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Einstein's universal antigravitation: from the Local Group to the world horizon

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Einstein's idea of universal cosmic repulsion/antigravitation represented by the cosmological constant Λ in the General Relativity equations leads to predictions about specific features of the local motions of galaxies. The predictions are tested with the use of recent observational data obtained with the Hubble Space Telescope at distances of 1–10 Mpc. The data provide clear evidence for the presence of antigravitation in the Local Universe and its domination in the dynamics of nearby expansion flows of galaxies.

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

1 Introduction

Since its creation one hundred years ago, Einstein's General Relativity (GR) theory has been focused on physical effects that were predicted by the theory and can be tested in laboratory experiments or astronomical observations. Einstein (1916) himself pointed out to three classical effects: Non-Newtonian precession of Mercury's orbit, gravitational redshift and bending of light by the Sun. Later four more GR tests were suggested: Gravitational lensing, Equivalence principle, strong field effects in binary pulsars and quasar OJ273, direct detection of gravitational waves (for details see, for instance, Byrd et al. 2015). Except for the last one which is not yet performed, all the effects have been tested and proved.

The most recent successful test has been targeted on the extended version of GR (Einstein 1917) which includes the idea of universal cosmic repulsion, or antigravitation, represented by the cosmological constant Λ (hereafter ΛGR). The Hubble Space Telescope (HST) has been used to observe the recessing motions of galaxies at the largest cosmic distances of 1000 Mpc, halfway to the world horizon. It has been found (Riess et al. 1998; Perlmutter et al. 1999) that Λ is non-zero and it is positive which means that Einstein's antigravitation exists in the Universe alongside with gravitation (2011 Nobel Prize in Physics). This global effect of ΛGR has revealed itself in

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the accelerating motion of the distant galaxies which implies that cosmic repulsion is stronger than attraction near the edge of the observed Universe.

In this paper (which is a brief version of the talk presented at the Annual Meeting of the International Astronomical Society, Moscow, 2015) local ΛGR effects are discussed. We address the motions of galaxies, but at relatively short distances from the Milky Way on the spatial scales of 1–10 Mpc. These effects have been tested with the use of the HST observational data (Karachentsev et al. 2003a,b; 2009; 2010; 2013) and proved (Chernin 2001, 2008, 2013; Chernin et al. 2003, 2004, 2009, 2013, 2015; Byrd et al. 2007, 2012, 2015; Teerikorpi et al. 2015). We have found that Einstein's antigravitation exists on local spatial scales and it dominates in the dynamics of the nearby expansion flows of galaxies making the galaxies move with acceleration. In combination with the global ΛGR test, the local test provides strong evidence for Einstein's antigravitation as a universal physical phenomenon.

We follow here the current (widely accepted) cosmological interpretation of the Λ term according to which cosmic antigravitation is produced by "dark energy" treated (Gliner 1965) as an unseen vacuum-like perfectly uniform medium of constant positive density and negative pressure. The physical nature and microscopic structure of dark energy are unknown; perhaps this is the most fundamental problem of modern physics and astronomy.

2 Antigravitation and dark energy

In macroscopic description, dark energy is characterized by the equation of state $P_\Lambda = -\rho_\Lambda c^2$, where ρ_Λ is the dark energy density, P_Λ is its pressure. With its positive density and negative pressure, dark energy has a negative effective gravitating density:

$$\rho_{\Lambda\mathrm{eff}} = \rho_\Lambda + 3P_\Lambda/c^2 = -2\rho_\Lambda. \quad (1)$$

It is because of this that dark energy produces repulsion, or antigravitation, not gravitation. ΛGR indicates also that the passive gravitational density of any fluid is the sum

$$\rho_{\mathrm{pass}} = \rho + P/c^2. \quad (2)$$

This sum is zero for dark energy. According to the equivalence principle, the passive gravitational mass is equal to the inertial mass. 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.

Measured at the global distances (Riess et al. 1998; Perlmutter et al. 1999), the dark energy density

$$\rho_\Lambda = \frac{c^2}{8\pi G}\Lambda \simeq (0.6-0.7)\times 10^{-29}\ \ \mathrm{g\ cm^{-3}}. \quad (3)$$

Hereafter we assume that the local density of dark energy is equal to the cosmological value of Eq. 3. This condition follows directly from ΛGR. It agrees also with independent local data (Byrd et al. 2012) which indicate that the local and global values of the dark energy density are equal at least on the order of magnitude, if not exactly.

The local dynamical effects of dark energy may be described in terms of Newtonian mechanics, since the velocities of the local motions 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 such a 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:

$$F_\Lambda = \frac{8\pi}{3} G \rho_\Lambda R. \tag{4}$$

The relation of Eq. 4 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

$$H_\Lambda = [\frac{8\pi}{3} G \rho_\Lambda]^{1/2} \tag{5}$$

is the "universal time-rate" (see below). With the dark energy density of Eq. 3, its value is $H_\Lambda \simeq 60$ km s^{-1} Mpc^{-1}.

