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# Astrometric detection feasibility of gravitational effects of quantum vacuum

M. Gai, A. Vecchiato

June 13, 2014

## Abstract

This work analyzes in some detail the feasibility of testing with astrometric measurements the hypothesis that Quantum Vacuum can have gravitational effects, as suggested in a series of recent papers ([3, 6, 5]). In particular, the possibility of detecting an excess shift of the longitude of the pericenter in the orbit of the trans-neptunian system UX25 and its satellite is investigated. The excess shift which might be experimented by the orbit of the satellite was estimated, under reasonable working hypothesis, to be about 0.23 arcsec per orbit. Several observing scenarios are explored here, including those using conventional and adaptive optics telescopes from ground, and some spaceborne telescopes.

Keywords: Physical data and processes: Gravitation; Astronomical instrumentation, methods and techniques: Techniques: high angular resolution; Astrometry and celestial mechanics: Astrometry; Kuiper belt objects: individual: UX25; Cosmology: dark matter, dark energy, inflation

## Introduction

In a recent paper Hajdukovic [6] speculated about the possibility that Quantum Vacuum has to be included in a complete and correct description of Gravity. Such “speculation” stems from the simple consideration that: a) the presently accepted model of the gravitational interaction can agree with the current experimental findings only by assuming the existence of entities like Dark Matter (DM) and Dark Energy (DE); b) there do exist another entity, namely the Quantum Vacuum (QV) whose existence is essential in the context of Quantum Physics for the Standard Model of Particle Physics to be in agreement with the experiments; c) the nature and the properties of DM and DE are currently unknown, and all the experimental attempts which tried to find evidences of the existence of any of their candidates have failed up to now. Given these premises, it is not unreasonable to assume that QV, DM, and DE can actually be the same entity or, in other words, that QV has the same gravitational effects that now are attributed to DM and DE.

This is actually not a completely new attempt. The existence of DE was postulated after the measurement of an accelerated expansion of the Universe at high redshifts, however, from a qualitative point of view, such kind of expansion can also be reproduced by a non-zero cosmological constant  $\Lambda$ , interpreted as the effect of a homogeneous fluid with constant negative pressure. In principle, it would be natural to identify such fluid with the QV because there is a mechanism in Quantum Field Theory (QFT) to produce a negative pressure. This elegant idea didn't work because of the so-called *cosmological constant problem* [9] i.e. because the energy of the QV predicted by the QFT was many orders of magnitude larger than the one which could be attributed to  $\Lambda$  from astrophysical measurements.

Stemming from the same premises, recently it was suggested that, on the assumption that particles and antiparticles forming the QV have opposite gravitational charge, the QV energy could be compatible with that attributed to DE [3] and that the same hypothesis could be used to explain the effects now attributed to DM. From the astronomical point of view, however, the consequences of attributing a gravitational effect to QV should in principle be considered at all scales, not just at the cosmological ones needed to explain the DE effect. In the simple context of the two body problem, e.g., the additional gravity source represented by QV would necessarily induce a deviation from the perfect symmetry of the gravity field which is necessary to have closed orbits, and therefore show itself up as an excess of the shift of the pericenter of a body orbiting around a central gravity source.

In the Solar System such deviations can be already induced by the Sun itself in a classical context, but they are negligible far from it, i.e. at the typical distances of the trans-neptunian objects, while those attributed to the QV energy would not decrease. This explains the potential relevance of accurate astrometric monitoring of trans-neptunian objects claimed in [4] as a target for Fundamental Physics tests, in particular for the detection of possible non-Newtonian contributions to their orbits.

Here we are exploring in more detail the feasibility of such kind of measurements for the UX25 trans-neptunian binary system.

