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The Origin of Galaxies and Clusters of Galaxies

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The large-scale distribution of matter is strikingly clumpy; we see stars in galaxies, galaxies in groups and clusters, and clusters in superclusters (*1*). Only in the average over scales beyond approximately 30 megaparsecs (*2*) does the homogeneity of the conventional cosmological model emerge (*3*). Debate on the origin of this arrangement goes back to the 1930's. Lemaître (*4*) proposed that the intersection of orbits of the primeval matter velocity field. Since the mass of a pancake could be comparable to that of a supercluster, pancakes could be the protoclusters that fragmented to make galaxies. This theory has attracted considerable attention because remnants of the pancakes might be seen in a filamentary or cellular character of the present galaxy distribution. However, there are

Summary. Debate on how galaxies and clusters of galaxies formed has reached an interesting stage at which one can find arguments for quite different scenarios. The galaxy distribution has a complex "frothy" character that could be the fossil of a network of protoclusters or pancakes that produced galaxies. However, there are galaxies like our own that seem never to have been in a protocluster but are physically similar to the galaxies in dense clusters. Some clues to be assessed in resolving this dilemma are the possible existence of galaxy filaments, the relative ages of galaxies and clusters of galaxies, and the continuity between cluster and field galaxies and between galaxies and clusters of galaxies.

density fluctuations develop as a result of the gravitational instability of the expanding universe. Because galaxies are denser than clusters of galaxies he found it natural to suppose that galaxies were formed before clusters (*4*). Hubble (*5*), however, noted that the fact that early-type galaxies (which contain relatively few young stars and little interstellar dust and gas) tend to be concentrated in the densest clusters might be evidence that galaxies formed within protoclusters that existed before galaxies. A definite form of this latter "top-down" scenario is Zel'dovich's pancake theory (*6*). Zel'dovich showed that under not unreasonable conditions the first generation of objects in the expanding universe could be sheets or pancakes of gas defined by problems, such as the puzzle of where galaxies like the one we are in came from; it is a member of a loose and young-looking group that is most naturally interpreted as forming by Lemaître's "bottom-up" scenario. The following is a list of the clues to be assessed in trying to decide which scenario (if either!) is closer to the truth.

Filaments

Two examples of filaments are seen in the map of bright galaxies in Fig. 1. A prominent band slopes down to the right on the right side of the map, and one also can discern a straight line running from 5^h, 70° to 10^h, 45°. Giovanelli and Haynes (*7*) noticed the latter and found that it appears also in the distribution of galaxies with known distances (from red shifts) in the range 40 to 70 Mpc, but not in the nearer and further galaxies. This is an example of discovery based on crude distance information and confirmed with a subset of accurate distances. Hence it is a strong candidate for a physical filament of galaxies.

The most natural interpretation of filaments is that they are fossils of preexisting linear structures, or of anisotropic stresses, or something equally interesting. Gravity could make large-scale filaments after galaxies had formed, just as it produced linear structures in the distribution of hydrogen in the pancake scenario, but that does require a special arrangement; the galaxies would have to approximate a "gas" with only large-scale density gradients. There is yet another possibility to consider: if galaxies were placed in a clustering pattern according to a random statistical process that had no preference for lines, the occasional filament would be produced by chance and, because the eye is so sensitive to patterns, we might attach undue significance to these accidents. To explain why some of us place so much emphasis on this point I will recall some cases where it has been a factor.

In the 1920's it was known that nebulae tend to be spirals, so it was natural to ask whether there are spiral patterns in globular star clusters, and it is not surprising that people were able to find some pretty good cases. In the example shown in Fig. 2, one can pick out a rudimentary four-arm spiral. Interest in the idea soon faded because, as ten Bruggencate (*8*) emphasized, the pattern is not reproduced in the fainter cluster members, and it is now doubted that there is any reason why globular clusters should have spirals or that there is any evidence of spirals. The eye was similarly deceived in the case of canals on Mars. That was what Maunder and others argued at the time, and to test it he and Evans (*9*) made maps of the observed features of Mars, excluding the

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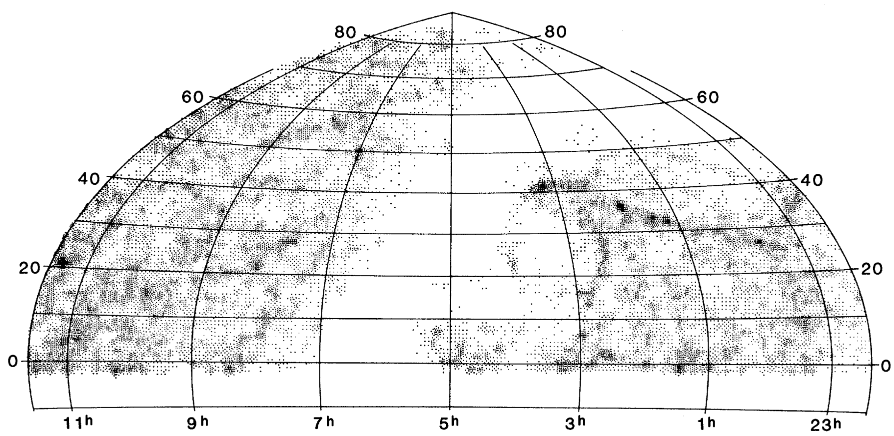


