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Testing the gravitational properties of the quantum vacuum within the Solar System

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Abstract: The existence of the quantum vacuum is well established in the Standard Model of Particles and Fields but completely neglected in contemporary Astrophysics and Cosmology. It is a major and absolutely urgent task to reveal if and how quantum vacuum contributes to the gravitational field of baryonic matter in the Universe. We point out that a first signature of the gravitational impact of the quantum vacuum might be seen in the perihelion precession of orbits of satellites of minor planets in outer part of the Solar System. As an example we consider the minor planet 2002 UX25 and its satellite.

1. Introduction

So far we had two scientific revolutions in our understanding of gravitation: the Newton law and the General Relativity of Albert Einstein. Whatever happens in the future, these two revolutions will remain among the greatest achievements of theoretical physics and human mind.

We know today that both theories have in common a wrong assumption. The wrong assumption is that matter of the Universe exists in classical, *non-quantum* vacuum.

While it is systematically neglected in Astrophysics and Cosmology, quantum vacuum is an inherent part of the Standard Model of Particles and Fields (see for instance [1-3]). If the existence of the quantum vacuum was not taken into account, quantum field theory would be in perfect disagreement with experimental findings.

Einstein said (and I agree): Imagination is more important than knowledge. So, I invite you to imagine that, you can switch off and switch on, the quantum vacuum in our Universe. As we live in the Universe with quantum vacuum switched on, you firstly must switch it off. What would happen? In fact I must warn you not to do it; after switching off the quantum vacuum, you will not stay alive to switch it on again! This is a prediction based on our best knowledge. For instance, sophisticated experiments [4] have revealed that proton is not

an elementary particle but a very complex system which in addition to three valence quarks contains virtual (or sea) quark-antiquark pairs and gluons. In simple words, quantum vacuum significantly contributes to the structure of protons (and neutrons as well). If this contribution is switched off, protons would be quite different particles. A radical change of constituents of atoms would perturb everything; the Universe without quantum vacuum would be a completely different place (and certainly without us). Hence, quantum vacuum is not only a strange state of matter in quantum field theory, but also the root of our existence.

Before we continue let us give a simplified (but basically true) description of the quantum vacuum for non-specialists readership. Quantum vacuum should be considered as a *state* of matter, completely different from familiar states (gas, liquid, solid, plasma...) but *as real as* they are [1-3]. Popularly speaking, quantum vacuum is a “sea” of short living virtual particle-antiparticle pairs (like quark-antiquark, neutrino-antineutrino and electron-positron pairs). According to our best knowledge: (1) quantum vacuum is a state with perfect *symmetry* between matter and antimatter; a particle *always* appears in pair with its antiparticle, which is totally different from mysterious matter-antimatter *asymmetry*, i.e. the fact that everything on the Earth (and apparently in the Universe) is made only from matter, with only traces of antimatter; (2) contrary to all other

states of matter which are composed from the long living particles (electrons and protons in stars and flowers, have existed before them and will exist after them), the quantum vacuum is a state composed from extremely *short living* virtual particles and antiparticles (for instance, the lifetime of a virtual electron-positron pair is only about 10^{-22} seconds).

Our knowledge about gravitational properties of the quantum vacuum is zero.

There are two possibilities. The first one is that quantum vacuum has no impact (or at least has no significant impact) on the gravitational field in the Universe. In fact, contemporary Astrophysics and Cosmology are based on this assumption.

The second possibility is that quantum vacuum contributes greatly to the gravitational field in the Universe. If so, any theory that neglects the existence of the quantum vacuum is blind for some crucial gravitational phenomena, and, as a compensation for the lost phenomena, must invoke some artificial stuff. The inevitable question is if dark matter and dark energy are such artificial stuff which (in our incomplete theory) mimics well the phenomena which are in fact caused by the quantum vacuum.

Contrary to the other candidates for new physics (supersymmetries, dark matter, dark energy...) quantum vacuum is not a speculation but a key feature of Quantum Electrodynamics, Quantum Chromodynamics and Electroweak theory, i.e. a key feature of the Standard Model of Particles and Fields, the most successful and the best tested theory in history of science. It is a major and absolutely urgent task to reveal if and how quantum vacuum contributes to the gravitational field of baryonic matter in the Universe. In the present article we point out that a first signature of the gravitational impact of the quantum vacuum might be seen in the perihelion precession of orbits of satellites of minor planets in outer part of the Solar System. As an example we consider the minor planet 2002 UX25 and its satellite.

