On the nature of filaments of the large-scale structure of the Universe

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Abstract

Observed properties of filaments which dominate in large-scale structure of the Universe are considered. A part from these properties isn't described within the standard ΛCDM cosmological model. The "toy" model of formation of primary filaments owing to the primary scalar and vector gravitational perturbations in the uniform and isotropic cosmological model which is filled with matter with negligible pressure, without use of a hypothesis of tidal interaction of dark matter halos is offered.

KEYWORDS: galaxies, galaxy clusters, large-scale structure, filaments, gravitational perturbations

1. Introduction

In modern studying of large-scale structure of the Universe it is possible to allocate two great areas for research. The first area is connected with carrying out and the analysis of large sky surveys in various radiation bands. The second area is devoted to numerical modeling of large-scale structure in an N-body approximation and also to modeling of surveys (catalogs) for identification of a role of systematic effects which need to be considered in the analysis of the date of the real surveys. The main result of both research areas is establishment of the fact that the dominant structural element of large-scale structure are filaments, i.e. the chains consisting of galaxies, groups of galaxies, clusters of galaxies, intergalactic gas and dust.

The first filaments were detected in the mid-1970s in the three-dimensional survey of bright galaxies distribution CfA Redshift Survey. The regions with the higher concentration of filaments have allocated in known already then several superclusters, moreover filaments bind superclusters in uniform network with too [1] – [3].

It is difficult to find filament because angular two-point correlation function and the angular power spectrum of galaxy distribution don't contain information on morphological structures of galaxy clustering. For allocation of filament in galaxy surveys the special methods of image processing have been developed (see e.g. [4] – [9]).

On the basis of visualization of numerical simulation results within the standard ΛCDM cosmological model the hypothesis that filaments are a consequence of the tidal interaction of dark matter halos containing galaxies at a nonlinear stage of evolution of large-scale structure has been offered (see e.g. [10] – [12] and references there). Halo's crossings with ellipsoidal forms can lead to an appearance of filaments with higher density of dark matter.

Potentially that within this model by means of selection of parameters, in particular properties of dark matter particles, it will be possible to describe observed properties of filaments. However still there are no direct proofs of existence of dark matter particles [13], [14].

The principal hypothesis of the theory of large-scale structure has also challenges: the baryon captures with dark matter halos. The issue is that before a recombination era the movement of baryon and dark matter at scales less sound horizon are various. Clumps of dark matter contract, clumps of radiation dominated plasma extend as relativistic sound waves. Thus, baryon matter has to move with respect to dark matter before a recombination era and after it. Speeds of this relative movement need to be considered in simulations because small dark matter halo can't gravitationally captures quickly moving streams of baryon matter. Therefore, growth of baryon density contrasts at small spatial scales has to be more slowly in comparison with model in which there are no relative speeds of baryon and dark matters [15]. So far an effect of galaxy speeds on three-point correlation function of their distribution isn't revealed [16]. It, of course, can be connected with quality of measurement of galaxy speeds and also with a hypothesis of dark matter. At last, in work [17] the valid arguments against a hypothesis of existence of dark matter in galaxies and clusters are put forward.

Below we give the facts collected in literature on observed properties of filaments. Some of them are not described (perhaps, so far) with standard ΛCDM model.

These facts and noted difficulties of a dark matter hypothesis stimulate consideration of alternative physical models of filaments. In this work we give a clear example of formation of the extended structures in distribution of matter owing to primary scalar and vector gravitational perturbations in uniform and isotropic cosmological model, staying within the general relativity theory and without use of a hypothesis of tidal interaction of dark matter halos.

Primary gravitational perturbations are described by small perturbations of a space-time metric. The metric perturbations in certain region of space lead to change of a reference system in the region in comparison with a reference system of background cosmological model. Scalar metric perturbation creates in the perturbation region the density of matter which decreases more slowly, than matter density in the extending background reference system. As a result the background observer will find growth of relative density contrast though direct inflow of matter does not happen in this region.