Fig. 1. Map of the angular distribution of the bright galaxies from Giovanelli and Haynes (*7*). The shade density in each cell is proportional to the logarithm of the surface density of galaxies brighter than apparent magnitude $m \sim 15.7$. The blank zone running through the middle of the map is caused by obscuration by the dust in the disk of our galaxy.

canals, and asked schoolboys to draw everything they could make out on the maps. Evans and Maunder found that when the maps were placed far enough away that the smaller features were just detectable, the students tended to add linear structures that look like the canals. [Details of this "small boy theory" are given by Hoyt (*10*).] Star chains are commonly seen, although not often reported because most people are convinced they really are accidents. The best example I could find in a brief survey of observers is the photograph in Fig. 3 that was kindly provided by Bob McClure (*11*). As the stars in this cluster are old, they surely have been thoroughly mixed since formation. Most striking are the two nearly horizontal chains of stars that define a branched path near the top of the figure, but one can pick out other chains, all of which are presumed to be accidents. It is true that this is the best example I could find, but then examples of galaxy filaments also are the results of searches for good cases. The moral I draw certainly is not that the filaments shown in Fig. 1 are only statistical accidents, but rather that we ought to bear that possibility in mind until we have tests that provide good evidence to the contrary.

It is more difficult to assess galaxy filaments because galaxies really are arranged in clusters. Hence one must judge the significance of chains of clumps of galaxies rather than chains of individual stars. We see a strikingly filamentary texture in the map in Fig. 4A of the angular distribution of the brightest one million galaxies (*12*, *13*). To test the significance of this texture, Ray Soneira and I (*14*) devised a prescription for a model galaxy distribution that matches the observed low-order galaxy correlation functions [the random process in this prescription is one of Mandelbrot's fractals (*15*)] and then made maps from the model. The result shown in Fig. 4B lacks some of the crispness of the real galaxy distribution, but one can pick out long sinuous filaments that we know are accidents because the model has no preference for lines. I am not aware of any test that reveals a significant difference in the abundance of large-scale linear arrangements in model and data (*16*).

Figure 5 shows a comparison of real and model galaxy distributions at about one-third the depth of Fig. 4, where we have distance information so we can look at three-dimensional structure. The radial coordinate in these maps is the galaxy red shift, which is presumed to be the sum of the cosmological term Hr and the Doppler shift from random motions, the latter introducing a scatter in the true relative radial distances of the galaxies. The two maps on the left are from the Cambridge Center for Astrophysics red-shift sample (*17*). The maps on the right are realizations of the random process mentioned above generalized to velocities as well as positions (*18*). One sees in model and data maps roughly similar clouds and knots and holes; no very prominent filaments as long (30 Mpc) as the Giovanelli-Haynes object (Fig. 1) are seen in the model maps or in the Center for Astrophysics red-shift maps (*17*).

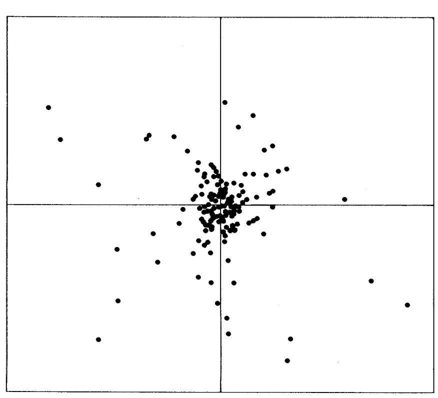


Fig. 2. Distribution of the 150 brightest stars in the globular star cluster M3 (*8*).

Remarkable indirect evidence of filaments emerged from Binggeli's study of the orientations of clusters of galaxies (*19*). He observed, as have others, that the long axis of the central brightest galaxy in a cluster tends to line up with the long axis of the cluster. That could be because both are remnants of a pancake, but arguing against this interpretation is that the other galaxies in the cluster generally show no marked alignment (*20*). Another interpretation is that we are seeing debris that tends to arrange itself symmetrically in the cluster potential well (*21*). Binggeli found that if a rich cluster happens to have a neighbor cluster at distance less than approximately 20 Mpc (compared to a mean separation of rich clusters of about 80 Mpc), the long axis of the cluster tends to point toward the neighbor. That could be a residuum of pancakes (*16*, *19*), but again other interpretations are possible; one could imagine the alignment was caused by tides operating at red shifts of $z \sim 10$ to 20 when these dense clusters might have been forming. Binggeli also found a tendency for the long axes of clusters to point at other clusters as far away as approximately 75 Mpc. This is a difficult measurement, and perhaps arguing against it is the fact that the clusters of rich clusters Bahcall and Soneira (*22*) identified do not look particularly elongated. Further tests of the Binggeli effect will be followed with great interest, for it is hard to see how alignment on scales of more than 20 Mpc or so could be anything but a new and very significant phenomenon.

