Kinematics of Galaxy Groups: Pressure of Dark Energy or Dissipative Fractal Acceleration?

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Abstract: In the last years, so-called ``coldness'' (low velocity dispersion of the Hubble flow) in periphery of loose galaxy groups is usually explained as the effect of dark energy pressure. We propose an alternative hypothesis: this is the effect of dissipative fractal acceleration acting from non-local fractal distribution of gravitating matter with dimension $D \approx 2$ on the galaxies escaping from groups, and directed against the galaxy velocity. The value of this acceleration is approximately equal to $a=Hc \approx 8\cdot10^{-8}$ cm/s^2, where c is the speed of light and H is the Hubble constant. We analyze both hypotheses for the Local Group of galaxies and make a conclusion that the observed low redshift dispersion of the so-called Hubble flow is better explained by the dissipative fractal acceleration. Some additional arguments in favor of the dissipative fractal acceleration effect are given.

1. Introduction

At the turn of XX and XXI centuries, the standard cosmological model has faced some difficulties. One of them was noted by Sandage et al. [1]: Why the Hubble flow in vicinity of the Local Group is so linear and cold?

Governato et al. [2] have studied in details an anomalous “coldness” of the velocity field in vicinity of the Local Group of galaxies till the radius of about 5 Mpc. The deviations from the ideal Hubble law do not exceed 60 km/s, whereas in different N-body cosmological models, the same velocity dispersions were several times greater. Further improvements of observed data have shown that the dispersion may be even less (< 40 km/s), and that can be explained by the uncertainties of observations.

Various versions of a standard cosmological model failed to explain this effect. On the other hand, at the end of the past century, some indications (due to supernovae data) were found [3] that the Universe on the large scales may expand with acceleration. This work has stimulated to develop a concept on the accelerated expansion of the Universe by ``pushing'' action to the galaxies of some substance, so-called dark energy, cosmological vacuum, or quintessence. These models were called the ΛCDM-models. Let’s note that, as we know, any alternative models to explain the supernovae data were not discussed in literature. Really, the ΛCDM-models have become new standard models in cosmology. In the cycle of papers [4-7], the ΛCDM-models were applied to explain the anomalous behavior of the galaxy velocity field near the Local Group and other nearby galaxy groups.

In the space region usually named the Local Volume (within 10 Mpc), the expansion is rather regular and has low velocity dispersion, although there are large clumps in the matter distribution (groups and clusters of galaxies). Moreover, we do not observe any signs of the fall of galaxies to the nearby groups [8].

Chernin et al. [4] assume that this effect is explained by domination of the dark energy pressure over the group gravity at the scales 1-2 Mpc and more. The authors [4] believe that the dark energy ``pushes'' the galaxies from the center of the group. They introduce a term “sphere of zero gravity”, in its surface the forces of gravity and ``pushing'' are approximately in balance. This radius for the Local Group is about 1.3 Mpc. Let’s note that the assumption about such “centering” action of the dark energy may be only justified in small vicinity of a group if the action of dark energy in neighbor groups is similar and then the galaxies escaping from their groups will cover each other and we’ll observe mixing of different velocity fields. The authors [4-7] consider a galaxy group as isolated system, although the nearby gravitating objects may change the situation radically.

Also let’s note that the model of local expansion [4] is qualitatively different from the classical de Sitter model with Λ-term. In the de Sitter model, the space itself expands with acceleration. In the model [4], a “pushing” of galaxy groups has to lead to appearance of additional accelerations of the group components ejected beyond the “sphere of zero gravity” with respect to the co-moving frame. Therefore, it is possible to observe both the excess redshifts and the deficient redshifts with respect to a whole Hubble flow.

The model [4] of the Local Universe describes it as a spherical “vacuole” inside a homogeneous matter distribution corresponding to the Einstein-Straus model [9]. The authors [4] try to agree the model of local vacuole with global cosmological flow and have found a connection between the radius R_V of the “sphere of zero gravity” of a galaxy system and the radius $R_L(t_0)$ of its vacuole at the present epoch t_0:

$$R_V \approx 0.6 R_L(t_0). \quad (1)$$

The dark energy dominates at the distances (0.6-1)$R_L(t_0)$ from the center of group. At the larger distances, the Universe has a cosmological expansion. On the other hand, the authors [4] say about a possibility of existence of many vacuoles with various masses and sizes. The vacuoles may fill almost the whole Universe forming a regular but inhomogeneous structure that expands with acceleration. The authors believe that the de Sitter solution is an asymptotic in the limit when the pressure of dark energy is a dominating factor.

