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Dwarfs and giants in the local flows of galaxies

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We use recent Hubble Space Telescope data on nearby dwarf and giant galaxies to study the dynamical structure and evolutionary trends of the local expansion flows of galaxies. It is found that antigravity of dark energy dominates the force field of the flows and makes them expand with acceleration. It also cools the flows and introduces to them the nearly linear velocity–distance relation with the time-rate close to the global Hubble's factor. There are grounds to expect that this is the universal physical regularity that is common not only for the nearby flows we studied here, but also for all the expansion flows of various spatial scales – from the 1 Mpc scale and up to the scale of the global cosmological expansion.

Keywords: Galaxies: groups: general – galaxies: kinematics and dynamics – (cosmology:) dark energy

1 Introduction

The concept of cold local expansion flows was introduced by Sandage (1986) (see also Sandage 1999; Sandage, Tammann & Hardy 1972; Sandage et al. 2006) for observed collective reseeding motions of galaxies on spatial scales from $\simeq$1 to $\simeq$300 Mpc. Two major features are characteristic for the flows: (1) their kinematic follows rather closely the linear velocity–distance relation $V \simeq HR$ known as Hubble's law; (2) their expansion time-rate H is near the global cosmological expansion time-rate (Hubble's factor) $H_0 \simeq 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. The flows are considered "cold" in the sense that the deviations from the relation $V = HR$ with $H = H_0$ are relatively small and so the corresponding radial velocity dispersion σ is low. The nearest and best studied (Sandage et al. 1972; Karachentsev et al. 2002, 2003a,b, 2009; Tully et al. 2013; Courtois et al. 2013) example of the cold expansion flows is the the Local Flow of Dwarfs (LFD) which involves two dozen dwarf galaxies moving away from the Local Group with velocities of 60–250 km $\mathrm{s^{-1}}$ at distances of $\simeq$1–3 Mpc

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from the group barycenter. Recent high accuracy observations with the Hubble Space Telescope (Karachentsev et al. 2002, 2003a, 2009) give the radial velocity dispersion $\sigma \simeq 30$ km s^{-1} at distances less than 3 Mpc and the mean expansion time-rate is 72 km s^{-1}Mpc^{-1} with 10% accuracy.

Another example of the nearest expansion flow is the Local Flow of Giants (LFG) recently studied observationally by Karachentsev et al. (2013, 2014) with the Hubble Space Telescope (HST). This is the reseeding motion of a dozen of the most luminous galaxies at distances up to 10 Mpc from the barycenter of the Local Group. These are galaxies M81, NGC5128, IC342, NGC253, NGC4736, NGC5236, NGC6946, M101, NGC4258, NGC4594, NGC3115, NGC3627, NGC3368 (see also McCall 2014). They are moving away from the Local Group with radial velocities of 100 to 900 km s^{-1} relative to the barycenter of the group. The flow follows Hubble's law with the local time-rate $H = 66$ km s^{-1} Mpc^{-1} and the rms radial velocity dispersion $\sigma \simeq 100$ km s^{-1}. Each of the giants is actually the main galaxy of a group which includes the galaxy itself and its extended dark matter halo together with companion galaxies therein. The masses of the objects range from 0.66 to $30 \times 10^{12}\, M_\odot$; the total mass of the LFG is $80 \times 10^{12}\, M_\odot$. The complete data on the local giant galaxies and their numerous companions are presented in the Updated Nearby Galaxy Catalogue (UNGC) by Karachentsev et al. (2013) (see also Karachentsev & Kudrya 2014). The unique resolution available in the HST observations allowed us to use the Tip of the Red Giant Branch (TRGB) method for precise measurements of distances to more than 300 nearby galaxies with the accuracy of 10%. Precise data on the radial velocities and the masses of the galaxies are also compiled in the UNGC. Modern accurate data on the distances and other parameters of nearby galaxies are also accumulated in the Extragalactic Distance Database (Tully et al. 2008) and in the Database of the Local Volume Galaxies (Kaisina et al. 2012).

In this work, we discuss the structure and evolution of the local expansion flows based mostly on the examples of the LFD and LFG. The local dynamical effects of dark energy is in the focus of our studies. Our treatment of the dynamics of the LFD (Chernin 2001, 2008; Baryshev et al. 2001; Byrd et al. 2007, 2012; Teerikorpi et al. 2008) and LFG (Chernin, Emelyanov and Karachentsev 2015) assumes that dark energy discovered at global cosmological distances (Riess et al. 1998; Perlmutter 1999) is a universal omnipresent physical phenomenon described by Einstein's cosmological constant Λ. A combination of the HST data on the two flows and our theory of the local gravity–antigravity interplay enables us to recognize the dynamical structure of the local flows, as well as their evolutionary trends. We will show that dark energy is the dominant physical factor in the present and future dynamics of the flows. The dark energy domination makes the flow expand with acceleration. It also cools the flows and introduces to them the nearly linear velocity–distance relation with the time-rate close to the global Hubble's factor.

