SUPERCLUSTERS AS NONDISSIPATIVE PANCAKES

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ABSTRACT: The formation of aspherical superclusters (SC's) is studied by 3-D N-body simulations that are confronted with the Local SC (LSC), and a simple model is developed. A nondissipative scenario, in which galaxies are formed from perturbations on smaller scales prior to the collapse of SC's, is found to be successful. It explains the disk-halo structure of SC's, their flattening and their low dispersions, which are nontransient because of the expansion along the long axes. The LSC has collapsed at $z \lesssim 0.5$. The large-scale velocity isotropy and the local 1-D infall indicate $\Omega<1$. The correlation of galaxies on a few Mpc scales grows nonselfsimilarly due to recent pancaking rather than gradual clustering. This may be tested by the lack of clustering among objects at $z>1$.

Observations of SC's have reached a stage where quantitative comparisons with formation scenarios may be attempted. The "western" picture suggests that structure that arises from small-scale peturbations (e.g. isothermal) evolves hierarchically from small to large, and that the clustering of galaxies is gradual and dissipationless. It is hard to see how do large aspherical SC's and holes form here. According to the "eastern" picture the structure evolves from large to small via fragmentation of SC's. Large-scale adiabatic perturbations that survive damping generate all structure, and the formation of asymmetric SC's and holes is an outcome of the large-scale velocity anisotropy (Zeldovich 1970). If the collapsing material is gaseous, dissipation produces thin pancakes (or cigars) that fragment to galaxies. This picture may allow for massive (∿30eV) neutrinos which collapse nondissipatively and let the baryons collapse dissipatively in them. It is hard to explain here the presence of many galaxies (∿40%) far from the LSC plane in which they are assumed to be born. Alternatively, consider a combination of the two scenarios, i.e., a nondissipative pancake scenario: if both small-scale and large-scale perturbations were present at recombination, galaxies or other substructures may already exist during the collapse of SC's so that they cross the SC planes (or lines) nondissipatively to form thicker pancakes, while galaxies that have not crossed the plane yet populate the SC halos. I summarize here a study of nondissipative pancakes and a confrontation with observations such as the flattening of SC's, the velocities in them and the clustering.

G. O. Abell and G. Chincarini (eds.), Early Evolution of the Universe and Its Present Structure, 249–254.

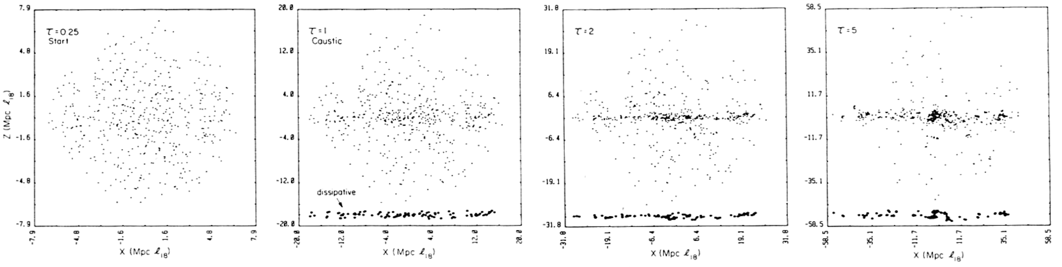

Fig. 1: Edge-on comoving snapshots.

The linear growth of nonspherical, adiabatic perturbations in a Friedman Universe is approximated by Zeldovich (1970): the position and the velocity at a time t of a particle at a comoving position $\vec{q}$ are

$$\vec{r} = a(t)[\vec{q} - b(t)\,\vec{\Psi}(\vec{q})]\ , \qquad \dot{\vec{r}} = (\dot{a}/a)\,\vec{r} - a\dot{b}\,\vec{\Psi}(\vec{q}) \qquad (1)$$

