Accretion mechanism of generation of large-scale structures in the universe

V. M. Lipunov and S. G. Simakov

P. K. Shternberg State Astronomical Institute

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A scenario for the formation of the filamentary large-scale structure of the universe is discussed. The primary physical mechanism is the accretion of matter into the wake of a rapidly moving massive body. Such bodies may be clusters of galaxies formed earlier than others (in the case of the entropy model) and nearly symmetric loops (in the model of the universe containing cosmic strings). Estimates are given showing that as a consequence of the development of gravitational instability, the wake of a loop breaks up into clumps with masses close to those of galaxies. Long-wavelength perturbations can lead to the gathering of these clumps into protoclusters.

1. Among the enormous variety of structures in the universe, one-dimensional structures whose transverse size is much less than their longitudinal size have recently been cited ever more frequently. For example, there is the "filament" in Boötes,[1] consisting of several dozen galaxies with a total mass $M \approx 10^{12}$-10^{13} $M_\odot$ and an extent of about 30 Mpc, and the "filament" in Perseus (50 Mpc), a formation consisting of a chain of galaxy clusters with $M \approx 10^{14}$-10^{15} $M_\odot$.

In the adiabatic theory such structures are obtained fairly naturally, as one of the types of caustic surfaces. This theory itself encounters a number of important difficulties, however, which brings into question its proposed explanation for the origin of filaments.

Lipunov and Simakov[2] advanced the hypothesis that one-dimensional structures may be formed by the motion of a massive body in a medium of low-mass particles (the protogalactic gas), compelling them by its gravitation to collect on an accretion axis along which a "tail" of increased density is drawn out. If the gas is collisional, then the transverse (with respect to the accretion axis) component of the gas velocity is radiated away. And the self-gravitation of the wake will prevent dissipation of the condensation that forms. The subsequent breakup of such a condensation into individual parts by the usual gravitational instability can provide the origin of galaxies and clusters of them.

2. From the parameters of filaments given above, the length L and the mass M, we can estimate the mass and velocity of the massive objects,

$$L \sim v_b t, \quad M = \dot{M} t. \tag{1}$$

where v_b is the velocity of the object. Here t must be understood as either the Hubble time or the characteristic dynamic time – the dynamic-friction time.

The rate of accretion of matter into the wake is determined as

$$\dot{M} = \pi R_i^2 \rho v, \tag{2}$$

where $R_i = R_g \mu$, R_g being the gravitational-capture radius and μ the Mach number. This relation differs from the generally accepted one (see Ref. 3) by the factor μ, the appearance of which is easy to understand from the following arguments: by its gravitational action, the massive body (with a mass M_b and a velocity v_b) alters the momentum of a background particle so that it acquires a velocity

$$v_1 \simeq \frac{2GM_b}{R^2} \frac{R}{v_b}. \tag{3}$$

For the disturbance not to be washed out by thermal motions, it is necessary that $v_1 \geq v_s$, where v_s is the speed of sound in the background component; hence the "effective interaction radius" is

$$R_i = \frac{2GM_b}{v_b^2} \frac{v_b}{v_s} = R_g \mu. \tag{4}$$

Equations 91), (2), and (4) allow us to make some estimates of the mass and velocity of the seed body. Taking $\Omega = 1$ and $\rho = 1/6\pi G t^2$ (plane model), we obtain

$$M_b \approx \left(\frac{ML^3}{G\mu^2\Omega_b t^2}\right)^{1/2} \approx 2\cdot 10^{13} L_{30}^{3/2} \mu_2^{-1} \Omega_b^{-1/2} h^{-1} M_{14} (M_\odot) \tag{5}$$

$$v_b \sim D/t \approx 10^3 L_{30} h^{-1} \text{ km/sec},$$

here we take $t \approx 1/H$, $h = H/100$ km·sec^{-1}·Mpc^{-1}, $\mu^2 = \mu/100$ = const, $L_{30} = L/30$ Mpc, and $M_{14} = M/10^{14}$ $M_\odot$. We emphasize that the mass of the filament is larger than M_b in this case.

The estiamtes (5) are fairly approximate, since they ignore the influence of expansion of the universe, as well as the fact that the massive body slows as it moves in a medium of low-mass bodies.

Nevertheless, it is clear that the object must have a mass on the order of the mass of a cluster or group of galaxies and a fairly high velocity. Such estiamtes are obtained under the assumption that the massive object was formed not very long ago, when the conditions in the universe were close to those existing today. Then a cluster that collapsed earlier than others and has a fairly high peculiar velocity can be proposed as such a body.