## 1 The target system: 2002 UX25

The trans-Neptunian object (55637) 2002 UX25 (hereafter, UX25 for short) orbits the Sun in the Kuiper belt (semi-major axis 42.869 AU) beyond Neptune, with period 280.69 years, and it has a single known moon with fairly large size. A more detailed description of its characteristics is available in the literature [1]. UX25 is located at about 43 AU from the Sun, and has visual magnitude close to 20 mag. The primary and secondary diameters are estimated to be about 670 km and 190 km (from spherical model of thermal emission). The angular diameters are then respectively 21.4 mas (primary) and 6.1 mas (secondary), mostly unresolved even by AO telescopes. The magnitude difference between primary and secondary is 2.7 mag (a factor 12 in brightness), fairly consistent

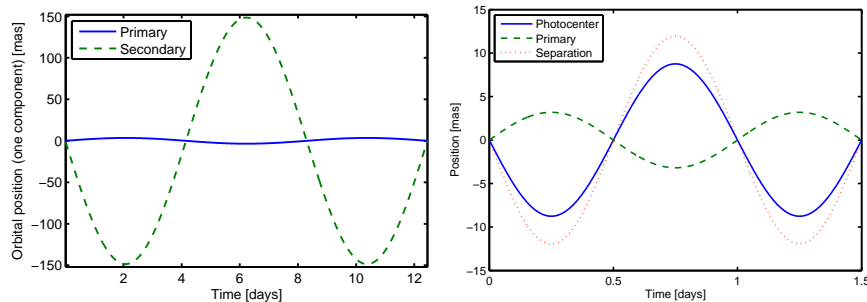


Figure 1: One-dimensional object position (left) and photocenter position (right) over 1.5 orbital periods

with the area ratio  $\sim 12.4$  associated to the estimated diameter ratio  $\sim 3.32$ , assuming similar composition and surface structure. The mass ratio is 43.85, and the semi-major axis of planet-stellite orbit is 4770 km, corresponding to about 152 *mas*.

The binary period is 8.3 days, and the eccentricity is  $\epsilon = 0.17$ . The orbit inclination is close to  $60^\circ$ , so that it is closer to the edge-on case than to the face-on case, but still well resolved in two dimensions.

As a binary system located in a remote region of the solar system, it is affected by small perturbations from other bodies, making it a convenient candidate for the quantum vacuum detection experiment. The drawback of the source is that its magnitude is not very bright, being slightly fainter than 20 mag for the primary, and close to 23 mag for the secondary.

In the approximation of circular orbits, the relative one-dimensional position of the two objects over a time elapse of 1.5 periods is shown in Fig. 1 (left). The photocenter motion for each component, and the overall photocenter, is shown in the right panel. This assumes that the two objects are unresolved, i.e. observed as a single spot of light, e.g. by a conventional ground based telescope.

The plot on the left panel in Fig. 1 is representative of what could be achieved by an AO-equipped telescope, able to resolve in most observations the primary and secondary components of the binary object UX25.

### 1.1 Astrometric signal amplitude

A qualitative representation of the orbit recession phenomenon is shown in Fig. 2. The position of the periastron, and of any other point in the orbit at a given time, evolve continuously with time, so that the orbit is no longer closed as in the standard Keplerian solution of the two-body problem. The amount of precession accumulated over five years, corresponding to about 220 orbits, is  $50''.55$ . This corresponds to a peak position displacement on the sky of a few ten micro-arcsec ( $\mu\text{as}$ ), as shown in Fig. 3. **In order to achieve a clear detection at the  $3\sigma$  level, then, we need a measurement precision**

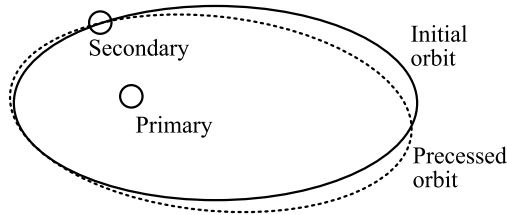


Figure 2: Representation of orbit precession (face-on view, not to scale)

**equivalent to about  $15 \mu\text{as}$ .**

The amplitude is rather small, however all orbital positions are displaced in a correlated way, so that the goal appears to be compatible with state of the art astrometry from the ground [ref. Cameron 2009], in particular with the use of large telescopes equipped with adaptive optics (AO).

Given the high competition for time allocation of large telescopes, it is necessary to formulate a good observing proposal, with strong (astro-)physical motivations, and a robust implementation plan. Besides, it is mandatory to demonstrate that the use of such facility is unavoidable, i.e. that the experiment cannot be carried on with smaller instrumentation. It is convenient to check the feasibility from ground based telescopes of small class, limited by atmospheric turbulence, before addressing large, adaptive optics (AO) equipped telescopes or space telescopes.

