

Local dark energy: HST evidence from the vicinity of the M 81/M 82 galaxy group

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The Hubble Space Telescope observations of the nearby galaxy group M 81/M 82 and its vicinity indicate that the expansion outflow around the group is dominated by the antigravity of the dark energy background. The local density of dark energy in the area is estimated to be near the global dark energy density or perhaps exactly equal to it. This conclusion agrees well with our previous results for the Local group vicinity and the vicinity of the Cen A/M 83 group.

Keywords: Groups of galaxies; the Hubble flow; Dark energy

1 Introduction

Dark energy was discovered in SN Ia observations at large cosmological distances, halfway to the cosmic horizon [1,2]. The discovery was confirmed by the WMAP observations of the cosmic microwave background isotropy [3,4]. It was found that dark energy contributes 70-80% the total energy of the observed Universe [1-4]. Dark energy drives the accelerated expansion of the Universe now and for the last 7 Gyr of the cosmic history. The physical nature and microscopic structure of

dark energy are entirely unknown. Its existence was not predicted by the current standard model of particle physics; the model cannot explain either the value of the observed dark energy density. It may only be assumed that dark energy reflects somehow the unification of gravity with the other fundamental forces and/or the effects of quantum physics (see, for instance, a review [5]). In particular, presently discussed ideas link the origin of dark energy with the interplay between gravity and electroweak physics in the very early Universe at the cosmic age of a few picoseconds [6].

Remarkably enough, the macroscopic properties of dark energy are well known and may be described in a rather complete way. Indeed, according to the simplest, straightforward and quite likely interpretation, dark energy is equivalent to the Einstein cosmological constant Λ , and it may be considered as a medium with the constant uniform density:

$$\rho_V = \Lambda/(8\pi G) > 0. \quad (1)$$

The dark energy equation of state has the form [7]:

$$p_V = -\rho_V. \quad (2)$$

Here p_V is the dark energy pressure, G is the gravitational constant and the speed of light $c = 1$.

The medium with the equation of state given by Eq.(2) is vacuum [7]: the rest and motion are not discriminated relative to this medium. The energy density of vacuum is invariant: it is the same in any reference frame. It was suggested [8] that the Λ -vacuum might be identical to the physical vacuum of the quantum fields; however this idea has not yet been proved or disproved.

It also follows from Eq.(2) that the vacuum produces antigravity. According to General Relativity, the effective gravitating density is determined by both density and pressure of the medium in combination:

$$\rho_V + 3p_V = -2\rho_V < 0. \quad (3)$$

Antigravity is due to the fact that the effective density of vacuum is negative. This means that two particles embedded in the vacuum will move apart each other with acceleration, if they are initially at rest relative to each other. It is the antigravity of dark energy that makes the Universe expand with acceleration.

The Hubble magnitude-redshift diagram obtained with the SN Ia observations [1,2] shows that antigravity of dark energy and the gravity of matter (baryons and dark matter) balance each other for a moment at the redshift $z_V \simeq 0.7$. The balance condition is

$$\rho_M(z_V) - 2\rho_V = 0, \quad (4)$$

where ρ_M is the matter density. Since the matter density scales with redshift as $(1+z)^3$ and the present-day matter density is considered known, $\rho_M(z=0) \simeq 0.3 \times 10^{-29} \text{ g cm}^{-3}$, the estimate of the dark energy density comes from Eq.(4):

$$\rho_V = \frac{1}{2}\rho_M(z=0)(1+z_V)^3 \simeq 0.7 \times 10^{-29} \text{ g/cm}^3. \quad (5)$$

If dark energy is indeed equivalent to the cosmological constant, it exists everywhere in space with the same perfectly uniform density (Eq.5), and all cosmic systems are imbedded in the uniform dark energy background. We demonstrated [9-20] that the presence of dark energy on relatively small scales could be recognized observationally due to its effect on the structure and dynamics of the Hubble flow of expansion. Dark energy dominates the dynamics of the expansion not only in the Universe as a whole, but also within the cosmic cell of uniformity on spatial scales $\leq 100 - 300 \text{ Mpc}$. Because of this, the flow has a regular structure: it follows the Hubble linear velocity-distance law, and the expansion rate (the Hubble constant) is approximately the same on practically all the spatial scale where the flow is observed.

