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THE HUBBLE FLOW: WHY DOES THE COSMOLOGICAL EXPANSION PRESERVE ITS KINEMATICAL IDENTITY FROM A FEW MPC DISTANCE TO THE OBSERVATION HORIZON?

¹ D.KARACHENTSEV¹, A.D.CHERNIN^{2,3,4}, P.TEERIKORPI² Received 25 April 2003

The problem of the physical nature of the Hubble flow in the Local Volume (D < 10 Mpc) stated by Sandage is studied. New observational data on galaxy motions and matter distribution around the Local Group and nearby similar systems are described. Dynamical models are discussed on the basis of the recent data on cosmic vacuum or dark energy.

Key words: Cosmology:expansion - galaxies.motions

1. Introduction. In a recent paper, Sandage [1] has emphasized evidence that the rate of the cosmological expansion in the Local Volume (D < 10 Mpc) is "similar, if not precisely identical", to the global rate (see also [2-5]). This is a severe challenge to the current cosmological theories, especially in view the fact that the linear expansion flow starts from the distances of a few Mpc from the Local Group [6-9]. Indeed, why is the galaxy velocity field fairly regular in the area where the galaxy spatial distribution is very irregular? And how can it be compatible with the bulk motion of the volume with a high velocity of about 600 km s⁻¹?

In this paper, we first describe new observational data on the kinematics and distribution of galaxies in the Local Volume and then suggest a theoretical framework which appears to offer a possible solution to the above mentioned problems. This approach is suggested by the recent discovery of the cosmic vacuum, or dark energy, and on the data on its energy density [10,11].

We note that the Local Volume is in many ways optimal for study of questions concerning the various components of the universe and their dynamics. Here we have relatively accurate distances and a good knowledge of the distribution of galaxies which turns out to be typical for the galaxy universe in general. In this volume the Hubble law starts and one may see both its linear form and to measure its dispersion. One may also detect minor deviations due to the differential velocity field caused by the Virgo cluster. The Local Volume is also deep inside the (unknown) volume which has the zero velocity relative to the cosmic background radiation. With its very clumpy galaxy distribution it is also deep inside the volume in which the distribution may be regarded as uniform.

2. Global expansion rate and cosmic vacuum. The global rate of the expansion is the rate on the spatial scales of a hundred Mpc and larger where the spatial matter distribution is considered smooth and uniform, on average (see, for instance, [12]). This is the realm of the standard isotropic cosmology which views the linear expansion flow as a direct consequence of the uniformity of matter distribution.

The precise value of the global expansion rate, or the Hubble constant, is still under discussion. However a value $H_0 = 70 \pm 6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ appears to cover most of the recent determinations on large (> 200 Mpc) and "intermediate" (30 - 200 Mpc) scales [13,2,5,14].

As to the theory, according to the Friedmann model H = a/a, where a(t) is the scale factor of the model. For cold (non-relativistic) matter with the density ρ_M and cosmological constant, or vacuum with the density ρ_V , the scale factor is given by the Friedmann equation:

$$a^{2} = 8\pi/3 \cdot G(\rho_{M} + \rho_{V})a^{2} - k.$$
 (1)

For the spatially flat model (k=0), the solution has a form:

$$a(t) = a_0 q^{-1/3} \sin h^{2/3} (3\alpha t/2), \qquad (2)$$

where $a_0 = a(t_0)$ is the present-day value of a(t), $q = \rho_V / \rho_M$, and $\alpha = [(8\pi/3)G\rho_V]^{1/2}$. Then

$$H(t) = \alpha(3/2 \cdot \alpha t). \tag{3}$$

On the other hand, the Hubble constant is expressed from Eq. (1) directly in terms of α and q

$$H = \alpha [(1 + q/q)]^{1/2} . \tag{4}$$

For the present-day universe, the "concordant" observational figures for the densities are:

$$\Omega_{\nu} = \rho_{\nu} / \rho_c = 0.7 \pm 0.1; \quad \Omega_M = \rho_M / \rho_c = 0.3 \pm 0.1, \quad (5)$$

where ρ_c is the critical density. As a result, one has a rather narrow interval for the present-day global rate in the flat $(\Omega_M + \Omega_V = 1)$ model: $H_0 \le (1.2 \pm 0.4)\alpha$. (6)

Actually, an approximate concordant estimate is possible for all the three figures involved in the equations above (see for a review [15]):

$$H_0 \sim t_0^{-1} \sim \alpha \,. \tag{7}$$

More precise numbers follow from the concordant observational evidence:

$$f_0 = (2 \pm 0.2) \times 10^{-18} \,\text{s}^{-1}; \quad t_0 = 15 \pm 1 \,\text{Gyr} = (4.5 \pm 0.3) \times 10^{17} \,\text{s}; \alpha = (1.4 \pm 0.4) \times 10^{-18} \,\text{s}^{-1}$$
(8)

H

In real observations, the global expansion rate appears as a *mean* value of many individual measurements. There are naturally some definite deviations from the mean value; but they are not too significant on the global scales. Indeed, galaxies, their groups, clusters and superclusters are able to produce peculiar velocities within the expansion flow in their vicinity; the absolute value of these velocities are practically within the interval 100-1000 km s⁻¹. Because of this, any real deviations are all below the 10% level for the distances of 200 Mpc and larger.

