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A surprise within the Solar system – islands of the quantum vacuum with a negative effective gravitational charge?

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Abstract

What if quantum vacuum fluctuations are virtual gravitational dipoles? As it was argued during the past decade, this hypothesis opens up the possibility to explain phenomena usually attributed to dark matter and dark energy by the gravitational polarisation of the quantum vacuum. Here, instead of large-scale considerations, we focus on the potentially testable impact of the quantum vacuum within the Solar System. While the effective gravitational charge of the quantum vacuum in Solar System is mainly positive, the most striking implication is a first prediction of well-located islands of the quantum vacuum with a negative effective gravitational charge. We have calculated masses and determined positions of these islands of the quantum vacuum corresponding to planets. It remains an unprecedented challenge to test if these islands (that repel the surrounding matter) exist.

It seems plausible that the quantum vacuum is a source of gravity. However, the number density of quantum vacuum fluctuations (i.e., the number of fluctuations per unit volume) is so large that, according to our current understanding of gravity, the quantum vacuum should produce extremely strong gravitational field, at least 40 orders of magnitude stronger than permitted by empirical evidence collected in experiments and observations of the Universe. This, perhaps the worst theoretical prediction in the history of physic, was kindly named the cosmological constant problem [1]. Among others, the cosmological constant problem prevents us from trying to explain phenomena usually attributed to mysterious dark energy by the gravitational impact of the quantum vacuum.

No one can answer the question what the real physical solution to the cosmological constant problem is. However, we can ask a different question, what is the simplest (not necessarily physical) solution that we can imagine? Apparently, the simplest solution (apart from physics, from the logical and mathematical point of view) is to assume that *quantum vacuum fluctuations are virtual gravitational dipoles* (in analogy with electric and magnetic dipoles which are well established in physics). At this point, it is very important to understand that there are two different questions related to the hypothesis of virtual gravitational dipoles. The first question is what the physical consequences of the hypothesis are, while the second question is what the nature of gravitational dipoles is (i.e., in which way quantum vacuum fluctuations are gravitational dipoles). In this paper, as well as in the previous work ([2-5] and references therein) we focus on the first question, i.e., on the intriguing consequences of the hypothesis. The second question is a fundamental one, but, while we can imagine different kinds of gravitational dipoles, it is premature to say which ones (if any) are realised by nature. Well known electric and magnetic dipoles teach us how dipoles can be realised in fundamentally different ways. An electric dipole is composed of a positive and a negative electric charge (for instance electron-positron pairs in the quantum vacuum); the essence is that there are positive and negative electric charges that exist as electric monopoles. Contrary to this, a magnetic dipole is not composed of magnetic charges (magnetic monopoles) but is a result of the dynamics of electric charges.

We do not know if gravitational dipoles are eventually similar to electric dipoles or to magnetic dipoles or to something else. If gravitational dipoles are like electric dipoles, an obvious and elegant possibility (considered to be very unlikely [6], but who knows) is that particles and antiparticles have the gravitational charge of opposite sign; this possibility is in the process of being tested at CERN [In fact, three competing experiments at CERN: ALPHA [7], AEGIS [8] and GBAR [9], work on measuring the gravitational acceleration of antihydrogen in the gravitational field of the Earth. However, it must

be made clear that experiments in CERN can reveal or dismiss only gravitational dipoles related to a negative gravitational charge of antimatter but cannot confirm or exclude any other kind of gravitational dipoles. Particle-antiparticle pairs as gravitational dipoles are a beautiful possibility and an excellent working hypothesis, but the existence of this kind of dipoles is not “to be or not to be” for the theory of the gravitational polarisation of the quantum vacuum. In any case, the consequences that agree with observations, should be considered as hints that gravitational dipoles in quantum vacuum somehow exist.

According to the hypothesis of virtual gravitational dipoles, the total gravitational charge of a quantum vacuum fluctuation is zero, but it has a non-zero gravitational dipole moment \mathbf{p}_g . Consequently, the total gravitational charge of any macroscopic volume of the quantum vacuum is also zero; however, an effective gravitational charge density,

$$\rho_{qv} = -\nabla \cdot \mathbf{P}_g \quad (1)$$

can be attributed to the quantum vacuum in regions of non-random orientation of virtual gravitational dipoles [2-4].