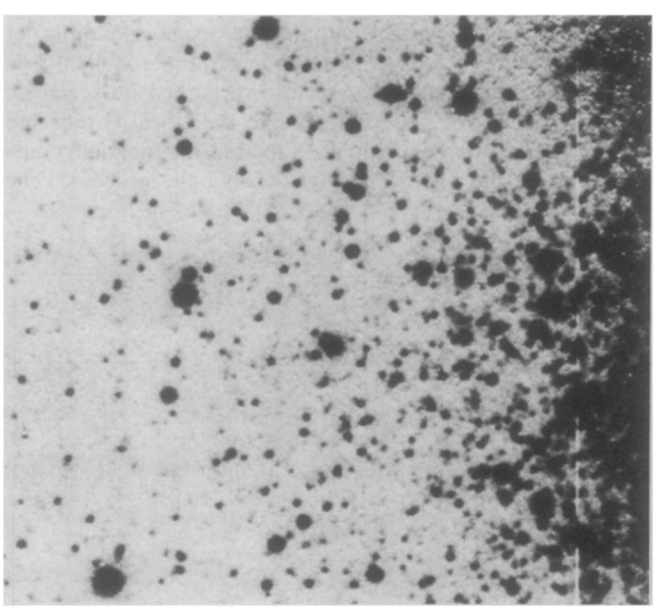
To decide whether structures like those seen in Fig. 1 could arise in the simplest "bottom-up" scenario where the clustering pattern develops in a more or less continuous progression of increasing mass, we need to have a better theoretical understanding of how often such linear structures might appear by chance in a chaotic "frothy" (*17*) distribution and how effective such gravitational effects as tides are at enhancing linearity. The bottom-up scenario will be most seriously challenged by the longest filaments that can be found, so attention will focus on the large-scale Binggeli effect and on the general large-scale three-dimensional clustering revealed as red-shift surveys proceed to greater depths.

The Ages of Galaxies and Clusters of Galaxies

The most direct evidence for the bottom-up scenario is the fact that parts of the pattern of galaxy clustering look young, as if just now forming, whereas galaxies by and large are old (*23*, *24*). The ages of the oldest stars in our Milky Way galaxy are found to be 14 to 20 billion years (*25*), which may be consistent with the age of the universe derived from the observed rate of expansion if these stars formed when the universe was fairly young. We see what other galaxies were like in the past by observing distant ones. Galaxies observed at red shifts of $z \sim 1$ (*26*), when the universe was about half its present age, have luminosities and colors similar to nearby galaxies (*24*, *27*); this suggests that large galaxies had reached a fairly mature state by $z = 1$. If a galaxy formed out of a gas cloud, a young galaxy would have to have been very bright to make the heavy elements in the spheroid while the cloud was collapsing (*28*). To account for the fact that no such objects have been discovered, it is presumed that the luminous phase is hidden by a high red shift or else obscured by intergalactic dust (*29*). As quasars with appreciable heavy element abundances are seen at red shifts of $z \sim 3.5$ (*30*), we would have to assume either that young galaxies managed to avoid the expected bright initial phase, or, what seems more likely, that the formation of large galaxies was nearly complete by red shift $z_f \sim 4$, say, where z_f represents the red shift at which galaxies form. At that epoch the radius of the universe was $1/(1 + z_f) \lesssim 1/5$ of its present value.

Youthful galaxy clustering is seen most directly in our immediate neighborhood. We are in a loose collection of galaxies, the Local Group (*31*, *32*). The two subgroups around us and around the other large spiral, the Andromeda nebula, are approaching with a closing time r/v about equal to the expansion time t_e for the universe. This suggests that the group is only now forming (*33*), and, consistent with that, one finds that the crossing times for the outlying group members all are comparable to t_e (*31*, *32*). De Vaucouleurs (*31*) calls the Local Group a "typical loose group" of galaxies. For example, our nearest neighbor, the Sculptor group in the Southern Hemisphere, has very similar size and internal velocities and so also is presumed to be young. The Sculptor group is 2.5 Mpc away (compared to a radius of 1 Mpc for the Local Group), and the group is moving away from us at 230 kilometers per second, about what is expected from Hubble's law. The same is true of the other nearby groups. If we extrapolate these motions back in time to the latest epoch ($z_f \sim 4$) at which the above evidence suggests galaxies might have formed, we find that the four nearest groups listed by de Vaucouleurs (*31*) all were within the bounds of the Local Group when galaxies formed, which is hard to reconcile with the idea that these groups existed when galaxies formed. We see evidence of youth on a still larger scale in the Local Supercluster. This is a loose cloud of galaxies, of which we are an outlying member, with a radius of about 15 Mpc centered roughly on the Virgo cluster of galaxies (*34*). The galaxies in our immediate neighborhood are moving away from the Virgo cluster at 1000 km/sec, which is less than would be expected from pure Hubble flow by some 30 percent (*35*). The conventional interpretation is that the mass concentration in the Local Supercluster is slowing the general expansion and causing the cluster to grow; that is, that this system is in the process of forming now. It is thought that indications of immaturity are seen in some other clusters, whereas there are others that look well relaxed (*36*, *37*).

