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ABOUT THE POSSIBLE RELATIONSHIP BETWEEN LONG-PERIOD COMETS AND TRANSNEPTUNIAN OBJECTS.1

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ABSTRACT

This paper investigates dynamical links between long-period comets (LPCs) and large trans-Neptunian objects (TNOs). Using updated catalogs (1495 LPCs with aphelion > 30 au and 37 bright TNOs with $H < 4.1$), we apply three complementary methods: (i) a statistical test of LPC orbital nodes relative to each TNO's orbital plane, (ii) counting of minimum orbit intersection distance (MOID) events, and (iii) backward numerical integrations. The nodal-plane analysis reveals a highly significant clustering of 53 comet passages near the orbit of TNO 2003 VS_2 and a weaker signal for 2010 KZ_{39}. The MOID statistics confirm that 2003 VS_2 exhibits an excess of encounters (19 comets within 0.1 au), while Salacia and 2010 KZ_{39} show more modest excesses. Orbital integrations of 31 candidate LPCs and the three selected TNOs indicate that comet C/1969 P1 likely passed ~ 0.05–0.20 au from 2003 VS_2 (circa 1951), while C/1937 D1 and C/2024 V2 passed ~ 0.15–0.30 au from Salacia. These results are consistent with earlier suggestions of an LPC–TNO association, implying that the largest Kuiper belt bodies may influence the orbital distribution of distant comets. Other possible relationships between these two populations cannot be excluded and should be investigated using more comprehensive datasets in future studies.

Key words: TNO - long-period comets – interrelation - orbit elements

1 INTRODUCTION

The study of comets and their dynamical evolution provides critical insights into the primordial conditions and ongoing processes that have shaped the Solar System. As relics of its early formation, long-period comets carry relatively unaltered material from the protoplanetary disk, allowing us to probe its chemical and physical properties. Likewise, trans-Neptunian objects (TNOs) occupy the distant, dynamically cold reservoir beyond Neptune, preserving records of planetary migration and resonance interactions.

By combining analyses of cometary trajectories and TNO orbital architectures, it is possible to reconstruct the dynamical history of the Solar System and to constrain models of its long-term stability. Such integrated investigations are essential for a comprehensive understanding of both local small-body populations and the broader mechanisms governing planetary system evolution.

The statistical aspects of a possible connection between long-period comets and trans-Neptunian objects have been addressed in several studies (Guliyev & Guliyev 2012; Guliyev & Nabiyev 2014; Guliyev & Guliyev 2017). The potential for a dynamical, kinematical, and possibly genetic relationship between these two populations of Solar System bodies has a number of underlying premises. It is known that a subset of long-period comets — judging by their minimum orbit intersection distance (MOID) values and distant nodes — tends to cluster near the orbits of the giant planets (Guliyev & Guliyev 2020). When the methods used to reveal these trends are applied to Kuiper belt objects, the resulting calculations often display similarly noteworthy patterns. This represents the principal conclusion of the aforementioned studies.

However, when analyzing such results for trans-Neptunian objects and long-period comets, any stochastic components must be examined with the utmost rigor, since at first glance such a connection appears highly improbable, if not impossible. Positive statistical findings should therefore be cross-validated using multiple independent approaches. Furthermore, these statistical results ought to be corroborated by numerical calculations of cometary and planetary orbital evolution.

In the search for dynamical interactions, primary focus should

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be directed towards the largest trans-Neptunian bodies. However, if the underlying mechanisms are of a different nature — such as collisional, tidal, or various eruptive processes — then other, purely physical characteristics of these objects may become paramount.

2 PRIMARY OBJECTIVE OF THE PRESENT WORK

Since the publication of the aforementioned studies on a possible connection between trans-Neptunian objects (TNOs) and long-period comets, the catalogs of these two populations have expanded substantially. Consequently, reassessing the results reported in those studies may prove critically important. Moreover, the modeling and statistical methods employed in those works, in the view of the authors, require refinement.

However, such refinement is not the sole objective of the present study. We contend that the findings derived from analyses of the distant nodes of cometary orbits must be independently validated using minimum orbit intersection distance (MOID) calculations. Should these two methodologies yield consistent results, it will then be necessary to undertake detailed investigations of cometary orbital evolution, incorporating the orbital parameters of the relevant TNOs.

We also acknowledge that expectations of identifying close encounters between comets and TNOs — either in the recent past or in the near future — may not always be fulfilled. Such limitations arise not only from temporal constraints but also from the accuracy of the orbital elements available for objects in both populations, which can significantly affect the results.