As for the effect of dark energy pressure on cooling of the local Hubble flow, the authors [4] believe that an additional decrease of velocity dispersion takes place due to accelerating expansion of the local vacuole. They think that the estimates of "coldness" of the Local Group are in agreement with observation data within 1-3 Mpc from the center of the group.

At the same time, some difficulties exist in concordance of the vacuole model and observations (some of them were mentioned in [4]):

1. The problem of contact between the local vacuole and the Hubble flow at the distances greater than the vacuole size.
2. The problem of contacts between vacuole expansions connected with neighbor galaxy groups (in particular, according to [10], at least six groups are placed within spherical belt of 3-6 Mpc around the Local Group).
3. The source of vacuole expansion and correspondence of the model under consideration to the matter heating to the thermodynamics laws are not clear (it is of interest to compare this with the ideas by Harrison [11]).
4. The mechanisms of dark energy pressure on the galaxies, as well as the dependence of the pressure force on effective cross-section and object mass are also unclear.

Thus, the description [4] of the matter in the Local Volume as a vacuole embedded in the global Friedmann Universe has some difficulties. Let's also note that the term "antigravity" used by these authors is not applicable to the situation as the acceleration due to the dark energy is proportional to the distance, not its inverse square as in the universe attraction law. This acceleration corresponds to the Hook law. We propose an alternative concept, whose basic items, some observational consequences, and the results of simulations are discussed below.

2. Dissipative fractal acceleration and the nature of redshift

As we mentioned in the Introduction, the standard cosmological model faces several essential difficulties:

1) The Hubble law has not to be valid within the Local Volume, because some non-homogeneities of the matter distribution in the groups and clusters are strong within these scales;
2) The contact between Hubble constant values in the Local Volume and cosmological scales in unclear (from general considerations, these two values can be different); here we can mention that cosmological expansion has to start beginning from the scales of homogeneity cell (see, e.g. [12], pp. 13-14);
3) The anomalously low galaxy velocity dispersion within the local Hubble flow.

The hypothesis of stationary fractal with gravitational redshift [13, 14] has also faced difficulties. As Baryshev wrote later in [15] (p. 354), the mass in near Universe can give a value of gravitational Hubble constant three orders of magnitude less than the observed one. Also one has to bear in mind the structure of the Local Group that consists of two giant galaxies (M31 and the Galaxy) and a few tens dwarf galaxies which total mass is at least one order less. Then the 3D map of gravitational potential of the Local Group is defined by these two giant galaxies (by the law r^{-1}), and the linear dependence of redshift on the distance cannot be explained.

However, the modified version of the fractal model can improve the situation. We propose a concept that is described in [16] in more details. The main idea is a special character of motion of the particle inside the self-gravitating fractal (SGF). In our case, the equation of particle motion has the form [16]

$$\frac{d\mathbf{v}}{dt} = \mathbf{a}_{\Sigma} - H_{dis} c \frac{\mathbf{v}}{|\mathbf{v}|}, \quad (2)$$

where $\mathbf{a}_{\Sigma}$ is vector sum of accelerations which act to the particle (excluding new dissipative term (see below)); H_{dis} is the dissipative Hubble constant (see below); c is the speed-of-light.

In our case, the reason of energy loss is different from that in [13, 14]. Baryshev assumed that a photon "reddens" when it goes corresponding difference of potentials (see Okun' et al. [17]). We think that a photon or massive particle lose the energy when they interact with the carriers of the gravity field (gravitons), whose totality is similar to the viscous medium, so the damping of the particle is a dissipative process.

If the fractal acceleration has a dissipative character then we can estimate in order of magnitude the variation of kinetic energy of the particle with the mass *m* that moves with velocity v through the SGF with dimension $D = 2$:

$$\frac{dE}{dt} \cong m\mathrm{v}a_H = m\mathrm{v}Hc = mc^2 H\frac{\mathrm{v}}{c} = mc^2\frac{\mathrm{v}}{R_H} \cong \frac{c^5}{G}\frac{m}{M_H}\frac{\mathrm{v}}{c}. \tag{3}$$

The typical rate of the photon energy loss is as follows

$$\frac{dE}{dt} \cong \frac{E}{T_H} \cong \frac{hc}{\lambda} = hH\frac{c}{\lambda}, \tag{4}$$

where $T_H = H^1$ is the Hubble time, R_H and M_H.are the Hubble radius and Hubble mass, λ is the photon wavelength.

