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DARK ENERGY AROUND US: FROM NEWTON'S GRAVITATION TO EINSTEIN'S ANTIGRAVITATION FOR THREE CENTURIES

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Abstract. Since the Newton times it has been unchallenged for 300 years that the universal gravitation is the force that moves the worlds. But the most recent discoveries in cosmology show that the expansion of the real Universe is controlled by the Einstein universal antigravitation.

1. INTRODUCTION

Recent events in cosmology have changed drastically the modern science of the Universe. Most impressive is the discovery of mysterious dark energy which has fundamental significance for a new physical picture of the world. The development which has led to this new concept started three hundreds yeas ago when Isaac Newton first realized that the laws of motion were the same here on the earth and there in the sky. It is his idea that falling apple and orbiting Moon or planets are controlled by the same force, and this force is universal gravitation. Gravitation is the inborn property of all the bodies in the Universe to attract one another. This is the only fundamental force which is effective on cosmic scales. Since Newton it has been taken for granted and unchallenged for three centuries that gravity is the force which moves the worlds.

But ten years ago it was found that the dynamics of the real Universe is controlled by antigravity, rather than gravity. Antigravity reveals itself as a force that speeds up the whole expansion of the Universe. It reveals itself also at relatively small distances in our close galaxy vicinity. Dark energy is behind this: it is the physical agent that produces cosmic antigravitation.

2. COSMOLOGICAL EXPANSION

The expansion motion of the Universe is the most grandiose phenomenon of nature, the largest on both space and time scales. As is well-known, it was predicted theoretically by Alexander Friedmann, a mathematician of St.Petersburg University in 1922-24. Friedmann used General Relativity theory by Einstein and found on this basis that the uniform distribution of matter in the Universe could not be at rest and would rather be in the state of expansion or contraction. Friedmann preferred the case of expansion, and he developed a cosmological model in which the Universe as a whole expanded, so that all the "particles" that constitute the cosmic matter moved apart one another.

The physical identity of these particles was realized soon after that. The building blocks of the Universe are galaxies, giant stellar systems which are similar to our Galaxy the Milky Way. Edwin Hubble, an astronomer of Mount Wilson Observatory made the major contribution to this understanding. Moreover, he discovered that observed galaxies were moving away from us - in a complete agreement with the prediction of the Friedmann theory of the cosmological expansion. From his observations Hubble found also the law of this motion, according to which the velocity of a moving away galaxy is directly proportional to its distance from us. This law also agrees with the Friedmann theory. Now the Hubble law is observed and studied on all the available scales of cosmos – from the very vicinity of the Milky Way to the cosmic horizon, some ten billion light years from us.

All this knowledge came from hard observational work of measuring velocities and distances of the moving away galaxies. This was and is an extremely difficult task in astronomy. It is enough to say that the first distances measured by Hubble were a factor about ten underestimated. And even now the most accurate galaxy distances measured with the best modern telescopes are known with the accuracy of 8-10 per cent, not better.

3. COSMIC ACCELERATION

To understand from observations the physics of the cosmological expansion, we need to know not only distances and the velocities (the first time derivatives of distances), but also galaxy accelerations which are the second time derivatives of the distances. According to the Newton second law of mechanics, acceleration is the direct indication on the force which rules the motion. Until recently cosmologists have not been able to measure accelerations: this is much more difficult than distance and velocity measurements. For the first time in cosmology, astronomers were lucky to do that with the use of the Hubble Space Telescope and the best ground-based instruments about 10 ears ago.

The cosmic acceleration was measured by two groups of astronomers (Riess et al. 1998, Perlmutter et al. 1999) who studied the galaxy motions with the observations of supernova stars in remote galaxies. Supernonae are so bright that they emit more light than a whole galaxy and so they can be seen at extremely large distances. It may seem surprising, but in fact acceleration may easier be recognized and measured far away from us, rather than at shorter distances. It is with these observations that both groups – independently, but in agreement with each other – discovered that the expansion of the Universe is actually speeded up.