where a(t) is the expansion factor, b(t) is the perturbation growth rate ($b \propto a \propto t^{2/3}$ when $\Omega=1$), and $\vec{\Psi}(\vec{q})$ is the spatial perturbation. It is likely that the perturbation is stronger in 1-D and is coherent over the critical damping length, ℓ. The velocity perturbation then leads to the formation of a thin, dense pancake at a finite time (a=b=t=1, say) due to focusing of trajectories while the pancake is still expanding along the orthogonal axes. Then the approximation breaks down. 500 particles were distributed at random in a sphere of a comoving radius ℓ, and with Hubble velocities. A 1-D adiabatic perturbation, with $\Psi_z=(\ell/\pi)\sin(\pi q_z/\ell)$ and $\Psi_x=\Psi_y<<\Psi_z$, was assumed to evolve according to eq. (1) until a=0.4. This was the start of a simulation based on the Aarseth code (1972), which integrates the softened, Newtonian equations of motion. A sequence of projections of one case is shown in fig. 1 in Hubble expanding coordinates. The flattening indeed becomes apparent at focussing (when ∿20% of the particles have crossed the plane) but it is clearly not a transient feature! The relative flattening becomes even more pronounced later, while the absolute thickness grows. The sizes of rich clusters (that depend on the two-body interactions and on the small-scale perturbations) eventually reach the pancake thickness and affect the global flattenting (here at t∿5).

The nondissipative flattening and cooling in Z is primarily due to the expansion in XY. When a particle oscilates about the plane with a period T that is smaller than the expansion time, there is an adiabatic invariant $\int_0^T \dot{Z}^2 dt \cong v^2 T \cong hv$, where h(t) and v(t) are some mean values of Z and $\dot{Z}$ at t. Out of an infinite, uniform disk, the gravitational field, $\mu(Z)$, is proportional to the surface density interior to $|Z|$. If μ is some mean value of $\mu(Z)$, $v \cong \mu T$, and therefore the thickness is expected to vary like $h \propto \mu^{-1/3}$. If r(t) is the radius of the pancake, $\mu \propto r^{-2}$, so that $h \propto v^{-1} \propto r^{2/3}$, i.e., when the pancake expands, its normal velocities are suppressed while it thickens, but it becomes relatively flatter as $h/r \propto r^{-1/3}$ ($\propto a^{-1/3}$ if the expansion in the plane is unperturbed). One may consider two limiting cases for the matter that governs the oscillation: in one, let it all be in a thin disk at Z=0, and in the other let it be spread uniformly in Z. A simple model for the Z motions can be constructed where each particle

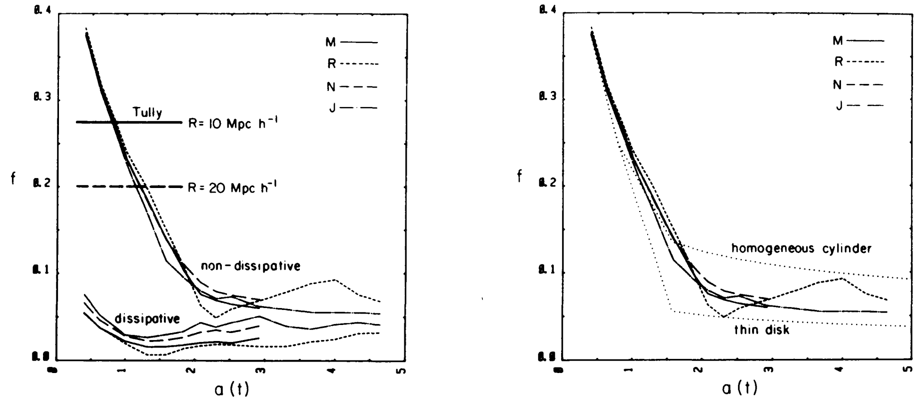

Fig. 2: Flattening in the simulations and in the analytic model (dotted).

obeys the Zeldovich approximation until it crosses the plane, and thereafter it oscilates about it subject to the adiabatic invariant in either of the above limits. The obtained limits on the flattening agree with the simulations (fig. 2b) and the model can serve as an approximation for other cases such as an open Universe (Dekel 1983a; Dekel and Aarseth 1983). The global spatial structure is found to be insensitive to Ωo.