## 1.2 Experimental approach

The first step is detection of a relevant precession; the second is the determination of its amplitude, in order to set proper bounds to the theory. In both cases, it is not convenient to evaluate just a single orbital position (which would anyway be impractical). The proposed approach consists in a set of observations mapping the whole orbit, in order to evidence its variation over a given period of time by comparing its basic geometric properties at different epochs.

It should be noted that the precision on our current knowledge of the UX25 system is sufficient to mark it as a convenient candidate for our study, but it is far from the level required by the experiment. In practice, this means that the initial orbital state must be measured with precision consistent with the experiment goal, as well as the final state. Moreover, the orbit must be monitored also throughout the intermediate period, although possibly with somewhat less demanding requirements, in order to detect potential disturbing effects to be modeled and removed.

The initial orbit is supposed to be known with sufficient precision. After a given time elapse, in which the periaster precession takes place, a set of position measurements is performed to estimate the new set of orbital parameters.

The first conceivable test is that of consistency of the new orbit with the initial one, i.e. the null test of no precession. Astrometric noise on the primary

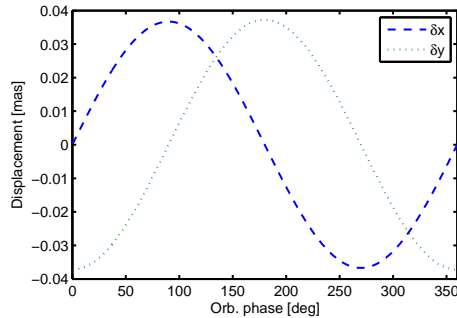


Figure 3: Amplitude of the astrometric signal associated to five year precession of the 2002 UX25 orbit

and secondary photo-centres may be induced by the real, non-spherical shape of the bodies, variations in the surface structure and reflectivity (albedo), rotation and so on. Accurate characterisation of the binary system is therefore required.

The measurement can be based either on the separation of the two components of the binary system, i.e. on the quantities shown in Fig. 1 (left), or on the separation between primary and photocenter position, represented in Fig. 1 (right). In the former case, the separation is roughly one order of magnitude larger, but the measurement is mainly limited by the SNR of the secondary. In the latter case, both primary and photocenter have comparable precision, corresponding to the overall SNR, but the separation is about one order of magnitude smaller. Moreover, it can be shown from current simulations that the precision on the secondary is about a factor three worse than that on the primary, when the two components are resolved, but the degradation becomes about one order of magnitude when the images are significantly superposed, i.e. at least over a significant fraction of the orbital period. The choice of data processing approach, from the same imaging observations, is therefore not clear cut.

## 2 Atmospheric limitations / characteristics

Atmospheric turbulence is one of the main limitations of ground based astrometry. However, in good observing conditions, and adopting thorough control of systematic errors, it was possible to achieve precision levels as good as  $0.15 \text{ mas}$  [8], referred to one hour exposures, using optimised conventional telescopes. Adaptive optics may provide even better results, over very small fields, e.g. order of  $100 \mu\text{as}$  over two minute exposures [2], and optical long baseline interferometry is progressing towards the  $10 \mu\text{as}$  goal (e.g. the ESO VLTI PRIMA facility, or the Keck Interferometer).

For the application currently investigated, it is convenient to extrapolate the results from Pravdo and Shaklan (1996)[8], in particular concerning *field averaging* of the atmospheric noise. The one-dimensional error  $\epsilon$  on the esti-

