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LETTER

Is dark matter an illusion created by the gravitational polarization of the quantum vacuum?

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Abstract Assuming that a particle and its antiparticle have the gravitational charge of the opposite sign, the physical vacuum may be considered as a fluid of virtual gravitational dipoles. Following this hypothesis, we present the first indications that dark matter may not exist and that the phenomena for which it was invoked might be explained by the gravitational polarization of the quantum vacuum by the known baryonic matter.

Keywords Dark matter · Gravitational polarization · Antimatter gravity · Quantum vacuum

Let us start with a major unresolved problem. The measured galaxy rotation curves remain roughly constant at large radii. Faster than expected orbits, require a larger central force, which, in the framework of our theory of gravity, cannot be explained by the existing baryonic matter. The analogous problem persists also at the scale of clusters of galaxies.

The favored solution is to assume that our current theory of gravity is correct, but every galaxy resides in a halo of dark matter made of unknown non-baryonic particles (for a brief review on dark matter see for instance: Einasto 2010). A full list of the proposed dark matter particles would be longer than this letter; let us mention only weekly interacting massive particles and axions. In spite of the significant efforts dark particles have never been detected. Let us note that in order to fit observational data for a galaxy, the radial mass density of dark matter in a halo should be nearly constant

$$\rho_r = \frac{dM_{dm}}{dr} \approx \text{const.} \tag{1}$$

The best developed alternative to particle dark matter is the Modified Newtonian Dynamics (MOND). It states that there is no dark matter and we witness a violation of the fundamental law of gravity (see brief review of Milgrom 2008).

In a recent series of papers (Blanchet 2007a, 2007b; Blanchet and Tiec 2008, 2009) it was shown that, in spite of the fact that MOND phenomenology rejects the existence of dark matter, it can be considered as consequence of a particular form of dark matter. The key hypothesis is that dark matter is a dipolar fluid composed from gravitational dipoles (in analogy with electric dipole, a gravitational dipole is defined as a system composed of two particles, one with positive and one with negative gravitational charge). Hence, Blanchet and Tiec have introduced dipolar fluid as a new candidate for non-baryonic dark matter; the galaxy rotation curves can be considered as result of the gravitational polarization of the dipolar fluid by the gravitational field of baryonic matter.

While the work of Blanchet and Tiec has attracted a significant attention, a very different idea concerning the gravitational polarization (Hajdukovic 2007, 2008) passed in silence. The key hypothesis advocated by Hajdukovic is the gravitational repulsion between matter and antimatter, i.e. particles and antiparticles have gravitational charge of opposite sign. Consequently the virtual particle-antiparticle pairs in the quantum vacuum should be considered as gravitational dipoles. Thus, the quantum vacuum may be considered as a dipolar fluid, what is much simpler and more elegant than the dipolar fluid composed from the unknown

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non-baryonic matter. As we would argue in this letter, in the framework of this approach, dark matter does not exist but is an illusion created by the polarization of the quantum vacuum by the gravitational field of the baryonic matter. Hence, for the first time, the quantum vacuum fluctuations, well established in quantum field theory but mainly neglected in astrophysics and cosmology, are related to the problem of dark matter.

The existing experimental evidence and our assumption of gravitational repulsion between matter and antimatter may be summarized as:

$$m_i = m_g; \qquad m_i = \bar{m}_i; \qquad m_g + \bar{m}_g = 0 \tag{2}$$

Here, as usually, a symbol with a bar denotes antiparticles; while indices i and g refer to inertial and gravitational mass (gravitational charge). The first two relations in (2) are experimental evidence (Will 1993; Gabrielse et al. 1999), while the third one is our assumption which dramatically differs from general conviction that $m_g - \bar{m}_g = 0$. Our hypothesis was very recently supported by a striking result (Villata 2011) that "antigravity appears as a prediction of general relativity when CPT is applied".

According to hypothesis $m_g + \bar{m}_g = 0$, a virtual pair may be considered as gravitational dipole with the gravitational dipole moment

$$\vec{p} = m\vec{d}; \qquad |\vec{p}| < \frac{\hbar}{c} \tag{3}$$

Here, by definition, the vector $\vec{d}$ is directed from the antiparticle to the particle, and presents the distance between them. Consequently, a gravitational polarization density $\vec{P}_g$ (i.e. the gravitational dipole moment per unit volume) may be attributed to the quantum vacuum. The inequality in (3) follows from the fact that distance between virtual particle and antiparticle must be smaller than the reduced Compton wavelength $\bar{\lambda}_m = \hbar/mc$ (for larger separations a virtual pair becomes real). Hence, $|\vec{p}|$ should be a fraction of $\hbar/c$.

