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GRAVITY-ANTIGRAVITY INTERPLAY IN THE LOCAL GALAXY FLOWS

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Abstract. The major physical features of the local expansion flows of galaxies are found to be due to antigravity domination in their dynamics.

Key words: cosmological parameters – cosmology: observations – cosmology: theory – dark energy

1. INTRODUCTION

The world of galaxies is a grandiose expansion flow studied first by Vesto Slipher, Ernst Öpik, George Lemaître and Edwin Hubble in 1910–20s. The most impressive discovery of those times is the linear velocity-distance relation, $V = HR$, known as Hubble's law of cosmic expansion, where V is the receding velocity of galaxies at the distance R, and H is the Hubble factor, which is the expansion time-rate. Hubble's law, which was found at local distances of 1–30 Mpc, was widely interpreted as the major property of the whole Universe. However, cosmological implications based on Friedmann's uniform model are valid only for global distances of the order of 1000 Mpc and larger where the spatial distribution of galaxies is statistically uniform. Because of this, Hubble's law at local distances was seen "mysterious" (Sandage et al. 1972, 2006) and "surprising" (Zeldovich 1978, 1993). The puzzle was resolved (Chernin 2001) soon after the discovery of dark energy.

In this paper we discuss the physical nature of the local linear expansion flows on the basis of modern observational data.

2. LOCAL ANTIGRAVITY

The discovery of dark energy in 1998–1999 (Riess et al. 1998; Perlmutter et al. 1999) opened broad new prospects in cosmology (see, for instance, Byrd et al. 2012, and references therein). The astronomical findings made near the cosmic horizon have also provided us 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 motions of galaxies at actually all the distances from $\sim$1 Mpc out to the cosmic horizon (Chernin 2001, 2008, and references therein).

Due to the discoveries made by Riess et al. (1998) and Perlmutter et al. (1999), we know 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 constitutes about 4%. Dark matter and dark energy do not emit, absorb, or scatter light. They manifest themselves only by their gravity and antigravity, correspondingly (a relatively small contribution to cosmic gravity is also provided by baryons). Antigravity was predicted theoretically by Einstein in 1917, when he proposed the equations of General Relativity that included antigravity represented by the cosmological constant Λ. The possible existence of Einstein's antigravity was taken into account in Friedmann's cosmological model where the cosmological constant Λ is included as an empirical parameter which should be measured in astronomical observations.

Modern cosmological data show that antigravity is stronger than gravity in the observable Universe as a whole. Because of the antigravity domination the global expansion proceeds with acceleration: the relative velocities of receding galaxies increase with time. Antigravity dominates at present and it has been dominating over the last 7 Gyr of the cosmic evolution; in the unlimited future, antigravity domination will be even stronger than now.

Do dark energy and Einstein's antigravity exist not only on global distances where they were discovered, but also at relatively small distances where the local expansion flows of galaxies were first observed?

It follows from General Relativity that Einstein's antigravity produced by dark energy is a universal physical factor (in the same sense as Newton's gravity) acting on both global and local astronomical scales. The density of dark energy is the same everywhere in the Universe and it is given by Einstein's cosmological constant:

$$\rho_\Lambda = \frac{\Lambda}{8\pi G}, \tag{1}$$

where G is the Newtonian gravitational constant; here the speed of light $c = 1$; the dark energy density ρ_Λ is positive and its currently adopted value is $\rho_\Lambda \simeq 0.7 \times 10^{-29}\ \mathrm{g\,cm^{-3}}$.

Based on these physics grounds and the most recent precise observational data on the local expansion flows and their environments (Karachentsev 2005; Karachentsev et al. 2003, 2006, 2007), we worked out a theoretical model that resolves the paradox of Hubble's law at relatively small distances; the model is a local counterpart of Friedmann's cosmological model.

For our model, we adopt from General Relativity the macroscopic description (Gliner 1965) of dark energy as vacuum-like continuous medium of perfectly uniform constant density with the equation of state

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

Here p_Λ is the dark energy pressure.