The limits on the mass and velocity of the heavy body can be lowered if we assume that it was formed at sufficiently large z, when the medium was denser, in which case short filaments can be formed which are then drawn out by Hubble expansion.

A similar analysis can be made in the model of "hierarchical" clustering. If the clusters that have formed include massive and rapidly moving ones, then existing low-mass galaxies and clusters will be "clustered together" in the wake in this case. If such a process is going on today, it

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is easy to estimate their peculiar velocities using Eq. (3), assuming that $v_1 \approx v_p$, where v_p are the observed peculiar velocities of galaxies,[4] $(6\text{-}8)\cdot 10^2$ km·sec^{-1}. We determine R from the condition $v_p = RH$, i.e., we define this quantity so that velocity perturbations are now washed out by the Hubble motion, and thus

$$v_p \approx 10^2 M_{13}^{1/2} h^{1/2} v_3^{-1/2} \text{ km/sec}, \qquad (6)$$

($v_3 = v_b/10^3$ cm·sec^{-1}), which is close to the value given above. For consistency with observations, we also note that the filament thickness $R_0 \approx v_p/H$ agrees to order of magnitude with the observed thickness,

$$R_0 \sim \frac{v_p}{H} \approx 10 h^{-1/2} M_{13}^{1/2} v_3^{-1/2} \text{ Mpc}. \qquad (7)$$

It is easy to see that the depth of the potential well of a filament is too little to keep galaxies with a peculiar velocity v from flying apart. This means that one-dimensional formations in such a picture have a finite lifetime, on the order of the time of passage through a cross section of the filament ($t \approx 1/H$), if the filament does not break up into clusters – clumps of nearly spherical shape, for which the potential well is deeper.

We emphasize that such a picture is possible under fairly specific conditions of formation, when a massive protocluster actually moves in a medium, i.e., relative to the surrounding background. In the case of the growth of density perturbations with a flat initial spectrum as a result of the development of gravitational instability, the surroundings of the protocluster move in accordance with it, since the cluster itself is formed by the flow of matter into the vicinity of the embryo of the protocluster.

3. A rather attractive version of this scenario for the generation of one-dimensional formations is the scenario with the participation of cosmic strings,[5] the theory of which is now being developed vigorously. They attracted particular interest after it was found that the correlation functions of strings, galaxies, and clusters of them coincide. We briefly describe the properties of cosmic strings required for understanding what follows, referring the reader to Vilenkin's review[6] for details.

Strings are singular, vacuum, stable topological configurations whose existence is predicted in a number of grand unified theories. They cannot have ends, so strings are either infinite or closed; we shall call the latter loops, as is now customary. They ar both created with an initial peculiar velocity $v_0 \approx 0.1c$ (c is the speed of light), and the typical size of loops is of the order of the size of the horizon at the time of creation. Loops of cosmic strings can have an almost regular circular shape, but they can also be tangled. Oscillations of a loop lead to the emission of gravitational waves by it (since a string tends to straighten out owing to the high internal tension), which is an important factor in its evolution, leading to its "evaporation" – radiation of its internal energy. Thus, the lifetime of a loop is limited, $\tau \approx R_\ell c/\gamma G\mu_\ell$, where R_ℓ is the size and μ_ℓ is the mass per unit length of the loop and $\gamma \simeq 10^2 = \text{const}$. Oscillations of loops lead to their tangling and acceleration. It is important that infinite strings do not exert gravitational influence on surrounding objects, whereas the gravitational field of a loop is close to the Schwarzschild field (at a distance on the order of several loop diameters), so it is capable of distorting the trajectories of background particles, i.e., of "drawing out a wake behind itself."

Let us consider the motion of a loop with acceleration. It is easy to see that the acceleration of a closed loop is $\dot{v} \approx c/\tau$ (since the characteristic time $\Delta t \simeq 2R/c$ (the oscillation period) of variation of the velocity is $\Delta v \simeq \frac{G\mu_l}{c^2}$) . We emphasize that μ_ℓ or the combination $\frac{G\mu_l}{c^2} = \varepsilon$ is the only parameter in the theory of cosmic strings. (Below we shall use the generally accepted value of $\varepsilon = 10^{-6}$.) Thus, from the instant of its creation a loop starts to decelerate (as $v = v_0 a^{-1}$, where a is a scale factor) and then, after reaching a minimum, accelerates to the initial velocity (if the gravitational wave pulses are strictly coherent).[7,8] Thus, the peculiar velocity varies with time as

