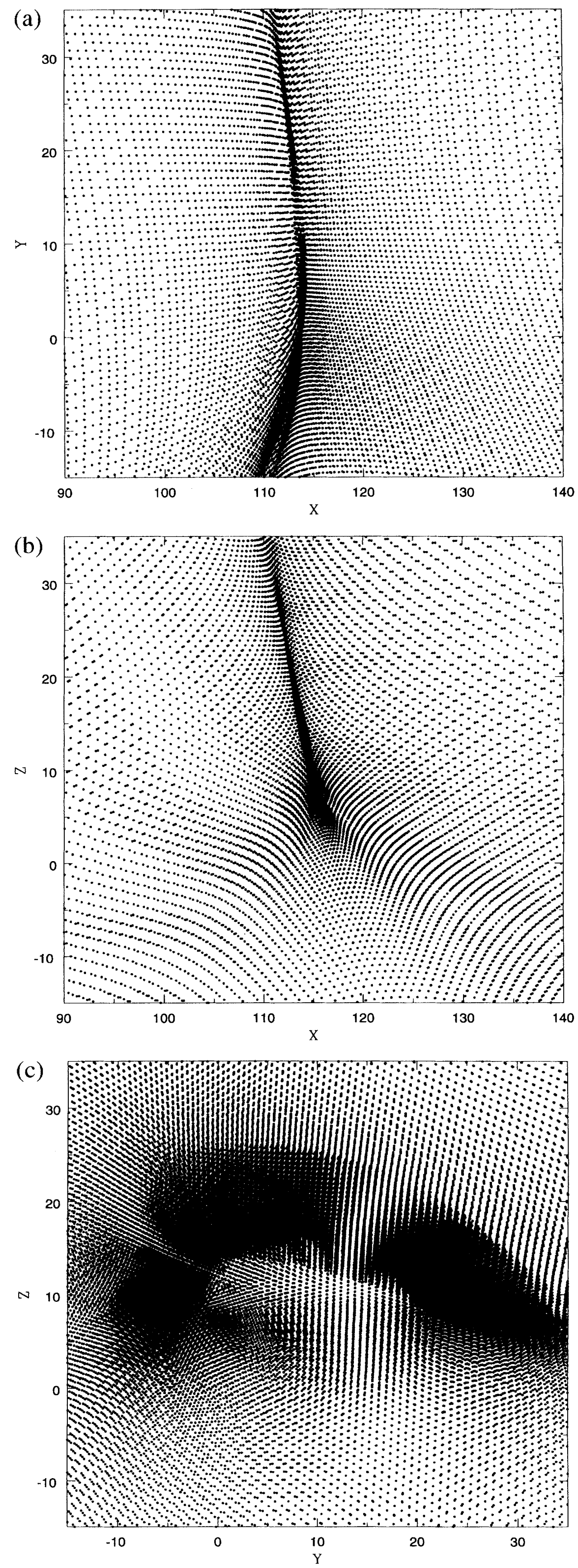

FIG. 3. The mass distribution in thin slices orthogonal to three principal axes: (a) z axis: $15 \leq z \leq 17$; (b) y axis: $10 \leq y \leq 12$; and (c) x axis: $112 \leq x \leq 114$.

possible gas cooling effects [15], but they should be second generation objects formed by flows inside sheets.

In the presence of small-scale perturbations in the initial spectrum (which is the most likely case in cosmology) these structures are not as smooth as the pancakes discussed in this paper. As mentioned before, there is a theoretical question concerning the type of the first collapse in a dustlike medium. Our results should not be interpreted as totally excluding first collapse to filamentlike structures. It is well known from second order perturbation theory that the rate of collapse along one principal axis depends on the rates of collapse along the other principal axes, which may change the type of collapse in some cases. On the other hand, the general solution with the maximal number (eight) of physically arbitrary functions of three variables in a dustlike medium suggests gravitational collapse is pancakelike [16,17]. Katz *et al.* [18] state that "the first objects form in filaments from almost two-dimensional collapses in agreement with the approximate analytic theory of Bertschinger and Jain," which appears to contradict our results. We did not investigate all options for Gaussian initial conditions. Our initial conditions were particular random realizations of Gaussian initial conditions, with formally k^{-1} power spectrum of density fluctuations in the range of $k_f \leq k \leq \sqrt{3}k_f$ (or $3k_f$ in one case). But we stress that they were mathematically generic.

We have presented detailed results of the simulation of one pancake. However, we studied five realizations of the initial conditions. All showed similar pancakelike structures (sometimes elongated); see Table I where we list the dimensions for the first collapsed objects in our first five realizations. We find neither a single filamentlike collapse in our simulations (filaments would be expected on the basis of the hypothesis of Bertschinger and collaborators [5,6]) nor pointlike collapse [4]. If we use a prior hypothesis that the ZA and HA [5,6] descriptions of first collapse are equally probable, we can reject this on the basis of our experiments with 97% confidence. Alternatively, we may assume pancakes and other structures form with some probabilities and try to estimate that probability. A sequence of five pancakes would be more probable than the sum of all other sequences' probabilities if the *a priori* probability of a pancake were 87%. Our objects are all smaller (much smaller in thickness) than the minimum wavelength in the initial perturbations, and thus represent the first generation of collapsed objects. Objects formed on any scale in heirarchical clustering N-body simulations, such as those of Katz *et al.* [18], are larger than the Nyquist wavelength of the initial spectrum, and therefore a later generation and irrelevant to the question studied here. However, such simulations might be expected to show one-dimensional collapse of the objects where the things are just becoming mildly nonlinear. Recently, observational evidence has appeared to suggest there are sheetlike neutral hydrogen clouds at moderate redshift [19]. Quantitative evidence for pancake-like morphology for such objects (as well as filaments existing at later stages of dynamical evolution) has been found in hierarchical clustering simulations [20]. However, this technique does not measure the distance between caustics, discussed in this paper, and does not take into account the thin bowlike shape of the first pancakes. The formation of the filamentlike structures, as well as compact clumps of higher density contrast than in pancakes, in the frame of ZA was emphasized by Arnold, Shandarin, and Zel'dovich [14]. This may explain why pancakes are not easily seen in low *mass* resolution N-body simulations.

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