The simulations illustrate the dissipative model when selecting pancake galaxies right after their formation (t=1), and following them evolve as N-bodies embedded in an N-body halo (neutrinos?). In fig. 1, the "dissipative" component is displaced from the center to the bottom ("*"). It remains flatter than the nondissipative pancake although it is more affected by local clustering. Note that the dissipation associated with galaxy formation is not determined by the theory and this example should be interpreted with caution.

The flattening of the LSC is estimated by Tully (1981) who counts galaxies in parallel layers of constant ΔZ, and by Yahil et al (1980) who count in bins of constant $\Delta\sin\beta$ (β is the Virgocentric latitude), both using redshifts as distance indicators. The N-body system is analyzed in both ways (Dekel 1983a). In order to compare to Tully's results we define a flattening by $f=Z(68\%)/R$, where $Z(68\%)$ is the normal width of the number count histogram. The evolution of f(a) in four of the simulations is shown in fig. 2a. The flattening of the nondissipative system resembles that of Tully near $a\sim1$ and becomes much flatter later. Neither local clustering (M vs. J) nor a slight decceleration in the plane (N), nor a rich cluster at the SC center (not shown) affect the flattening significantly. When correcting the numerical flattening according to Tully's estimate that the local thickness is roughly 2/3 of the global one, the qualitative conclusion remains the same with a preferred age $a\sim1.5$. The apparent flattening of external SC's agrees with the conclusion that a nondissipative scenario can account for the flattening of SC's in general.

The theory predicts three regions in the velocity field normal to th pancake plane, V_z: a) at large $|Z|$, the deviation from a Virgocentric

https://doi.org/10.1017/S0074180900039085 Published online by Cambridge University Press

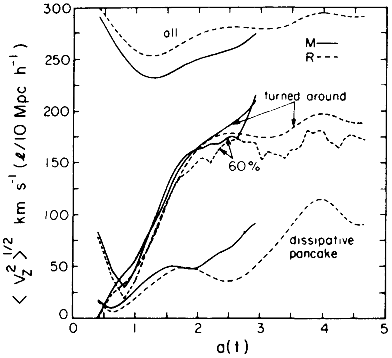

Fig. 3: Velocity dispersion

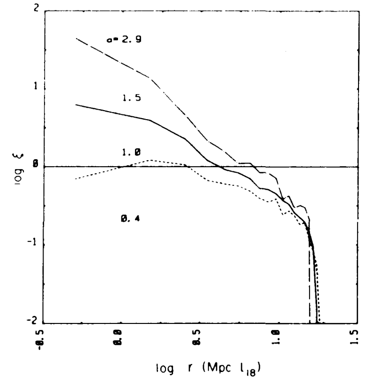

Fig. 4: Correlation function

flow is small, especially in a young SC or in an open Universe, b) interior to some $|Z|_t$, which is strongly dependent on Ωo, galaxies are falling back in, and c) in the pancake galaxies may oscilate about the plane and V_z may be virialized. Regions b and c may, in principle, provide important information about the formation of the pancake, its age and on Ωo. The simulations (fig. 3 with Ω=1) predict for the velocity dispersion in the 60% flat component $\sigma_z \sim 100$ km s^{-1} at a$\sim$1, and $\sigma_z \sim 175$ km s^{-1} at a $\geq$ 2, in agreement with the spatial flattening. Unfortunately, the observed velocities of pancake galaxies (low $|Z|$) are dominated by their fast expansion parallel to the XY plane, which makes the measure of V_z possible only for a few nearby galaxies at high $|SGB|$, and out of the Local Group. We find (Dekel 1983b), in a sample of $\sim$400 galaxies with redshift independent measured distances, no evidence for anisotropies in the Virgocentric flow at $|Z|$ larger than a few Mpc, and a weak evidence for an infall and excess V_z of both signs closer to the plane. This indicates an early stage in the 1-D collapse, in agreement with the conclusion from the flattening, and possibly an open Universe where the LSC halo is "frozen-in" the Hubble expansion.