$$v_{pl} \simeq 10^4 \left(\frac{t}{t_0}\right) + 3\cdot 10^9 \left(\frac{t_0}{t}\right)^{4/3}, \qquad (8)$$

where t_0 is the instant of creation of the loop. Its value at the minimum is

$$v_{pl_{\min}} \simeq 1.3c \left(\frac{v_0}{c}\right)^{2/5} \left(\frac{G\mu_l}{c^2}\right)^{2/5} \approx 6\cdot 10^2 \text{ km·sec}^{-1} \qquad (9)$$

regardless of its mass. Integrating (8), we also obtain the distance traveled by the loop:

$$L \approx c\tau \simeq 3M_{11} \text{ MPc}. \qquad (10)$$

Here $M_{11} = M_\ell/10^{11}\ M_\odot$ is the mass of the string (from now on we shall normalize all the parameters to the values corresponding to a loop with a mass of the order of the mass of a galaxy; the size of such a string is $R_\ell \simeq ct_0 = 1$ kpc, and it is created at the time $t_0 = 10^{11}$ sec or $z = 10^4$; it is assumed everywhere that $\Omega = 1$). Since $\tau = 10^4 t_0$ or $\tau = 10^{15} M_{11}$ sec $= 3\cdot 10^7 M_{11}$ yr, a loop with a mass $M_{11} = 1$ ends its existence at z = 34, and hence the length of the "tail" drawn out in a filament increases by about a factor of 34 in Hubble recession. It must be considered, however, that the velocity of the string is fairly high at the start and end of its life, i.e., the capture cross section is small, so the wake filament formed, from which the embryos of clusters and galaxies could then be formed, must be somewhat shorter (by about a factor of 10), which is close to the presently observed values. We estimate the total mass of a filament, just as we did at the start of the paper; in the given case it is (in $M_\odot$)

$$M \sim \mu^2 \cdot 10^{11} M_{11} (M_\odot) \sim 10^{15} \mu_2{}^2 M_{11}{}^2. \qquad (11)$$

The wake obviously must possess an internal structure. Owing to the perturbation by the moving mass, a dense tail, bounded by a cylindrical shock wave with a cross section $\sim R_g^2$, can be drawn out immediately behind it, similar to what happens as a galaxy moves in the intergalactic medium,[9] and a rarefied "halo" farther away, at $R_g < R < R_i$. Assuming that such a shock wave is formed in the wake of a loop, let us estimate some parameters of this dense spur. The temperature behind the front of a cylindrical shock wave is easily determined from the relation $T_s \approx 0.1 m_p v^2/k$, where m_p is the proton mass, v is the velocity ahead of the gront, and k is the Boltzmann constant. Using (8) and converting from t to z, we rduce this simple expression to the form

$$T_s \simeq 0{,}4(1+z)^2 (1+10^5 (1+z)^{-3/2} M_{11}{}^{-5/3})^2 M_{11}^{4/3} \text{ K}. \qquad (12)$$

From this it is seen that the temperature varies along the tail. At the very start of its formation, at $z \approx 10^3$, let us say, $T_S \approx 4 \cdot 10^5$, while at $z \approx 30$ we have $T_S \approx 10^5$ K. this would occur if there were no cooling. At $z \gtrsim (8\text{-}10)$, however, the process of cooling on photons of the microwave background radiation through inverse Compton scattering is very efficient, and it is lowers the temperature of the wake to about the recombination temperature, due to which considerable compression of the matter is achieved. The density of the wake behind the shock wave is estiamted as

$$\rho \simeq 4\rho_{cr}\Omega_B(1+z)^3\frac{T_s}{T_a}$$

$$= 10^{-34}(1+z)^5(1+10^5(1+z)^{-5/2}M_{11}^{-5/3})M_{11}^{4/3}\,\Omega_B \text{ g/cm}^3,$$

$$T_a = 10^4 \text{ K}. \tag{13}$$

From this we see the pronounced variation of density with z, the maximum of which is reached at $z = 10^3$. If we assume that the wake then breaks up into individual bodies, then we must thus expect that at large z dense formations could exist whose evolution could significantly alter our scenarios of the evolution of the universe in late stages (the early formation of quasars, explosions which could lead to th epicture discussed by Ostriker and Cowie[9] (also see Refs. 10 and 11), heating of matter at moderate z, and enrichment of the gas with heavy elements).