It is well-known that the expansion flow starts at distances of a few Mpc from us, in the vicinity of the Local groups of galaxies. These very local scales of the expansion are especially interesting. Systematic observations of distances

and motions of galaxies in the Local Group and in the flow around it have been carried out over the last years with the Hubble Space Telescope (HST) during more than 200 orbital periods [21-36]. High precision measurements were made of the radial velocities (with 1-2 km/s accuracy) and distances (8-10 % accuracy) for about 200 galaxies of the Local Group and neighbors from 0 to 7 Mpc from the group barycenter. We use these data to detect dark energy and estimate its density at the shortest distances.

In our close galactic vicinity, the gravity is produced by the matter (dark matter and baryons) of the Local group, and the antigravity is produced by the local dark energy background. The effect of dark energy is strong there. The velocity-distance diagram based on the HST data [21-36] indicates [9-11] that the local gravity-antigravity balance takes place at a distance R_V which is between 1 and 2 Mpc from the Local group barycenter; R_V is the radius of the zero-gravity sphere around the Local group [9-20]. At the smaller distances, the gravity of matter controls the dynamics of the bound and quasi-stationary group, while at the larger distances, the antigravity of dark energy dominates and controls the dynamics of the local expansion flow.

With the known value of the zero-gravity radius R_V and the measured mass of the Local group $M_{LG} = (1.3 \pm 0.3) \times 10^{12} M_\odot$ [22,34], we estimate the local dark energy density [12] around the Local group:

$$\bar{\rho}_V = \frac{3M_{LG}}{8\pi R_V^3} = (0.2 - 1) \times 10^{-29} \text{ g/cm}^3. \quad (6)$$

The local density of dark energy proves to be near, if not exactly equal to, the global figure of Eq.5. This result is completely independent of, compatible with, and complementary to the largest-distance observations [1,2]. Note that in both global and local cases, the estimates have a direct character (contrary to the result [3,4]) and follow essentially the same logic based on the condition of the gravity-antigravity balance (Eq.4).

The HST data [21-36] may also be used to the study of the expansion outflows

around other galaxy groups in the local volume. We have recently studied the outflow around the group known as the Cen A/M83 complex [19] and demonstrated that the dynamical structure of the flow is significantly affected by the antigravity of the dark energy background. The local density of dark energy has been estimated to be near the global cosmological density, or exactly equal to it, – in agreement with the result (Eq.6) of the Local group studies.

In the present paper, we use the HST observations [21-36] and extend our studies to the nearby M81/M82 galaxy group and its vicinity. In Sec.2, we give a general discussion of the dark energy domination effect on the expansion flows within the cosmic cell of uniformity; in Sec.3, the basic data on the outflow around the M81/M82 group are presented and analyzed; in Sec.4 the results are summarized.

2 Expansion flows dominated by dark energy

It has long been recognized and recently confirmed [37-48] that the regular ('cool') flow of expansion is clearly seen from a few Mpc distance up to the limits of the observed Universe. At all these distances, the flow preserves its kinematic identity: 1) it follows the Hubble linear velocity-distance relation, and 2) the expansion rate (the Hubble factor) is the same – within the measurement errors – for both local and global scales. This is puzzling because the regular cosmological expansion could only be expected beyond the scale of the cosmic cell of uniformity, at distances $\geq 100 - 300$ Mpc where the matter distribution is statistically uniform and the Universe is isotropic on average. How may the flow be regular within the cell of uniformity where the matter distribution is highly irregular and chaotic?