Despite these challenges, we revisit and rigorously examine the question of a possible dynamical linkage between long-period comets and the largest TNOs. This re-evaluation constitutes the principal aim of the present work.

The present study comprises three stages of computation. In the first stage, the distant nodes of cometary orbits are examined with respect to the planes of motion of the trans-Neptunian objects (TNOs). In the second stage, a minimum orbit intersection distance (MOID) analysis of the cometary orbits relative to Kuiper belt objects is carried out. Finally, in the third stage, orbital evolution simulations are performed for the comets, taking into account the most relevant TNO parameters for this investigation.

3 THE DATA USED

In previous studies (Guliyev & Guliyev 2012; Guliyev & Nabiyev 2014; Guliyev & Guliyev 2017), the number of comets employed in the calculations ranged from 1 040 to 1 190. Those works also incorporated orbital parameters for up to 92 trans-Neptunian objects (TNOs) with absolute magnitudes not exceeding $H \leqslant 5.5$ mag.

In the present study, we use a more extensive sample of 1 495 long-period comets observed prior to early 2025, whose aphelion distances exceed 30 au. Low-perihelion comets are excluded, and for any comet that has undergone fragmentation, the orbital elements of its largest component (designated "A") are adopted. Such selection criteria minimize the risk of spurious correlations and enhance the robustness of the results within the scope of our objectives.

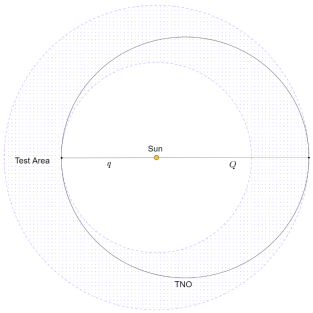

Figure 1. Schematic representation of the testing area for a representative TNO orbit.

For the TNO sample, we initially impose a stricter upper limit on absolute magnitude of $H \leqslant 4.1$ mag, yielding 37 objects observed through 2025. Their orbital data are retrieved from the JPL Small-Body Database[1]. Cometary orbital elements are sourced from the Marsden (2007) catalog and relevant issues of the Minor Planet Electronic Circulars (MPEC)[2] archive, covering the period 2007–2025.

4 FEATURES OF THE DISTRIBUTION OF COMETARY ORBITAL NODES RELATIVE TO THE PLANE OF TNOS

The methodology and computational scheme in this part of the study closely follow those described in Guliyev & Guliyev (2012) and Guliyev & Nabiyev (2014). The number of cometary passages within the orbital zone of a selected trans-Neptunian object (TNO) is compared with that obtained for 205 simulated ("dummy") zones (67 in the cited works), which differ from the actual zone only in their fundamental plane parameters — the longitude of ascending node Ω_p and the inclination i_p.

In all cases, comet–TNO intersections are analyzed strictly within the heliocentric distance interval $[q, Q]$, corresponding to the perihelion and aphelion distances of the selected TNO (see Fig. 1). In contrast, earlier studies allowed a contraction of this interval in order to optimize the statistics of intersections. Specifically, Ω_p is varied from 0° to 330° in 15° increments (previously 30°), and i_p from 0° to 90° in such a way that the poles of the corresponding planes are equally spaced on the celestial sphere. This equal-spacing condition is achieved by dividing the interval into equal parts of $\cos i$. Note that the reference plane (for each zone, including dummy ones) is not the ecliptic, but the orbital plane

[1] https://ssd.jpl.nasa.gov/sb/orbits.html
[2] https://projectpluto.com/mpecs.htm

of the TNO itself, with its ascending node taken as the zero point.

For each TNO (real or dummy), we compute:

- N — the number of cometary passages within its q–Q zone;
- $\bar{n}$ — the mean number of passages across the 205 dummy zones;
- σ — the standard deviation of those 205 counts;
- t — the normalized difference, $t = (N - \bar{n})/\sigma$;
- α — the one-sided confidence level associated with t.

The reliability of t and α is assessed using a one-sample Student's t-test. Values exceeding $t = 1.67$ (corresponding to $\alpha = 0.95$) indicate statistical significance at the 5% level.