If protoclusters made galaxies, where did the Local Group come from? Could it and the whole Local Supercluster have been produced by one pancake? We would want this to have happened at red shift $z_f \gtrsim 4$, when the mean density of the universe was $(1 + z_f)^3 > 100$ times the present value, and the collapse of the pancake would have made the local density higher than the mean. But if the



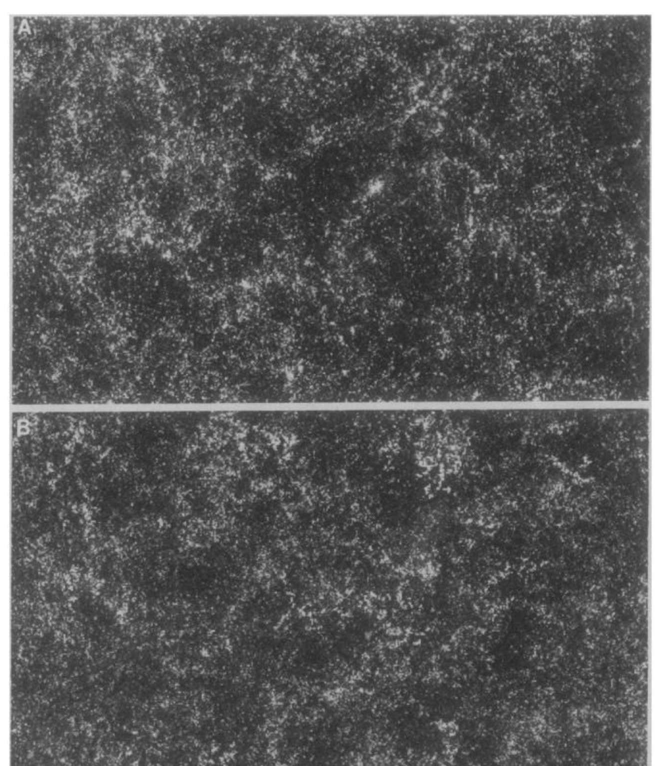


Fig. 3 (left). The south side of the globular star cluster NGC 2257 (courtesy of R. D. McClure). Fig. 4 (right). (A) Map of the angular distribution of the brightest million galaxies (*12*, *13*) at typical distances of 300 Mpc. The map covers 40 by 70 degrees centered on the north pole of the galaxy. (B) Model galaxy distribution that matches the observed low-order galaxy correlation functions (*14*). This model has no preference for lines or filaments.