Introducing the de Broglie wavelength,

$$\lambda = \frac{h}{m\mathrm{v}}, \tag{5}$$

we find Eq. 3 from Eq. 4. This fact leads to the idea that the processes of the energy loss by massive particle and photon have the same dissipative nature. When photon or massive particle goes the distance λ, it loses the energy *hH*. The photon decreases its frequency (increases its wavelength, i.e., it "reddens"), and the massive particle loses its kinetic energy. These formulae (3) - (5) connect two processes: braking of the spacecrafts "Pioneers" and a smoothness of the Hubble flow.

The presence of the second term in the right part of Eq. 2 leads to that the work on the shift of the particle in the space depends on the concrete trajectory like the viscous medium. Therefore the SGF is a non-conservative system. Therefore, the notions `potential` and `difference of potentials` may be used with care and only within the limited regions of space.

Let's note that there is a significant difference between the behavior of the particle or photon in the local gravitational field (e.g. on the Earth) and at the Hubble scales (for comparison see Okun' et al. [17]). When there is a local condensation of gravitating matter the force lines of gravity field form a divergent structure. In this case the energy density of the gravitational field may be calculated using the following formula

$$\rho_G = \frac{(\nabla\varphi)^2}{8\pi G c^2}. \tag{6}$$

In the case under consideration (a stochastic fractal with $D = 2$), the force lines are "randomized", and the energy of gravity field has to be calculated by other ways. Let's estimate by the orders of magnitude. Let's consider the density of gravitational field as a constant, and at the Hubble scales it is comparable with the matter density (this is a consequence from the thermodynamic ideas formulated below), then we have

$$\rho_G \cong \frac{M_H}{R_H^3} \cong \frac{H^2}{G} \cong \frac{\mathrm{a}_H^2}{Gc^2}. \tag{7}$$

Then the scalar $\boldsymbol{a}_{\mathrm{H}}^2$ dominates in the most part of the SGF volume. Unlike the potential field, where the acceleration vector of the particle in the system of gravitating masses is calculated by the superposition principle and it is directed to the center-of-mass of the system, in this case, the vector $\boldsymbol{a}_{\mathrm{H}}$ is directed along the tangent to the trajectory. When a particle moves inside the SGF, the linear dependence of the redshift on the distance has also to be valid. However, in this case, it is defined not by the difference of potentials between two points, but by the effect of irreversible energy loss during the motion through a homogeneous "viscous" medium. Thus, here a field of gravitons looks like the "dark energy", however it does not push, but it damps the photons and massive particles. As a result, we have no problems with the thermodynamics laws in contrast to pushing dark energy, because this process is irreversible. Here we have an energy transfer to the "heat" (radiation of gravitational waves).

We'll use the Local Group of galaxies as the observed input data to test the models. Fig. 1 shows the dependence between the separation from the center of the group (we suggest that it is placed between our Galaxy and M31 two times closer to M31) and redshift of the galaxy with respect to this center according to Karachentsev et al. data [18]. A large dispersion of velocities *cz* is seen at the distances less than 1.3 Mpc (velocity dispersion is about 100 km/s). This is a virialized part of the group. Then we observe an approximately straight linear increase of the velocity when the distance grows till ~ 3 Mpc. When the separation increases further, the function *cz*(*R*) does strongly change: a cloud of "dispersed points" is observed. This effect is probably connected with other nearby virialized galaxy groups, where the velocity dispersion may be significant (~ 100 km/s).

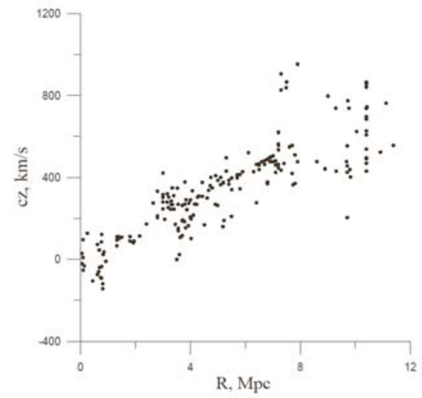

Fig. 1. The dependence of redshift on the distance from the center of mass of the Local Group.

