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Local and global dynamical effects of dark energy

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Local expansion flows of galaxies were discovered by Lemaître and Hubble in 1927–29 at distances of less than 25–30 Mpc. The global expansion of the Universe as a whole was predicted theoretically by Friedmann in 1922–24 and discovered in the 1990s in observations at truly cosmological distances of more than 1 000 Mpc. On all these spatial scales, the flows follow a (nearly) linear velocity–distance relation, known now as Hubble's law. This similarity of local and global phenomena is due to the universal dark energy antigravity which dominates the cosmic dynamics on both local and global spatial scales.

Keywords: Groups of galaxies, local cosmic flows, dark energy

1 Introduction

The truly cosmological distances of ≥1000 Mpc scale have become available for observations in the mid-1990s with the start of operation of the Hubble Space Telescope and other big modern astronomical instruments. The observations at these distances have directly confirmed Friedmann's theory of the cosmological expansion and led to further great discoveries in the global Universe. Most important of them is the discovery of dark energy (Riess et al. 1998, Perlmutter et al. 1999; Nobel Prize in physics of 2011). The astronomical findings made near the cosmic horizon have provided us as well with new reliable grounds for the better understanding of astronomical phenomena at relatively small, non-cosmological distances. With dark energy, a new "antigravity" force has entered the cosmic scene, and it has been soon realized that the gravity–antigravity interplay is the major dynamical factor that controls the observed motions of galaxies at actually all distances – from global ones to ∼1 Mpc from us – see the reviews by Chernin (2001, 2008, 2013), Byrd et al. (2007, 2012, 2015) and references therein.

Due to these discoveries, it is known now that dark matter and dark energy are the basic components of the present-day universe. The fractions of dark energy and dark matter in the entire mass/energy balance of the observed Universe are about 70 and 26%, respectively. The "usual" (baryonic) matter of stars, the Earth, and all the

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things on the Earth constitutes about 4%. These data have recently been confirmed (and refined) in the space investigations in the WMAP and Planck missions.

Dark matter and dark energy do not emit, absorb, or scatter light. They manifest themselves only by their gravity and antigravity, correspondingly. Antigravity was predicted theoretically by Einstein in 1917, when he proposed the equations of General Relativity in their final form. In Einstein's equations, antigravity is represented by the cosmological constant Λ. The possible existence of Einstein's antigravity was taken into account in Friedmann's cosmological model of 1922–24. His theory contains the cosmological constant Λ as an empirical parameter which should be measured in astronomical observations.

The cosmological data show also that antigravity is stronger than gravity in the observed universe as a whole. The antigravity dominates at present and during the last 7 Gyr of the cosmic evolution; in the unlimited future, antigravity domination will be even stronger. Because of the antigravity domination, the global expansion proceeds with acceleration: the relative velocities of receding galaxies increase with time.

2 Antigravity law

General Relativity implies that 1) the antigravity produced by dark energy is a universal (in the same sense as gravity is universal) physical factor acting everywhere in space, on both global and local astronomical scales, 2) antigravity on the local scales is described by Einstein's equations, and 3) the density of dark energy is the same in space and time and its value is given by Einstein's cosmological constant: $\rho_\Lambda = \Lambda/(8\pi G)$, where G is the Newtonian gravitational constant; the speed of light $c = 1$ here. The dark energy density ρ_Λ is positive and its currently adopted value $\rho_\Lambda \simeq 0.7 \times 10^{-29}$ g/cm^3 (Riess et al. 1998, Perlmutter et al. 1999).

In addition to General Relativity, a macroscopic description (Gliner 1965) of dark energy treats it as a vacuum-like continuous medium of perfectly uniform constant density with the equation of state

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

Here p_Λ is the dark energy pressure.

General Relativity indicates that the "effective gravitating density" is determined by both density and pressure of the medium:

$$\rho_{eff} = \rho + 3p. \tag{2}$$

The effective density of dark energy, $\rho_\Lambda + 3p_\Lambda = -2\rho_\Lambda < 0$, is negative, and it is because of this sign minus that dark energy produces not attraction, but repulsion, or antigravity.