Thus we see that the concordant model enables one to put the observational data on the global expansion rate (see above) in general agreement with the cosmic age and the vacuum density. The model indicates that in the present state of the universe, the global rate is determined in terms of α by the vacuum alone with a practically perfect accuracy. This new conclusion follows directly from the discovery of the cosmic vacuum with its energy density which is larger than the total energy density of all the other forms of cosmic matter.

3. Matter distribution in the Local Volume. Galaxies are distributed on the sky very inhomogeneously. This basic property of galaxies had been known long before their extragalactic nature was established. Clustering of galaxies towards each other is seen in a wide range of scales: from a typical galaxy diameter, ~10 kpc, up to a scale of ~30 Mpc exceeding a supercluster dimension. New optical and infrared sky surveys led to the conclusion that galaxy distribution is not homogeneous even on a scale of ~500 Mpc [16], which reaches about 1/10 of the horizon of the universe. Over the last decades, old nomenclature has described small and large galaxy systems: pairs, groups, clusters and superclusters, was updated with an idea of the large scale structure consisting of cosmic "filaments" and "walls" framing giant empty volumes.

Generally, in the Local Volume one may see examples of all the components visible on larger scale 3-D maps: groups, elongated structures, filaments and voids. In addition, the local (< 10 Mpc) spatial distribution appears to be fractal, with $D \approx 1.8$ [17], in agreement with the distribution on larger scales, up to about 100 Mpc [18,19,12,20].

All mentioned properties of the large scale structure are seen in Fig.1, which presents the sky distribution of 5272 nearest galaxies in the equatorial coordinates. They are selected from the last version of the Lyon Extragalactic Database (=LEDA) [21] by the condition that their corrected radial velocities are $V_{LG} < 2300 \text{ km s}^{-1}$. The galaxies are shown as filled circles with sizes nversely proportional to their distances (radial velocities). The gray belt corresponds to the Zone of Avoidance in the Milky Way (galactic latitude of $\pm 10^{\circ}$), where the lack of galaxies is caused by strong Galactic extinction. As seen in the figure, the nearby galaxies are concentrated towards the Local

Supercluster plane, and the Virgo cluster is the most dense part of it. The Virgo cluster is located near the center of Fig.1 (marked with the character "V") and has a distance of 17 Mpc from us. The distribution of these galaxies



Fig.1. Distribution in the equatorial coordinates of 5272 galaxies with radial velocities less than 2300 km s⁻¹. The Zone of Avoidance in the Milky Way is shaded. The Virgo cluster ("V") is situated near the map center.

in the supergalactic coordinates is presented in Fig.2. About half of the galaxies within the radius of 32 Mpc is situated in the Local Supercluster disk.

In the southern supergalactic hemisphere (SGL ~ 250° , SGB ~ -40°) another less rich cluster of galaxies, Fornax, alined along the supergalactic longitude is seen. The Fornax cluster has a distance of 20 Mpc. In the



-90°

Fig.2. Distribution in the Supergalactic coordinates of the same 5272 galaxies.

northern hemisphere there is a significant deficit of galaxies with radial velocities $V_{LG} < 1500 \text{ km s}^{-1}$. This almost empty volume in Hercules-Aquila with a linear diameter of 20 Mpc was called "Local Void" [22]. In the opposite direction (the Orion constellation) there is another smaller empty region called "Local Minivoid" [7].

Projection of nearby and distant galaxies onto the sky makes difficult viewing the 3D structure of the Local Volume. Passing to the Cartesian supergalactic coordinates allows us to see the local relief in a new aspect. Fig.3 presents the distribution of galaxies with radial velocities $V_{LG} < 1500 \text{ km s}^{-1}$ in projection onto the supergalactic plane. The radial velocity of each galaxy, $V_{LG} = H_0 \times D$, is used as the galaxy distance, D, where the Hubble parameter $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is assumed from modern data. Fig.3a shows the distribution of nearby galaxies situated within the Local supercluster plane. The thickness of this slice is taken to be $\pm 300 \text{ km s}^{-1}$ along the SGZ axis. Fig.3b and Fig.3c present the distribution of remaining galaxies situated above (SGZ > 300 km s⁻¹) and below (SGZ < -300 km s⁻¹) the Supercluster disk, respectively. The main feature of the local landscape, the Virgo cluster, is elongated approximately along the +SGY axis. To a considerable extent, its



Fig.3. Distribution in Cartesian supergalactic coordinates of nearby galaxies with $V_{LG} < 1500 \text{ km s}^{-1}$: a) galaxies situated within the Local supercluster plane.



