Gravitation astrometric tests in the Solar System with JWST

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**ABSTRACT**

JWST will deliver unprecedented capabilities for high precision narrow angle astrometry, photon limited to the $\mu$as level even for comparably faint sources. It is therefore the candidate of choice for Fundamental Physics tests in the Solar system, able to set stringent constraints on the competing theories of gravitation, including General Relativity, and for the first time on effects induced by Quantum Field Theory.

The expected level of gravitational effects of Quantum Vacuum on the trans-neptunian binary system UX25 results in precession amplitude $\sim 0.23''$/orbit. The build-up of precession over 5–10 years can therefore be clearly detectable by microarcsecond astrometry used to monitor the binary orbit against reference field stars.

**JWST has the appropriate combination of sensitivity and precision for detecting it.**

We propose a long term observing campaign for monitoring the orbit of UX25 and other trans-neptunian candidates, to detect possible deviations from strict Newtonian dynamics by measuring the effective gravitational field in the external regions of the Solar system. Precision astrometry of trans-neptunians and other convenient probes provides stringent constraints on the ephemerides of the whole Solar system, i.e. on gravitation in weak field. This constrains the allowed constant values, i.e. $\gamma$ and $\beta$ in Parametrised Post-Newtonian formulation, testing e.g. $f(R)$ theories, and the acceleration constant $a_0$ in MOND.
Quantum Vacuum behaviour vs. Gravitation

"Standard model":
matter and anti-matter attract each other

Cosmological constant catastrophe! [Adler et al., 1995]
Vacuum energy not consistent with Solar System dynamics (e.g. Mercury’s precession)?

Alternative theories:
matter and anti-matter repulse each other
[matter attracts matter, A-M attracts A-M]
Suggested e.g. from CPT symmetry

Effects may be tested by astrometry
[Villata, 2011; Kaplan et al., 2014; Villata, 2015]
Polarisation of virtual pairs in Quantum Vacuum

External gravitation field attracts particle and repulses anti-particle
Separation: ~ Compton wavelength

Result: polarisation of virtual pairs
Effect similar to electromagnetic case of charge in dielectric medium

Modified effective gravitation field

Acceleration: \[ a_0 \approx 10^{-11} \text{ m/s}^2 \]

[Hajdukovic, 2014]
MOdified Newtonian Dynamics [MOND]

Alternative framework to Cosmological Concordance Model $\Lambda$-CDM, successfully interpreting e.g. the galactic rotation curves and the empirical Tully-Fisher relation without relying on dark matter halos

[Milgrom, 1983; Blanchet, 2011]

**Baryonic Tully-Fisher relation**

Characteristic acceleration constant: $a_0 \approx 1.2 \times 10^{-10}$ m/s$^2$

Limit from Solar System ephemerides: $a_0 \leq 2 \times 10^{-10}$ m/s$^2$

[Fienga, 2010]
Precision Astrometry in the Outer Solar System

Binary system as test particle:
Newtonian physics => Keplerian closed orbit
Additional interactions => orbit perturbation, in particular precession

⇒ Precession of binary orbit in external field

Orbit no longer closed
Rotation of ellipse on its plane
Periastron precession
Larger displacement of apastron

Orbit monitoring ⇔ detection of external force

Requirement: Observation against field stars over several orbits
Study case: UX25

Trans-neptunian binary system

<table>
<thead>
<tr>
<th>UX25 Mass</th>
<th>1.25x10^{20} kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>UX25 Semimajor axis</td>
<td>42.869 AU</td>
</tr>
<tr>
<td>UX25 Orbital Period</td>
<td>280.69 years</td>
</tr>
<tr>
<td>Satellite Semimajor axis</td>
<td>4770 km</td>
</tr>
<tr>
<td>Satellite Orbital Period</td>
<td>8.3094 days</td>
</tr>
<tr>
<td>Satellite Eccentricity</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Newtonian precession from the Sun:
\[
\Delta \omega_N = \frac{3\pi}{2} \left( \frac{T_P}{T_{\text{Sun}}} \right)^2 \approx 6 \text{ mas/orbit}
\]

Estimated precession from vacuum polarisation:
\[
\Delta \omega_{qv} \approx 0.23 \text{ arcsec/orbit}
\]

Cumulative effect on 5 years (~200 orbits): 46 arcsec precession

[Hajdukovic, 2014, hal-00908554]

First experimental goal of the QVADIS
[Quantum Vacuum [effects] Astrometric Detection In the Solar system] collaboration [Inst. Phys., Astroph., Cosmology (ME); INAF-OATo (I)]
Previous observations... [M. E. Brown, ApJL 2013]

Figure 1. Observations of the 2002 UX25 system with HST/HRC and Keck LGS-AO/NIRC2. The northward orientation arrow is 0.25 arcsec long, for scale. In the first column, we show the image of both 2002 UX25 and its satellite. From this image we simultaneously fit a PSF to both the primary and satellite. In the second column we show the image with the primary part of the fit subtracted. In the final column we show both components subtracted. The HST observation is from JD 2453939.98322 and is the most blended of the detections.
...and reconstructed orbit

Semi-major axis angular amplitude:  ~150 mas

System unresolved by conventional telescopes

Faint visible magnitude:
- 20 mag primary
- 22 mag secondary
Observing problem

Orbit variation over 5 years

[Gai & Vecchiato, 2014]

Challenge: reliable µas astrometry on faint objects, narrow field

Unperturbed orbit (1D)

Requirement: few µas final precision

Small field (~10-20 arcmin) to have several reference stars (e.g. from Gaia)
Observation setup

Multiple samples of orbital period

Determination of positions and velocity against field stars

Orbital fit: parameter estimate

Long term monitoring with significant cadence sampling required:

- measure time sequence of positions AND velocity
- measure shape / brightness distribution
- measure albedo / surface composition
- deduce mass distribution
- cross-check actual dynamics with high fidelity model predictions
Performance estimate on JWST

Feasible with limited observing time requirements: 20 – 40 hours/year

- Observation from visible to near infrared bands
- Photon noise, near diffraction limited imaging
- Exploit best instrument performance

Key achievements:
- First detection of Quantum Vacuum polarisation effects
- Crucial constraints on MOND and General Relativity