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DETERMINING THE ORBIT OF THE TEMPORARY EARTH SATELLITE OF ASTEROID 2024 PT5

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ABSTRACT. This study investigates the gravitational influence of the major planets and the Moon on the orbital dynamics and mechanical energy of near-Earth asteroid 2024 PT5 during its temporary capture by Earth. Discovered on 7 August 2024 by the ATLAS Sutherland survey, the asteroid transitioned onto an elliptical geocentric orbit in late September 2024 and returned to a heliocentric trajectory in mid-November 2024.

The primary objective is to determine which massive bodies of the Solar System specifically the Moon and the nearest planets facilitated the capture process, induced changes in the asteroid's total mechanical energy during the capture phase, and provided the key perturbations leading to its escape from Earth's gravitational field. High-precision geocentric ephemerides and osculating orbital elements were obtained from the JPL Horizons service. Numerical analyses of the time series for kinetic, potential, and total mechanical energy, as well as eccentricity, were performed to characterize both the capture and release phases.

Particular attention was given to the temporal correlations between the asteroid's close approaches to the Moon and to the major planets, and the corresponding variations in its orbital elements. This approach isolates the intervals during which 2024 PT5 experienced the most pronounced dynamical changes, thereby informing targeted numerical simulations. The methodology includes a detailed statement of the problem and computational procedure, including the criteria used to define the start and end of the temporary satellite phase and efforts to identify the bodies exerting the strongest gravitational influence. The results lay the groundwork for developing a general algorithm to assess the probability of capture for any near-Earth object, and to evaluate its potential hazard or scientific value for future sample-return missions. Application of these techniques promises to enhance the precision of asteroid trajectory forecasts and to support ongoing planetary defense initiatives.

Keywords: temporarily captured objects; orbital dynamics; N-body integration; IAS15; REBOUND.

АНОТАЦІЯ. Виконано дослідження гравітаційного впливу великих планет та Місяця на орбітальну динаміку та механічну енергію астероїда 2024 PT5 під час його тимчасового захоплення Землею. Виявлений 7 серпня 2024 року за допомогою огляду ATLAS Sutherland, астероїд перейшов на еліптичну геоцентричну орбіту наприкінці вересня 2024 року та повернувся на геліоцентричну траєкторію в середині листопада 2024 року. Основна мета полягає у визначенні того, які тіла Сонячної системи, зокрема Місяць та найближчі планети, сприяли процесу захоплення, викликали зміни у повній механічній енергії астероїда під час фази захоплення та створили ключові збурення, що призвели до його виходу з гравітаційного поля Землі. Високоточні геоцентричні ефемериди та оскулюючі орбітальні елементи були отримані з сервісу JPL Horizons. Чисельний аналіз часових рядів для кінетичної, потенційної та повної механічної енергії, а також ексцентриситету, був проведений для характеристики як фаз захоплення, так і фаз вивільнення.

Особливу увагу було приділено часовим кореляціям між близькими зближеннями астероїда з Місяцем та великими планетами, а також відповідним змінам його орбітальних елементів. Цей підхід виокремлює інтервали часу, протягом яких 2024 PT5 зазнавав найбільш виражених динамічних змін, тим самим надаючи інформацію для цілеспрямованих числових моделювань.

Методологія включає детальне формулювання проблеми та обчислювальної процедури, зокрема критерії, що використовуються для визначення початку та кінця тимчасового захоплення супутника, та зусилля щодо ідентифікації тіл, що чинять найсильніший гравітаційний вплив.

Результати закладають основу для розробки загального алгоритму оцінки ймовірності захоплення будь-якого навколоземного об'єкта, а також для оцінки його потенційної небезпеки або наукової цінності для майбутніх місій з повернення зразків. Застосування цих методів обіцяє підвищити точність прогнозів траєкторії астероїдів та підтримати поточні ініціативи планетарної оборони.

Ключові слова: тимчасово захоплені об'єкти, орбітальна динаміка, інтеграція N-тіл, IAS15, REBOUND.