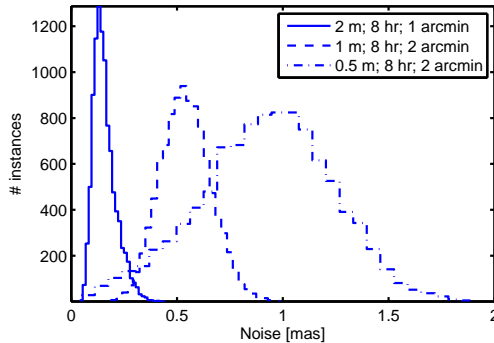


Figure 4: Residual atmospheric noise over one night

mated position of a target with respect to a set of  $N$  reference stars in the field, located at distances  $d_{01}$  from the target along the measurement direction, from an exposure of  $T$  seconds, with a telescope having diameter  $D$ , has variance

$$\epsilon^2 = \frac{2.9 \times 10^{-5}}{N^2 T} \left[ \frac{1}{D^{4/3}} \sum_{m,n=1}^N \left( d_{0m}^2 - \frac{1}{2} d_{mn}^2 \right) - 192 \frac{1}{D^2} \sum_{m,n=1}^N \left( d_{0m}^{8/3} - \frac{1}{2} d_{mn}^{8/3} \right) \right],$$

where  $d_{mn}$  are the separations among the reference stars, and the result is in  $\text{arcsec}^2$ . The equation was derived from a simple model [7], assuming a Kolmogorov turbulence spectrum with profile described according to Hufnagel (1974), and a seeing parameter  $r_0 = 10 \text{ cm}$ . The parameters correspond to a good quality observing site. All distances are in radians.

It may be noted that the limiting error can be easily computed for any field, in given observing conditions, providing results highly dependent on the star separations. In practice, it may be convenient to limit the range for locating reference stars around a given target, since further objects at a longer distance may not help significantly in improving on the error. Also, the residual atmospheric noise depends on the telescope diameter  $D$ .

The model is used to assess the potential performance of astrometric observations from ground, by means of small telescopes (primary mirror diameter  $D = 0.5 \text{ m}$  and  $D = 1 \text{ m}$ ), with exposure time of five minutes and one hour, assuming the availability of  $N = 10$  stars within a field of either  $2'$  or  $5'$ . The target is assumed to be located between the centre of the field and the mean of the reference star photocentres. A set of  $N_I = 10,000$  random star positions, with a uniform distribution, has been generated for each condition, with results evidenced by the histograms in Fig. 4. Favourable conditions of higher stellar density may result in further precision improvement. Moreover, the measurement can, in principle, be averaged over a whole night (eight hours) of observations, providing the results shown in Fig. 4, including the case of a  $D = 2 \text{ m}$  telescope with  $N = 10$  reference stars within a field of  $1'$ .

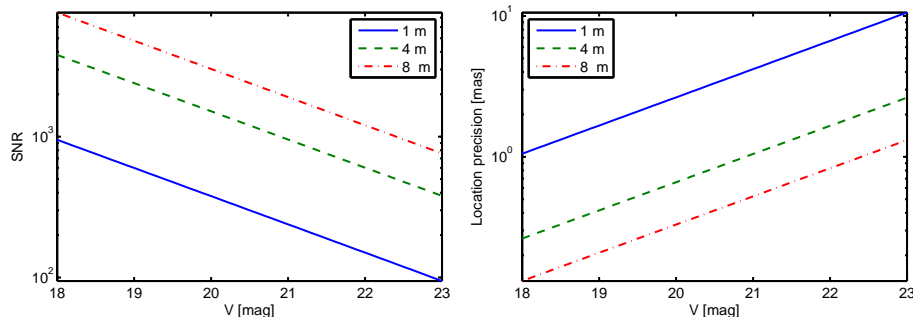


Figure 5: SNR in one hour for different telescopes.

### 3 Assessment of orbit determination from conventional telescopes

The following assessment is somewhat simplified in many respects, but it is considered adequate with respect to the order of magnitude estimation. In the elementary exposures, the image of unresolved objects has size related to the seeing, e.g.  $w \simeq 1''$ . The signal to noise ratio (SNR) achieved in broadband imaging in V band, over one hour, with different telescopes, is shown in Fig. 5 (left). The location precision  $\sigma_p$  as a function of the magnitude can roughly be derived as

$$\sigma_p \simeq \frac{w}{SNR},$$

and it is shown in Fig. 5 (right).

The order of magnitude of observing time requirements can be derived by scaling the precision on the secondary component of UX25 to the  $15 \mu\text{as}$  requirement from Sec. 1.1. We assume an average of 8 hours per each night of observation. Even assuming usage of a 8 m telescope, the number of nights required for  $3\sigma$  detection is 960, i.e. clearly not feasible within reasonable implementation constraints.