2 Local antigravity

The local dynamical effects of the universal dark energy are studied (see for review Chernin 2001, 2008, 2013; Byrd et al. 2007, 2012) since the discovery of dark energy

in cosmological observations. Here we give some basic relations needed for the description of the force field in the local flows of expansion. The relations come from General Relativity with non-zero Einstein's cosmological constant Λ and the currently standard ΛCDM cosmology.

According to Gliner (1966), dark energy may be treated as a continuous medium with the density $\rho_\Lambda = c^2\Lambda/(8\pi G)$ that is positive and constant in space and time in any reference frame (here G is the Newtonian gravitational constant and c is the speed of light). The currently adopted value of the dark energy density $\rho_\Lambda \simeq 0.7 \times 10^{-29}\,\mathrm{g\,cm^{-3}}$. Dark energy produces the cosmic repulsion, or antigravity, which dominates the dynamics of the observed universe as a whole.

Dark energy as a medium is characterized by the equation of state (Gliner 1966):

$$p_\Lambda = -\rho_\Lambda c^2. \tag{1}$$

Here p_Λ is the dark energy pressure. Dark energy is a vacuum-like medium: it cannot serve as a reference frame, and it is co-moving to any matter motion – similarly to trivial emptiness (Gliner 1966).

In General Relativity, the effective gravitational density is determined by both density and pressure of any fluid:

$$\rho_{\mathrm{eff}} = \rho + 3p/c^2. \tag{2}$$

The effective density of dark energy, $\rho_{\Lambda\mathrm{eff}} = \rho_\Lambda + 3p_\Lambda/c^2 = -2\rho_\Lambda < 0$, is negative, and it is because of this that dark energy produces the repulsion, or antigravity, not gravity.

General Relativity indicates also that the passive gravitational density is the sum $\rho_{\mathrm{pass}} = \rho + p/c^2$ for any fluid. The value is zero for dark energy. According to the equivalence principle, the passive gravitational mass is equal to the inertial density. Thus, the inertial density of dark energy is zero as well. This implies that dark energy is affected neither by the external gravity of matter nor by its own antigravity.

We assume here that this interpretation of dark energy may be borrowed from ΛCDM cosmology and applied to relatively small, non-cosmological spatial scales of $\simeq$1–300 Mpc, no matter that the isotropic cosmology itself is not valid on these local scales where the matter distribution is highly non-uniform. We will describe the local dynamical effects of dark energy in terms of Newtonian mechanics; it is possible because the velocities of the local flows of galaxies are small compared to the speed of light, and the spatial differences in the gravity–antigravity potential are much smaller (in absolute value) compared to the speed of light squared.

In this weak field approximation, Einstein's law of universal antigravitation says: any body in the universe is affected by the repulsive force which is proportional to the dark energy density ρ_Λ and to the distance R of the body from the origin of the adopted reference frame and acts along the direction from the origin:

$$F_\Lambda = \frac{8\pi}{3} G\rho_\Lambda R. \tag{3}$$

The relation of Eq. (3) gives the force per unit mass of the body, i.e. acceleration, in the projection on the body radius-vector. It may be rewritten in the form $F_\Lambda = H_\Lambda^2 R$, where

$$H_\Lambda = \left(\frac{8\pi}{3} G\rho_\Lambda\right)^{1/2} = 61\ \ \mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{4}$$

is the "universal time-rate" (see below).

An exact analytical solution for two-body problem on the dark energy background with the antigravity force of Eqs. (3)–(4) has recently been given by Emelyanov & Kovalyov (2013).

3 LFD: Light-particle model

The LFD around the Local Group of galaxies at distances of 1–3 Mpc from us is the closest expansion flow. The Local Group together with the flow may be considered as an isolated physical system. In a simple model (Chernin et al. 2000; Chernin 2001, 2013), the group is represented by a spherical mass $M = (3\text{–}4)\times 10^{12}\, M_\odot$ with a radius $R_0 \simeq 1$ Mpc. The dwarfs of the flow are considered as "light (test) particles" moving along radial trajectories in the force of gravity produced by the matter (baryonic and dark matter) mass M of the group and the force of antigravity produced by the dark energy background. In this approximation, the force (per unit mass) acting on a flow particle comes from Eq. 4:

$$F(R) = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_\Lambda R. \tag{5}$$

This is the equation of motion which gives the particle acceleration in the field of the Newton's force of gravity and Einstein's force of antigravity. It is also seen from Eq. 5 that gravity may dominate at small distances from the mass M, while antigravity is stronger than gravity at large distances. Gravity and antigravity balance at the distance

$$R = R_\Lambda = \left(\frac{M}{\frac{8\pi}{3}\rho_\Lambda}\right)^{1/3}, \tag{6}$$

which is the radius of the "zero-gravity sphere" (Chernin et al. 2000; Chernin 2001).