Just a brief clarification of the fundamental equation (1). The key point [4] is that the otherwise randomly oriented virtual gravitational dipoles, are aligned (to some extent – completely or only partially) with the external gravitational field caused by matter immersed in the quantum vacuum (See figures 1a and 1b to get a useful mental picture). In a region of non-random orientation of virtual gravitational dipoles, the gravitational polarization density \mathbf{P}_g , i.e., the gravitational dipole moment per unit volume, can be attributed to the quantum vacuum. It is obvious that the magnitude $|\mathbf{P}_g|$ of the gravitational polarization density \mathbf{P}_g satisfies the inequality $0 \leq |\mathbf{P}_g| \leq P_{gmax}$ where 0 corresponds to the random orientations of dipoles, while the maximal magnitude $P_{gmax} \approx 0.06 \text{ kg/m}^2$ [4] corresponds to the case of saturation (when all dipoles are aligned with the external field). Hence, while the gravitational charge density of the quantum vacuum is everywhere zero, an *effective* gravitational charge density that acts as a real one can be attributed to the quantum vacuum.



Figure 1a. Randomly oriented gravitational dipoles (in absence of an external gravitational field)



Figure 1b. Halo of non-random oriented gravitational dipoles around a body (or a galaxy) with baryonic mass M_b . This halo of the polarized quantum vacuum is an alternative to dark matter.

In general [4], the gravitational polarization density \mathbf{P}_g and the corresponding Newtonian acceleration \mathbf{g}_N point in the same direction, while the magnitude $|\mathbf{P}_g|$ is a function of the used coordinates. However, if we focus only on the case of saturation defined by $|\mathbf{P}_g| \equiv P_{gmax}$, the gravitational polarization density takes simple form $\mathbf{P}_g = P_{gmax} \mathbf{g}_N / |\mathbf{g}_N|$, and Eq.1 reduces to:

$$\rho_{qv} = -P_{gmax} \nabla \cdot \frac{\mathbf{g}_N}{|\mathbf{g}_N|} \quad (2)$$

A single point-like body immersed in the quantum vacuum perturbs the random orientation of dipoles and creates around itself *a single spherical halo* of the polarized quantum vacuum. Because of spherical symmetry, it is natural to use spherical coordinates (r, θ, φ) ; the unit vector $\mathbf{g}_N/|\mathbf{g}_N| = -\mathbf{r}_0$, where \mathbf{r}_0 denotes the unit vector of the radial coordinate r . So, according to Eq. (2), the effective gravitational charge density, the total gravitational charge of the quantum vacuum within a sphere of radius r , and the corresponding acceleration are respectively given by:

$$\rho_{qv}(r) = \frac{2P_{gmax}}{r}; \quad M_{qv}(r) = 4\pi P_{gmax}r^2; \quad g_{qvmax} = 4\pi G P_{gmax} < 6 \times 10^{-11} \frac{m}{s^2}. \quad (3)$$

For a body of mass M_b , Eq.2, and consequently results given by Eq.3, are a good approximation (Hajdukovic 2020a) to distances of about $\sqrt{M_b/4\pi P_{gmax}}$. For the Sun, this distance is roughly $10^4 AU$; hence, it is an excellent approximation to consider the whole Solar System as a region of saturation.

Now, let us focus on the case of two point-like bodies with masses M and m at mutual distance D . Because of cylindrical symmetry we will use the cylindrical coordinates (See Figure 2) usually denoted (z, ρ, φ) ; however, in order to avoid confusion between density ρ_{qv} and coordinate ρ , we will use the notation (z, s, φ) and will denote the corresponding unit vectors $(\mathbf{e}_z, \mathbf{e}_s, \mathbf{e}_\varphi)$. In cylindrical coordinates Eq.2 can be rewritten as:

$$\rho_{qv}(z, s, \varphi) = -P_{gmax} \left[\frac{\partial}{\partial z} \left(\frac{g_{Nz}}{g_N} \right) + \frac{1}{s} \frac{\partial}{\partial s} \left(s \frac{g_{Ns}}{g_N} \right) \right] \quad (4)$$