In case of vector gravitational perturbations there are no density contrasts of matter. The space region with the changed reference system extends also as the background space. Vector perturbation transfers change of a reference system to the neighboring regions of background space. The background observer will treat this movement as process of appearance of the directed movement of matter. For example, it is so possible to describe appearance of rotational motion of matter without change of its density.

Let changes of a reference system in the space region be caused by scalar and vector metric perturbations. Then vector perturbation transfers a reference system with scalar perturbation to the neighboring regions of background space. In this case the background observer will see rotation of density contrast or the directed movement of density contrast, or a combination of these movements. Similar movement of several contrasts of density will be observed as the extended structure like filament.

The primary density contrast for formation of a cluster of galaxies will appear in the region of crossing of two or more vector perturbations which transfer the density contrasts. Such filament can be primary structural elements of large-scale structure of the Universe.

Attenuation of vector perturbations has to lead to gradual destruction of primary filament. While the vector perturbation attenuates the scalar perturbations perturbations continue to grow therefore maintaining primary filamentary structure can be provided with collective interaction of contrasts of density, but already at a quasilinear stage of evolution of large-scale structure. In these primary filament galaxies will be formed earlier than in single density contrasts. Besides in primary filamentary structures collisions and merges of protogalaxies are more probable therefore in them more massive galaxies have to be formed.

2. Data analysis

Filaments are found up to red shifts of $z \sim 4$. Now owing to complex analysis of data of reviews CfA2, 2dF, SDSS, 2MASS, 6dF, GAMA, VIPERS, 2MPZ, WISExSCOS ([18] – [24]) the following facts are established:

1. Length of filaments 50 — 200 Mpc, width one order less. About a half of all observed galaxies belong to filaments, and no more than 20% from them belong to clusters and groups in these filaments. Clusters of galaxies are on crossing of filaments, but there are no clusters in all crossings of filaments. Superclusters of galaxies consist of the filaments including which are crossed. Superclusters are connected with each other by filaments and form the cosmic web (large-scale structure) [25] – [29].

2. The analysis of observations relatively close filaments with red shifts of $z < 0.9$ in several spectral bands (infrared, optical, x-ray) allowed to establish that there is a lot of warm gas in them. It is revealed that red galaxies with larger masses are mainly inside or closer to a filament, than blue low-massive galaxies. The larger galaxies (were formed earlier) are inside or closer to filament in comparison with small galaxies (were formed later). The distinction of the population of galaxies (passive, early types, red) in clusters and in the filaments connecting these clusters is not revealed [30] – [34].

3. Big axes of galaxies have the allocated direction: they are aligned (statistically significantly) along the direction of the filament which contains them, or along the filament to which they are the closest. This alignment is stronger expressed for the bright galaxies formed during earlier era than for the pale galaxies formed later [35] – [39].

4. The analysis of line-of-sight speeds of galaxies allowed to find out that galaxies move mainly towards the nearest filament, and galaxies move to the nearest cluster of galaxies in a filament [40] – [42]. It means that galaxies of the filament, most likely, were formed in the filament. Speeds of galaxies are large, and a characteristic time of crossing of the filament by them is less than age of galaxies therefore they could leave a filament if they got to it from external space.

Galaxy clusters accrete intergalactic gas and galaxies from the filaments at whose intersections they are located. It is confirmed by the facts, first in clusters the speeds of galaxies and temperature of intergalactic gas are exceeded by values which would be for clusters in the virial equilibrium. Secondly, scale relations between x-ray luminosities of clusters, temperatures of intergalactic gas in clusters and dispersions of galaxy speeds in clusters considerably differ from relations for clusters in the virial equilibrium (see [43] and references there). Let's note what deviations from virial equilibrium is often treated as sign of presence of dark matter.

5. Huge filaments with scales from several hundred megaparsecs to gigaparsecs are found in distribution of galaxies and clusters, quasars, gamma bursters (Great Wall, Great GRB Wall, Hyperion, LQG) [44] – [54]. The extent of these structures is greater by several times the maximum scale of clustering for correlation function of galaxies in standard cosmological ΛCDM-model.