### 4 Assessment of orbit determination from space

Several telescopes are currently being used for astrophysical observations from space, and more advanced ones will be launched in the coming years. Most of them are specialised in terms of wavelength, operating mode and so on with respect to their science goal, but several offer the option for conventional observation proposals or targets of opportunity.

The Hubble Space Telescope (HST) has comparably small size, i.e. 2.4 m diameter, but operating outside the Earth's atmosphere it can routinely achieve near-diffraction limited performance. The preliminary assessment refers to the UVIS channel of the WFC3 instrument, at wavelength  $\sim 550 \text{ nm}$ , with charac-



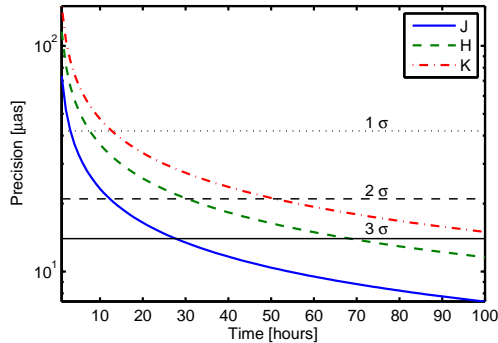


Figure 6: Detection performance vs. time

teristic image width  $\lambda/D = 48 \text{ mas}$ . This results in a location precision on the UX25 secondary of about  $0.5 \text{ mas}$  in ten minutes. A total of about  $200 \text{ hours}$  seems to be required to fulfill the science case. Even spread over several months, the amount seems to be fairly large with respect to the existing competition.

Gaia will provide extremely valuable constraints on our problem, in the sense of accurate determination of the reference star frame against which the position and motion of our target is tracked. However, due to its fixed scan law, the sampling and exposure time are such that the precision on the UX25 secondary motion is simply insufficient with respect to the goal.

The James Webb Space Telescope (JWST), planned for launch in 2018, will provide a much better chance for implementation of the current experiment. Given the larger size ( $6.5 \text{ m}$  diameter), and higher sensitivity, the location performance may be quite adequate: the characteristic image width at wavelength  $\lambda = 650 \text{ nm}$  is  $21 \text{ mas}$ , resulting in a location precision on the UX25 secondary of about  $0.2 \text{ mas}$  in ten minutes. Therefore, the basic measurement sequence for orbit determination with the required precision will require about  $27 \text{ hours}$ , interspersed over the 8.3 days period. This is much more manageable with respect to time allocation competition with other science proposals.

## 5 Assessment of orbit determination from adaptive optics telescopes

In case of AO telescopes, the available photon flux and SNR are comparable, but the astrometric precision improves by about one order of magnitude thanks to the higher image resolution, close to the diffraction limit. The diffraction limit is order of  $\lambda/D$ , where  $\lambda = 1.1; 1.65; 2.2 \mu\text{m}$  is the wavelength respectively in the J, H and K near infrared bands. As a reference case, we consider the case of a  $D = 8 \text{ m}$  diameter AO telescope. Then, the characteristic image size is  $\sim 28, 44, 57 \text{ mas}$ , respectively.

The location performance in J, H and K band vs. total exposure time

Band	Wavelength [ $\mu m$ ]	$\lambda/D$ [ $mas$ ]	Time [hours]	Time [nights]
J	1.1	28	24	3
H	1.65	44	59	7.5
K	2.2	57	100	12.5

Table 1: Observation requirements on a 8 m AO telescope

is shown in Fig. 6, respectively as solid, dashed and dash-dot curves. The horizontal lines corresponding to detection level  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  are also shown, respectively as dotted, dashed and solid thin lines. It may be noted that semi-ideal response is assumed, whereas additional degradation factors are expected; e.g., the AO performance is expected to degrade at shorter wavelength, reducing the gap between the performance curves.

Applying the same simple SNR extrapolation as above, the number of hours and full nights required on a semi-ideal AO telescope is listed in Table 1. As a baseline, K band operation is considered.