In General Relativity, there is an exact solution to Einstein's equation that may be implied to study local effects of dark energy. This is Köttler's solution for spherically-symmetrical spacetime known also as the Schwarzschild–de Sitter spacetime. The solution gives the metric outside a spherical matter mass M imbedded in the dark energy of the constant density ρ_Λ:

$$ds^2 = Y dt^2 - R^2 d\Omega^2 - Y^{-1} dR^2. \tag{3}$$

Here R is the distance from the center of the mass, $d\Omega^2 = \sin^2\theta d\phi^2 + d\theta^2$ and

$$Y(R) = 1 - 2\frac{GM}{R} - \frac{8\pi}{3}\rho_\Lambda R^2. \quad (4)$$

The metric of Eqs. 3, 4 is static, contrary to Friedmann's cosmological time-dependent spacetime. As is seen from Eq. 4, at infinitely large distances, the gravity of the mass M becomes negligible in comparison with the dark energy antigravity, and the Köttler metric tends to the de Sitter metric which is determined by the dark energy only:

$$Y \simeq 1 - \frac{8\pi}{3}\rho_\Lambda R^2, \quad R \to \infty. \quad (5)$$

It is remarkable that the Friedmann cosmological solution has the same de Sitter static asymptotic at infinitely large time in standard cosmology.

When the gravity–antigravity field is weak and deviations from the Galilean metric are small, the metric of Eqs. 3, 4 may be reduced to the Newtonian description in terms of the gravity–antigravity potential U:

$$Y^{1/2} \simeq 1 + U, \quad U(R) = -\frac{GM}{R} - \frac{4\pi G}{3}\rho_\Lambda R^2. \quad (6)$$

In this approximation, the force (per unit mass) comes from Eq. 6:

$$F(R) = -\frac{dU}{dR} = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_\Lambda R. \quad (7)$$

We see in the rhs here the sum of the Newtonian force of gravity produced by the mass M and Einstein's force of antigravity produced by dark energy (the forces are for unit mass, i.e. acceleration). It's interesting that the relation in Eq. 7 for the antigravity force looks like the Newtonian law of universal gravitation, $F = -G\frac{M}{R^2}$, if the mass M is taken to be the effective mass of dark energy in the sphere of the radius R:

$$M_{eff} = \frac{4\pi}{3}\rho_{eff}R^3 = -\frac{8\pi}{3}\rho_\Lambda R^3. \quad (8)$$

It is also seen from Eq. 7 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

$$R = R_\Lambda = (\frac{M}{\frac{8\pi}{3}\rho_\Lambda})^{1/3} \quad (9)$$

which is the radius of the "zero-gravity sphere" (Chernin 2001).

3 Local cosmic structure

The basic elements of the local cosmic structure at the distances less than 1–10 Mpc are groups of galaxies and the expansion flows of galaxies around the groups. Receding motions of galaxies were first observed by Vesto Slipher a century ago. He measured the velocities of galaxies and found that many galaxies moved away from us. In 1927,

these data were analyzed by George Lemaître who used published distances to galaxies up to 3 Mpc and discovered the linear relation, $V = H_0 R$ (referred now as Hubble's law), between the velocity V and the distance R. In 1929, Edwin Hubble confirmed the result basing on mostly the same observational material. Later it was realized that the distances estimated in the 1920s need an almost order-of-magnitude revision: they were not up to 3 Mpc, as Lemaître and Hubble believed, but rather up to 25–30 Mpc. Allan R. Sandage, who was Hubble's successor in observational cosmology on Mount Wilson and Mount Palomar, accepted Hubble's law for local distances of 1–30 Mpc as an important well-established empirical fact. He introduced the notion of "expansion flows" for local systems of receding galaxies with nearly linear velocity–distance relation. When deviations from linearity (velocity dispersion) are small, the flow is considered "cool and quiet".

A modern high accuracy data-set on groups and flows of galaxies up to the distances about 10 Mpc have been obtained by Karachentsev et al.(2003a,b, 2009, 2013). The data include, in particular, information on velocities and distances of about 300 galaxies that were observed with the Hubble Space Telescope (HST) during 300 its orbital periods, as well as with the 6-m Telescope (Special Astrophysical Observatory, Russian Academy of Sciences), Arecibo radio telescope, and other large instruments. The accuracy of the measurements of velocities is no worse than 1–5 km/s (primarily from the observations at the 21 cm line). The accuracy of the determination of distances measured by the method of the Tip of the Red Giant Branch is 8–12%.

These data indicate that our close galactic environment up to the distances of about 3–10 Mpc is very far from uniformity in the matter distribution. Two giant galaxies – the Milky Way and the Andromeda Galaxy – together with half-hundred less massive companions form the Local group of about 2–2.4 Mpc across. Its total mass (dark matter and baryons) is $M = (2-4) \times 10^{12} M_{\odot}$. Dark matter concentrates mostly in the extended invisible dark-matter halos of the giants. The giants are at the distance of 0.7 Mpc from each other and they move towards each other with a velocity of 110 km/s. Within the group volume, its member galaxies have both positive (directed out of the center) and negative (to the center) line-of-sight velocities. Relative to the group barycenter, the velocities are in the range from - 150 to +170 km/s. The average radial velocity of the galaxies in the group is close to zero, and the linear velocity dispersion is 72 km/s.