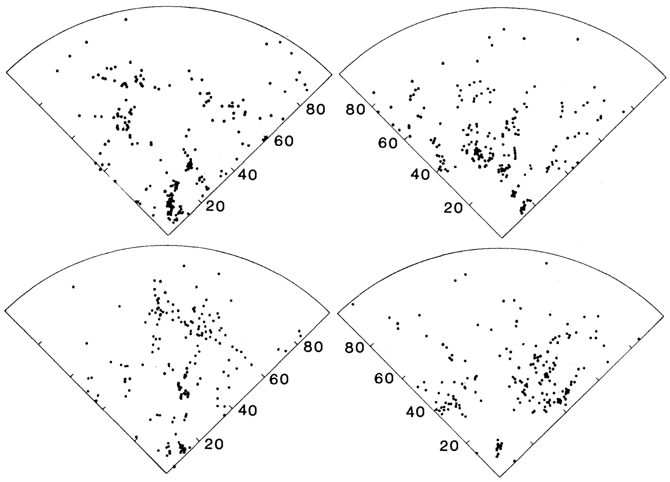


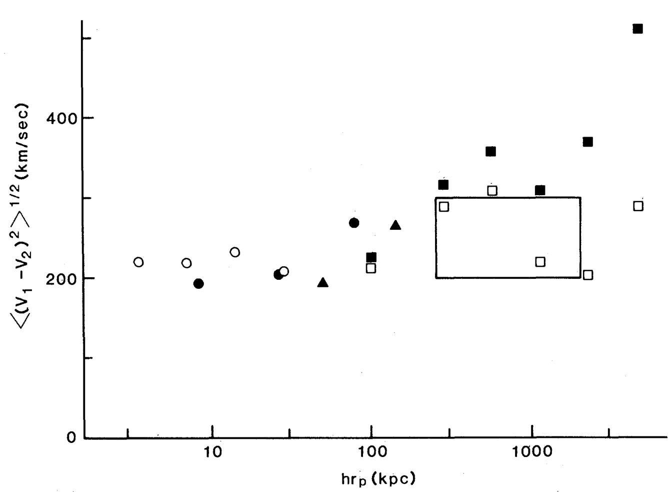
Fig. 5. Maps of galaxy red shifts. The radial coordinate is recession velocity in units of 100 km/sec, the angular coordinate is right ascension (azimuthal angle), and each map is a slice 10° thick in declination (polar angle θ at θ close to 90°). The two maps on the left are real distributions (*17*), and the two on the right are realizations of a random process originally designed for comparison with the deeper map of angular distributions in Fig. 4.

Local Supercluster formed at such high density, how do we account for the fact that the density of galaxies in our neighborhood averaged over spherical shells is only two or three times the present large-scale mean (*38*)? It is hard to imagine that gravity could have caused the pancake to collapse but then allowed its mean density to drop by such a large factor (*39*). Numerical simulations of the pancake theory point to the same problem: a pleasingly frothy structure is obtained, but the froth is young, tending to appear in regions that collapsed only recently. If at some point galaxy formation in the model is stopped, and the model expands by another factor of 5 or so to hide the young galaxies, much of the froth ends up in dense clumps (*40*, *41*).

Could cluster and field galaxies (found, respectively, in high- and low-density environments) form by different processes? Arguing for it is Hubble's point that there is a higher proportion of disk-shaped galaxies in the field, whereas elliptical galaxies tend to be concentrated in clusters (*5*, *36*). One could easily imagine that the difference in the collapse of "minipancakes" and "maxipancakes" that produced field and cluster galaxies would have produced the observed differences in morphologies. On the other hand, there is a striking similarity in the masses of large galaxies (*42*, *43*), which suggests that they all formed in much the same way (*44*). The circular velocity, v_c, in a spiral galaxy is a measure of the mass within a fixed radius, and v_c correlates well with the luminosity and morphology class of the galaxy. A similar measure for elliptical galaxies is the star velocity dispersion, σ, which correlates closely with luminosity. Spirals are found in a wide range of environments, from dense spots like the Virgo cluster to the edges of voids, and there is a like spread of environments for ellipticals; these correlations leave little room for a new parameter representing present ambient conditions. That is, whatever piled mass up into the structures we see as galaxies did so in quite a reproducible way, which suggests that galaxies formed under conditions a good deal more uniform than what we observe. As it is hard to find a parent protocluster for the Local Group, this argues against the idea that cluster galaxies formed in protoclusters.

Hybrid Scenarios and Continuity Between Galaxies and Clusters of Galaxies

It is consistent with the above arguments to assume that creation was a two-step process, groups and clusters forming by gravity and galaxies forming some other way. As Dekel (*41*) stressed, the advantage is that galaxies could form in the very early universe so that young galaxies are not seen, and clusters could form recently by pancaking of the "gas" of galaxies so that we get filaments. In a new version of this composite scenario, Ostriker (*44*) showed that galaxies might form at the surfaces of bubbles evacuated either by explosions or by isolated underdense spots in an otherwise initially homogeneous mass distribution. An isolated bubble tends to expand, which may eliminate overproduction of rich clusters, and remnants of the bubbles are a good source of filaments. Perhaps the major problem is that special initial conditions are needed to get bubbles to more or less fill space by red shift $z_f \gtrsim 4$ without strongly overlapping, since that would initiate the usual hierarchy of cluster formation. Another difficulty is that this really is a composite scenario, since objects like the Local Group and the Local Supercluster are not now growing by the bubble process. The



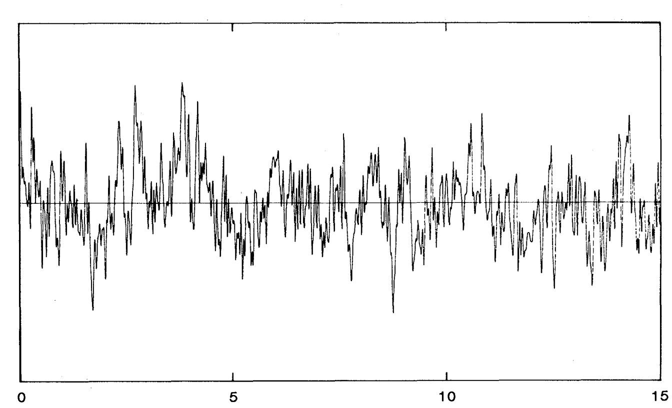


Fig. 6 (left). Estimates of the root-mean-square [$<(v_1 - v_2)^2>^{1/2}$] relative velocities of physical pairs of galaxies as a function of their projected separation r_p. The scale factor h reflects the uncertainty in the distance scale; $h = 0.75$ is adopted in this review. Fig. 7 (right). Hydrogen distribution in linear perturbation theory in a cosmological model dominated by low-pressure weakly interacting matter.

problem with a composite scenario is that it does not fit very naturally with the following evidence of continuity of the mass-clustering hierarchy.