The observers argued reasonably that known forms of mass and energy could not be responsible for the acceleration force. The known forms produce gravity force and therefore they may only slow down the expansion. So something absolutely new is needed, and in this way the idea of dark energy emerges as a source of antigravity which can produce cosmic acceleration.

To drive the accelerating expansion, antigravity of dark energy should be stronger than the gravity of the ”ordinary” mass and energy. It means that the amount of dark energy must be big enough in the Universe. The acceleration measurements show that the Universe is indeed dominated by dark energy which contributes about 3/4 the total cosmic energy.

The second largest (20-22 %) contribution is provided by dark matter. It is different from dark energy. Dark matter is a gas of stable non-relativistic particles, and they produce gravity. The particles are unseen and reveal themselves via their gravity only. Dark matter is seemingly not so mysterious as dark energy. But we do not know exactly what the dark matter particles are. They are surely not atoms or known elementary particles like protons, neutrons or electrons. Most probably, these are new particles which are thousand times more massive than the protons. Attempts to catch the particles in laboratory are now in progress. There are some hopes that they will be found with the Large Hadron Collider which goes to operation soon. The nature of dark matter is a big problem for astronomy and particle physics; but it is perhaps not so difficult and so fundamental as the nature of dark energy.

As we realize now, at least 95 per cent of the mass/energy of the Universe are unseen and dark. The ordinary matter – protons, neutrons, electrons together with cosmic electromagnetic radiation and neutrinos contribute less than 5 % to the total cosmic mass/energy content.

4. DARK ENERGY

Before the discovery of cosmic antigravity, nothing like that had been seen in laboratory experiments or astronomical observations. But in physical theory there was an idea of antigravity: it was put forward by Einstein as early as in 1917. He suggested the most general form of his gravity equations for General Relativity and antigravity was represented there in a very simple and elegant way: by only one constant value which was called the cosmological constant Λ.

Einstein’s antigravity has been discussed in cosmology for decades. Big theorists like Wolfgang Pauli and Lev Landau were strongly against it. But de Sitter, Eddington, Lemaitre studied Einstein’s idea in various its aspects. When antigravity was discovered in observations the astronomers addressed first of all the cosmological constant as the simplest and straightforward physical interpretation of their results. According to this approach, the cosmological constant is the major physical characteristic of dark energy.

A clear link from the cosmological constant to dark energy is suggested by a macroscopic interpretation given by Erast Gliner (1965) (then at Ioffe Institute in St.Petersburg). Gliner argues that Einstein’s idea is equivalent to an assumption that a special fluid fills all the space of the Universe. The density of the fluid is directly related to the cosmological constant:

$$\rho = \frac{c^2}{8\pi G}\Lambda.$$

This density is identified with the observed dark energy density. If true, the basic properties of dark energy follow from this.

First, the dark energy density is a constant which is the same in any reference frame. It means that dark energy presents in any cubic centimeter of the space in equal amount, including the space here around us and inside us. The concordant observational data give the value of the density (Spergel et al. 2003, 2006):

$$\rho = 0.75 \pm 0.05 \times 10^{-29} \quad g/cm^3.$$

Second, dark energy has negative pressure:

$$p = -\rho c^2.$$

Such a relation between density and pressure (equation of state) is a unique property of dark energy.

Third, dark energy produces antigravity because its effective gravitating density is negative:

$$\rho_{eff} = \rho + 3p = -2\rho < 0.$$

(By the way, factor 3 here is because our space is tridimensional.)

Fourth, passive gravitating mass of dark energy (= inertial mass) is zero:

$$\rho + p = 0.$$

It means that dark energy is not affected by any gravity/antigravity force. It is because of this that the dark energy background remains unchanged in time.

Finally, dark energy is vacuum because rest and motion are not discriminated relative to it.