Beyond the group, about 30 dwarf galaxies are observed at distances of 1.3 to 3 Mpc from the barycenter of the group. All these galaxies move away from the Local group and constitute the Very Local Flow (VLF) of receding galaxies. In the VLF area outside the group, the positive radial velocities are in the range from 60 km/s near the distance of 1.3 Mpc to 250 km/s at the distance of 3 Mpc. The observed velocity–distance relation for the VLF is near Hubble's linear law, $V = HR$, with the median expansion time-rate (local Hubble's factor) $H = 66$ km/s/Mpc. The VLF radial velocity dispersion is 25 km/s [20] which is by a factor of about 3 smaller than that in the Local Group; this means that the VLF is "cool and quiet", in Sandage's terminology.

A dozen of groups of galaxies are observed at the distances up to 10 Mpc. All of them are similar to the Local group: they contain giant galaxies and have expanding flows around them (Karachentsev et al. 2009, 2013).

4 Local model

The observed local cosmic structure is the arena of the gravity–antigravity dynamical interplay on the local scale (Chernin 2008, 2013). The Local group with its outflow is the basic element of this structure. It may adequately be described by a theory model based on Köttler's solution for spherically-symmetrical spacetime (see above). It the model, the group together with the flow are treated as an isolated physical system. The group itself is represented by a spherical mass $M = (3-4) \times 10^{12} M_\odot$ with a radius $R_0 \simeq 1$ Mpc. According to Eq. 9, the zero-gravity radius of the group proves to be $R_\Lambda = 1.1 - 1.3$ Mpc which is near its observed radial size R_0. The dwarf galaxies of the expansion flow around the group are considered as "test particles" moving along radial trajectories in the force field produced by the matter (baryonic and dark matter) mass M of the group and the dark energy background in which both group and outflow are imbedded.

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. In the flow area, the antigravity of dark energy dominates. It may be seen that outside the group (like, for instance, the Local group with its two giants inside) the gravity field produced by the group may be considered – with good accuracy – as spherically symmetrical. Since that the flow particles are unbound and moving with acceleration away from the group.

The flow dynamics is given by the equation of motion which follows from Eq. 7:

$$\ddot{R}(t) = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_\Lambda R. \tag{10}$$

The sum in the rhs of Eq. 10 is acceleration which 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:

$$\frac{1}{2}\dot{R}^2 = \frac{GM}{R} + \frac{4\pi G}{3}\rho_\Lambda R^2 + E, \tag{11}$$

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

Equation 11 is the major theory relation which gives the phase trajectories of the flow in the velocity–distance space. The trajectories are showed in Fig. 1. They demonstrate the structure and evolution of the flow, in the model. As is seen from Fig. 1, the observed velocities and distances of the flow particle find their place in a quite natural way in the set of theory trajectories.

5 Cooling effect

Equation 11 and Fig. 1 show that the model phase trajectories of the flow are not linear, generally. But they approach the linear relation with growing distance from the group center. The exact linear law is reached asymptotically at $R \to \infty$:

$$V = \dot{R} \to H_\Lambda R, \tag{12}$$

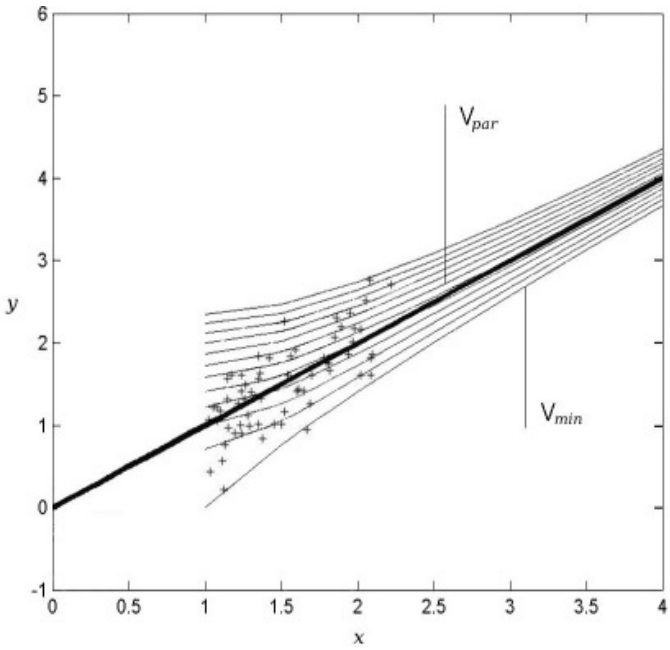


Figure 1 The collective phase portrait of 4 expansion flows around nearby groups of galaxies in dimensionless coordinates. Thin lines represent a bunch of phase trajectories predicted by the ΛGR local model. The bold line is the phase attractor. The trajectories with the minimal ($V_{\rm min}$) and parabolic ($V_{\rm par}$) velocities are shown.

where

$$H_\Lambda = (\frac{8\pi}{3} G\rho_\Lambda)^{1/2} \tag{13}$$

is the "asymptotic Hubble factor" which is a constant given by the local dark energy density only: $H_\Lambda = 61$ km/s/Mpc.