This problem which is referred to as the Hubble-Sandage paradox has found its solution with the discovery of dark energy. We argue [9-15] that the dark energy background with its perfectly uniform density makes the Universe much more

uniform than it might seem from the matter distribution only. It is important that the dark energy density is considerably higher than the mean matter density even inside the cell of matter uniformity, except the areas of strong matter concentrations like galaxies, galaxy groups or clusters. Because of the dark energy domination, the Universe may be described – in the first and main approximation – by the Friedmann isotropic model on all scales larger than, say, 5-10 Mpc. And so on all these scales, one may expect the Hubble flow of expansion with the Hubble factor:

$$H = H_V[1 + \rho_M/\rho_V]^{1/2}, \quad (7)$$

where

$$H_V = \left(\frac{8\pi G}{3}\rho_V\right)^{1/2} = 64 \pm 3 \text{ km/s/Mpc} \quad (8)$$

is the ‘universal’ expansion rate which is determined by the dark energy density alone. Here the dark energy density is taken as $\rho_V = (0.75 \pm 0.07) \times 10^{-29} \text{ g/cm}^3$ [4]; it is also taken into account that the cosmological expansion proceeds in the parabolic regime corresponding to the flat co-moving space [1-4]. At the present epoch, $t = t_0 \simeq 14$ Gyr, the ratio $\rho_M/\rho_V \simeq 1/3$, which leads to

$$H(t_0) \simeq 74 \pm 6 \text{ km/s/Mpc}. \quad (9)$$

This figure agrees very well with the most precise current measurements of the ‘global’ expansion rate reported by the WMAP [4]: $H_G = 74 \pm 4 \text{ km/s/Mpc}$.

According to Sandage’s et al. [42], the expansion rate is $H_0 = 64 \pm 7 \text{ km/s/Mpc}$ in the scale interval from 4 to 200 Mpc. This observational figure is also rather close to the theory values of Eqs.8-9. Such a coincidence looks impressive, especially if one takes into account how different the ways are in which the figures H_G , H_0 and $H(t_0)$ are obtained. The considerations above suggest that the two observed values for the expansion rate, H_G and H_0 , are close to each other because each of them is close to the universal value determined by the dark energy density alone.

The argument may be inverted: one may consider the regular expansion flow on the scales 4-200 Mpc as an indication on a physical factor that acts on all these

scales and makes the flow regular with a common expansion rate, despite the irregularity of the matter distribution. Then, in the first and main approximation, one may identify the universal rate H_V with the observed expansion rate on these scales H_0 , and find from this identity the estimate of the local dark energy density:

$$\bar{\rho}_V \simeq \frac{3}{8\pi G} H_0^2 \sim 10^{-29} \text{ g/cm}^3. \quad (10)$$

This estimate shows that the local density is near the global density of dark energy. The result is completely independent of the global density measurements [1-4]; it indicates that the dark energy density may really be the same on both local and global scales.

Let us turn now to the smallest spatial scales, 1-3 Mpc, on which the Hubble expansion flow takes its start. It is clear that cosmology considerations described above cannot be applied directly to these scales. Indeed, in our close galaxy vicinity, our Galaxy, the Milky Way, and the Andromeda galaxy move towards each other, and galaxies around them form a group, the Local group, in which there is no general expansion. The local expansion outflow starts in a close vicinity of the group. According to the HST data [23,34], the ‘very local’ expansion rate $H_L = 72 \pm 6 \text{ km/s/Mpc}$. Note again a close coincidence of the expansion rates $H(t_0)$, H_G , H_0 and H_L which are found completely independently of each other.

The local dynamical background of the expansion outflow is controlled by the gravity of the central group and the antigravity of the dark energy background in which all the galaxies of the group and the flow are embedded [9-20]. Considering only the most important dynamical factors, we may take the gravity field of the group as nearly centrally-symmetric and static (this is a good approximation to reality, as exact computer simulations prove [16-18]). Then, according to the Newtonian gravity law, a galaxy of the flow is given an acceleration

$$F_N = -GM/R^2, \quad (11)$$

at its distance R from the group barycenter (which is the origin of the adopted

reference frame).

The local antigravity is produced by the dark energy of vacuum with the uniform local density $\bar{\rho}_V$. According to the ‘Einstein antigravity law’, the dark energy produces acceleration

$$F_E = G2\bar{\rho}_V(\frac{4\pi}{3}R^3)/R^2 = \frac{8\pi}{3}G\bar{\rho}_VR, \quad (12)$$

where $-2\bar{\rho}_V$ is the local effective gravitating density of dark energy (for details see [9-11]). Eqs.11,12 describe the force field in the terms of the Newtonian mechanics; a General Relativity equivalent is given by the static Schwarzschild-de Sitter space-time [11].