As an independent test of the method, we apply it to a fictitious TNO defined by

$$q = 30\,\text{au}, \quad Q = 40\,\text{au}, \quad \Omega_p = 100^\circ, \quad i_p = 20^\circ$$

using the same comet dataset. The results are:

$$N = 76, \quad \bar{n} = 70.07, \quad \sigma = 8.08, \quad t = 0.73, \quad \alpha \ll 0.95$$

At this stage, one might argue that, owing to the moderate eccentricity of the orbit, the "width" of the tested region — only 10 au — is too narrow. However, if we increase the aphelion distance to 50 or 60 au, the resulting t-values become 0.37 and 0.43, respectively.

Thus, for the simulated TNO, the criterion is not met, confirming that the procedure does not produce false positives under these conditions.

If any apparent correlation between a TNO and long-period comets is purely coincidental and lacks a physical basis, we would consistently obtain t-values below the critical threshold in all cases.

However, when the test was applied to the 37 selected trans-Neptunian objects, one body exhibited highly significant results. This object, designated 2003 VS_2, has the following orbital parameters used in the base calculations:

$$q = 36.46\,\text{au}, \quad Q = 42.98\,\text{au}, \quad \Omega_p = 302.77^\circ, \quad i_p = 14.77^\circ$$

The specific outcomes for 2003 VS_2 are:

$$N = 53, \quad \bar{n} = 37.06, \quad \sigma = 5.87, \quad t = 2.72, \quad \alpha = 0.996$$

The positive result of the applied test is likewise apparent for the TNO 2010 KZ_{39}, whose statistical parameters are:

$$N = 33, \quad \bar{n} = 23.45, \quad \sigma = 4.79, \quad t = 1.99, \quad \alpha = 0.976$$

If the lower bound for the confidence parameter α is relaxed to 0.90, then Salacia and 2018 VG_{18} also emerge as noteworthy, with α-values of 0.90 and 0.93, respectively.

The proposed testing scheme was also applied to the hypothetical planet advocated by Guliyev (2019). The calculations indicate that a planet with parameters $\Omega_p = 271.7^\circ$, $i_p = 86.2^\circ$, within the semi-major axis range 268–378 au, would yield a value of N exceeding $\bar{n}$ with a confidence level of 0.98.

While periodic application of this methodology to other planetary hypotheses — such as those proposed by Batygin & Brown (2016b) — is scientifically justified, such investigations extend beyond the scope of this study.

In summary, the quantitative results obtained for the trans-Neptunian objects (TNOs) considered herein — particularly for 2003 VS_2 — provide sufficient justification for undertaking more detailed analyses within the framework of the stated objective.

5 MOID ANALYSIS IN THE CONTEXT OF THE RELATIONSHIP BETWEEN TNOS AND LPCS

Within the framework of the present investigation into the relationship between trans-Neptunian objects (TNOs) and long-period comets (LPCs), the MOID analysis represents a more precise method. Accordingly, in the second phase of the study, MOID values were computed for 1 495 comets with respect to 37 selected planetary bodies, yielding a total of 55 315 individual calculations. As regards the computational approaches used to determine the MOID, we employed the numerical method of Wiśniowski & Rickman (2013) and the "classical" method of Gronchi (2005). The former is applied to elliptical orbits (including comets with extreme eccentricities, $e \approx 0.99$), whereas the latter is used for nearly parabolic ($e = 1.0$) and hyperbolic ($e > 1$) cometary orbits.As the limiting distances in our analysis for each TNO, we adopted the radii of the sphere of influence (Abalakin 1977), which are determined from the relation

$$h = a \left(\frac{m_{\text{pl}}}{M_{\text{S}}} \right)^{2/5} \tag{1}$$

where a is the semi-major axis of the planet's orbit, m_{pl} is its mass, and M_{S} is the mass of the Sun.

When conducting the MOID analysis in the context of our investigation, it is difficult to rely on the parameter r (gravitational sphere) for planetary bodies, since their masses are known with insufficient precision. The same uncertainty applies to the orbital elements of long-period comets.

Quantitative estimates demonstrate that a trans-Neptunian object with a mass of 10^{20}–10^{21} kg at a heliocentric distance of 40 au has a sphere of influence ranging from approximately 0.003 to 0.008 au. Nevertheless, we restrict ourselves to analyzing only the aggregate MOID values for various choices of the parameter r.

The final results of this analysis are compiled in Table 1.

Applying statistical criteria to ascertain the degree of randomness in the data of Table 1 proves methodologically challenging. However, an analysis of the distribution $r(N)$ nonetheless underscores the relevance of the present investigation. It emerges that close and minimal-distance encounters between long-period comets and trans-Neptunian objects are, in fact, rather common. Meanwhile, within the broader field of Solar System small-body research, this issue has not yet received sufficient attention.