The first of the listed facts well is reproduced in numerical simulations within ΛCDM-model (see, for example, [55], [56] and references there). According to these simulations filaments of dark matter appear at red shifts of $z \sim 3-5$, two-dimensional structures which limit voids are gradually formed of them at $z < 1$. The maximum scales of voids do not exceed 300 Mpc for cosmological parameters of modern ΛCDM-model. This maximum scale places upper limit of the filament size and this contradicts existence of the huge filaments (fact 5). Authors of simulations of large-scale structure assume that the huge filaments are a consequence of a projection, but not real objects. However, evidences of alignments of red galaxies and quasars along the huge filament LQG are already found [57], [58]. It confirms reality of the filament LQG and indicates difficulty of ΛCDM-model.

Facts 2 — 4 indicate that galaxies in filaments were formed right in these filaments. The filaments are primary structures and galaxies were formed in them earlier (are observed as massive red galaxies) than galaxies out of filament (are observed as low-massive blue galaxies).

3. Model of formation of primary filament from scalar and vector gravitational perturbations

For clarity we will choose uniform and isotropic cosmological model which is filled with matter with negligible pressure (dust) and has a synchronous metrics:

$$ds^2 = g_{ik} d\mathrm{x}^i d\mathrm{x}^k = a^2(d\eta^2 - d\mathrm{x}^2 - d\mathrm{y}^2 - d\mathrm{z}^2), \tag{1}$$

where Latin indexes run values 0, 1, 2, 3; large-scale factor $a = a_0\eta^2 = a_0\left(\frac{t}{t_0}\right)^{2/3}$; t is a cosmological time; η is a conformal time; x, y, z are spatial coordinates. We will adhere to the terminology used in the classical book [59].

Gravitational perturbations are described by means of small perturbations to a background metric (1) (synchronous gauge):

$$g_{ik} \to g_{ik} + h_{ik}$$

$$h_{00} = 0 = h_{0\alpha}, \tag{2}$$

Here the Greek indexes run values 1, 2, 3. In linear approach small perturbations satisfy to the equations

$$\delta G_i^k = \kappa \delta T_i^k, \tag{3}$$

where κ is Einstein gravitational constant, δG_i^k is perturbation of Einstein tensor, δT_i^k is a perturbation of the energy-momentum tensor of matter. For dust we have the equation

$$\delta T_i^k = \varepsilon(u_i \delta u^k + u^k \delta u_i) + \delta\varepsilon u_i u^k.$$

Here $\delta\varepsilon$ is a perturbation of matter density, $\varepsilon = \varepsilon_0 \left(\frac{a_0}{a}\right)^3$, components of four-dimensional speed u^k and its perturbation δu^k are in accord with the conditions: $u^\alpha = 0$, $u^0 = \frac{1}{a}$, $\delta u^0 = 0$.

In the space-time with a metric (1) there can be three types of gravitational perturbations: scalar, vector and tensor. Here we will consider scalar and vector perturbations. At tensor perturbations (gravitational waves) the matter remains uniform and does not get the additional speed therefore formation of filament cannot be connected with them.

Let's submit a scalar metric perturbation $(h_\alpha^\beta)_{S,n}$ in the form of a flat wave with a wave vector n_α and as the sums of isotropic (amplitude μ_n) and anisotropic (amplitude λ_n) of tensors:

$$(h_\alpha^\beta)_{S,n} = \left[\mu_n \frac{1}{3}\,\delta_\alpha^\beta + \lambda_n \left(\frac{1}{3}\,\delta_\alpha^\beta - \frac{n_\alpha n^\beta}{n^2}\right)\right] e^{in_\alpha \mathrm{x}^\alpha}. \tag{4}$$

Scalar gravitational perturbation creates the following density contrast:

$$\left(\frac{\delta\varepsilon}{\varepsilon}\right)_n = \frac{a}{3\kappa\varepsilon_0 a_0^3}\left[n^2(\lambda_n + \mu_n) + 3\,\frac{a'}{a}\,\mu_n'\right] e^{in_\alpha \mathrm{x}^\alpha},$$

where the stroke means differentiation with respect to η. It is known [59] that the equations (3) for scalar perturbations (4) have the solution with the growing density contrast $\frac{\delta\varepsilon}{\varepsilon} = \delta_0\,\frac{a}{a_0} = \delta_0 \eta^2$ and there is no perturbation of usual three-dimensional speed:

$$(a\delta u^\alpha)_{S,n} = \frac{1}{3\kappa\varepsilon_0 a_0^3}\, a\, n^\alpha (\lambda_n + \mu_n)' e^{in_\alpha \mathrm{x}^\alpha} = 0.$$