Fig.3. b) and c) Galaxies above and below the Local super cluster plane, respectively.

elongation is fictituous, being caused by internal virial motions with a dispersion $\sigma_v = 650 \text{ km s}^{-1}$. Apart from the Virgo cluster, in the Supergalactic plane there are other more scattered structures: the Ursa Majoris cloud, the Canes Venatici cloud, the Triangulum spur, etc., which have been revealed by Tully owing to their contrast above the average number density. The map of the southern supergalactic hemisphere shows the disposition of nearby galaxy clouds in Fornax, Leo, and Antlia. The presence of the Local Void is well seen in the galaxy distribution North of the Supergalactic disk.

It appears that our Galaxy is located not in the richest, nor in the poorest region of the Local supercluster. Kraan-Korteweg & Tammann [23] proposed to call the space region around the Local Group with radial velocities of galaxies $V_{LG} < 500 \text{ km s}^{-1}$ "Local Volume". After ommiting the Virgo cluster members having $V_{LG} < 500 \text{ km s}^{-1}$ because of their virial motions, the Local Volume population contains 179 galaxies, being rather representative in number. During the last years, special effort has been undertaken to increase the Local Volume population. "Blind" surveys of the sky in the 21 cm line [24], infrared and radio surveys of the Zone of Avoidance [25] and searches for new dwarf galaxies of very low surface brightness based on the POSS-II and ESO/SERC plates [26,27] led to the increasing of the total number of the Local Volume galaxies more than two times.

Radial velocities of galaxies, especially situated within groups and clusters,



Fig.4. Distribution of the Local volume galaxies within 6 Mpc around the Milky Way, projected onto the Supergalactic plane. The brightest members of eight nearest groups are shown as asterisks.

give only an approximate estimate of distances to these galaxies. That was a reason to initiate a vast program of distance measuring to nearby galaxic, independently from their radial velocities. Over the last 10-15 years many nearby galaxies have been resolved into stars for the first time. The luminosity of their brightest blue and red stars have been used to determine galaxy distances with a typical accuracy of (20-25)% [28,29]. Later, the distance measurement error was decreased to ~10% by using the luminosity of the tip of the red giant stars. This labour-consuming program requiring a lot of observing time with the largest ground-based telescopes, as well as the Hubble Space Telescope, is yet not complete. So far, the distances have been measured for about 150 galaxies situated within 6 Mpc [30]. The distribution of these galaxies is presented in Fig.4. The Local Volume galaxies are projected onto the Supergalactic plane, SGX, SGY, and shown as filled circles. In this region there are eight known groups whose principal galaxies: the Milky Way, M 31, IC 342, M 81, Cen A, M83, NGC 253 and M 94 are indicated with asterisks. Comparing the true 3D map of the Local Volume in Fig.4 with its approximate analogy in the redshift space (Fig.3), we recognize a higher density contrast of groups in Fig.4 and also the absence of the "virial tail" directed towards the Virgo cluster.

Note that the total number of 5272 galaxies, being averaged over the D=32 Mpc volume, yield the expected number of galaxies within D=6 Mpc to be 35. This number is 7 times as low as their observed number in the Local Volume. However, the excess is caused completly by the faintest galaxies unseen in more distant regions of the Local Supercluster.

4. Galaxy kinematics in the Local Volume. Extensive measurements of distances to galaxies independent of their radial velocities provide us with a possibility to study the peculiar velocity field on different scales. Analysing the peculiar velocity map, we can establish reasons (inhomogeneities of gravitational potential) which generate the observed deviations in galaxy motions with respect to the regular Hubble flow. Surprisingly, such a kind of data on very nearby galaxies have turned out to be known over the last 2-3 years only!

A sample of observational data on radial velocities and distances for ~150 nearby galaxies given by [30] is presented in Fig.5. The galaxies with accurate (~10%) distances measured from the luminosity of cepheids or red giants are shown by filled circles. The galaxies with less reliable distances (via the brightest stars or Tully-Fisher relation) are indicated by crosses. The radial velocities of galaxies are reduced to the Local Group centroid. The solid line in Fig.5 corresponds to the Hubble relation, $V_{LG} = H_0 \times D$ with $H_0 = 72$ km s⁻¹ Mpc⁻¹, when a decelerating gravitational action of the Local Group mass, $1.3 \cdot 10^{12} M_{\odot}$, is taken into account. Apart from the presented galaxies, the Local Volume of radius D < 6 Mpc contains about 100 galaxies, whose dis-

tances are still unknown.

The largest deviations from the Hubble relation take place for the galaxies situated within two nearby groups around M 81 and Cen A. As it was noted in [8,31], significant deviations from the regular Hubble flow are caused by aniso-



Fig.5. Radial velocity - distance relation for 156 Local Volume galaxies. The galaxies with accurate distance estimates are shown as filled circles, and galaxies with less reliable distances are indicated as crosses. The members of M 81 and Cen A groups are shown by open circles and squares.

tropic expansion of the Local Volume. The local value of the Hubble parameter can be described by a tensor H_g with the main axial ratios $(81 \pm 3):(62 \pm 3):(48 \pm 5) \text{ km s}^{-1} \text{ Mpc}^{-1}$. Here the minor axis of the Hubble ellipsoid is directed towards the Local Supercluster poles, and the major axis is pointed $(29 \pm 5)^{\circ}$ away from the direction to the Virgo cluster. The nature of this phenomena remains unclear yet. In any case, it does not agree with the idea of sphericallysymmetric Virgo-centric flow, which has been discussed by many authors.