We take from General Relativity also an indication that the "effective gravitating density" is determined by both density and pressure of the medium:

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

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

Finally, we borrow from General Relativity the Köttler exact solution for spherically-sym-metrical spacetime (also known as the Schwarzschild-de Sitter spacetime). The solution gives the metric outside a spherical matter of mass M imbedded in the dark energy of the constant density ρ_Λ. In the weak field approximation where the gravity-antigravity field is weak and deviations from the Galilean metric are small, the Köttler solution reduces to the Newtonian description in terms of the gravity-antigravity potential U:

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

In this approximation, the force (per unit mass) follows from Eq. 7:

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

We see in the right-hand side 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 can also be seen from Eq. 5 that gravity dominates at small distances from the mass M, while antigravity is stronger than gravity at large distances. Gravity and antigravity are balanced 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 2001).

The zero-gravity radius R_Λ appears as the local spatial counterpart of the "zero-gravity time" in the global expansion of the Universe, which occurred about 7 Gyr ago (see above).

The Newtonian approximation is appropriate for our purposes here since the velocities of the local flows are very small compared to the speed of light, and the spatial variations of the gravity-antigravity potential are very small (in absolute value) compared to the speed of light squared.

3. VERY LOCAL FLOW

The nearest flow of galaxies is observed at the distances of 1–3 Mpc from the barycenter of the Local Group. This "Very Local Flow" (hereafter VLF) has been well studied in observations over the last decade (Karachentsev 2005; Karachentsev et al. 2003, 2006, 2007, and references therein), and it reveals most obviously the characteristic features that looked so "surprising" to Zeldovich and "mysterious" for Sandage (Sec. 1): these are approximately linear velocity-distance relation (Hubble's law) with the expansion time-rate H which is near the Hubble global factor H_0.

Based on these data and the theoretical relations of Sec. 2, we suggested an analytical model of gravity-antigravity interplay which controls the dynamics of local flows of expansion (Chernin 2001, 2008, 2013, and references therein). When applied to VLF, our model treats the Local Group as a spherical mass of $M = (3-4) \times 10^{12} M_\odot$ with a radius of $\simeq 1$ Mpc. According to Eq. 6, the zero-gravity radius of the group proves to be $R_\Lambda = 1.1 - 1.3$ Mpc, which is near its observed radial size. The model treats galaxies (dwarfs) of the expansion flow around the group as "light (test) particles" moving along radial trajectories in the force field produced by the (baryonic and dark) matter of mass M of the group and the uniform dark energy background in which both the group and outflow are embedded.

Inside the group, $R < R_\Lambda$, 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 is quasi-stationary and gravitationally bound. In the VLF area, the antigravity of dark energy dominates. Because of this, the VLF particles are unbound and accelerate away from the group. The particle dynamics is ruled by the equation of motion which follows from Eq. 5:

$$\ddot{R}(t) = -\frac{GM}{R^2} + \frac{8\pi G}{3}\rho_\Lambda R. \tag{7}$$

The sum in the right-hand side of Eq. 7 is positive and increases with distance at $R > R_\Lambda$.

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

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

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

Eq. 8 gives the phase trajectories of the accelerating flow in the velocity-distance space. The trajectories are shown in Fig. 1 together with the observed distances and velocities of the VLF dwarfs (Karachentsev 2005; Karachentsev et al. 2003, 2006, 2007). As we see, the model is completely compatible with the data. It can also be seen that generally the phase trajectories of the flow are not exactly linear. However, with increasing distance R, they converge to the stable phase attractor of the system, which is the line $V = \dot{R} = H_\Lambda R$. Here, $H_\Lambda = (\frac{8\pi}{3}G\rho_\Lambda)^{1/2}$ is the "asymptotic Hubble factor", which is a universal constant determined by the dark energy density exclusively: $H_\Lambda = 61$ km s^{-1} Mpc^{-1}. The attractor indicates the evolutionary trend of the system and it is because of this physics that the flow acquires its nearly linear structure.

It is known from the standard cosmology that the expansion rate $H_\Lambda = (\frac{8\pi}{3}G\rho_\Lambda)^{1/2}$ is the time asymptotic for the global expansion as well. It is therefore is not too surprising that the local and global rates of expansion are so close to each other.