This growth of density contrast is connected not with inflow of matter to region with the perturbed metric of space, but with the fact that in this region a density of matter decreases more slowly $\delta\varepsilon = \delta_0\varepsilon_0\eta^{-4}$, than decrease of density in a background reference system $\varepsilon = \varepsilon_0\eta^{-6}$.

We will submit the vector metric perturbation $(h_\alpha^\beta)_{V,m}$ in the form of a cross vector wave with a wave vector m_α and an amplitude σ_m:

$$(h_\alpha^\beta)_{V,m} = \sigma_m \frac{l_\alpha m^\beta + l^\beta m_\alpha}{m} e^{im_\alpha \mathrm{x}^\alpha}, \; l_\alpha m^\beta = 0\,. \tag{5}$$

It is known [59] that the equations (3) for vector perturbation (5) have the solution with a perturbation of speed $(a \cdot \delta u^\alpha)_{V,m} = -\dfrac{ml^\alpha}{2\kappa\varepsilon_0 a_0^3}\, a\,\sigma' e^{im_\alpha \mathrm{x}^\alpha}$ which decreases as η^{-2}. The vector perturbation does not create density contrasts of matter. The space region with the vector perturbation extends also as well as background space. Owing to the perturbation of speed the vector perturbation of a reference system is transferred to the neighboring regions of background space. Thus, vector metric perturbation belongs to the effects of the general relativity theory (see [60]).

Small perturbations (4) and (5) satisfy to the equations (3). The same goes for the gravitational perturbation which is described by the sum of perturbations of (4) and (5). For such scalar and vector perturbation from the equations (3) it is possible to find the following equations for amplitudes λ_n, μ_n, σ_m:

$$\begin{gathered}
\lambda_n'' + 2\frac{a'}{a}\,\lambda_n' - \frac{n^2}{3}(\lambda_n + \mu_n) = 2\frac{m_\alpha n^\alpha}{mn}\frac{l_\beta n^\beta}{n}\left(\sigma_m'' + 2\frac{a'}{a}\,\sigma_m'\right) e^{i(m_\alpha - n_\alpha)\mathrm{x}^\alpha}, \\
\mu_n'' + 2\frac{a'}{a}\,\mu_n' + \frac{n^2}{3}(\lambda_n + \mu_n) = 0, \\
a\delta u^\alpha = \frac{a}{2\kappa\varepsilon_0 a_0^3}\left[\frac{2}{3}\,n^\alpha(\lambda_n + \mu_n)' e^{in_\alpha \mathrm{x}^\alpha} - ml^\alpha \sigma_m' e^{im_\alpha \mathrm{x}^\alpha}\right], \\
\frac{\delta\varepsilon}{\varepsilon} = \frac{a}{3\kappa\varepsilon_0 a_0^3}\left[n^2(\lambda_n + \mu_n) + 3\frac{a'}{a}\,\mu_n'\right] e^{in_\alpha \mathrm{x}^\alpha}.
\end{gathered} \tag{6}$$

Let's emphasize that generally $m_\alpha n^\alpha \neq 0$, $l_\alpha n^\alpha \neq 0$, therefore the solution (6) describes imposing of two types of gravitational perturbations in one space region.