The two-point correlation function within the simulated SC, on scales of a few Mpc, grows in a non-self-similar way due to the large-scale collapse to a pancake rather than due to local clustering (fig. 4). From simple geometry, a 1-D (2-D) collapse of a 3-D Poissonian distribution leads to $\xi \propto r^{-1}$ (r^{-2}) without local clustering. $\xi(r) \propto r^{-1.5}$ as measured in the LSC (Rivolo and Yahil 1981, private comm.) is obtained at a$\sim$1.5 (Dekel 1983c). Hence, the clustering of galaxies according to the nondissipative pancake scenario was still very weak at z>1, and is compatible with the lack of measurable clustering among the L_α absorption clouds along the lines of sight to quasars (Dekel 1982), and among the quasars themselves.

We conclude that the data is consistent with a nondissipative pancake scenario which is a natural combination of the "eastern" pancakes and the "western" clustering, where both adiabatic and isothermal perturbations play a role in the formation of structure in the Universe.

REFERENCES

Aarseth, S.J. 1972, in Gravitational N-Body Problem, ed. M. Lecar (Dordrecht: Reidel), p. 373.
Dekel, A. 1982, Ap. J. L., 261, L13; 1983a, Ap. J., 264 (Jan. 15); 1983b, 1983c in preparation.
Dekel, A. and Aarseth, S.J. 1983, in preparation.
Tully, R.B. 1981, Ap. J., 255, 1.
Yahil, A., Sandage, A., and Tammann, G.A. 1980, Ap. J., 242, 448.
Zeldovich, Ya.B. 1970, Astr. Ap., 5, 84.

Discussion

Palmer: Once you allow structure on scales smaller than the damping scale of adiabatic perturbations, then a density profile focuses material into a core, which disrupts the thin pancake as it tries to form, unless the expansion velocities in the plane are large.

Dekel: An expansion in the plane is indeed required for the formation of a thin, long-lived pancake. Note further that the main reason for the rapid formation of a thin pancake is the large-scale, coherent velocity perturbation along the axis of collapse that causes the focusing of particle trajectories in the plane at a given time.

Bonometto: Your picture claims to involve an adiabatic fluctuation component, but a scenario starting from pure entropy fluctuations would present adiabatic fluctuations above M_J (Jeans mass before recombination).

If Ωh^2 is not too small, these fluctuations are large because of their collapse continuing after their entry in the horizon, while isothermal fluctuations with $M < M_J$ stay frozen.

I wonder whether the Dekel picture is not just the full picture we would expect in the primeval entropy fluctuation case. By this, I am not denying that it can also apply to a mixed adiabatic-isothermal scenario, I am only suggesting an alternative interpretation for it.

Dekel: Any truncated, adiabatic spectrum that provides coherent velocity perturbations on the scale of superclusters can do. My impression, however, is that the pre-recombination Jeans mass is too large.

Hoffman: In the simulations, how did you suppress density fluctuations on scales smaller than the damping scale in the initial conditions?

Dekel: Only the dominant wavelength was considered for the adiabatic perturbation. Perturbations on smaller scales were only Poissonian. This is still an idealistic, first approximation. Next, one should start from a generic spectrum of perturbations and investigate the structure of the individual superclusters that are formed (see the papers by Shandarin and by Efstathiou in this symposium, and an ongoing work by Aarseth and me simulating 10,000 particles and a truncated adiabatic spectrum).

Thompson: You ascribe the stability of a disk system in your N-body simulation to adiabatic cooling from the expansion parallel to the disk. Would you expect a similar cooling in a filamentary system, and do you have N-body simulations which show the stability of such filamentary structures?

Dekel: Yes. The estimates based on the adiabatic invariant are applicable to the case of a two-dimensional collapse as well. There the elongation is expected to become pronounced even faster, like $R^{-2/3}$. An experiment that explores various triaxials is currently in progress (Dekel and Aarseth 1983).

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