In quantum field theory, a virtual particle-antiparticle pair (i.e. a gravitational dipole) occupies the volume λ_m^3, where λ_m is the (non-reduced) Compton wavelength. Hence, the number density of the virtual gravitational dipoles has constant value

$$N_0 \approx \frac{1}{\lambda_m^3} \tag{4}$$

In order to grasp the key difference between the polarization by an electric field and the eventual polarization by a gravitational field, let's remember that, as a consequence of polarization, the strength of an electric field is reduced in a dielectric. For instance, when a slab of dielectric is inserted into a parallel plate capacitor, the electric field between plates is reduced. The reduction is due to the fact that the electric charges of opposite sign attract each other. If, instead of attraction, there was repulsion between charges of opposite sign, the electric field inside a dielectric would be augmented. But, according to our hypothesis, there is such repulsion between gravitational charges of different sign. Consequently, outside of a region in which a certain baryonic mass M_b is confined, the eventual effect of polarization should be a gravitational field stronger than predicted by the Newton's law (but without violation of the Newton law in the same way as electric polarization is not violation of the Coulomb law). In more technical words we have the case of anti-screening by virtual particle-antiparticle pairs. The most important question is if the gravitational polarization of the vacuum can produce the same effect as the presumed existence of dark matter.

If the quantum vacuum "contains" the virtual gravitational dipoles, a massive body with mass M_b (a star, a black hole ...), but also multi-body systems as galaxies should produce vacuum polarization, characterized with a gravitational polarization density $\vec{P}_g$.

As well known, in a dielectric medium the spatial variation of the electric polarization generates a charge density $\rho_b = -\nabla \cdot \vec{P}$, known as the bound charge density. In an analogous way, the gravitational polarization of the quantum vacuum should result in a gravitational bound charge density of the vacuum

$$\rho_v = -\nabla \cdot \vec{P}_g \tag{5}$$

If we assume the spherical symmetry, (5) may be reduced to

$$\rho_v(r) = \frac{1}{r^2}\frac{d}{dr}\left(r^2 P_g(r)\right); \qquad P_g(r) \equiv |\vec{P}_g(r)| \geq 0 \tag{6}$$

or, as we are interested in the radial gravitational charge density (as in (1))

$$\rho_r = 4\pi \frac{d}{dr}\left(r^2 P(r)\right) \tag{7}$$

In principle the space around a spherical body can be divided in 3 regions which we define with two critical radiuses denoted by R_0 and R_h, ($R_0 < R_h$); the values of R_0 and R_h would be estimated later.

In the region ($r < R_0$) the gravitational field is sufficiently strong to align all dipoles along the field and consequently $P_g(r)$ has a constant value (in fact a maximum value) which according to (3) and (4) may be written as

$$P_g(r) \equiv P_{g\,\max} = \frac{A}{\lambda_m^3}\frac{\hbar}{c} \tag{8}$$

where A should be a dimensionless constant of order of unity. The (7) and (8) lead to the radial gravitational charge density proportional to r, producing a constant radial acceleration towards the body, which may be related to the Pioneer anomaly (Hajdukovic 2010a).

For $r > R_h$ the gravitational field is so weak that dipoles are randomly oriented and hence $P_g(r)$ is zero (we may also allow non-zero values, for instance $P_g(r)$ decreasing as $1/r^2$ or faster but it is not important for the present study).

Inside the spherical shell (with the inner radius R_0 and the outer radius R_h) the external gravitational field is not sufficiently strong to align all dipoles, but also not so weak to allow random orientation; hence the polarization density $P_g(r)$ should decrease with distance. Only in the region of this spherical shell, we may attempt to describe phenomena by the gravitational polarization instead of particle dark matter.

With

$$P_g(r) \sim P_{g\,\max} \frac{R_0}{r} \tag{9}$$

(7) leads to

$$\rho_r \sim 4\pi P_{g\,\max} R_0 = 4\pi A \frac{\hbar}{c} \frac{R_0}{\lambda_m^3} \tag{10}$$

Now, it is necessary to estimate λ_m and R_0 in the above relation.

Recently, two independent approaches (Urban and Zhitnitsky 2009, 2010, and Hajdukovic 2010b, 2010c, 2010d) have supported the point of view that only QCD (quantum chromodynamics) vacuum is significant for gravitation (Let us note that speculations concerning the gravitational properties of the quantum vacuum have their roots in the work of Zeldovich 1967). Roughly speaking the QCD vacuum is a gas of virtual pions (quark-antiquark pairs); consequently λ_m in (10) should be identified with the Compton wavelength of pion ($\lambda_m = \lambda_\pi$).