4. CONCLUSION

Accelerating expansion flows of galaxies which are similar to the Very Local Flow can also be found around several nearby groups and clusters of galaxies (Karachentsev et al. 2007; Chernin 2013). Their spatial scales differ by one order of magnitude, from ~ 1 to ~ 10 Mpc. They nevertheless all reveal the same nearly linear velocity-distance kinematic structure with time-rates about the Hubble's global factor. In common, they constitute a new class of extragalactic systems whose observational appearance and physical nature are due entirely to the antigravity domination in their dynamics.

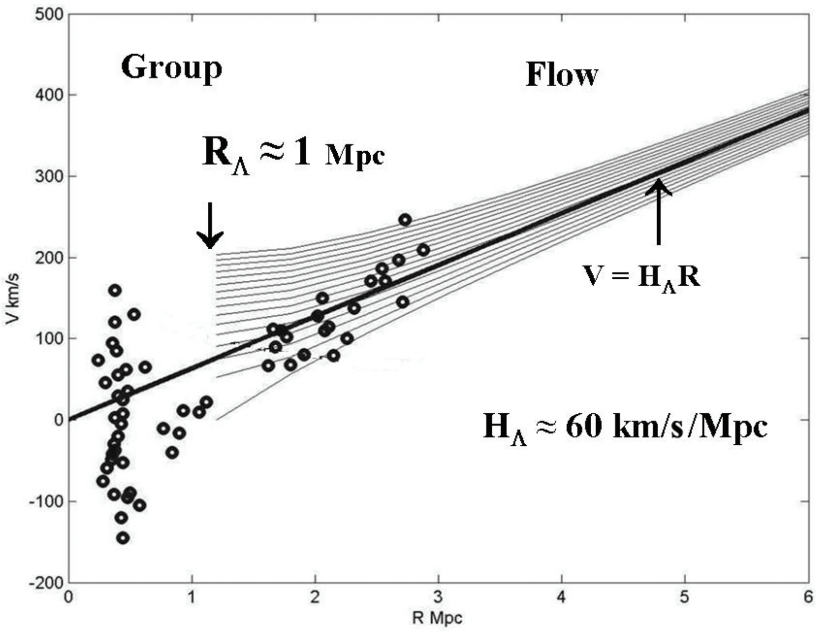

Fig. 1. Velocity-distance diagram for the expansion flow around the Local Group. The zero-gravity distance R_Λ is about 1 Mpc. The gravitationally bound group is located at the distances $R < R_\Lambda$ where gravity dominates; the flow is at $R > R_\Lambda$ where antigravity dominates. The phase trajectories of the flow are given by Eq. 8; they converge with distance to phase attractor shown as the bold line $V = H_\Lambda R$.

REFERENCES

Byrd G. G., Chernin A. D., Teerikorpi P., Valtonen M. J. 2012, *Paths to Dark Energy*, De Gruyter Publ., Berlin/Boston

Chernin A. D. 2001, Physics Uspekhi, 44, 1099

Chernin A. D. 2008, Physics Uspekhi, 51, 253

Chernin A. D. 2013, Physics Uspekhi, 183, 741

Gliner E. B. 1965, JETP, 49, 542

Karachentsev I. D. 2005, AJ, 129, 178

Karachentsev I. D., Chernin A. D., Teerikorpi P. 2003, Astrophysics, 46, 399

Karachentsev I. D., Dolphin A., Tully R. B. et al. 2006, AJ, 131, 1361

Karachentsev I. D., Tully R. B., Dolphin A. et al. 2007, AJ, 133, 504

Perlmuter S., Aldering G., Goldhaber G. et al. 1999, ApJ, 517, 565

Riess A. G., Filippenko A. V., Challis P. et al. 1998, AJ, 116, 1009

Sandage A., Tamman G. A., Hardy E. 1972, ApJ, 172, 253

Sandage A., Tamman G. A., Saha A. et al. 2006, ApJ, 653, 843

Zeldovich Ya. B. 1978, in *The Large Scale Structure of the Universe*, eds. M. Longair & J. Einasto, IAU, p. 409

Zeldovich Ya. B. 1993, *Selected Works of Yakov Borisovich Zeldovich, vol. 2. Particles, Nuclei, and the Universe*, Princeton Univ. Press, Princeton