The most enigmatic property of the local Hubble flow turns out to be its "coldness". According to [6], the typical random velocity of galaxies is 70 km s⁻¹. Just the same value has been derived in [31] for galaxies within 7 Mpc from us. Later, Karachentsev & Makarov [8] showed that for the nearest galaxies with D < 3 Mpc their radial velocity dispersion does not exceed 30 km s⁻¹. Also, using Cepheid distances only, Ekholm et al. [9] derived a local dispersion of 40 km s⁻¹. These results are as was predicted by Sandage: the smaller the distance measurement error the lower the observed peculiar velocity dispersion.

In the Local Group and in the other nearby groups the characteristic virial velocity is also about 70 km s^{-1} . However, the group centroids themselves have

much lower chaotic motions. Fig.6 presents the Hubble diagram for centroids of the eight nearby groups shown in Fig.4. Their velocities and distances are taken with respect to the Local Group centroid situated between M 31 (Andromeda) and our Galaxy. It appears that the group centroids have a scatter of only 29 km s⁻¹ in regard to the Hubble relation with $H_0 = 72$ km s⁻¹ Mpc⁻¹. The distance measurement errors are shown by horizontal bars. As seen, for the galaxy groups with radial velocities $V_{LG} \sim 250$ km s⁻¹ their ~10% distance errors lead to the Hubble velocity errors ~25 km s⁻¹ comparable with the observed value of σ_{n} .



Fig.6. The Hubble diagram for centroids of the eight nearest groups.

Finally, the most complete and accurate data on radial velocities and distances of nearby galaxies demonstrate that the local Hubble flow has almost the same value of the Hubble parameter as the global flow: $H_0 = (71 \pm 4)$ km s⁻¹ Mpc⁻¹ [32]. However, some uncertainty in the classically measured Hubble constant remains until the suspected extragalactic Cepheid distance bias is fully investigated [33].

5. Where are we moving towards? Together with our Sun and our Galaxy we take part in different cosmic motions whose value and direction have been discussed by many authors. The initial data on these motions were controversal because of the low quality of determination of galaxy distances. However, at the present time, one can recognize a rather concordant picture of cosmic motions described below.

Taking part in the rotation of the Galaxy, our Sun moves at a velocity of (220 ± 20) km s⁻¹ towards $l = 90^{\circ}$, $b = 0^{\circ}$ in the galactic coordinates [34].

500

Apart from the regular circular rotation the Sun has its individual velocity of 16 km s⁻¹ towards $l = 53^{\circ}$, $b = 25^{\circ}$ with respect to surrounding stars [34]. Considering velocities and distances of nearby galaxies, Karachentsev & Makarov [8,31] established that the Sun moves with respect to the Local Group centroid with the velocity $(316 \pm 11) \text{ km s}^{-1}$ in the direction $l = (93 \pm 2)^{\circ}$, $b = (-4 \pm 1)^{\circ}$. When these vectors are substracted, we derive that the motion of the Galaxy center with respect to the Local Group centroid is 91 km s⁻¹ towards $l = 163^{\circ}$, $b = -19^{\circ}$. As it is known, the centers of the Galaxy and Andromeda (M 31) are approaching each other at a velocity of -120 km s^{-1} . If the Galaxy mass is twice as low as the M 31 mass, our Galaxy should move towards M 31 at a velocity of 80 km s⁻¹. After excluding this expected velocity component, a residual (random) velocity of the Galaxy is only 23 km s⁻¹ towards $l = 56^{\circ}$, $b = 0^{\circ}$. Its value and direction can be easily explained by a not strickly radial motion of the Galaxy in the Sun's neighbourhood.

Measurements of the dipole anizotropy of the cosmic microwave background (CMB) showed that our Sun moves with respect to the CMB at a velocity of $(370 \pm 3) \text{ km s}^{-1}$ towards $l = (264.4 \pm 0.3)^\circ$, $b = (48.4 \pm 0.5)^\circ$ [35]. Therefore, in the absolute frame (CMB) the Sun's motion is known with an accuracy of better than 1%. Because of the Sun's motion with respect to the Local Group and its motion with respect to the CMB have nearly opposite directions, the velocity of the Local Group centroid itself with respect to the CMB has a huge value, $(634 \pm 12) \text{ km s}^{-1}$, towards $l = (269 \pm 3)^\circ$, $b = (48.4 \pm 0.5)^\circ$. The origin of such a fast motion of the Local Group was a puzzle for many observers trying to determine the Local Group velocity with respect to nearby and distant galaxies. The most defined results were obtained by Tonry et al. [36] who measured accurate $(\pm 10\%)$ distances to 300 early-type galaxies with radial velocities < 3000 km s⁻¹. An analysis made from these observational data reveals that the Local Group takes part in different kinds of motion:

a) towards the Virgo cluster center ($l = 274^{\circ}$, $b = 75^{\circ}$) at a velocity of 139 km s⁻¹,

b) towards so-called "the Great Attractor" in Hydra-Centaurus ($l=291^{\circ}$, $b=17^{\circ}$, D=44 Mpc) at a velocity of 289 km s⁻¹ and

c) in the direction away from the Local Void (i.e. towards $l = 228^{\circ}$, $b = -10^{\circ}$) at a velocity of ~200 km s⁻¹.