The distribution of galaxies approximates a scale-invariant clustering hierarchy, one of Mandelbrot's fractals (*15*), density (ρ) scaling with size as $\rho \propto r^{-\gamma}$, $\gamma = 1.77 \pm 0.04$, at $r \lesssim 15$ Mpc (*45*). When observed by starlight, galaxies stand out from the hierarchy as distinct islands, but, as Rubin (*43*) has described, the mass distribution in at least some galaxies is a good deal more spread out than the light (*43*, *46*, *47*). A measure of the mean mass around a galaxy is the root-mean-square relative velocity w of neighboring galaxies. One assumes that the mean relative acceleration w^2/r is balanced on the average by the gravitational acceleration due to the mass in the neighborhood, since otherwise the clustering pattern we see on small scales would dissolve well within the ages of the galaxies. Figure 6 shows estimates of w as a function of the projected separation r_p of the galaxy pair (*48*). At separations typical of the optical sizes of galaxies ($\sim$ 10 kpc), $w = 210 \pm 20$ km/sec, about what would be expected from observed star and gas motions within bright galaxies (*43*, *47*). The striking result is that $w(r_p)$ is close to flat from 5 kpc to 1 Mpc. Of course that just extends the by now familiar observation that the circular velocity of rotation in the disk of an isolated spiral is quite flat (*43*, *47*), and the interpretation is the same: if, as we almost always assume, Newtonian mechanics is an adequate approximation (*49*), the mean value of the mass (M) within distance r of a galaxy has to scale as $M (< r) \propto r^{\epsilon}$ with ϵ equal to or slightly larger than unity (*46*). This applies from within the galaxy ($r \lesssim 10$ kpc) to $r \sim 1$ Mpc, where we run out of data on $w(r_p)$, but since the galaxy clustering scales as the number of galaxies $N (< r) \sim \rho r^3 \propto r^{1.2}$, we see that if mass clusters like galaxies, the power law is a reasonable approximation to $r \sim 15$ Mpc, where $\rho(r)$ starts to flatten into the homogeneous mass distribution observed on very large scales.

Now we must assess the significance of these two clues. When measured by the distribution of starlight, galaxies stand out as islands in the clustering hierarchy. That means there are differences in the processes by which galaxies and clusters of galaxies form. But as we have seen, the mass distribution within galaxies and clusters is joined by a scaling law; the mean value of the mass within distance r of a galaxy scales as $M (< r) \sim r^{1.2}$ from within the galaxy out to $r \gtrsim 1$ Mpc. This scaling continuity suggests galaxies and clusters of galaxies formed by scaled versions of the same process. The formation of visible stars is poorly understood but surely is sensitive to physical conditions, so it seems to me easier to imagine that star formation broke the scaling symmetry, producing concentrations of starlight as frosting on the peaks of the mass distribution, than that the observed continuity in the mass distribution was the result of distinct processes of formation of galaxies and clusters of galaxies. If that is so, we are led to a bottom-up picture because galaxies are old and stable objects, whereas, at the top end of the hierarchy, superclusters are still forming. In a hybrid scenario we would need a special arrangement to hide the seams of the two-step process.

Non-Gaussian Large-Scale Density Fluctuations

If a sphere is placed at random, the root-mean-square fluctuation in the number of bright galaxies it contains is $\delta N/N = 1$ when the diameter (D) is 20 Mpc (*3*). This marks the transition from strongly nonlinear fluctuations on small scales to fluctuations that are small on the average at larger D. One might expect that at $D > 20$ Mpc the distribution of the number of bright galaxies contained rapidly approaches a Gaussian, reflecting simple initial conditions, but there are indications this is not so. The great void in Böotes (*50*) has a radius of about 40 Mpc, and if it is nearly empty, it is roughly a 3-standard-deviation downward fluctuation (*45*). Because the volume of the void is a few percent of the volume of space surveyed to its distance, we might not have expected to have seen such a large fluctuation in a Gaussian distribution. The largest known prominent concentration of galaxies is the Serpens Virgo cloud discovered by Shane and Wirtanen (*12*); it is number 14 in the Bahcall-Soneira catalog of clusters of rich clusters of galaxies (*22*). The galaxy density in the cloud averaged over a diameter of 30 Mpc is about ten times the large-scale mean, which is roughly a 10-standard-deviation upward fluctuation.