1. Introduction

Small bodies temporarily captured by Earth (so-called temporary satellites, TCOs — temporarily captured objects) are of scientific interest both in planetary dynamics and in applied problems — ranging from developing detection methods to assessing potential risks and mission planning. The analysis of temporary capture phases provides unique data on the interaction of a low-mass body with the multi-body Earth–Moon–planet system and allows for evaluating the contribution of individual bodies to changes in orbit and energy. In this work, we reconstruct the geocentric trajectory of asteroid 2024 PT5 and analyze its energetic characteristics during the period when the object behaved as a temporary satellite of Earth. The main objectives of the study are: (I) to determine the onset and termination of the capture phase, (II) to investigate changes in orbital elements and specific mechanical energy, and (III) to evaluate the contribution of the Moon and other bodies to the dynamics and energetics of the object.

2. Methodology

2.1. Data sources

Initial state vectors and orbital elements were obtained from the JPL Horizons service (JPL/NASA).

2.2.Construction of the dynamical model

For numerical integration we used the open-source N-body code REBOUND with the adaptive, high-accuracy integrator IAS15 (the integrator tolerance in this work was set to 10^{-9}). The model includes the Sun, the major planets, the Moon, and the asteroid itself. All initial vectors (positions and velocities) were brought to a common epoch (the start of the integration interval) and used as heliocentric input conditions.

2.3.Integration period and output grid

Integration was performed over the interval 25 September 2024 — 30 November 2024 with an output cadence of 1 day; all data were obtained at 00:00 UTC for each date (resolution can be increased for local events if required).

2.4.Energy calculations and capture criteria

Specific kinetic energy: T (km^2/s^2);
Specific potential energy relative to Earth: U (km^2/s^2);
Specific total mechanical energy (geocentric): E=T-U;
Criteria for temporary capture:
Geocentric eccentricity $e < 1$.
Specific energy $E < 0$.
Both criteria were used in parallel to check for consistency.

2.5.Sensitivity — assessment of the Moon's contribution

To evaluate the contribution of individual bodies, a series of control integrations was performed: in each experiment the mass of one body was set to zero while the initial positions and velocities of all bodies were preserved. Comparison of time series of orbital elements and E(t) between the base model and the variations allows isolating the influence of a specific body. For further statistical analysis we computed the difference series dE(t) and the correlation coefficients between distances r(t) and E(t).

2.6.Data processing and numerical details

All calculations were implemented in Python using the numpy, pandas, matplotlib and scipy libraries. Central-difference methods were applied for smoothing and differentiating the energy time series.

3. Results

3.1.Main time boundaries and capture duration

Based on the analysis of E(t) and geocentric eccentricity, it was determined that the transition into the captured state occurred on 29 September 2024 (the moment when E crossed zero), and the end of the capture phase took place on 25 November 2024. The duration of the temporary satellite phase was approximately 57 days.

Table 1: E(t) e(t)

Date (UTC)	**E, km^2/s^2($\pm 2 \times 10^{-9}$)**	**e ($\pm 10^{-9}$)**
2024-09-28	0.01023	1.0361500465
2024-09-29	0.00456	1.0160313087
2024-09-30	-0.00092	0.9967642306
2024-10-01	-0.00619	0.9782629997
...	...	...
2024-11-24	-0.00903	0.9581747075
2024-11-25	-0.00365	0.9830847857
2024-11-26	0.00197	1.0091820203
2024-11-27	0.00782	1.0369552086

3.2.Orbital elements and trajectory

The time series of geocentric orbital elements shows a decrease in eccentricity at the end of September,

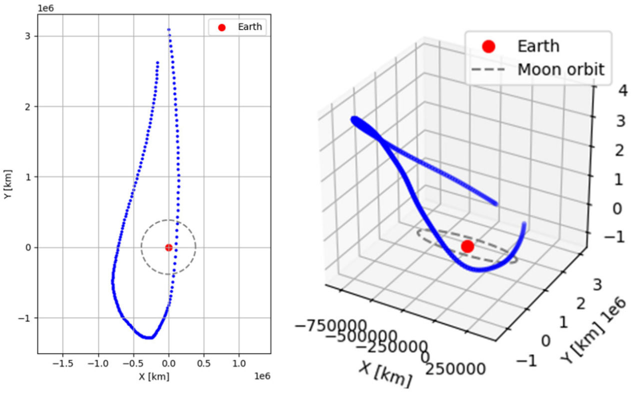

Figure 1: Complete geocentric orbit of asteroid 2024 PT5 for the interval 27 June 2024 – 31 January 2025. (Left): projection of the orbit onto the X–Y plane with the geocentric orbit of the Moon (dashed line) and the position of the Earth (red dot) indicated. (Right): three-dimensional view of the trajectory.