3. Toy Models

Let's consider two toy models. Let's assume that the galaxy of mass *m* escapes from the group of mass *M* along the radial orbit and has a positive energy. If the dark energy pressure acts to the galaxy, then the equation of relative motion has the form

$$\ddot{r} = -\frac{G(M+m)}{r^2} + \Lambda r, \tag{8}$$

where the constant

$$\Lambda = \frac{8\pi}{3} G\rho_V \approx 3.8 \cdot 10^{-30} s^{-2}, \tag{9}$$

and ρ_V is the density of dark energy. One example of acceleration change for toy model is shown in Fig. 2 (the model parameters are given below). We can see a sharp increase of acceleration (according to the law of inverse squares) when we have the withdrawal from gravitating mass and then the transition to the linear regime after crossing the sphere of zero gravity.

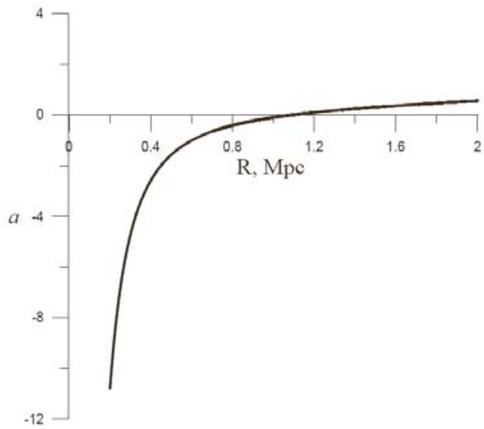

Fig. 2. The dependence of acceleration on the distance from the center of mass of the group for the model with dark energy.

On the other hand, one can assume that the dissipative fractal (DF) acceleration acts to the galaxy escaping from the galaxy group. Then the galaxy will move with acceleration

$$\ddot{r} = -\frac{G(M+m)}{r^2} - a, \tag{10}$$

where a = const ≈ $8 \cdot 10^{-8}$ cm/s^2 is the constant acceleration that is directed against the velocity vector and acts while the orbit of escaping galaxy is hyperbolic [16]. The nature of this effect is unclear but it is observed in motion of as the spacecrafts "Pioneers", as in the galaxy groups.

Let's numerically integrate Eq. 8 and Eq. 10 at the same initial data: V_0 = 200 km/s, R_0 = 1.3 Mpc, M=10^{12} $M_{\odot}$, m=10^{10} $M_{\odot}$. The results are shown in Fig. 3 and Fig. 4. In the first case, the velocity of escaping is approximately linear function of separation at the large separations. In the second case, due to DF acceleration the velocity rapidly decreases till the parabolic one and then (when the action of this acceleration stops) the gravitational force is the only factor that manages the motion. The only first term is in the right part of Eq. 10. Then the velocity slowly decreases as $R^{-1/2}$ till the escaping galaxy comes into the sphere of action of another attracting center, e.g. neighbor galaxy group.

Let's note that in the first case, the galaxies can eject beyond the sphere of zero gravity with different velocities and at different times. This leads to dispersal of radial velocities of the distant components of the group. The pressure of dark energy slightly decreases the dispersion of radial velocities beyond the sphere of zero gravity, however it is conserved rather high and can reach ~ 100 km/s. Moreover, the effects of neighbor groups can increase the velocity dispersion. At the same time, the presence of DF acceleration abruptly decreases the velocity dispersion of escaping galaxies, which is in agreement with the data of observations for nearby galaxies [18].

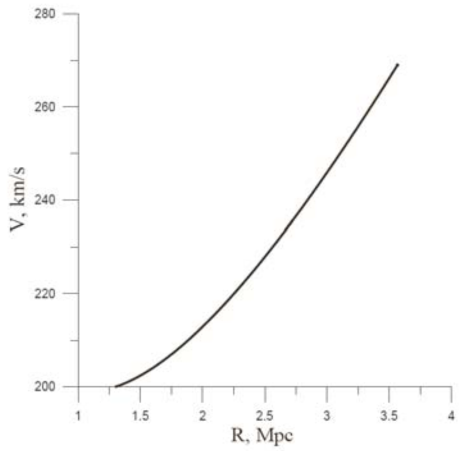

Fig. 3. The dependence of radial component of velocity on the distance from the center of mass of the group for the case of dark energy pressure.