3 Local flows of expansion

In the ΛGR local test, the HST data are used on velocities and distances of nearby galaxies. Most of the galaxies are collected in groups and clusters which are the largest local overdensities in the cosmic matter distribution. Around them, "flows of expansion" are observed which are collective motions of galaxies away from the groups and clusters. The nearest and best studied system of this kind is the Local Group with the expansion flow of galaxies around it. The group (which includes the Milky Way) has the mass of $(2-4) \times 10^{12} M_\odot$ and the radial size of $\simeq 1$ Mpc; the expansion flow contains about 30 dwarf galaxies at the distances of $\simeq 1-3$ Mpc from the group center (Karachentsev et al. 2003b; 2009; Tully et al. 2013). Systems of a similar structure are also observed at distances up to 100–200 Mpc (Sandage 1999; Sandage et al. 2006).

The common feature of the local flows is that their kinematic follows rather closely the linear velocity-distance relation $V \simeq HR$ known as Hubble's law. The flows are considered "cold" (Sandage 1999) in the sense that the deviations from this relation are relatively small and the corresponding radial velocity dispersion is low in most of them. We use the flows as natural "devices" for the search and measurement of the local dynamical effects of Einstein's antigravitation.

4 Local model

In the ΛGR global test, Friedmann's model of cosmological expansion is used as a theory basis of the studies. This model assumes that matter is uniformly (on average) distributed in space, and it cannot be used in the ΛGR local test since the distribution of matter is highly non-uniform on the spatial scales less than 100–300 Mpc. Because

of this, a new theory model is needed for the local test that takes into account the observed overdensities and underdensities in the local distribution of galaxies. Having in mind the example of the Local Group, we construct a simple model (Chernin et al. 2001), in which the group is represented by a spherical mass $M = 3 \times 10^{12} M_\odot$ with a radius $R_0 \simeq 1$ Mpc. The dwarf galaxies of the flow are treated as "light (test) particles" moving along radial trajectories in the force of gravitation produced by the (baryonic and dark) matter mass M of the group and the repulsion field of antigravitation produced by the dark energy background in which both group and flow are embedded. In the model, the force (per unit mass) acting on a flow particle comes from Eq. 4:

$$F(R) = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_\Lambda R. \tag{6}$$

It is seen from Eq. 6 that gravitation dominates at small distances, while antigravitation is stronger than gravitation at larger distances. Gravitation and antigravition balance at the distance

$$R = R_\Lambda = [\frac{3}{8\pi}\frac{M}{\rho_\Lambda}]^{1/3} \tag{7}$$

which is the "zero-gravity radius" (Chernin et al. 2001).

(Note that the zero-gravity radius R_Λ appears here as the local spatial counterpart of the "zero-gravity moment" in the history of the global cosmological expansion at the cosmic redshift 0.7 about 7 Gyr ago. In a sense, what happens in time in the Universe as a whole happens in space in the local volume).

With the local density of dark energy of Eq. 3 and the known mass of the group, the zero-gravity radius is near 1 Mpc which is approximately equal to the observed group radius. Thus, in the volume of the group, gravitation is stronger than antigravitation, but outside the group in the flow area, at $R > R_\Lambda$, antigravitation dominates and the flow particles are moving with acceleration away from the group center.

This is the major prediction of the theory: the local expansion flows are accelerating. In this way, Einstein's antigravitation is expected to reveal itself on the local scales.

5 Theory implications

The model of the section above suggests a number of definite features of the flows dominated by dark energy that can be checked – proved or disproved – in observations. That may serve as a direct test for ΛGR on relatively small distances.

5.1 Phase attractor

The equation of motion of a flow particle, $\frac{1}{2}\dot{R}^2 = F(R)$, comes from Eq. 6, and its first integral is the law of the mechanical energy conservation for the particle:

$$\frac{1}{2}\dot{R}^2 = \frac{GM}{R} + \frac{4\pi G}{3}\rho_\Lambda R^2 + E, \tag{8}$$

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. 8: when the distance R of the particle is growing, the particle velocity increases and tends to the linear velocity–distance relation, $V = H_\Lambda R$ with the universal time-rate H_Λ of the section above. (It is the same asymptotic time-rate which is also known in cosmology in the limit of infinite time.)

It is also evident from Eq. 8 that the phase trajectories of the flow particles in the velocity-distance space converge asymptotically to the straight line $V = H_\Lambda R$ which is not a flow trajectory. This line is the phase attractor of the flow. The attractor is stable: any initially weak deviations from the attractor line decreases with the distance growth. The decrease of the deviations means that the flow is "cooling" during its expansion. This is the physical mechanism which is responsible for the observed low velocity dispersion in the local cold flows (see Sec. 3 above).