In order to estimate R_0, let us note that according to (4), λ_π can be interpreted as the mean distance between two dipoles which are the first neighbors. The gravitational acceleration produced by a pion at the distance of its own Compton wavelength is:

$$a_o = \frac{G m_\pi}{\lambda_\pi^2} = \left(\frac{c}{h}\right)^2 G m_\pi^3 \approx 2 \times 10^{-10}\ \mathrm{m/s^2} \tag{11}$$

what is intriguingly close to the value of the fundamental acceleration conjectured in the MOND phenomenology.

In the region $r < R_0$, the acceleration (11) should be dominated by the acceleration produced by the baryonic mass M_b. Hence, R_0 may be estimated from the condition of equality between a_0 and the Newtonian acceleration GM_b/R_0^2

$$R_0 = \lambda_\pi \sqrt{\frac{M_b}{m_\pi}} \tag{12}$$

For a mass $M_b \approx 4 \times 10^{41}$ kg (corresponding to the mass of our galaxy) the numerical value is $R_0 \approx 3.55 \times 10^{20}$ m $\approx$ 11.5 kpc.

Including these estimations, relation (10) may be written as

$$\rho_r = \frac{B}{\lambda_\pi} \sqrt{m_\pi M_b} \tag{13}$$

where B is a dimensionless constant of order of unity.

The relation (13) is an intriguingly simple rule: find the geometrical mean of the mass of pion and baryonic mass of a galaxy and divide it with the Compton wavelength of pion, what you get is the order of the radial dark matter density. An additional feature is that (13) leads to the Tully-Fisher empirical relation between the asymptotic flat velocity and the luminosity of spirals (Tully and Fisher 1977). In fact, for large radii, the (13) together with the well known result for rotational velocity at a circular orbit, $V_{rot}(r) = \sqrt{GM(r)/r}$, leads to

$$V_{rot}^4 = G^2 \rho_r^2 = B^2 G^2 \frac{m_\pi M_b}{\lambda_\pi^2} \tag{14}$$

what is (assuming proportionality between the luminosity and baryonic mass) Tully-Fisher relation $L \sim V_{rot}^4$. Let us note that in a recent paper (McGaugh 2011) it was argued that the Tully-Fisher relation is universally valid for all types of galaxies.

Introducing the ratio

$$\frac{M_{dm}}{M_b} = \frac{\Omega_{dm}}{\Omega_b} \tag{15}$$

where dimensionless parameters Ω_{dm} and Ω_b denote "dark matter" and baryonic matter density, (13) leads to the following estimation of the size of "dark matter" halo

$$R_h = \frac{1}{B} \frac{\Omega_{dm}}{\Omega_b} R_0 + R_0 = \frac{1}{B} \frac{\Omega_{dm}}{\Omega_b} \lambda_\pi \sqrt{\frac{M_b}{m_\pi}} + R_0 \tag{16}$$

As observations suggest, the ratio Ω_{dm}/Ω_b is a little bit smaller than 5, while R_h is presumably more than 20 times larger than R_0; hence according to (16), B must have a value close to Ω_b/Ω_{dm}. In principle, observational data may serve to determine the appropriate value of B, but the trouble is that they are not very accurate; for instance the halo's viral mass of our Galaxy has not be constrained to better than a factor of 2–3. Taking again $M_b \approx 4 \times 10^{41}$ kg and $B = \Omega_b/\Omega_{dm} \approx 0.212$, formula (16) gives $R_h \approx 266$ kpc what is a surprisingly good result for the halo size of our Galaxy (let us remember that we have used a toy model with spherical symmetry not taking into account real distribution of baryonic matter in galaxy).

Let us give one more numerical illustration concerning our galaxy. Xue et al. (2008) have found that the mass enclosed within 60 kpc is $(8 \pm 1.4) \times 10^{41}$ kg, while our toy model estimate is 7.7×10^{41} kg.

In conclusion, we have revealed the first indications that what we call dark matter may be consequence of the gravitational repulsion between matter and antimatter and the corresponding gravitational polarization of the quantum vacuum by the existing baryonic matter. Of course, this is not a claim, just possibility. A lot of work would be needed before such a claim would be eventually possible. Our work is in progress to see if the formalism developed by Blanchet and Tiec can be applied in our case and produce accurate results in the framework of General Relativity.

Let us end by pointing that the rotational curves of galaxies are not the only phenomenon which is currently explained by Dark Matter. For instance, CMB data are apparently in favor of the presence of dark matter as a key for understanding of density fluctuations and the structure formation in the Universe (see review of Einasto 2010). While our Letter gives indices that the gravitational vacuum polarization could be an alternative to dark matter in the explanation of the galactic rotational curves, a tremendous work would be needed, to reveal if the other phenomena could be alternatively explained by the vacuum polarization.

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