In the above equation g_{Nz} , g_{Ns} and $g_N \equiv |\mathbf{g}_N|$ are two components and the magnitude of the Newtonian acceleration $\mathbf{g}_N = g_{Nz}\mathbf{e}_z + g_{Ns}\mathbf{e}_s$ that can be easily deduced from Fig. 2,

$$\mathbf{g}_N = - \left\{ \frac{GMz}{(z^2+s^2)^{3/2}} - \frac{Gm(D-z)}{[(D-z)^2+s^2]^{3/2}} \right\} \mathbf{e}_z - \left\{ \frac{Gms}{(z^2+s^2)^{3/2}} + \frac{Gms}{[(D-z)^2+s^2]^{3/2}} \right\} \mathbf{e}_s \quad (5)$$

The corresponding magnitude of acceleration is:

$$|\mathbf{g}_N| \equiv g_N = G \sqrt{\frac{M^2}{(z^2+s^2)^2} + \frac{2mM(z^2+s^2-Dz)}{(z^2+s^2)^{3/2}[(D-z)^2+s^2]^{3/2}} + \frac{m^2}{[(D-z)^2+s^2]^2}} \quad (6)$$

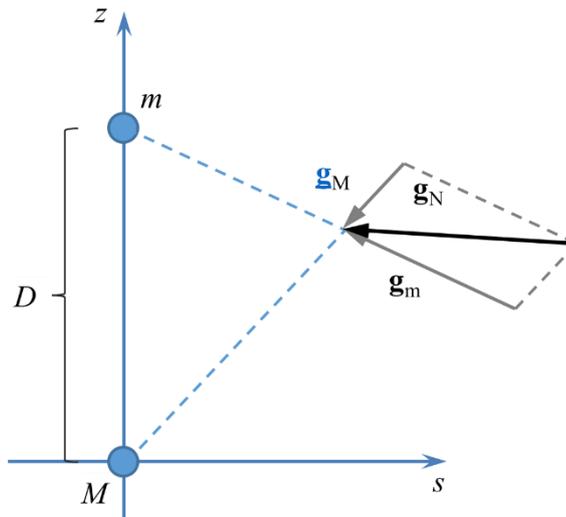


Figure 2. The resultant Newtonian gravitational field \mathbf{g}_N of two point-like bodies with mass M and m at mutual distance D , has cylindrical symmetry that trivially leads to Eq. (5).

Finally, using equations (4), (5) and (6), for *the region of saturation*, the effective gravitational charge density, induced by 2 bodies of masses M and m at mutual distance D, can be written as an explicit function of all variables:

$$\rho_{qv}(z, s, \varphi) = P_{gmax} \left(\frac{G}{g_N} \right)^3 \left\{ \frac{2M^3}{(z^2+s^2)^{7/2}} + \frac{2m^3}{[(D-z)^2+s^2]^{7/2}} + \right. \\ \left. M^2 m \frac{6z^4+6s^4+12s^2z^2-16Dz^3-16Ds^2z+14D^2z^2+3D^2s^2-4D^3z}{(z^2+s^2)^3[(D-z)^2+s^2]^{5/2}} + \right. \\ \left. Mm^2 \frac{6z^4+6s^4+12s^2z^2-8Dz^3-8Ds^2z+2D^2z^2-D^2s^2}{(s^2+z^2)^{5/2}[s^2+(D-z)^2]^3} \right\} \quad (7)$$

Unfortunately, the explicit function given by Eq. 7 is relatively long and complicated, so that main features are practically hidden; the use of numerical methods is inevitable. However, despite complexity, we can show analytically the most fundamental feature; in principle, in the region of saturation, and hence in the Solar system, the effective gravitational charge density can be negative.

Let us consider the case of two bodies with equal mass (M=m) at $z=D/2$. According to Eq. 7, the corresponding density as function of s is given by:

$$\rho_{qv} \left(z = \frac{D}{2}, s, \varphi \right) = \frac{2P_{gmax}}{s} \frac{s^2 - D^2/8}{s^2 + D^2/4} \quad (8)$$

The effective gravitational charge density determined by Eq. (8) is negative for $s < D/\sqrt{8}$.