It is seen from Eqs.11 and 12 that the gravitational force ($\propto 1/R^2$) dominates over the antigravity force ($\propto R$) at small distances, and the acceleration is negative there. At large distances, antigravity dominates, and the acceleration is positive. Gravity and antigravity balance each other, so the acceleration is zero, at the zero-gravity surface which has the radius

$$R_V = (\frac{3}{8\pi}M/\bar{\rho}_V)^{1/3}. \quad (13)$$

The zero-gravity surface remains almost unchanged since the formation of galaxy groups some 10-12 Gyr ago, as the computer simulations [16-18] indicate.

The zero-gravity radius R_V is a local spatial counterpart of the ‘global’ redshift z_V : the both reflect the gravity-antigravity balance. However, there is a significant difference between the global Friedmann theory and the local theory of Eqs.11-13. Indeed, the global gravity field is uniform and time-dependent, while the local field is non-uniform and static. Globally, the gravity-antigravity balance takes place only at one proper-time moment (at $z = z_V$) in the whole Universe. On the contrary, the local gravity-antigravity balance exists since the formation of the central group, but only at one distance ($R = R_V$).

According to our approach [9-20], the motions of the flow galaxies originate from the early days of the galaxy group when its major and minor galaxies participated

in violent non-linear dynamics with multiple collisions and mergers. Our theory and computer simulations incorporate the concept of the ‘Little Bang’ [49,50] as a model for the origin of the local expansion flow. The model shows that some of the dwarf galaxies managed to escape from the gravitational potential well of the group after having gained escape velocity from the non-stationary gravity field of the forming group.

When the escaped galaxies occur beyond the zero-gravity surface ($R > R_V$), their motion is controlled mainly by the dark energy antigravity and their trajectories are nearly radial there. The trend of the dynamical evolution controlled by dark energy is seen from the fact that (as Eqs.11-13 show) at large enough distances where antigravity dominates over gravity almost completely, the velocities of the flow are accelerated and finally they grow with time exponentially: $V \propto \exp[\bar{H}_V t]$. Because of this, the expansion flow acquires the linear velocity-distance relation asymptotically: $V \rightarrow \bar{H}_V R$. Here the value $\bar{H}_V = (\frac{8\pi G}{3}\bar{\rho}_V)^{1/2}$ appears as the local expansion rate (compare Eq.8) which is constant and determined by the local dark energy density.

Finally, if the local and global densities of the dark energy are indeed identical, $\bar{\rho}_V = \rho_V$, the small-scale expansion flow around a galaxy group (or a cluster) becomes a cosmological phenomenon which is consistent with the whole dynamics of the Universe. In this way, the dark energy antigravity takes the control over the expansion flows on practically all spatial scales – from a few Mpc to the observation horizon – and tends to give them the common expansion rate H_V which is determined by the dark energy density alone.

3 M 81/M 82 group and the outflow around it

The M 81/M 82 galaxy group has recently been systematically observed, alongside with other nearby groups, with the use of the HST [21-36]. The data on the

group are summarized in the Catalog of Neighboring Galaxies [33] and the recent paper [22]. This is one of the closest groups in the local Universe. Its barycenter is located at the distance about 3.5 Mpc from the Local group barycenter. The M 81/M 82 group contains two major galaxies, M 81 and M 82, which have masses $M_{M81} \simeq 7 \times 10^{11} M_{\odot}$ and $M_{M82} \simeq 4 \times 10^{11} M_{\odot}$, respectively [21]. They are separated by the distance of about 40 kpc and move towards each other with the relative radial velocity of about 240 km/s. This massive galaxy binary is similar to the major galaxy binary of the Local group formed by the Milky Way and the M 31 galaxy; but the M 81 and M 82 galaxies are considerably closer to each other and consequently their relative velocity is (two times) larger than that for the Milky Way and the M 31 galaxy. The M 81/M 82 binary is surrounded by a family of smaller galaxies; 18 of them have precise velocities and distances measured with the use of the HST [22,33]. The binary and the galaxies around it form a group which is elongated in shape with the largest size of about 2 Mpc across. The mean velocity dispersion in the group is near 70 km/s.