It is also seen from Eq. 11 and Fig. 1 that the trajectories converge to the straight line $V = H_\Lambda R$ with the growing distance, so that the velocity dispersion around this line decreases with the distance. The line $V = H_\Lambda R$ is a "phase attractor" of the system. It is because of this that the flow is getting more and more regular with the growing distance from the group. This is a "cooling" effect which is completely due to the dynamical domination of dark energy in the flow at distances $R > R_\Lambda$. A quantitative measure of this effect may be found from Fig. 1. Indeed, the width Δ of the bunch of the phase trajectories may be characterized by the dimensionless ratio

$$\Delta \equiv (V_1 - V_2)/(RH_\Lambda), \tag{14}$$

where V_1, V_2 are the largest and smallest velocities, respectively, at the same distance R. Figure 1 shows that this ratio is $\Delta = 2.4$ at, say, $R = 1.4$ Mpc and it is $\Delta = 0.74$ at $R = 3$ Mpc. In this way, the width of the bunch of the trajectories decreases by more than 3 times when the distance increases 2 times. In the same distance interval, the "dimensionless mean expansion factor",

$$< h > \equiv (V_1 + V_2)/(2RH_\Lambda), \tag{15}$$

decreases from 1.6 to 1.1. The last figure indicates that $< h >$ at $R = 3$ Mpc differs by only 10% from its asymptotic value $< h >= 1$.

6 Conclusion: global–local similarity

Cosmology has sometimes been referred to as a "science of two numbers": one of them is the Hubble factor, or the expansion rate H_0, and the other is the deceleration parameter q_0. Now we may use both to clarify in a quantitative way the similarity between the global expansion and the local expansion flow.

In cosmology, the dimensionless deceleration parameter is defined as

$$q(t) = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}(1 - \frac{3}{1 + \rho_{\rm M}/\rho_{DE}}). \tag{16}$$

Here $a(t)$ is the cosmological scale factor, $\rho_M(t) = \rho_M(t_0)[a(t_0)/a(t)]^3$ is the density of the non-relativistic matter (dark matter and baryons), $\rho_M(t_0) = 0.28 \times 10^{-29}$ g/cm^3 is its present ($t_0 = 14$ Gyr) value. The scale factor as a function of time is given by Friedmann's "equation of motion":

$$\ddot{a}(t) = -\frac{4\pi}{3}G[\rho_M(t) - 2\rho_\Lambda]a(t). \tag{17}$$

The expansion velocity, $v(t) = \dot{a}$, follows from the first integral of Eq. (17):

$$\frac{1}{2}v^2 = \frac{4\pi}{3}G[\rho_M(t) + \rho_\Lambda]a(t)^2 + E_0, \tag{18}$$

which is the mechanical energy conservation law for the global expansion (if we use the terms of Newtonian mechanics), and $E_0 = const$ is the total mechanical energy per unit mass. According to the recent observational data, the energy E_0 is zero with a good accuracy, and the global expansion follows the parabolic trajectory (this is already taken into account in Eq. 16 above).

It is seen from Eq. 17 that the epoch of dark energy domination begins when $\rho_M(t_0)[a(t_0)/a(t_\Lambda)]^3 - 2\rho_\Lambda = 0$. In accordance with the data above, the corresponding cosmic age $t_\Lambda = 7$ Gyr, and the zero-gravity redshift

$$(1 + z_\Lambda) = 1.7. \tag{19}$$

The redshift z_Λ is the cosmological temporal counterpart of the zero-gravity radius R_Λ in our local model.

Equation 18 shows also that the global expansion evolves towards the de Sitter static regime,

$$\dot{a}(t) = H_\Lambda a(t), \quad a(t) \propto \exp(H_\Lambda t), \tag{20}$$

which is reached in the limit of infinite expansion, when cosmic time t goes to infinity. Here H_Λ is the same asymptotic Hubble factor as in the local model above (Eq. 13). As we see, the cosmological time asymptotic of Eq. 20 is identical to the local spatial asymptotic of our model (see Eq. 12).

To summarize, there is a high degree of similarity between the local and global flows of expansion. It is this similarity in physics that makes global and local flows be almost identical in their internal dynamics and major observed features. The key dynamical factor that controls the structure and evolution of both observed cosmological expansion at the present epoch and local expansion flows is omnipresent dark energy with its universal domination.

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