Now, let's have a look at Fig.3a resulting from numerical calculations based on Eq. (7). In the *zeroth approximation* (i.e., when the Sun is considered as the only source of gravity), there is a single, spherically symmetric halo of the polarised quantum vacuum, described by Eq.3; the effective gravitational charge density ($\rho_{qvSun} = 2P_{gmax}/r$) is always positive (we denoted it by green in figures). If a second body (in our case the planet Saturn) is included in calculations as a second source of gravitational polarization, this simple pattern of gravitational polarization is replaced by a more complex one. There are three main features of the new distribution of the effective gravitational charge density.

First, spherical symmetry converts to cylindrical symmetry; consequently, both the polarised quantum vacuum inside and outside the orbit have gravitational impact on Saturn.

Second, the effective gravitational charge density $\rho_{qv}(z, s)$, caused by the Sun and Saturn is different from the corresponding density $\rho_{qvSun}(z, s)$ calculated when the Sun was considered as the only source of polarization; as presented on Figure 3b, there are large regions (respectively denoted by blue and orange) in which $\rho_{qv}(z, s) > \rho_{qvSun}(z, s)$ and $\rho_{qv}(z, s) < \rho_{qvSun}(z, s)$.

Third, in a relatively large region around Saturn (with linear size of about one astronomical unit), the magnitude of the effective gravitational charge density is *much larger* than $2P_{gmax}/r$; and, in addition to positive there are also regions with a negative effective charge density (denoted by red colour). This region is visible at the top of Fig.3a. Hence there are "islands" (we may also say "clouds") of the quantum vacuum with negative effective gravitational charge.

Before we continue let us underscore a major difference between phenomena related to Fig.3b and Fig.4. Fig.3b is about global distribution of the effective gravitational charge density within the Solar System. We can calculate densities and over-densities corresponding to the presence of the Sun and Saturn, but they are not robust; for instance, if Jupiter (in orbit between the Sun and Saturn) is included in calculations, the distribution of over-densities would be significantly different. Contrary to this Fig.4 is about local polarization near the planet and calculated densities are sufficiently robust, i.e., not crucially dependent on Jupiter and other planets. Because of this robustness in the rest of the paper we focus on the islands with a negative effective gravitational charge.

Figure 4 presents the red island of the quantum vacuum (with a negative effective gravitational charge density) which is the closest one to the Earth. In fact, the island is volume obtained by rotation of the red surface for π around z axis (or rotation for 2π of the left or right half of the red surface).