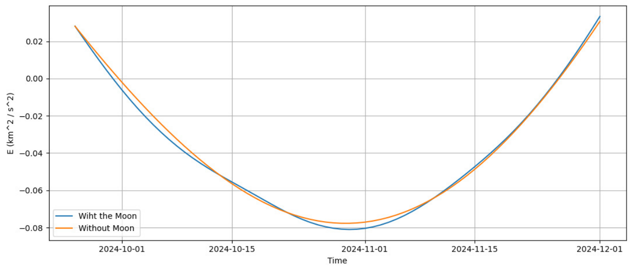

Figure 2: The specific energy of the asteroid and the specific energy of the asteroid without accounting for the influence of the Moon during the period from 2024-09-25 to 2024-11-30.

followed by a return to higher absolute values toward the end of November. The period during which e < 1 correlated with the interval E < 0. The trajectory in geocentric coordinates has a horseshoe-like shape during the capture phase.

3.3.Role of the Moon and other bodies

The analysis of the "without Moon" integration series showed local deviations of $dE(t) = 4.729 \times 10^{-3}$ $km^2 s^2$ compared to the base model. Correlation analysis revealed a strong correlation between the asteroid–Moon distance and energy variations; the absolute value of the correlation coefficient was approximately 0.95, while for other bodies it was less than 0.1.

4. Discussion

The results indicate that short-term fluctuations in the total mechanical energy of the asteroid relative to Earth are mainly determined by local gravitational in-

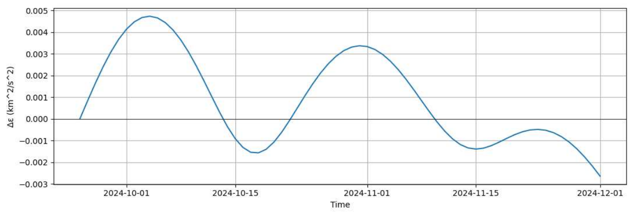

Figure 3: The difference in energy (model without the Moon minus model with the Moon).

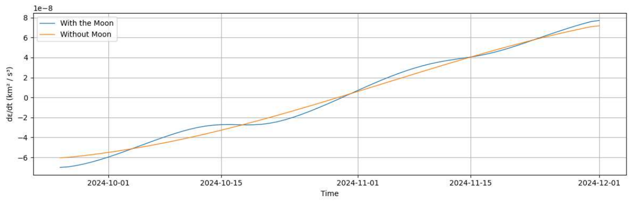

Figure 4: Energy variation over time (with the Moon and without the Moon).

fluences, among which the Moon plays the dominant role. The weak contribution of other planets within the considered interval is explained by their large distances and less favorable configurations for momentum transfer to the asteroid. The results of the "mass=0" test series confirm that the local asymmetry of the E(t) curve is caused by gravitational "impulses" from the Moon during close approaches.

It is important to note the sources of error and limitations:

Uncertainty in the asteroid's initial mass and internal parameters (in this work it was treated as a test particle).

Errors in initial vectors (influence of observational and interpolation errors from Horizons).

Neglect of minor non-gravitational effects (e.g., Yarkovsky), which are insignificant for short-term evolution but may affect long-term behavior.

Proposed improvements for future studies include refining GM values based on SPICE/NAIF data, performing ensemble integrations to assess sensitivity to initial condition uncertainties, and, if necessary, accounting for non-gravitational forces for longer integrations.

5. Conclusion

It was established that asteroid 2024 PT5 entered a temporary capture state on 29 September 2024 and remained in it for about 57 days, until 25 November 2024.

Analysis of the orbital elements and energy confirms the phase transition: entry into the state with $e < 1$ and $E < 0$ at the end of September and exit from it at the end of November.

The series of control integrations showed that the Moon provides the most significant contribution to local deviations of the energy curve; the correlation between the asteroid–Moon distance and E was approximately 0.95.

The applied methodology (JPL Horizons → REBOUND (IAS15) → series of mass-zero runs) is effective for assessing the influence of individual bodies on the orbit of a low-mass object and can be used for further studies of other temporary satellites.

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