The vicinity of the group up to the 3-4 Mpc from the group barycenter has also been observed with the use of the HST [22,33]. Around the group, dwarf galaxies are located, and 22 of them have precise velocities and distances measured with the use of the HST [22,33]. These outer smaller galaxies move from the group forming a regular expansion outflow.

Observational data [22,33] on the velocities and distances for the M 81/M 82 group and the outflow around it are presented in the Hubble diagram of Fig.1. The velocities and distances are given relative to the group barycenter. The flow of expansion is clearly seen in Fig.1 at the distances 1.5-3 Mpc from the group barycenter. The flow reveals the linear velocity-distance relation (the Hubble law) with the expansion rate $H_L = 60 \pm 5$ km/s/Mpc. The flow is cool enough: the velocity dispersion is about 30 km/s; as this value is affected significantly by the distance determination errors, the true value is still lower.

Since the major part of the total mass of the group and the flow is concentrated in the central close binary, the gravity field produced by the group is practically spherical at distances ~ 1 Mpc and more from the group barycenter. Because of this, the simple relations of Sec.2 may be used as a good approximation for the description of the dynamical background of the flow. With the general relation of Eq.13, one may estimate the zero-gravity radius for the M 81/M 82 group. Taking the mass of the group $M = M_{M81} + M_{M82} \simeq 1 \times 10^{12} M_{\odot}$ and the dark energy density $\rho_V = 0.75 \times 10^{-29} g/cm^3$, we find: $R_V \simeq 1$ Mpc.

According to the considerations of the section above, the members of the galaxy group must be located within the zero-gravity surface, and this is really obvious from Fig.1. In particular, all the galaxies with negative velocities are located within the zero-gravity sphere. The considerations of Sec.2 indicate as well that the flow of expansion is expected to approach the linear velocity-distance relation outside the zero-gravity surface where the antigravity of dark energy is stronger than the gravity of the group matter. Indeed, Fig.1 shows that the linear velocity-distance relation emerges from the distance $R \simeq 1.5 - 2$ Mpc, and all the galaxies at the distances $R > 1.5$ Mpc move apart of the group.

The theory of Sec.2 makes a definite prediction: the expansion rate at distances $R > 1.5 - 2$ Mpc must be near the universal expansion rate $H_V = 64 \pm 3$ km/s/Mpc, if dark energy has the same density everywhere in space. The data of Fig.1 agree well with this prediction, since $H_L \simeq H_V$. On the other hand, identifying the observed local value H_L with the value \bar{H}_V (see Sec.3), one may get an estimate of the local density of dark energy in the area around the M 81/M 82 group:

$$\bar{\rho}_V = \left(\frac{3}{8\pi G} H_L^2 \right)^{1/2} = (0.6 \pm 0.2) \times 10^{-29} g/cm^{-3}. \quad (14)$$

As we see, the local density $\bar{\rho}_V$ is very near the global density ρ_V , if not coinciding with it exactly.

The theory makes also another specific prediction: the velocities of the local

expansion flow must be not less than a minimal velocity V_{esc} :

$$V_{esc} = \left(\frac{2GM}{R_V}\right)^{1/2} \left(\frac{R}{R_V}\right)^{1/2} \left[1 + \frac{1}{2}\left(\frac{R}{R_V}\right)^3 - \frac{3}{2}\left(\frac{R}{R_V}\right)\right]^{1/2}. \quad (15)$$

The minimal velocity corresponds to the minimal total mechanical energy,

$$E_{esc} = -\frac{3GM}{2R_V}, \quad (16)$$

needed for a particle to escape from the gravitational potential well of the group. Due to the antigravity of dark energy, this energy is negative. The condition $V \geq V_{esc}$ is comfortably satisfied, if one assumes that $\bar{\rho}_V = \rho_V$ and also adopts somewhat larger value for the total mass of the group, namely $M = M_{M81} + M_{M82} = 1.3 \times 10^{12} M_\odot$ (which is within the limits of its observational determination). Then the zero-gravity radius $R_V = 1.3$ Mpc. With this mass and the assumed dark energy density, all the galaxies of the flow are located above the critical line $V_{esc}(R)$ showed by a bold curve in Fig.1. The critical velocity is zero at the distance $R = R_V = 1.3$ Mpc.