Even assuming conservatively that the longest wavelength were imposed e.g. by operation constraints, it appears that quantum vacuum effects detection at  $3\sigma$  could be attained using less than two weeks of observation.

This is not a negligible amount of time on an advanced AO telescope, but quite compatible with several current observing programs, so that it may represent the reference for a realistic observing program.

Moreover, it may be noted that the science case does not require continuous observation, but just sparse coverage of the binary orbital period at known times over a time elapse of order of a few months. Therefore, service mode observations, using fractions of nights not efficiently used by other high priority science programs, may be adopted.

**Remark:** an AO system based on laser guide star is required, since the target does not happen to be close enough to bright natural stars with sufficient frequency to ensure that the required exposure time is accumulated in a reasonable calendar time. The issue may however be further investigated.

**Remark:** the exposure time requirement for e.g. a 4 m class AO telescope grows by a factor 4, due to both resolution and photon budget, so that it remains fairly acceptable in J band, but quite demanding in K band.

## 6 Preliminary simulation of detection performance

The simulation is based on least square estimation of the rotation angle (precession) of the orbit between the beginning and end of the observation period (5 years, corresponding to about 50 *arcsec* precession. A number of experimental conditions have to be better defined for a more detailed estimate. Two cases have been considered:

- an AO equipped telescope, allowing better determination of the individual component motion;

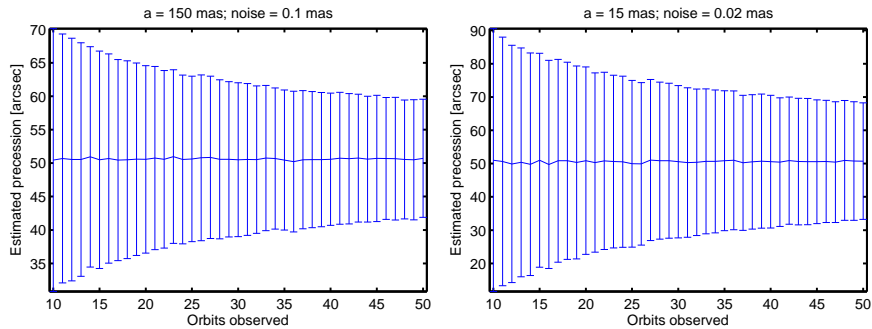


Figure 7: Detection performance of an AO telescope (left) and a conventional telescope (right)

- a conventional telescope, able only to “see” the photo-centre motion.

The main difference considered between AO equipped and conventional imaging telescopes (respectively AOT and CIT) is the assumption that the images taken in the former case, over most of the orbital period, are resolved, thus allowing direct observation of the full angular excursion associated to the orbital motion, whereas in the latter case the observed quantity, i.e. the photocentre motion, only spans a range approximately 10 times smaller.

Given the astrometric noise associated to an elementary period of observation, order of one night, we generate a set of noisy observations over a period of several orbits, and evaluate the mean and standard deviation of the estimated precession angle.

A meaningful detection is considered successfully achieved when, in a few months, i.e. few ten orbits, the standard deviation of the estimated precession is 2-3 times the average value. The assessment is qualitatively consistent with the requirement in Sec. 1.1.

As shown in Fig. 7, both an AO-equipped and a conventional telescope are able, in principle, to detect the quantum vacuum precession at the amplitude level mentioned in Hajdukovic (2013)[4]. However, in the latter case, an extremely low noise is required, which could be achievable in principle by merging the observations of many conventional telescopes over a long time.

## 7 Discussion

The preliminary assessment of astronomical quantum vacuum detection appears to provide encouraging results, in the sense that the best currently available instrumentation seems to be able, over a time frame of a few years (due to the need of cumulating the precession effects), to reach unambiguous results.

**The observing time requirement in K band is in the range of two weeks, for an 8 m telescope equipped with adaptive optics using a laser guide stars (e.g. Keck), possibly spread over several months.**

Usage of conventional ground based telescopes appears to be quite impractical.

The HST may achieve the proposed goal, but the total exposure time required seems to raise doubts on practical feasibility.

The issue requires further investigation in terms of observation improvement based on the considerations from Sec. 1.2, and the characterization of the UX25 binary system should be addressed in more detail.

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