Thus, the antigravitation force introduces kinematic order to the flows making them follow the linear velocity–distance relation $V = HR$. Moreover, because of this force, the time-rate H of the flows tends to the universal value $H_\Lambda \simeq 60$ km s^{-1} Mpc^{-1}. Both features are confirmed by old and new local observations.

5.2 Velocity lower limit

It may also be seen from basic Eq. 8 that if the velocity of a flow particle is positive at $R = R_\Lambda$, it will be positive as well at any larger distances. The condition $V(R = R_\Lambda) > 0$ implies that there is a lower limit to the flow velocity,

$$V_{\min} = [2\frac{GM}{R} + H_\Lambda^2 R^2 - 3\frac{GM}{R_\Lambda}]^{1/2}, \tag{9}$$

that corresponds to the particle total energy $E = E_{\min} = -\frac{3}{2}\frac{GM}{R_\Lambda}$. Note that all the particle trajectories in the flow are unbound, even if their total mechanical energy E may be negative.

Thus, the lower limit to the expansion velocity is a newly found feature of the flows which may directly be proved or disproved in observations (see below).

5.3 Self-similarity

Equation 8 may be re-written in the dimensionless form:

$$y = x(1 + 2x^{-3} + 2\alpha x^{-2})^{1/2}. \tag{10}$$

Here $\alpha = E/(H_\Lambda R_\Lambda)^2$, y is the velocity V measured in units of $H_\Lambda R_\Lambda$, and x is the distance R measured in units of R_Λ.

The acceleration of the flow, $\ddot{R}$ (see Eq. 6), may also be given in a dimensionless form:

$$f(x) = \frac{F}{T_\Lambda H_\Lambda^2} = \frac{\ddot{R}}{T_\Lambda H_\Lambda^2} = x - x^{-2}. \tag{11}$$

The structure of the flow in the dimensionless variables as given by the equations above looks exactly or approximately the same for systems of various physical sizes and masses. Because of this, the observed local flows are expected to constitute a class of self-similar systems. Thus, self-similarity of the expansion flows is a new feature that can be checked in observations.

6 Observations and Conclusion

To test the critical predictions of the ΛGR local theory, we used the dataset (Karachentsev et al. 2003a,b; 2009; 2013) that includes the recent results of the HST high accuracy local observations for more than 300 HST orbital periods. More than 300 nearby galaxies were studied and their distances have been measured with a record accuracy of about 10%. The velocities of the objects were measured with the 6-m Telescope of SAO RAS, Arecibo Disk and other instruments. The observed galaxies belong to the Local Group, the groups M81/82, Cen A/M83, CV I and the Virgo and Fornax Clusters, as well as to expansion flow around these objects.

The data on the galaxies within the groups and clusters were used to estimate the masses of the objects (Karachentsev & Kudrya 2014) and their zero-gravity radii. The zero-gravity radii of the groups and clusters prove to be near 1 and 10 Mpc, respectively, on the order of magnitude. The data on 125 galaxies of six expansion flows are presented as dots in Fig. 1 which is the velocity-distance phase plane in the dimensionless variables.

The bunch of the phase trajectories in Fig. 1 form a phase portrait of the typical expansion flow in dimensionless variables as it is given by the theory model of Eqs. 9 and 10.

The trajectories of Fig. 1 have different "initial conditions", but all of them and the bunch as a whole converge to the bold straight line which represents the phase attractor, $y = x$, of the flow. The trajectory of the minimal energy and the minimal velocity $V_{\rm min}$ indicates the lower limit of the velocity in the flows. The trajectory of zero mechanical energy (parabolic velocity $V_{\rm par}$) shows that phase trajectories of both negative and positive energy are possible in the flows. We may see from the distribution of the dots in Fig. 1 that each of the observed galaxies of the six local flows find comfortably its place in the theory typical phase pattern despite about 10 times difference in the physical sizes between the flows around the groups and the flows around the clusters and a factor of nearly 1000 difference in their masses. This is possible because of self-similarity of the observed flows as indicated by the theory model above.