The great void could be due to a suppression of galaxy formation in the region (*50*), but because it is hard to explain the Serpens Virgo cloud that way, it does suggest that the mass distribution on scales greater than approximately 20 Mpc has non-Gaussian tails; that is, in the primeval mass distribution, regions of extremely high or low density occur more often than would be expected for a Gaussian probability distribution (*23*, *36*, *51*). This finds a natural interpretation in the top-down scenario as remnants of the network of protoclusters (*6*). It may be an embarrassment in the bottom-up scenario because the most popular candidate for the source of departures from homogeneity, quantum fluctuations in a nearly free field, leads to Gaussian noise. However, other sources, like the "vacuum strings" predicted in some gauge theories, could produce non-Gaussian perturbations (*52*).

Galaxy Formation with "Inos"

The preceding sections have dealt with general interpretations of clues to the formation of galaxies. I turn now to two more specific theories, both based on the idea that the dark matter needed to account for the dynamics of galaxies and clusters of galaxies might be weakly interacting particles left over from the very early universe.

Neutrinos with nonzero mass are a particularly attractive candidate because we know that neutrinos really do exist, and because there is a beautiful coincidence in the wanted neutrino mass. The abundance of neutrinos produced at high red shift in the Big Bang is known; if these neutrinos make an interesting but not excessive contribution to the mean mass density of the universe, their mass may be about 50 electron volts. That agrees with the lower bound on the mass if neutrinos are to be stuffed into galaxies to attain the wanted density without violating the exclusion principle (*53*). The mass also fixes the velocity distribution. Because these are weakly interacting particles, they move almost freely so that the velocity fixes the length smoothed by thermal motions; the result is comparable to that of superclusters. Thus we are led to a top-down pancake theory (*1*, *6*). There is, however, a problem. Analytic and numerical N-body model studies both suggest the predicted mass clustering length is too large (*54*). The analytic approach might be questionable because it is hard to be sure nonlinearities are properly handled, and the N-body approach is vexed by the limited dynamic range in space and time, which makes it hard to be sure the freedom of adjusting the initial spectrum of density fluctuations has been properly taken into account. But the fact that the two approaches yield such similar results suggests they are correct. Attempts to relieve the problem by adjusting the scenario of annihilation and decay of particles at high red shift have so far not been encouraging (*55*).

A new version of the bottom-up scenario has emerged from the realization that the dark matter could be weakly interacting particles with velocities much less than those in the massive neutrino model. These particles have names like "axions," "photinos," "selectrons," and "gravitinos" (*56*). It suffices for our purposes to notice that there is no empirical evidence that any of these particles exist; they are discussed in elementary particle physics because they appear in theories that are untested but attractive generalizations of successful theories, and they are considered in cosmology because they have some interesting and conceivably beneficial properties.

Density fluctuations in the very early universe are tightly constrained because at high density even a small mass excess promotes relativistic collapse to black holes. This must be avoided because it would produce an unacceptably high mean mass density. A currently fashionable assumption is that the initial density fluctuations on all scales are a fixed fraction of the threshold for black hole production (*57*). Figure 7 shows what the resulting hydrogen distribution would look like at fairly recent epochs ($z \sim 100$) if the universe were dominated by these low-velocity "inos" (*58*). The horizontal axis is evaluated at the present epoch under the assumption that the distribution followed the general expansion instead of breaking up into bound objects. The spikes are produced by gas pressure that suppresses density fluctuations on smaller scales. The spikes tend to appear in clumps (whose size is fixed by radiation pressure). It is an interesting and perhaps suggestive coincidence that the clump masses are comparable to masses of galaxies (*59*). The spikes tend to develop into gas clouds. Such a cloud, if left alone, would shrink until the hydrogen was hot enough to be ionized and then would collapse, presumably forming a star cluster (*60*). The result would be similar to the globular star clusters common in halos of galaxies. The idea that globular clusters were formed this way has not attracted wide enthusiasm but still seems viable (*59, 61*).

An interesting consequence of this picture is that the gas clouds would be born containing inos that would be left as dilute massive dark halos around the candidate globular star clusters. That could be observable, as is illustrated in the star cluster model shown in Fig. 8 (*62*). The upper curve is the surface density run of stars; it looks not unlike a real globular cluster. The bottom curve shows the star velocity dispersion. In standard models all three components decrease with increasing radius to produce the observed sharp drop in density at the cluster "surface." A dark massive halo can make the density drop another way, by the increase in gravity. In the model, the star orbits are isotropic in the core and close to radial near the surface, as might be expected if the stars in the envelope came from the core because of relaxation in the core. That makes the line-of-sight velocity dispersion, σ_l, decrease with increasing radius, about as observed from red-shift measurements (*63*). The dispersion, σ_r, in the plane of the sky and along the cluster radius vector is nearly constant; if there were no dark halo, σ_r would have to drop at the cluster surface. Cudworth (*64*) has shown that one can use proper motion measurements to estimate σ_r as a function of the angular distance θ from the cluster center, and the azimuthal component, $\sigma_a(\theta)$, so with some improvements in the data an interesting test may be possible.