On the other hand, a clear structure of the Hubble diagram of Fig.1 enables to recognize independently the position of the zero-gravity sphere in the diagram. Indeed, since the zero-gravity surface lies outside the group volume, it should be that $R_V > 1$ Mpc. The fact that the linear velocity-distance relation is seen from a distance of about, say, 2 Mpc suggests that $R_V < 2$ Mpc. If so, Eq.13 leads directly to the robust upper (from $R > 2$ Mpc) and lower ($R < 3$ Mpc) limits of the local dark energy density:

$$0.2 < \bar{\rho}_V < 1 \times 10^{-29} \text{ g/cm}^3. \quad (17)$$

This result is in good agreement with the estimate of Eq.14 and the considerations above. The lower limit in Eq.17 is most significant: it means that the dark energy does exist in the area. In combination, both limits imply that the value of the local dark energy density is near the value of the global dark energy density, or may be exactly equal to it.

One may see from Fig.1 that the structure of the flow follows the trend of the minimal velocity: the linear regression line of the flow (the thin line in Fig.1) is nearly parallel to the minimal velocity curve, at $R > R_V$. It may easily be seen from the theory of Sec.2 that in the limit of large distances, the minimal velocity and the real velocity of the flow galaxies have a common asymptotic, $V = V_{esc} = H_V R$, independently on the initial conditions of the galaxy motions.

For a comparison, a minimal escape velocity, $(\frac{2GM}{R_V})^{1/2}(\frac{R}{R_V})^{1/2}$, is showed in Fig.1 for a ‘no-vacuum model’ with zero dark energy density (dashed line). The real flow is obviously ignores the trend of the minimal velocity in this case: the velocities of the flow grow with distance, while the minimal velocity decreases. It is seen also that two galaxies of the flow at $R > R_V$ violate obviously the no-vacuum model: they are located below the dashed line, in the diagram. This comparison is clearly in favor of the vacuum model and against the model with no dark energy.

4 Conclusions

As is well-known, galaxy groups and their close environment are more or less similar to each others in the local Universe [51-54]. Similar conclusion follows also from large N-body Λ CDM cosmological simulations [55-60]. The structure with a massive galaxy group (or cluster) in its center and a cool expansion outflow outside – a ‘Hubble cell’ [19] – seems to be characteristic for the local Universe.

High accuracy observations of the local volume with the use of the HST [21-36] enabled us to study the Local Group and the cool expansion outflow around it as an archetypical example of the structure. The major new physics here is the presence of dark energy and its domination in the dynamics of the expansion flows. The basic physical quantity of the cell is the zero-gravity radius R_V introduced in [9-13]. For the Local Hubble cell, $R_V = 1.25$ Mpc. The central group of the cell is located within the zero-gravity surface ($R < R_V$) and controlled mostly by

the gravity of the group matter (dark matter and baryons). The cool expansion outflow develops outside the surface ($R > R_V$), and its structure and evolution are determined mainly by the antigravity of the dark energy background. The HST observations [22,33] enable us also to study a similar dynamical structure in the area of the Cen A/M 83 galaxy group [19]; the third clear example of the structure is demonstrated above in the present paper.

Our observations and analysis of the three nearby Hubble cells lead to the following conclusions: 1) dark energy is definitely present in the local Universe on the spatial scales of a few Mpc; 2) the antigravity of dark energy dominates the dynamics of the expansion outflows on these scales; 3) the local density of dark energy is near the global density of dark energy or perhaps exactly equal to it. The conclusions form a strong evidence for dark energy as cosmic vacuum which is equivalent to the Einstein cosmological constant.

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Figure caption

Fig.1. The Hubble velocity-distance diagram for the M 81/M 82 galaxy group and its vicinity, according to the HST observations [22,33]. The velocities and distances are given relative to the group barycenter. The galaxies of the group are located within the zero-gravity sphere of the radius $R_V = 1.32$ Mpc. The flow of expansion starts in the outskirts of the group; all the galaxies at distances $R > R_V$ Mpc move apart of the group (positive velocities). The flow reveals the linear velocity-distance relation (see also the text).

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