To conclude, the three specific features of the local expansion flows predicted by the ΛGR – phase attractor, lower velocity limit, self-similarity – have been checked and confirmed by the observational data. The features are completely due to antigravitation that dominates in the dynamics of the flows. It is because of this that the flows expand with acceleration. The physical nature of the accelerating local flows is exactly the same as that found in the observations of the global cosmological expansion: acceleration is produced by Einstein's antigravity. In combination, the global (Riess et al. 1998, Perlmutter et al. 1999) and the local tests provide clear evidence

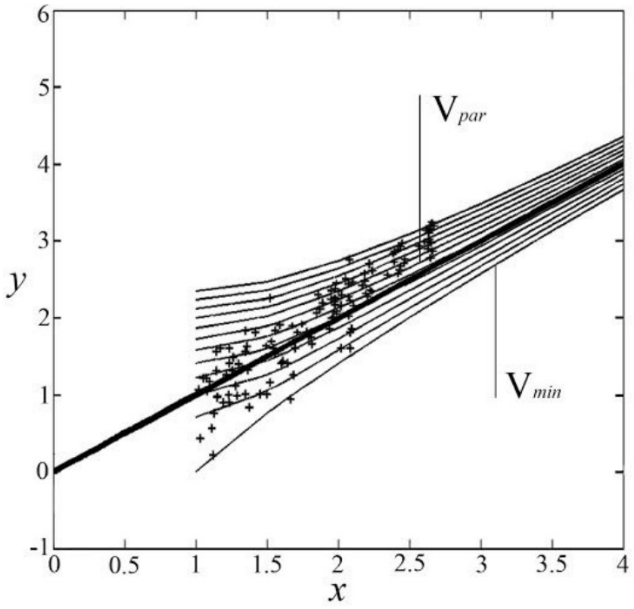


Figure 1 The collective phase portrait of six expansion flows around nearby groups and clusters of galaxies in dimensionless coordinates. Thin lines represent a bunch of phase trajectories predicted by the ΛGR local model. The bold line is the phase attractor. The trajectories with the minimal ($V_{\rm min}$) and parabolic ($V_{\rm par}$) velocities are showed. The dots indicate the positions of 125 galaxies of the flows on the velocities-distances plane.

for Einstein's idea of antigravitation as a universal physical phenomenon acting effectively in a wide interval of distances – from the Local Group to the edge of the observed world.

Note that additional independent arguments in favor of local ΛGR have come from recent data on the expansion flow of giant galaxies (Chernin, Emelyanov & Karachentsev 2015) and studies of the internal structure of the massive clusters of galaxies (Bisnovatyi-Kogan & Chernin 2012, Chernin et al. 2013).

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References

Bisnovatyi-Kogan G.S., Chernin A.D. (2012) Astrophys. Space Sci. 338, 337

Byrd G.G., Chernin A.D., Valtonen M.J. (2007) *Cosmology: Foundations and Frontiers*, Moscow, URSS

Byrd G.G., Chernin A.D. , Teerikorpi P., Valtonen M.J. (2012) *Paths to Dark Energy*, Berlin/Boston, De Gruyter
Byrd G.G., Chernin A.D., Teerikorpi P., Valtonen M.J. (2015) In Carlo Rovelli (Ed.): *General Relativity: The Most Beautiful of Theories*, Berlin/Boston, De Gruyter, pp. 112–164
Chernin A.D. (2001) Physics Uspekhi 44, 1099
Chernin A.D. (2008) Physics Uspekhi 51, 253
Chernin A.D. (2013) Physics Uspekhi 56, 704
Chernin A.D., Teerikorpi P., Baryshev Yu.V. (2003) Advances in Space Research 31, 459
Chernin A.D. et al. (2004) Astron. Astrophys. 415, 19
Chernin A.D. et al. (2009) Astron. Astrophys. 507, 1271
Chernin A.D. et al. (2010) Astron. Astrophys. 520, 104
Chernin A.D. et al. (2013) Astron. Astrophys. 553, 101
Chernin A.D., Emelyanov N.V., Karachentsev I.D. (2015) MNRAS 449, 2069
Einstein A. (1917) Akad. Wiss. 1, 142
Gliner E.B. (1965) JETP 49, 542
Karachentsev I.D. et al. (2003a) Astron. Astrophys. 398, 479
Karachentsev I.D., Chernin A.D., Teerikorpi P. (2003b) Astrophysics 46, 399
Karachentsev I.D., Kashibadze O.G., Makarov D.I., Tully R.B. (2009) MNRAS 393, 1265
Karachentsev I.D., Makarov D.I., Kaisina E.I. (2013) AJ 147, 13
Karachentsev I.D., Kudrya Yu.N. (2014) AJ 148, 50
Perlmutter S. et al. (1999) Astrophys. J. 517, 565
Riess A.G. et al. (1998) Astron. J. 116, 1009
Sandage (1999) Astrophys. J. 527, 479
Sandage A., Tammann G.A., Saha A. (1998) Phys. Rep. 307, 1
Sandage A. et al. (2006) Astrophys. J. 653, 843
Teerikorpi P. et al. (2015) Astron. Astrophys. 577, 144
Tully R.B. et al. (2013) Astron. J. 146, 86