When all the three motions have been taken into account, the residual velocity of the Local Group towards $l = 281^{\circ}$, $b = 43^{\circ}$ is only 166 km s⁻¹. According to [36], the error in the residual velocity is about 120 km s⁻¹ that is why they considered the Local Group to be practically at rest relative to remote galaxies.

The bulk galaxy motion within a radius of ~(100-200) Mpc with respect to

the CMB was studied by different observational teams. Most of the approaches relied on the Tully-Fisher relation in estimating distances to spiral galaxies from the amplitude of their internal motions. As a result, Giovanelli et al. [37] and Dekel et al. [38] derived the bulk motion parameters: $V = 200 \text{ km s}^{-1}$, $l = 295^{\circ}$, $b = 25^{\circ}$, and $V = 370 \text{ km s}^{-1}$, $l = 305^{\circ}$, $b = 14^{\circ}$, respectively. To study coherent large-scale motions, Karachentsev et al. [39] created a special catalog of flat disk-like galaxies seen edge-on. This catalog (FGC) covers homogeneously the whole northern and southern sky. Based on the FGC sample, Karachentsev et al. [40] derived the dipole solution: $V = (300 \pm 75) \text{ km s}^{-1}$, $l = (328 \pm 15)^{\circ}$, and $b = (7 \pm 15)^{\circ}$. Applying for the FGC sample of new photometric data from the 2MASS sky survey yields the following parameters of the galaxy bulk motion: $V = (199 \pm 61) \text{ km s}^{-1}$, $l = (301 \pm 18)^{\circ}$, and $b = (-2 \pm 15)^{\circ}$ [41].

Table 1

					-	_	
Motion type	V	/°	b°	V _x	V,	V	Note
	km/s	-	-	km/s	km/s	km/s	
Sun vs. LSR	16	53	+25	9	12	7	Vaucouleurs et al. [34]
Calactic rotation	220±20	90	0	0	220	0	Vaucouleurs et al. [34], $R_{\odot} = 8$ kpc
Sun vs. LG centroid	316±11	93±2	-4±1	-16	315	-22	Karachentsev, Makarov [8,31]
MW vs. LG	91	163	-19	-25	83	-29	
MW vs.M31	80	121	-23	-38	64	-29	Expected
Residual MW	23	56	0	13	19	0	Non-radial orbit?
Sun vs. CMB	370±3	264±.3	48±.5	-24	-244	276	Kogut et al. [35]
LG vs. CMB	634±12	269±3	28±1	-8	-559	298	
LG vs. Virgo	139	274	75	3	-36	134	$D_{\star} = 17 \text{ Mpc}$, Tonry et al. [36]
LG vs. Great Attractor	289	291	17	98	-258	86	$D_{G4} = 44$ Mpc. Tonry et al. [36]
LG vs. Anti- Local Void	200	228	-10	-132	-146	-36	Local Void, D~20 Mpc
Residual LG	166	281	43	23	-119	114	(-VA-GA+LV)
		278	38	- 74			2MASS gg centroid
		258	30		- D-		IRAS gg centroid
		315	30				Shapley concentracion
bulk vs. CMD	200	295	25	77	-164	85	Giovanelli et al. [37], D~90 Mpc
bulk vs. CMD	370	305	14	206	-294	90	Dekel et al. [38], D - 70 Mpc
bulk vs. CMD	300±75	328±15	7±15	252	-157	37	FGC, D~100 Mpc, Karachentsev et al. [40]
bulk vs. CMD	199±61	301±18	-2±15	102	-170	-7	FGC+2MASS, D~150 Mpc, Kudrya et al. [41]

COSMIC MOTIONS OF THE SUN, THE GALAXY AND THE LOCAL GROUP

THE HUBBLE FLOW

A survey of galaxy motions on different scales is presented in Table 1 and Fig.7. Apart from M 31, Virgo (VA) and the Great Attractor (GA), the position of the centroid of IRAS sources [42], 2MASS sources [43], and the Shapley concentration of rich clusters (ShC) with its typical distance of \sim 13000 km s⁻¹ are shown in the galactic coordinates. As seen from the map, all the large-scale attractors (gray circles), as well as the apexes of bulk galaxy motions (crosses) are concentrated in an approximately the same sky region,



Fig.7. Different apex positions from Table 1 in galactic coordinates (crosses). Positions of the Virgo attractor, the Great Attractor, the Shapley concentration, as well as centroids of IRAS and 2MASS sources are shown as gray circles.

cosmic "Bermudas trianglum". Such an association of apexes and attractors can be easely understood if the distribution of Dark Matter on large scales follows the galaxy distribution. It should be emphasized that the residual velocity of the Local Group, $V=166 \text{ km s}^{-1}$, $l=281^{\circ}$, $b=43^{\circ}$ (indicated in Fig.7 as a diagonal cross) is directed almost towards the clustering dipole of the 2MASS sources, $l=278^{\circ}$, $b=38^{\circ}$. It means that the residual motion of the Local Group with respect to the CMB can be generated by the largescale structure seen in the 2MASS survey.