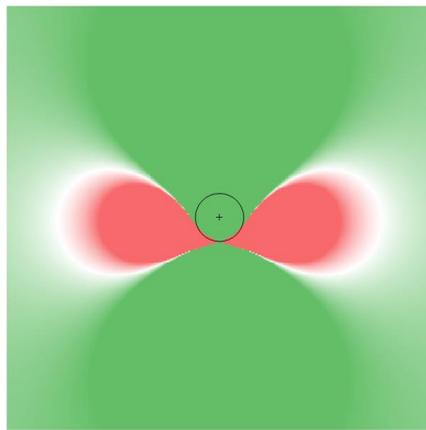
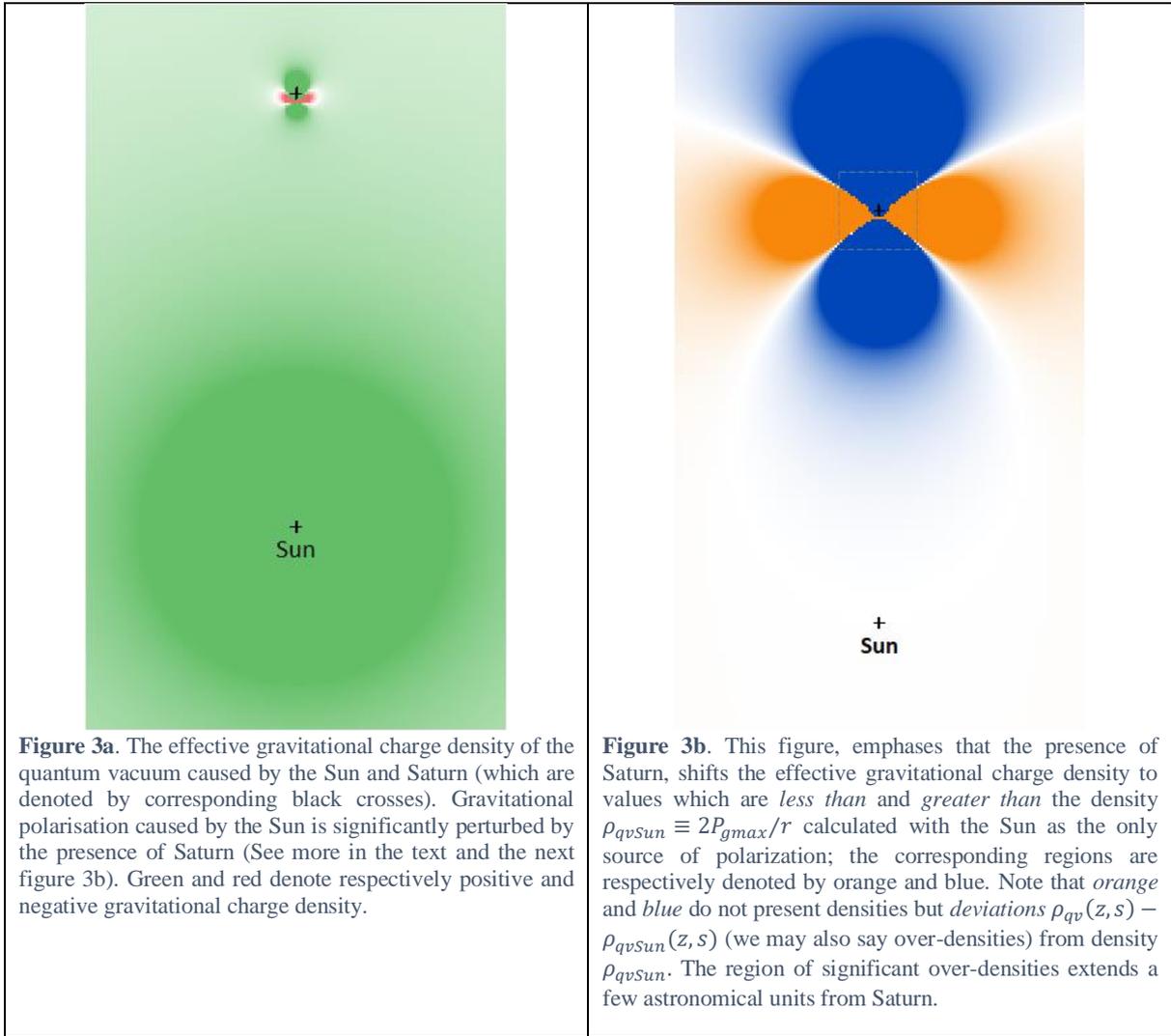


Figure 4. The island of the quantum vacuum with a negative effective gravitational charge (denoted by red) within the sea of positive charge (denoted by green). This is a typical form for all the planets but here we present calculations for the Earth and the Sun. The Earth is denoted by the black cross, while the Sun is far below and not visible on this plot. The radius of the circle around the Earth is 260 000 km, while the orbit of the Moon is 384 000 km and hence a part of the orbit of the Moon goes through the red region producing its perturbation.

The radius of the small circle around Earth is $r_c = D / (1 + \sqrt{M/m})$ where M and m are respectively the mass of the Sun and planet (in this case Earth) and D is the distance between them (For Earth $D = 1.5 \times 10^8 \text{ km}$). Let us underscore that on the z axis at distance $z_c = D\sqrt{M/m}$ from the Sun and distance r_c from the Earth, Newtonian accelerations caused by the Sun and the Earth cancel each other.