This is a quite significant set of dark energy properties. And all of them are directly deduced from the identification of dark energy with the cosmological constant. What is even more important, all the bulk of observational data collected in the current decade are in complete agreement with this identification.

5. LAW OF UNIVERSAL ANTIGRAVITATION

Dark energy and its antigravity effect are essentially relativistic phenomena, and so they may adequately be described only in terms of General Relativity. Nevertheless some basic relations of dark energy physics can be presented with the use of the classical language of Newtonian mechanics. The Newton law of universal gravitation is well-known: this is the inverse square law. (By the way, the square here is because the space is tridimensional, as it was first realized by Kant. If the number of space dimensions would be, say, four, the law would be of the inverse cube of the distance. In this case, no stable planet orbits are possible, and so high forms of life and intelligence would hardly develop in cosmos.)

A counterpart of the Newton law of universal gravitation is the Einstein law of universal antigravitation. If one uses the Newtonian language of forces, it may be said that any two bodies are pushed away from each other with the force which is directly proportional to the distance. (And in this case there is no relation to the number of space dimensions: the law is the same for any number of dimensions.) The fact that the force increases with distance is quite understandable: the force is produced by dark energy which is present in the space between two bodies under consideration. And the amount of this energy is obviously larger for larger distances.

The standard cosmological model of our days includes dark energy represented by the Einstein cosmological constant as its key element. In this model, the dark energy density is constant and time independent. But the density of matter falls with the cosmological expansion: this is because the matter distribution dilutes when the space volume occupied by a given mass grows with time. As a result, matter dominates in the first half of the cosmic history, and dark energy does in the second one. When the cosmic age is less than 7 Gyr, the dynamics of the expansion is ruled by matter gravity, and so the expansion is slowed down. For the next 7 Gyr antigravity is stronger and so the expansion is speeded up.

It is great that astronomers may observe now not only the current stage of the cosmic acceleration, but also the early stage of cosmic deceleration. Indeed, the observers can look at the distances which are larger than 7 Giga-light-years, so they can observe the Universe in the state in which its age was less than 7 Gyr. And they definitely see there/then that the cosmic expansion is slowed down – in complete agreement with the Friedmann standard model.

Since the dilution of matter will further proceed in the future, the dynamical dominance of dark energy will only increase with time. Because of this, the cosmological expansion will be going on forever. And this is the forecast of the fate of the Universe that can be done on the basis of all we know about the Universe now.

6. LOCAL UNIVERSE

As it was said above, dark energy described by the cosmological constant is omnipresent. May we verify by observations that dark energy exists indeed around us, in our close galactic environment? Yes, and the cosmological expansion observed in the vicinity of the Milky Way may serve as a natural tool to do that. In 2000 we suggested that in the nearest part of the expansion flow with the distances of only a few Mpc from, the dynamical effect of dark energy is as strong, as near the cosmic horizon where dark energy was first discovered.

Let us look at the local volume of, say, 6 Mpc across. The Local Group of galaxies is the most prominent object here. It consists of two giant galaxies, the Milky Way and the Andromeda Galaxy, with their families of dwarf companions. The system is about 2 Mpc across, and its total mass $M \sim 10^{12} M_{\odot}$, on the order of magnitude. Out of the system, at the distance interval of 1-3 Mpc from the group barycenter, two dozen dwarf galaxies are seen which move away from us. This is the very local Hubble flow.

It is obvious that the standard Friedmann cosmology does not work on the the spatial scale of a few Mpc. Instead we may suggest a simple treatment in terms of Newtonian mechanics. Consider an isolated spherical mass M embedded in the static and uniform dark energy distribution of the density ρ. In the reference frame of the mass center, the mass produces at distance R the force of gravity (per unit mass) given by the Newton gravity law:

$$F_N = -\frac{GM}{R^2}.$$

In the same reference frame, the dark energy produces at the same distance the force of antigravity, according to the Einstein law of universal antigravitation:

$$F_E = G\frac{8\pi}{3}\rho R.$$

Gravity gets weaker with the distance R, but antigravity gets stronger. And there is a distance at which they balance each other:

$$R_0 = [\frac{3M}{8\pi\rho}]^{1/3}.$$

This is the zero-gravity distance (Chernin et al. 2000-07). In global cosmology, the acceleration is zero for only one moment of time, but for the entire space. In the local static picture I discuss, the gravity is zero for only one distance, but at any time since the formation of the Local Group.