We use the first two equations of system (6). Let's sum up these two equations and after simple transformations we will receive the equation connecting $(\lambda_n + \mu_n)$ and σ_m':

$$\left(a^2(\lambda_n+\mu_n)'\right)' = 2\frac{m_\alpha n^\alpha}{mn}\frac{l_\beta n^\beta}{n}\left(a^2\sigma'_m\right)' e^{i(m_\alpha-n_\alpha)\mathrm{x}^\alpha}. \tag{7}$$

The equation (7) has the solution:

$$\begin{gathered}(\lambda_n+\mu_n)' = 2\frac{m_\alpha n^\alpha}{mn}\frac{l_\beta n^\beta}{n}\sigma'_m e^{i(m_\alpha-n_\alpha)\mathrm{x}^\alpha} + \frac{\mathrm{C}_1}{a^2}\,,\\ \lambda_n+\mu_n = (\lambda_n+\mu_n)_0 + 2\frac{m_\alpha n^\alpha}{mn}\frac{l_\beta n^\beta}{n}(\sigma_m-(\sigma_m)_0)e^{i(m_\alpha-n_\alpha)\mathrm{x}^\alpha} + \mathrm{C}_1\int_{\eta_0}^{\eta}\frac{d\eta}{a^2}\,,\end{gathered} \tag{8}$$

where the lower index zero indicates the value of functions at the initial moment $\eta_0 = 1$, C_1 is the integration constant which is equal

$$\mathrm{C}_1 = 2\frac{m_\alpha n^\alpha}{mn}\frac{l_\beta n^\beta}{n}\left(a^2\sigma'_m\right)_0 e^{i(m_\alpha-n_\alpha)\mathrm{x}^\alpha} - \left(a^2(\lambda_n+\mu_n)'\right)_0.$$

Using the solution (8), we receive expressions for the speed $a\cdot\delta u^\alpha$ and the density contrast $\dfrac{\delta\varepsilon}{\varepsilon}$:

$$\begin{gathered}a\cdot\delta u^\alpha = \frac{a}{2\kappa\varepsilon_0 a_0^3}\left[\left(\frac{4}{3}n^\alpha\frac{m_\alpha n^\alpha}{mn}\frac{l_\beta n^\beta}{n} - ml^\alpha\right)\sigma'_m e^{im_\alpha\mathrm{x}^\alpha} + \frac{2}{3}n^\alpha\frac{\mathrm{C}_1}{a^2}e^{in_\alpha\mathrm{x}^\alpha}\right],\\ \frac{\delta\varepsilon}{\varepsilon} = \frac{a}{3\kappa\varepsilon_0 a_0^3}\left[n^2\left((\lambda_n+\mu_n)_0 + 2\frac{m_\alpha n^\alpha}{mn}\frac{l_\beta n^\beta}{n}\,(\sigma_m-(\sigma_m)_0)e^{i(m_\alpha-n_\alpha)\mathrm{x}^\alpha} + \right.\right.\\ \left.\left. + \mathrm{C}_1\int_{\eta_0}^{\eta}\frac{d\eta}{a^2}\right) + 3\frac{a'}{a}\mu'_n\right]e^{in_\alpha\mathrm{x}^\alpha}.\end{gathered} \tag{9}$$

Apparently from expressions (9), in the absence of vector perturbation we have the classical increasing mode [59] for the density contrast: $\dfrac{\delta\varepsilon}{\varepsilon} = \dfrac{a}{3\kappa\varepsilon_0 a_0^3}\,n^2(\lambda_n+\mu_n)_0\,e^{in_\alpha\mathrm{x}^\alpha} = \delta_0\eta^2$ and $(\lambda_n+\mu_n) = const$, $\mathrm{C}_1 = 0$. In this case three-dimensional speed is equal to zero $a\cdot\delta u^\alpha = 0$, i.e. the space region with the scalar metric perturbation does not move with respect to the background reference system. Because of the scalar perturbation the matter density decreases more slowly, than the matter density in the background reference system, therefore the density contrast grows in perturbed region, but there are no matter streams to this region.

In the presence of vector perturbation the speed $a\cdot\delta u^\alpha$ of density contrast $\dfrac{\delta\varepsilon}{\varepsilon}$ depends on amplitudes of scalar and vector perturbations of a metrics.