For Earth $r_c \approx 260\,000 \text{ km}$, while the linear size of the red surface is nearly four million kilometres (about $15r_c$). Note that the radius of the Moon's orbit around Earth is about $1.5r_c$; hence, the orbit of the Moon partially goes through the island. It remains a challenge to reveal if the predicted island (cloud) of the negatively charged quantum vacuum within the Earth-Moon system produces a measurable gravitational impact. In a similar way it remains a challenging question if the existence of such a cloud might be eventually revealed by careful study of the trajectory of a spacecraft launched from the Earth and approaching Jupiter or Saturn through the cloud.

Negative effective gravitational charges (denoted by m_{qv}^-) of islands corresponding to planets of the Solar System are given in Table 1. The volume element in cylindrical coordinates is $dV = sdzdsd\phi$ and because of cylindrical symmetry results in Table 1 follow from numerical integration ($m_{qv}^- = 2\pi \iint \rho_{qv}(z, s) s dz ds$). Islands corresponding to the four big planets have a relatively big mass close in magnitude to the mass of significant dwarf planets as for instance (55637) 2002 UX25 and 90482 Orcus. The total negative effective gravitational charge in the Solar System should be close in magnitude to the total mass of the main asteroid belt between Mars and Jupiter.

Planet	m_{qv}^- [kg]	g_{qv}^- [m/s^2]
Mercury	-3.21×10^{14}	-4.83×10^{-12}
Venus	-1.27×10^{16}	-4.80×10^{-12}
Earth	-2.94×10^{16}	-4.80×10^{-12}
Mars	-9.12×10^{15}	-4.83×10^{-12}
Jupiter	-9.62×10^{19}	-4.18×10^{-12}
Saturn	-1.29×10^{20}	-4.45×10^{-12}
Uranus	-1.11×10^{20}	-4.68×10^{-12}
Neptune	-3.12×10^{20}	-4.66×10^{-12}

Table 1. Second column gives negative effective gravitational charge m_{qv}^- of islands corresponding to planets. As an illustration of the size of the gravitational impact of these islands, the third column gives the acceleration caused by an island at the centre of the planet.

The simplest way to get a rough idea of the gravitational impact of a negatively charged island is to calculate acceleration g_{qv}^- caused by that island at points on the z axis close to the island. Acceleration at a point ($z = z_0, s = 0$) is given by integration over the volume of the island:

$$g_{qv}^- = 2\pi G \iint \rho_{qv}(z, s) \frac{(z-z_0)s}{[(z-z_0)^2 + s^2]^{3/2}} dz ds \quad (9)$$

Equation (9) is a consequence of the fact that to each surface element $dzds$ corresponds to a ring of volume $dV = 2\pi s dz ds$ with the effective gravitational charge $dm_{qv}^- = 2\pi \rho_{qv}(z, s) s dz ds$. The acceleration caused by this elementary ring is $dg_{qv}^- = G(z - z_0) dm_{qv}^- / [(z - z_0)^2 + s^2]^{3/2}$ leading to Eq. (9). As an example, the numerical value for acceleration at point $z = D$ (i.e., at the centre of the planet) is given for all islands in the third column of Table 1.

Figure 3a and numerical values for acceleration in Table 1 raise the question if the gravitational impact of the quantum vacuum causes a tiny violation of the Weak Equivalence Principle (i.e., universality of free fall) that is a cornerstone of both, Newtonian and general relativistic gravity. Imagine that in Figure 3a, instead of Saturn there is a planet of a different mass. As intuitively expected, (and confirmed by Eq. 7) a different mass leads to a different distribution of the effective

gravitational charge density; hence it seems likely that the gravitational impact of the quantum vacuum on a body depends on its mass m .

In brief, we revealed an unprecedented possibility that the Solar System contains islands of the quantum vacuum with a negative effective gravitational charge density. Theoretical physics is in crisis, perhaps in the greatest crisis in its history (let us mention only the unsolved mysteries of phenomena usually attributed to hypothetical dark matter and dark energy and not the less mysterious asymmetry between matter and antimatter in the Universe); hence, we must stay open-minded to different scenarios even if they look very unlikely from the point of view of our current knowledge. Hopefully this paper would stimulate astronomers and physicist for further considerations.

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