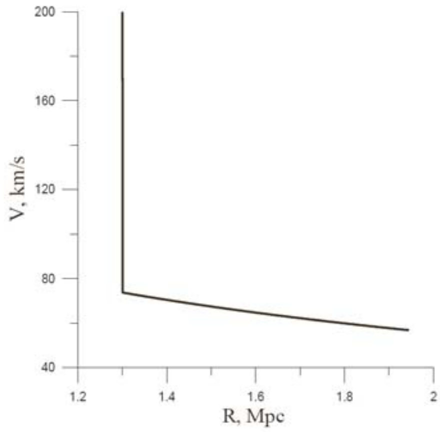

Fig. 4. The dependence of radial component of velocity on the distance from the center of mass of the group for the case of fractal acceleration.

In Fig. 5 and Fig. 6, we show the dependences of radial velocities on the distance from the center of mass of the group for the simulated groups similar to the Local Group: two heavy galaxies with the masses $2{\cdot}10^{12}\ M_{\odot}$ (analog of M31) and $10^{12}\ M_{\odot}$ (analog of the Galaxy), as well as 30 smaller galaxies with the masses $10^{10}\ M_{\odot}$. These dependences are shown at the time of 10^{10} yrs from the start of evolution.

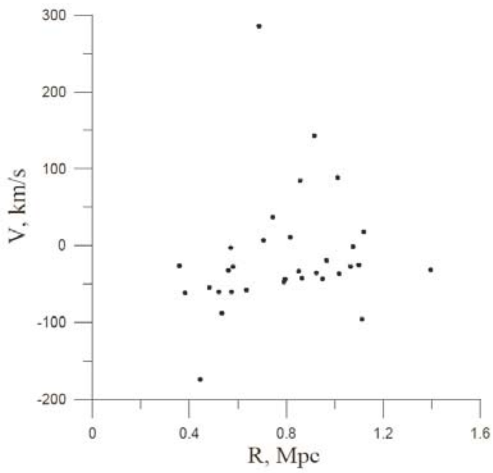

Fig. 5. The dependence of radial component of velocity on the distance from the center of mass of the group for the case of dark energy pressure in the N-body model.

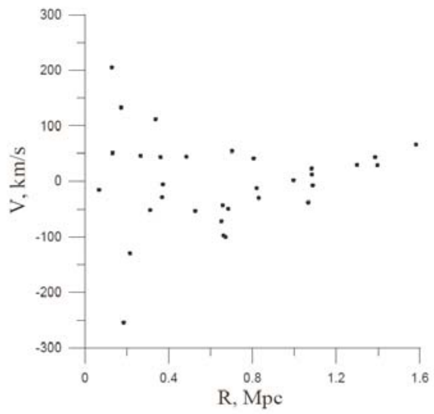

Fig. 6. The dependence of radial component of velocity on the distance from the center of mass of the group for the case of fractal acceleration in the N-body model.

In case of dark energy pressure (Fig. 5), the dispersion of peculiar velocities in outer parts of the galaxy group is significantly higher than in case of DF acceleration (Fig. 6) and it is in disagreement with observations of the Local Group. In the second case, the dispersion of velocities beyond the sphere with radius ≈ 0.8 Mpc is about 30 km/s and that agrees with data of observations. Moreover, the pressure of dark energy leads to "blowing" of the galaxies from the central part of the group (Fig. 5). As a result, the "cavern" with the radius ≈ 0.4 Mpc is formed around the center of the group. This also contradicts to the observations. Thus, the numerical toy models evidence in favor of DF acceleration and contradict to the models with dark energy pressure.

4. Discussion

Usually, in the Newtonian dynamics of stellar systems, motions of individual objects are considered as random walk in the fluctuating gravitational field. We consider the bi-component system: the sources of gravity field and "porters" of gravitational interaction (gravitons). According to thermodynamic ideas, the gravitons, moving with velocities c tend to smooth the local non-homogeneities of energy density for the gravity field (Raikov [19]). Also they manage the evolution of the 3D distribution of the massive component constructing it in the fractal of dimension $D = 2$. These qualitative ideas help to understand the evolution of the self-gravitating systems and can shed light on the problem that is known in cosmology as thermodynamics paradox. Within the framework of this bi-component model, we can also explain the gravitational paradox of Neumann-Seeliger.