6. Dynamic background in the Local Volume. Turning to the theory, we argue now that the local expansion rate could be due to the dynamical effect of the vacuum.

From the data on the matter distribution in the Local Volume (Sec.3), one can see that the bulk of mass (this is mostly dark matter) is concentrated in several groups like the Local Group, if one consider the distances $1 \le R \le 7$. Matter dominates, dynamically near the Local Group, while outside this region vacuum must dominate. A rough, but obvious and robust estimate shows this.

Indeed, the mass of the Local Group M_{LG} is less than the effective gravitating mass of the vacuum in a surronding volume of the size (radius) R, if R is large enough:

$$M_{1G} < (4\pi/3) \cdot 2\rho_V R$$
, (9)

(here we take into account that the effective gravitating density of the vacuum is $-2\rho_V$) and the vacuum dominates at distances

$$R > R_V = (3M_{LG}/8\pi\rho_V)^{1/3}.$$
 (10)

With $M_{LG} = (1.5 - 2.0) \times 10^{12} M_{\odot}$, and the vacuum density of Sec.2, one has [44,15]:

$$R_{\rm V} = 1.5 - 2.0 \,{\rm Mpc}$$
, (11)

and the dynamical effect of vacuum dominates at distances of a few Mpc and larger.

A detailed computer model that takes into account the motion of the two major galaxies of the Local Group shows [45] that the surface of "zero gravity" where the gravity of the Local Group is exactly balanced by the anti-gravity of the cosmic vacuum is very near to sphere with the radius of 1.8 Mpc. This sphere changes very slowly during the life time of the Group. It means that outside this surface the gravitational potential is spherically symmetrical and static (practically) for the last 12-13 Myr.

It is significant that vacuum domination in the Local Volume is at least as strong as on the average, all over the Universe (i.e. on the global spatial scales). One may see this in terms of the effective mass that produces gravity at a given distance R from the barycenter of the Local Group. Two kinds of estimates can be made for this. The first and simplest assumes that all the mass in the volume (up to a certain distance) is collected in the Local Group within a region of ~1 Mpc in size. If so, the ratio of the matter mass, $M_N = M_{LG}$, to the vacuum mass in the volume of the size (radius) R around the Local Group scales with R as

$$M_{\mathcal{V}}/M_{\mathcal{M}} \propto (R/R_{\mathcal{V}})^3, \qquad (12)$$

in accordance with Eq. (8). It means that at an intermediate distance of, say, R = 3 Mpc the mass ratio is $M_V/M_M \approx 5$.

A more accurate estimate may take into account the contribution to the matter mass M_N by the galaxies (and intergalactic matter) distributed around the Local Group. According to the data of Sec.3, the mass distribution is fractal, and $M_M \propto R^D$, where $0 < D \le 3$. In this case,

$$M_V / M_M \propto (R/R_V)^{D-3}$$
. (13)

At a distance R=3 Mpc (as above), the ratio is now $M_V/M_M \approx 1.8$, if D=2, and $M_V/M_M \approx 3.1$, if D=1. For the most popular fractal dimension D=1.8 [46,17] extended to, say, 20 Mpc, the mass ratio M_V/M_H is larger

than the global effective ratio 14/3 in almost all (>95%!) the volume of space with this (20 Mpc) radius. This means that dynamical dominance of the vacuum in the Local Volume is actually even stronger than on the global scales.

7. Expansion rate in the Local Volume. The considerations above suggest that the present-day dynamics in the Local Volume outside the zerogravity sphere can be considered as controlled by the vacuum alone, - with the same (at least) accuracy as on the global scales. This enables one to study trajectories in the Local Volume neglecting the dynamical effect of matter, in the first (and main) approximation. In addition, the one may consider spherically symmetrical trajectories as a good approximation to the real motion of small galaxies in this volume.

In this approximation, the radial component of the equation of motion in the reference frame of the Local Group barycenter has a simple form:

$$\ddot{R} = \alpha^2 R \,. \tag{14}$$

The solution to the equation may be written as

$$R(t) = R_0(\chi)F(t,\chi), \qquad (15)$$

where

 $F = \exp \left[\alpha(t + T(\chi)) \right], \quad \cos h \left[\alpha(t + T(\chi)) \right], \quad \sin h \left[\alpha(t + T(\chi)) \right], \quad (16)$ for parabolic, hyperbolic and elliptical trajectories, correspondingly.

The solution describes the radial trajectory of a body (a dwarf galaxy) with the Euler radial coordinate R and Lagrangian coordinate χ . The solution is exact and nonlinear. The solution is also general in the sense that it contains two arbitrary functions of the Lagrangian coordinate, $R_0(\chi)$ and $T(\chi)$, and so it can fit all (reasonable) initial conditions for positions and velocities at the start of the motion.