These simple relations represent the local dynamical field around an isolated mass which may be not only a group, but also a cluster of galaxies. Since a typical group has the mass $M \sim 10^{12} M_\odot$, with the concordance figure for the dark energy density, we may estimate the zero-gravity radius:

$$R_0 = [\frac{3M}{8\pi\rho}]^{1/3} \sim 1 \quad Mpc.$$

As we see, gravity dominates at distances $R < R_0 \sim 1$ Mpc, and so a gravitationally bound group can exist only within this size limit. At the larger distances, $R > R_0$, antigravity dominates and tends to drive any body away from the center. Therefore we may expect that a typical group has a size ≤ 1 Mpc, and at distances $R > 1$ Mpc around it, external galaxies – that are dwarf galaxies in reality – move apart with acceleration produced by the antigravity force.

Special observations made with the Hubble Space Telescope for nearly 200 orbits (Karachentsev et al. 1999-2006) demonstrate that this is really so. The Local Group of galaxies is indeed located in the region of the radius $R \leq R_0 \simeq 1$ Mpc. In the outer area, $R > 1$ Mpc, only positive (recession) velocities of galaxies are seen, and the velocity dispersion is much smaller here than in the central area. The linear velocity-distance relation (the Hubble law) is clearly seen here.

Thus, the observed picture of the very local expansion flow agrees well with our theory expectations. Moreover, our dynamics considerations suggest that this part of the expansion flow may be used as a ”measurement setup” for dark energy – in just the same way as the most remote part of the flow is used. In particular, we may obtain an independent estimate of the local density of dark energy.

To do that we need to find the zero-gravity distance R_0 in the local flow. If it is known, the local density (let it be ρ_x now) comes from the simple relation

$$\rho_x = \frac{3M}{8\pi R_0^3},$$

where M is the mass of the Local Group.

Looking closely at the observational data, we may see that the value of the zero-acceleration radius is most probably larger than 1 Mpc and smaller than, say, 2 Mpc. If so, we get from this the upper and lower limits for the local dark energy density:

$$0.16 < \rho_x/\rho < 1.3.$$

We see (Chernin et al. 2007) that the local value ρ_x is near the global value ρ within at least one order of magnitude. It is not excluded as well that both are exactly equal to each other. It is clear that the result is completely independent from the global measurements; to get it, we use only local figures M and R_0 (and ρ is used only for the comparison here).

7. CONCLUSION: BIG PROBLEM

Finally, let me turn to the physics of dark energy. We know very well its macroscopic properties when it is treated as a kind of fluid. But what is it microscopic structure? What is the fabric it is made up of? This question remains completely open now. One attempt to find an answer for this question was made by Yakov Zeldovich (1967) from Moscow. His approach was quite reasonable. Indeed, dark energy or the cosmological constant is vacuum. On the other hand, it is long known (since the end of 1920s) that quantum theory describes "quantum vacuum" as the lowest energy state of all physical fields. Both Einstein vacuum and quantum vacuum are not emptiness – they have energy. Perhaps they are identical? It would be extremely beautiful if they are just the same physical entity.

This is indeed a brilliant idea. Unfortunately, the current state of fundamental physics is so poor that it does not tell us how to check this idea. It is not known how to develop it on theory grounds. And there are no suggestions on how it can be proved or disproved in laboratory experiment or astronomical observation. Astronomers ask physicists: tell us what should we measure in the sky to verify Zeldovich's idea? And the answer is: we are just thinking about that... Will it take 300 years more?

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