It is well known that an infinite homogenoeus cylinder is unstable against perturbations propagating along its axis.[12] Our wake, having an approximately cylindrical shape, is evidently just as unstable. Using the results of Ref. 12, we estiamte the mass of the clouds into which a homogeneous cylinder, having the density determined by Eq. (13) and a temperature $T \approx 10^4$ K, breaks up. The critical length of the perturbation in this case is

$$\lambda_0 \simeq 7 \cdot 10^3 v_s \rho^{-1/2} = 7 \cdot 10^{19} \rho_{20}^{-1/2} \text{ cm}, \tag{14}$$

(here it is assumed that $v_S = 10^6$ cm/sec, which corresponds to the temperature $T = 10^4$ K; $\rho_{20} = \rho/10^{-20}$ g/cm³). Thus, the mass of a perturbation (in $M_\odot$) with a typical size $\sim\lambda_0$ is

$$M_1 \simeq 6 \cdot 10^8 \rho_{20}^{-1/2}. \tag{15}$$

Since ρ varies with z, it is easy to find, for example, that $M_1 \approx 10^{11}\, M_\odot$ at $z \approx 10^2$. Thus, the masses of the clumps into which the tail breaks up are of the order of the masses of galaxies. Long-wavelength perturbations may lead to their subsequent clustering together and the formation of clusters and groups, more precisely, their seeds, onto which accretion then occurs from a cylinder of radius R_i. The limiting time of development of instability of a homogeneous cylinder is $T_0 \approx 3 \cdot 10^8$ yr. The epoch of nonlinear evolution of these perturbations begins at $z \approx (20\text{-}30)$, and possibly earlier if self-gravitation is taken into account.

Thus, in the string scenario we can obtain bound formations fairly early and explain the formation of large-scale one-dimensional structures – filaments.

Up to now we have considered only accelerating loops. Similar estimates and arguments can be made for strings without acceleration. In this case the length and mass of the filament formed in the wake are smaller than in the preceding variant. In fact, the velocity of such a string varies as $v = v_0 a^{-1}$. The distance traveled by a loop by the end of its life is

$$L \simeq 3 v_0 t_0^{2/3} \tau^{1/3} = 2 \cdot 10^{22} M_{11} \tag{16}$$

and after stretching by Hubble recession, $L \approx 1$ Mpc for a string with $M_{11} = 1$. Such strings evidently will not yield significant filaments, and the model of spherical accretion is applicable in this case, since it is assumed in the existing literature.

But strings satisfying the inequality

$$\left(\frac{c}{v_0}\right)^3\left(\frac{t_0}{t}\right)\left(\frac{a(t)}{a(t_0)}\right)^3\frac{G\mu_l}{c^2} > 1 \tag{17}$$

undergo strong deceleration from background particles, so that extneded one-dimensional structures will not be formed.

4. Thus, one-dimensional structures may be the wakes of rapidly moving massive bodies. Nearly symmetric cosmic strings or massive protoclusters, for example, may play the role of such objects. On the whole, the structure of the universe in the proposed scenario will have a blown-out cellular form, resembling foam, since the gravitational interaction of neighboring wakes can lead to the coalescence of parts of them and the formation of continuous structures of irregular shape.

It is still difficult to give a definite answer to the question of how the filaments thus formed are related to those observed today. The closeness of the calculated parameters – the length and mass – to the observed values indicates that at least some of them have survived to our day. At the same time, filaments are rather unstable formations.

The appearance of one-dimensional formations is a natural property of each of the cosmological scenarios assuming the existence of sufficiently massive bodies moving in a low-mass background medium. For example, it is hard to imagine that all clusters of galaxies in the entropy model have the same mass and peculiar velocity. More likely they have certain mass and velocity distributions, i.e., under certain conditions we can expect the existence of high-velocity clusters with a mass higher than some mean value. In this case lower-mass clusters are clustered toward the accretion axis. The massive clusters themselves gradually decelerate and can provide the start for very massive, nearly stationary giant clusters.

Filaments also appear naturally in a model of the universe containing cosmic strings, among which loops of nearly regular shape should exist, i.e., loops with acceleration. The wake of a loop is broken up into clumps by gravitational instability. The masses of such clumps are close to the masses of today's galaxies. Thus, the formation of massive objects at fairly large red shifts is a second important feature of the proposed scenario. The total mass and length of the wake of a cosmic string, as estimates show, equal the values of the mass and length of the observed filaments.

The proposed scenario is not conclusive, of course, and requires further study.

[1] E. Tago, J. Einasto, and E. Saar, Mon. Not. R. Astron. Soc. 218, 177 (1986).

[2] V. M. Lipunov and S. G. Simakov, Astrophys. Space Sci. 123, 393 (1986).