The solution describes regular "unperturbed" Friedmann-Hubble trajectories, if $R_0(\chi) = \chi$, $T(\chi) = 0$. In its general form, the solution describes a "perturbed" trajectory with arbitrary $R_0(\chi)$ and $T(\chi)$. The solution is valid (practically) since the time of the formation of the Local Group, i.e. since the moment $t_1 = 1-3$ Gyr when the most of the material in the volume was assembled into the two major galaxies of the Local Group.

The solution gives the rate of expansion R/R measured for a given trajectory at a moment t as a function of both t and χ . For a regular (unperturbed) trajectory the rate is simply $H_0 = \alpha$, as it is in the global solution (Sec.2). For a perturbed trajectory one may use, for instance, a hyperbolic solution:

$$H(t,\chi) = R/R = \alpha[\alpha(t+T(\chi))].$$
(17)

The dependence on χ is due to perturbations described by the arbitrary function $T(\chi)$; the other arbitrary function $R_0(\chi)$ does not enter this rela-

tion. The expansion rate does not depend on χ and coincides with the regular one, $H_0 = \alpha$, in the limit of large times; in this limit, the perturbations vanish.

On the contrary, at the moment of the Local Group formation, $t = t_1$, and soon after that, most of the trajectories might be highly disturbed, so that for a typical trajectory the rate of expansion was significantly different from α . And nevertheless big initial perturbations are compatible with the present rather regular linear flow. For example, if $T(\chi) = 0.2/\alpha$, then $H(t_1) = 3\alpha$ initially $(t_1 = 0.11/\alpha)$, while the present expansion rate $= \alpha$ for the same T.

Another simple solution can easily be obtained for radial trajectories in the case when gravity of matter is taken into account and the motion is parabolical. The solution has a form of Eq. (2), where one has now $t+T(\chi)$ instead of t. Similarly, the expansion rate is given by Eq. (3) with the same change of the argument. It is interesting that this new expression for the expansion rate is the same as for the hyperbolical trajectories considered above. Therefore the conclusions we made above extend directly to this new case.

Our analysis of the trajectories and conclusions about the expansion rate for the Local Volume are completely confirmed by computer models that trace back the observed kinematics of real galaxies of the local expansion flow [47].

Summing up, we may say that an answer to the question in the title of the paper may be like this: the rate of the cosmological expansion in the Local Volume is similar to the global rate because the cosmic vacuum with its perfectly uniform density dominates the present-day dynamics of the Hubble flow both locally and globaly. The bulk motion does not affect this result basically because vacuum is co-moving with any motion (see, for instance, [15,48].

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- Special Astrophysical Observatory RAS, Russia e-mail: ikar@luna.sao.ru
- ² Tuorla Observatory, Turku University, Piikkiö,
- Finland, e-mail: pekkatee@oj287.astro.utu.fi
- ³ Sternberg Astronomical Institute, Moscow University, Russia, e-mail: chernin@sai.msu.ru
- ⁴ Astronomy Division, University of Oulu

THE HUBBLE FLOW

ХАББЛОВСКИЙ ПОТОК: ПОЧЕМУ КОСМОЛОГИЧЕСКОЕ РАСШИРЕНИЕ СОХРАНЯЕТ СВОЮ КИНЕМАТИЧЕСКУЮ ИДЕНТИЧНОСТЬ ОТ РАССТОЯНИЯ В НЕСКОЛЬКО Мтк ДО НАБЛЮДАТЕЛЬНОГО ГОРИЗОНТА?

И.Д.КАРАЧЕНЦЕВ¹, А.Д.ЧЕРНИН^{2,3,4}, П.ТЕРИКОРПИ²

Рассматривается проблема физической природы Хаббловского потока в местном объеме (D < 10 Мпк), сформулированная Сандейджем. Представлены новые наблюдательные данные о движениях галактик и распределении материи в окрестностях Местной группы и соседних подобных систем. Обсуждаются динамические модели, основанные на современных данных о космическом вакууме или темной энергии.