(Note that the zero-gravity radius R_Λ appears here as the local spatial counterpart of the "zero-gravity moment" in the global expansion of the Universe which occurred at the cosmic redshift 0.7 about 7 Gyr ago.)

With the known mass of the group (see above), the LFD zero-gravity radius is near 1 Mpc which is equal almost exactly to the group radius. Thus, in the volume of the group, $R \leq R_\Lambda$, the gravity of the matter mass M is stronger than the antigravity produced by the dark energy background in the same volume. Because of this the group may be quasi-stationary and gravitationally bound. Outside the group in the flow area, the antigravity of dark energy dominates. Because of this, the LFD particles are unbound and moving with acceleration away from the group. The flow acceleration is positive and growing with the distance at $R > R_\Lambda$.

The first integral of the equation of motion is the law of the mechanical energy conservation for the particle:

$$\frac{1}{2}\dot{R}^2 = \frac{GM}{R} + \frac{4\pi G}{3}\rho_\Lambda R^2 + E, \tag{7}$$

where $\dot{R} = V$ is the particle radial velocity, E is a constant which is the total mechanical energy of the particle.

The evolutionary trend of the flow is seen from Eq. 7: when the distance R of the particle from the group is growing, the particle velocity tends with time to the linear velocity–distance relation, $V = H_\Lambda R$, with the universal time-rate H_Λ. It is the same asymptotic time-rate which is also known in cosmology. Thus, the antigravity domination is able to "cool" the flow introducing Hubble's law with the nearly cosmological time-rate to the LFD.

4 LFG: ΛN-body model

Being a typical local flow, the LFG differs significantly, however, from the LFD. Indeed, the galaxies of the LFD are moving in the external gravity–antigravity field produced by the Local Group and the dark energy, while the mutual gravity of the bodies is practically negligible (Sec. 3). The dynamics of the LFG is also controlled by the gravity–antigravity force field, but in contrast to the LFD, there is no single dominating matter concentration in the LFG; each of its member galaxies contributes more or less equally to the total matter mass of the system, and the gravity is due to the mutual attraction of the bodies. The model of the flow we suggest is the "ΛN-body" model which treats the LFG as a gravitational N-body system embedded in the universal dark energy background.

Note that the ΛN-body model has strong limitations: 1) it is valid only when and where the distances between the LFG bodies (giant galaxies with their dark matter halos) are large enough compared to the sizes of the bodies; 2) it does not describe the origin and early evolution of the flow. The first limitation is well satisfied for the observed present-day state of the flow; it is clearly satisfied as well in the flow future. The second limitation comes not only from the first one, but also from more fundamental physical reasons according to which the origin and early evolution of local systems is a complex nonlinear process dominated by the LSS environment (Klypin et al. 2003; Aragon-Calvo et al. 2011, Peebles & Nusser 2010). This process resulted with time in the presently observed physical state of the flow; the observational data on its spatial and kinematic structure are used below for the formulation of "initial conditions" of the model.

In the ΛN-body model, the LFG is treated as a non-relativistic isolated conservative system of point-like masses interacting with each other via Newton's mutual gravity and undergoing Einstein's antigravity (3)–(4) produced by the dark energy background. The equations of motion for the system have the following form (see, for comparison, books by Duboshin (1975), and Roy (1978) on the N-body problem without dark energy):

$$\frac{d^2x_i}{dt^2} = G{\sum_{j=1}^{N}}' m_j \frac{x_j - x_i}{r_{ij}^3} + H_\Lambda^2 x_i, \tag{8}$$

$$\frac{d^2y_i}{dt^2} = G{\sum_{j=1}^{N}}' m_j \frac{y_j - y_i}{r_{ij}^3} + H_\Lambda^2 y_i, \tag{9}$$

$$\frac{d^2z_i}{dt^2} = G{\sum_{j=1}^{N}}' m_j \frac{z_j - z_i}{r_{ij}^3} + H_\Lambda^2 z_i, \tag{10}$$

where

$$r_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}. \quad (11)$$

Here x, y, z are the Cartesian coordinates with the origin in the barycenter of the LFG; m_i is the mass of the body of the number i, the symbol prime ($'$) at the summation symbol means the absence of the item with $j = i$. In Eqs. (8)–(11), Newton's gravity force depends on the distance between gravitating bodies, while Einstein's force depends only on the distance of the body from the coordinate origin.