A more immediate test for the bottom-up theory is whether it can account for the character of the galaxy distribution. Numerical *N*-body model simulations of the growth of galaxy clustering fail to produce quite as good an approximation to a scale-invariant (power law) clustering hierarchy as is observed, and in the models the clustering hierarchy is transient (*40, 41, 65*). The observed galaxy-clustering pattern is so close to scale-invariant (extending from 15 Mpc down to about 10 kpc, and, as discussed above, to the mass distribution within galaxies) that I am reluctant to believe it could be a transient effect. Perhaps these problems are only a reflection of the difficulties with *N*-body models, which have very limited dynamical range and deal with nongravitational forces crudely if at all. Perhaps the problems are due to errors in the details of the theory, like the assumption of initially Gaussian density fluctuations. Perhaps they are a reflection of something fundamentally wrong with the scenario.

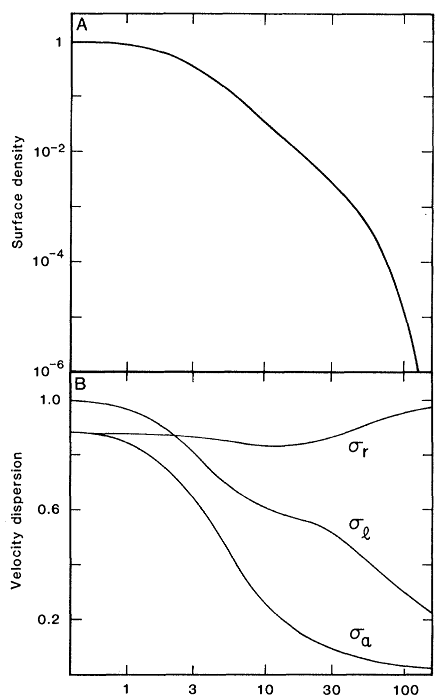


Fig. 8. Globular star cluster model. The top graph is the projected density of stars. The lower graph shows the star velocity dispersion σ_l along the line of sight and the dispersion σ_r and σ_a in the plane of the sky and along the radial and azimuthal directions.

Outlook

The strong divisions of opinion on how galaxies might have formed are a positive sign: it is only recently that the subject has advanced to the point that we can make out positions that seem defensible. It is proper that we should be guided by our assessment of what fundamental theory is telling us. The situation is not all that good: the "best" version of the top-down scenario, based on massive neutrinos, encounters problems with the galaxy-clustering length, the "best" bottom-up theory is based on matter whose existence is only conjectured; but neither problem need be permanent. The clustering length discrepancy arises in models that treat galaxy formation only crudely, and it is conceivable that as the treatment of nongravitational processes is sharpened the problem will go away (*1*). On the phenomenological side, perhaps the best motivation for the top-down scenario is that it offers a way to account for the large-scale character of the galaxy distribution. On the other hand it seems hard to avoid the conclusion that the bottom-up process has been operating because we see groups and clusters that surely are younger than the galaxies they contain, and the continuity arguments mentioned above support the idea that this has been the dominant process. The list of things to be done is promising; we have some fairly direct questions to address, like the significance of large-scale linearity in the galaxy distribution, and some interesting "long shots." I would count among the latter the point that in a universe dominated by low-pressure inos, one would expect to see the formation of objects like globular star clusters with dark halos. I also count as a long shot the possibility that discoveries in elementary particle physics will offer sharper constraints on the possible macroscopic properties of exotic dark matter, but this is a rapidly moving field so I will be watching the newspapers for developments. On the astronomical side there is the chance that galaxies in a bright initial phase might be detected at high red shift; if we saw what young galaxies are like it would settle a lot of arguments. Galaxies are detected at red shifts near unity, when the universe was about half its present age. The galaxy distribution at that depth is not well measured because of the confusion of clustering seen overlapping in projection, but statistical methods for dealing with that are known and I believe that in the next few years we will have a clean test of the prediction that the clustering pattern is growing because the universe is gravitationally unstable. The clustering pattern of relatively nearby galaxies can be studied in detail because it has become feasible to measure relative distances (through red shifts) wholesale (*17*). These data will strengthen the test of the proposed continuity of masses in galaxies and clusters of galaxies, but of course the main excitement will be the search for the largest possible things—holes or lines or sheets that might be fossils of something interesting.

References and Notes

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