REFERENCES

- 1. A.Sandage, Astrophys. J., 527, 479, 1999.
- 2. A.Sandage, Astrophys. J., 307, 1, 1986.
- 3. P. Teerikorpi, Ann. Rev. Astron. Astrophys., 35, 101, 1997.
- 4. T. Ekholm, P. Teerikorpi, G. Theureau et al., Astron. Astrophys., 347, 99, 1999.
- 5. R. Giovanelli, D. Dale, M. Haynes, E. Hardy, L. Campusano, Astrophys. J., 525, 25, 1999.
- 6. A.Sandage, G.A.Tammann, E.Hardy, Astrophys. J., 172, 253, 1972.
- 7. I.Karachentsev, M.Sharina, D.Makarov et al., Astron. Astrophys., 389, 812, 2002.
- 8. I.D.Karachentsev, D.I.Makarov, Astrofizika, 44, 5, 2001.
- 9. T. Ekholm, Yu. Baryshev, P. Teerikorpi, M. Hanski, G. Paturel, Astron. Astrophys., 368, L17, 2001.
- 10. A.G.Riess, A.V.Filippenko, P.Challis et al., Astron. J., 116, 1009, 1998.
- 11. S.Perlmuter, G.Aldering, G.Goldhaber et al., Astrophys. J., 517, 565, 1999. 12. K.K.S.Wu, O.Lahav, M.J.Rees, Nature, 397, 225, 1999.
- 13. G. Theureau, M. Hanski, T. Ekholm et al., Astron. Astrophys. 322, 730, 1997.
- 14. W.L.Freedman, B.Madore, B.K.Gibson et al., Astrophys J., 553, 47, 2001.
- 15. A. Chernin, Physics-Uspekhi, 44, 1009, 2001.
- 16. G.S. Busswell, T.Shanks, P.J. Outram et al., astro-ph/0302330, 2003.
- 17. A. Tikhonov, D. Makarov, A. Kopylov, Bull. Special Astrophys. Observ., 50, 39, 2000.
- 18. F.Sylos Labini, M.Montuori, L.Pietronero, Phys. Rep., 293, 61, 1998.
- 19. P. Teerikorpi, M. Hanski, G. Theureau et al., Astron. Astrophys., 334, 395, 1998.

- 20. Yu. Baryshev, P. Teerikorpi, Discovery of Cosmic Fractals (World Scientific Publishing Co.), 2002.
- 21. G.Paturel, L.Bottinelli, H.Di Nella et al., Catalogue of Principal Galaxics, Saint-Genis Laval, Observatoire de Lyon (LEDA), 1996.
- 22. R.B. Tully, Nearby Galaxy Catalog, Cambridge University Press, 1998.
- 23. R.Kraan-Korteweg, G.A. Tammann, Astron. Nachr., 300, 181, 1979.
- 24. E.Ryan-Weber, B.S.Koribalski, L.Staveley-Smith et al., Astron. J., 124, 1954, 2002.
- 25. R.C.Kraan-Korteweg, O.Lahav, Astron. Astrophys., 10, 211, 2000.
- 26. V.E.Karachentseva, I.D.Karachentsev, Astron. Astrophys. Suppl. Ser., 127, 409, 1998.
- 27. V.E.Karachentseva, I.D.Karachentsev, Astron. Astrophys. Suppl. Ser., 146, 359, 2000.
- 28. I.D.Karachentsev, N.A.Tikhonov, Astron. Astrophys., 286, 718, 1994.
- 29. I.Karachentsev, I.Drozdovsky, S.Kajsin et al., Astron. Astrophys. Suppl. Ser., 124, 559, 1997.
- 30. I.D.Karachentsev, D.I.Makarov, M.E.Sharina et al., Astron. Astrophys., 398, 493, 2003.
- 31. I.Karachentsev, D.Makarov, Astron. J., 111, 535, 1996.
- 32. D.N.Spergel, L.Verde, H.V.Peiris et al., astro-ph/0302209, 2003.
- 33. P. Teerikorpi, G. Paturel, Astron. Astrophys., 381, L37, 2002.
- 34. G. de Vaucouleurs, A. de Vaucouleurs, R.G.Buta et al., Third Reference Catalog of Bright Galaxies, N.Y., Springer-Verlag, 1991.
- 35. A.Kogut, C.Lineweaver, G.F.Smoot et al., Astrophys. J., 419, 1, 1993.
- 36. J.L. Tonry, J.P. Blakeslee, E.A. Ajhar, A. Dressler, Astrophys. J., 530, 625, 2000.
- 37. R.Giovanelli, M.P.Haynes, W.Freudling et al., Astrophys J., 505, L91, 1998.
- 38. A. Dekel, A. Eldar, T. Kollat et al., Astrophys J., 522, 1, 1999.
- 39. I.D.Karachentsev, V.E.Karachentseva, S.L.Parnovsky, Astron. Nachr., 314, 97 (FGC), 1993.
- 40. I.D.Karachentsev, V.E.Karachentseva, Yu.N.Kudrya, S.L.Parnovsky, Astron. Reports, 44, 175, 2000.
- 41. Yu.N.Kudrya, V.E.Karachentseva, I.D.Karachentsev et al., Astron. Astrophys, submitted, 2002.
- 42. M. Rowan-Robinson, J. Sharpe, S.J. Oliver et al., Mon. Notic. Roy. Astron. Soc., 314, 375, 2000.
- 43. A.H.Maller, D.H.McIntosh, N.Katz, M.D.Weinberg, astro-ph/0303592, 2003.
- 44. Yu. Baryshev, A. Chernin, P. Teerikorpi, Astron. Astrophys., 378, 729, 2001. 45. V.P.Dolgachev, L.M.Domozhilova, A.D.Chernin, in press, 2003.
- 46. P.J.E. Peebles, Principles of Cosmology, Princeton: Princeton, Univ. Press, 1993.
- 47. I.D.Karachentsev, A.D.Chernin, M.J.Valtonen et al., in press, 2003.
- 48. A. Chernin, P. Teerikorpi, Yu. Baryshev, Adv. Space Res., 31, 459, 2003.