2. The simplest gravitational signature of new physics

The simplest problem in celestial mechanics is to determine the orbit of a point-like body in a central gravitational field. The orbit is an ellipse *fixed* with respect to the centre of gravity *if and only if* the central gravitational field has a perfect spherical symmetry and the gravitational force strictly follows the Newton inverse square law. Any departure from the spherical symmetry

and/or the inverse square law of gravity, leads to the precession of the perihelion (see for instance [5-6]).

General Relativity (describing a spherically symmetric central gravitational field by Schwarzschild metric) is more accurate than Newton theory and it predicts a tiny precession even in the case of spherical symmetry. The general relativistic precession is well approximated by

$$\Delta\omega_{GR} = \frac{3\pi}{1-e^2} \frac{R_s}{a} \approx 3\pi \frac{R_s}{a} \quad (1)$$

where $\Delta\omega_{Gr}$ is the extra rotation *per orbit* in radians, a the semi-major axis of the orbit, e the eccentricity of the ellipse and R_s the Schwarzschild radius of the central body.

It is worth to note that the perihelion precession of planets predicted by classical theory (Newtonian mechanics together with the inverse square law for gravity) is close to the observed values; the largest discrepancy occurs for the Mercury (Mercury's orbit precess at a rate that is about 8% greater than the predicted one). The discrepancy has been explained by general relativistic correction (1) which must be added to the Newtonian result.

In brief, in the case of a central gravitational field with the exact spherical symmetry, Newtonian precession of perihelion is zero and the general relativistic result (1) is too small to be detected (with the current accuracy of measurements) for satellites of small central bodies like minor planets in the outer part of the Solar System.

Of course, a minor planet (which orbits around the Sun with a period T_{Sun}) and its satellite (which orbits around the planet with a period T_p) are not an isolated system but subject of an external gravitational field dominated by the Sun. This external gravitational field produces a Newtonian perihelion shift in the orbit of the satellite: the shift per orbit is well approximated [5, 7] with

$$\Delta\omega_N = \frac{3\pi}{2} \left(\frac{T_p}{T_{Sun}} \right)^2 \quad (2)$$

Any significant difference between observed precession and the expected value (2) must be

considered as signature of new physics. Typical value of the shift (2) for satellites of trans-Neptunian minor planets is a few tens of arc seconds per century. As we will argue, the shift caused by quantum vacuum might be greater more than one order of magnitude.

However, independently of any theoretical argument it is of major importance to observe and see if there is any anomalous perihelion shift in orbits of satellites of trans-Neptunian minor planets. With the existing infrastructure of satellites and telescopes it would be less expensive but potentially not less important than LHC experiments at CERN or detectors devoted to search for dark matter.

3. An illustration of hypothetical gravitational effects of quantum vacuum

Let us assume that a satellite (with mass m) orbiting about a minor planet (with mass M) is subject of both Newtonian gravitational force and a tiny additional radial acceleration $A(r)$ caused by the presence of the quantum vacuum

$$g(r) = \frac{GM}{r^2} + A_{qv}(r) \quad (3)$$

In the simplest but illuminating case, $A(r)$ has a constant value denoted by A_{qv} . In this case the perihelion shift per orbit can be written [5, 8] in the following way

$$\Delta\omega_{qv} = 2\pi A_{qv} \sqrt{1-e^2} \frac{a^2}{G(M+m)} \quad (4)$$

Hence, the internal precession (4) caused by the quantum vacuum is mixed with the precession (2) induced by external Newtonian gravitational field dominated by the Sun. Let us note that according to equations (2) and (4) quantum vacuum might be dominant only for small systems far from the Sun.

Now, as an example let us consider the minor planet 2002 UX25; the needed data taken from Reference [9] are given in Table 1

According to Table 1 and Equation (2)

$$\Delta\omega_N \approx 3.09 \times 10^{-8} \text{ rad} \approx 0.0064 \text{ arc sec} \quad (5)$$

Table 1
Parameters for 2002 UX25 and its Satellite

UX25 Mass	$1.25 \times 10^{20} \text{ kg}$
UX25 Semimajor axis	42.869 AU
UX25 Orbital Period	280.69 years
Satellite Semimajor axis	4770 km
Satellite Orbital Period	8.3094 days
Satellite Eccentricity	0.17

while $\Delta\omega_{qv}$ depends on the choice of A_{qv} in the Eq. (4). As an interesting choice suggested recently [10-11], let us take $A_{qv} = 6.673 \times 10^{-11} \text{ m/s}^2$.

It leads to

$$\Delta\omega_{qv} \approx 0.23 \text{ arc sec} \quad (6)$$

Comparison of (5) and (6) shows that in this example the effect of quantum vacuum is strongly dominant (it is larger nearly two orders of magnitude). Hence, there is potential for a clear signal of new physics.

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