The number of giants at the distances up to 10 Mpc is 15 including the Milky Way and the Andromeda Nebula; in our model, these two are considered as one mass. Another close gravitationally bound binary galaxy, NGC5236 plus NGC5128, is also considered as one mass. Together with the giant galaxies, we include to the model also two nearest clusters of galaxies outside the flow, the Virgo and Fornax clusters, located at distances about 20 Mpc from the Local Group. Thus, the total number of bodies is 15 in the model. The initial conditions for each of the bodies are specified at the present moment of cosmic time $t = t_0 = 13.8$ Myr; these are the observed positions of the flow bodies and their measured radial velocities re-calculated to the barycenter of the Local Group (see references in Sec. 1).

Note that observations provide us with the radial velocities of the galaxies, but say nothing about their tangential (transverse) velocities. This is an obvious flaw in any dynamical model of extragalactic astronomy where the full velocity vector is needed for correct formulation of initial conditions. Being cognizant about the situation, we have in mind that the angular momentum conservation leads to decreasing transversal velocity with time during the flow expansion. Anyway we assume that the transversal velocities are zero in the initial conditions for the model.

It is well-known (see again Duboshin (1975) and Roy (1978)) that the N-body equations of motion have 10 first integrals; they correspond to the spacetime symmetries of the equations which imply respective conservation laws, the angular momentum conservation including. The ten integrals of Eqs. (8)–(11) are employed to ensure accuracy in our computer integrations: the integrals are computed and their deviations from the initial values are calculated at the end of each computation session. The integrals prove to be conserved unchanged, and the deviations are found to be zero with all the accuracy of the number representation in the computer. As for efficiency of integration, the solution of ΛN-body problem with, say, $N = 15$–40 on the cosmic time interval of 15 Gyr takes less than 5 seconds of computing time. Numerical integration of Eqs. (8)–(11) is performed with the use of Everhart's (1974) standard computer method with the automatic choice of the integration step.

We have performed computer integration of Eqs. (7)–(11) for the time interval of 15 Gyr, from the cosmic age at $t = 10$ Gyr in its past to the present age of $t = 13.7$ Gyr and further to $t = 25$ Gyr in the future. The lower age here comes from the model limitations mentioned above: the history of the flow can be traced back in time to narrower spatial configurations of the LFG bodies that still allow their approximate treatment as point-like masses. As for the future, the integration is limited by the condition of non-relativistic velocities of the accelerating expansion. The description of the system for 15 Gyr time interval proves to be long enough to recognize its dynamical structure and major trends of its evolution.

The result of the integration gives the state of the system by its position in the 6N-dimension phase space at any instant in the cosmic time interval from 10 to 25

Gyr. The result shows that the lengths of the phase trajectories are relatively short for the bodies with low initial velocities and they are long for the high-velocity galaxies and the clusters (which might be expected). It is less trivial that all the trajectories reveal clearly the major evolutionary trend of the flow: with the distance growth, the trajectories converge to the straight line $V = H_\Lambda R$ going from the coordinate origin. As a result, the mean radial velocity dispersion decreases with the distance growth, and the flow becomes increasingly regular and cold since the spread of the phase trajectories around the line $V = H_\Lambda R$ systematically decreases with the increase of the distances. For instance, the width of the LFG trajectory bunch decreases by a factor of 3 when the distance R increases from 7.5 to 17 Mpc. This is a clear quantitative measure of the cooling effect in the expansion flow.

The analysis of the phase trajectories shows also that in its asymptotic state the flow bodies follow the linear velocity–distance relation, $V = H_\Lambda R$, with the universal expansion time-rate $H_\Lambda = 61\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. This time-rate is constant and depends on the dark energy density only. Its value is not far from the present value of the time-dependent cosmological time-rate $H_0 \simeq 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ found in global observations.

5 Conclusions

In our work, the structure and evolution of the Local Flow of Dwarfs and the Local Flow of Giants are adequately described by the Light-Particle Model and the ΛN-body model, respectively. The models demonstrate that despite their obvious difference in the gravitating mass distribution, the flows prove to be similar in their basic dynamical structure and evolutional trends. This similarity is due to the gravity–antigravity interplay that controls the physics of the systems. We find that in both flows Einstein's antigravity produced by dark energy is stronger than Newton's gravity produced by the matter masses, and the antigravity domination increases with time in the systems. It is because of this strong local dynamical effect of dark energy that the expansion flows in the universe tend to an asymptotic state with the linear velocity–distance relation, $V = H_\Lambda R$, and the expansion time-rate H_Λ which is determined by the dark energy density only. We have good grounds to expect that this is the universal asymptotic state that is common not only for the two nearby flows we studied here, but also for all the expansion flows of all the spatial scales – from the 1 Mpc scale and up to the scale of the global cosmological expansion.

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