For example, for the classical solution with $C_1 = 0$, $m_\alpha n^\alpha = mn$, $l_\alpha n^\alpha = 0$ and $\sigma_m = \dfrac{(\sigma_m)_0}{\eta^3}$ the density contrast gets the speed $a \cdot \delta u^\alpha$ which direction is perpendicular to a wave vector n^α, i.e. the vector perturbation creates rotation of scalar perturbation. The rotation speed decreases as η^{-2}, therefore the rotation moment is conserved: decrease of speed is compensated by increase in the sizes of space region because of the general expansion of space.

Two types of power solutions of the equations (6) for the growing modes of density contrasts are given in Table 1. For scalar and vector perturbation at $m_\alpha n^\alpha \neq 0$, $l_\alpha n^\alpha \neq 0$ the equation (6) have the solutions describing a combination of two types of movements of density contrast — rotation and the directed movement. The moment of impulse is conserved $a(a \cdot \delta u^\alpha) \cdot \delta\varepsilon = const$ for $k = 4$.

Such directed movement of several density contrasts will create the extended structure from the contrasts of density which will be primary perturbation for future filament.

The described "toy" model shows the basic physical elements of formation of primary filaments. And appearance of such filaments is connected with vector perturbations of a reference system and therefore is effect of the general relativity theory.

Table 1: The power solutions of the equations (6) for the growing modes of density contrasts

<table>
<tr><th>Classical solution</th><th>Solution for scalar and vector perturbation</th></tr>
<tr><td>Scalar metric perturbation:
$(\lambda_n+\mu_n)=const,$
$\dfrac{\delta\varepsilon}{\varepsilon}=\delta_0\eta^2,$
$a\cdot\delta u^\alpha=0$</td>
<td rowspan="2">$\sigma'_m=\dfrac{(\sigma_m)_0}{\eta^k}$
$(\lambda_n+\mu_n)'=2\mathrm{C}_{lmn}\dfrac{(\sigma_m)_0}{\eta^k}e^{i(m_\alpha-n_\alpha)\mathrm{x}^\alpha}+\dfrac{\mathrm{C}_1}{a_0^2}\dfrac{1}{\eta^4},$
$\mathrm{C}_{lmn}=\dfrac{m_\alpha n^\alpha}{mn}\dfrac{l_\beta n^\beta}{n}$
$(\lambda_n+\mu_n)=(\lambda_n+\mu_n)_0+\dfrac{2}{k-1}\mathrm{C}_{lmn}(\sigma_m)_0\times$
$\times\left(1-\dfrac{1}{\eta^{k-1}}\right)e^{i(m_\alpha-n_\alpha)\mathrm{x}^\alpha}+C\left(1-\dfrac{1}{\eta^3}\right)$
$a\cdot\delta u^\alpha=\dfrac{\eta^2}{2\kappa\varepsilon_0 a_0^2}\left[\left(\dfrac{4}{3}\mathrm{C}_{lmn}n^\alpha-ml^\alpha\right)\dfrac{(\sigma_m)_0}{\eta^k}\;e^{im_\alpha\mathrm{x}^\alpha}+\right.$
$\left.+\dfrac{2\mathrm{C}_1}{3a_0^2}\dfrac{n^\alpha}{\eta^4}\;e^{in_\alpha\mathrm{x}^\alpha}\right]$
$\dfrac{\delta\varepsilon}{\varepsilon}=\dfrac{n^2\eta^2}{5\kappa\varepsilon_0 a_0^2}\left[\left((\lambda_n+\mu_n)_0+\dfrac{\mathrm{C}_1}{3a_0^2}\right)\;e^{in_\alpha\mathrm{x}^\alpha}+\right.$
$\left.+\;\dfrac{2\mathrm{C}_{lmn}(\sigma_m)_0}{k-1}\;e^{im_\alpha\mathrm{x}^\alpha}\right]$</td></tr>
<tr><td>Vector metric perturbation:
$\sigma_m=\dfrac{(\sigma_m)_0}{\eta^3},$
$\dfrac{\delta\varepsilon}{\varepsilon}=0,$
$a\cdot\delta u^\alpha=\dfrac{3ml^\alpha}{2\kappa\varepsilon_0 a_0^2}\dfrac{(\sigma_m)_0}{\eta^2}\;e^{im_\alpha\mathrm{x}^\alpha}$</td></tr>
</table>

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