Simple estimates show that the relative volume of space where the accelerations are big is extremely narrow. So, e.g. the accelerations of ~ 10^3 cm/s^2 are observed in vicinity of the Earth, and the ones of ~ 1 cm/s^2 are observed at the separations of order of 1 AU from the Sun etc. The volume in the solar neighborhood with a radius of about 0.01 pc on the boundary of which the solar acceleration is comparable with that from regular galactic field is less than that where the regular Galactic field dominates (with a typical size corresponding to the average distance to the star that is the nearest neighbor ~ 1 pc) by about six orders of magnitude.

It is of interest to estimate the typical accelerations in physical units and draw the 3D "acceleration map", revealing the regions of large accelerations (near the massive and compact objects – stars, planets etc.) and zones of small accelerations (far from the massive objects). So, e.g. the acceleration of regular Galactic field in solar neighborhood is ~ 10^{-8} cm/s^2 that is comparable with the anomalous accelerations of the Pioneer spacecrafts. The accelerations from individual galaxies at the scales of galaxy groups (~ 1 Mpc) are ~ 10^{-11} cm/s^2 that is by three orders smaller. Thus the peculiar accelerations in galaxy groups are weak in the main part of the volume and they change rather weakly. One can make a general remark concerning the observed hierarchical systems of gravitating bodies. Within the system of lower level of hierarchy in larger volume the accelerations created by the system of higher level of hierarchy dominate, and only within a minor fraction of the volume the system of lower level of hierarchy itself dominates.

One can make the following assumption concerning the relation between the regions where the force lines of gravity field have a diverging structure and the local accelerations $a_{\rm loc}$ dominate, and the regions where the DF acceleration $a_{\rm H}$ dominates and the force lines are randomized. One can make an analogy with small ripple on the ocean surface: the height of the "ripple" $a_{\rm loc}/a_{\rm H}$ may be rather large (many orders of the magnitude), however the whole volume of "ripple" regions is very small – many orders smaller than $R_{\rm H}^3$.

We can generalize the Mattig formula [20] for cosmological redshift

$$z_{\cos} = z_{Dop} + z_{grav} + z_{dis} = \frac{v}{c} + \frac{\Delta\varphi}{c^2} + \frac{H_{dis} r}{c}. \tag{11}$$

In the right part of this formula, the first term corresponds to the well-known Doppler effect due to the inner motions in the galaxy systems; the second term gives an usual gravitational redshift (which is the one that was measured in classical experiment by Pound and Rebka [21]); at least, the third term connected with dissipative effects explains the observed smoothness and linearity of the local Hubble flow. In the Local Group, using its mass $2\cdot10^{12}\,M_\odot = 4\cdot10^{45}$g at the distance of 1 Mpc from the center-of-mass of the group we have $z_{\rm Dop} \approx \pm\, 5\cdot10^{-4}$, $z_{\rm grav} \approx 10^{-7}$, $z_{\rm dis} \approx 2\cdot10^{-4}$. We can see that the Doppler's term is dominating in Eq. 11. Therefore, we can determine the vector of Galaxy motion and the radial velocities connected with the motions of nearby galaxies within the Local Group using Eq. 11.

It is of interest to compare the generalized Mattig formula (Eq. 11) and Eq. 2 for acceleration. They are similar: the term $\mathbf{a}_\Sigma$ in Eq. 2 and the term in Eq. 11 connected with gravitational potential describe the processes akin to the ones for the particle and photon. The kinship of the last terms in Eq. 2 and Eq. 11 follows from the estimates (3)-(5).

It seems that the dissipation is caused by interaction of the particle with the "porters" of the gravity field (the details of this interaction are not investigated now). One can assume that the porter wavelength is about the Hubble radius and their total number is $\sim M_H c^2/(hH) \sim 10^{123}$. Let's note that in the theory of dark energy, there is no attempt to come out of the framework of phenomenological consideration. Thus, the DF acceleration is the one of the effects where we come out the Newtonian theory of gravitation. However, this is non-relativistic effect (*Gc*), but the effect that is connected with the porters of interaction – gravitons (*Gh*). One more similar effect was predicted by Baryshev and Raikov [22] where the authors have shown that the Newtonian law demands a modification when the masses of bodies satisfy a relation $M_1 M_2 < M_{\text{Plank}}^2$ (see also [23, 24]).

Thus, the model of stationary fractal of dimension $D = 2$ and dissipative redshift better explains the Sandage paradox and the "coldness" of the local Hubble flow than the hypothesis of dark energy pressure.

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