As anticipated from prior analyses, 2003 VS_2 dominates the statistics: it exhibits the highest frequency of MOID val-

Table 1. Number of MOID values for 1 495 comets and 37 TNOs at different r

r [au]	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
N	3	5	6	9	12	17	17	18	18
r [au]	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
N	19	45	75	97	121	146	175	198	219
r [au]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
N	235	513	767	1047	1316	1562	1820	2073	2318

ues across all thresholds of r, significantly outperforming the other 36 TNOs.

Table 2 shows the number of MOID values for long-period comets relative to 2003 VS_2 at r up to 0.1 au.

At the upper limit $r = 0.10$ au, the number of MOID values among the 37 trans-Neptunian objects ranges from 2 to 19. In particular, for 2003 VS_2 the outcomes are:

$$N = 19, \quad \bar{n} = 6.35, \quad \sigma = 3.85, \quad t = 3.28, \quad \alpha = 0.999$$

The next TNO exhibiting a notable excess of small MOID values is Salacia. Across the interval $r = 0.10$ au, the count of comet–Salacia MOID pairs ranges from 1 to 13. At the upper limit, its statistics are:

$$N = 13, \quad \bar{n} = 6.35, \quad \sigma = 3.85, \quad t = 1.72, \quad \alpha = 0.953$$

Table 2 presents the number of MOID values for long-period comets relative to 2003 VS_2 for different values of r up to 0.1 au.

6 PRELIMINARY ORBITAL EVOLUTION ANALYSIS OF THREE TNOS AND 31 LPCS

This section presents backward integrations of the orbits of the selected comets, including three trans-Neptunian comets, over a 10,000-year interval. The goal of these computations is to identify Actual close encounters between the two categories of small bodies are considered. Comets were selected using a MOID threshold of $\leqslant$ 0.1 au; the resulting sample of 31 objects is listed in Table 3.

In the course of our dynamical study of comets, we deliberately excluded certain bodies — in particular, historical comets such as C/1880 G1, whose last recorded observations date back more than a century, as well as objects for which the observational arc is demonstrably insufficient or lacking reported uncertainties ("sigmas"), which makes it impractical for the proper construction of orbital clones.

Although these objects satisfy our selection by the MOID criterion, their uncertainties are too large to permit reliable dynamical modelling. As the basis for our simulations, we adopted a heliocentric model of the Solar System including the four Jovian planets and the three trans-Neptunian objects (TNOs) under consideration. For numerical integration, we employed the Bulirsch–Stoer algorithm as implemented in the MERCURY N-body simulations package (Chambers 1999). To account for the uncertainties in the cometary orbits and to ensure the robustness of the results, we generated a swarm of virtual orbits (1000 so-called clones) for each massless test particle.

To generate a set of orbital "clones" for each nominal Cartesian state vector (X, Y, Z, V_X, V_Y, V_Z), we proceeded as follows:

(i) We denote the nominal state vector by

$$\mathbf{x}_0 = [X_0,\, Y_0,\, Z_0,\, V_{X,0},\, V_{Y,0},\, V_{Z,0}]^{\mathrm{T}},$$

and the one-sigma uncertainties for each component by

$$\boldsymbol{\sigma} = [\sigma_X,\, \sigma_Y,\, \sigma_Z,\, \sigma_{V_X},\, \sigma_{V_Y},\, \sigma_{V_Z}]^{\mathrm{T}}.$$

(ii) We assume that the six components are uncorrelated, so that the covariance matrix is diagonal:

$$\mathbf{C} = \mathrm{diag}(\sigma_X^2,\, \sigma_Y^2,\, \sigma_Z^2,\, \sigma_{V_X}^2,\, \sigma_{V_Y}^2,\, \sigma_{V_Z}^2).$$

(iii) Each $\mathbf{x}_k$ is drawn from the multivariate normal distribution

$$\mathbf{x}_k \sim \mathcal{N}(\mathbf{x}_0,\, \mathbf{C}),$$

which, under the diagonal-covariance assumption, is equivalent to sampling each component independently:

$$X_k \sim \mathcal{N}(X_0,\, \sigma_X^2), \quad \ldots \quad V_{Z,k} \sim \mathcal{N}(V_{Z,0},\, \sigma_{V_Z}^2).$$

(i) Each sampled vector $\mathbf{x}_k$ thus represents one "clone" of the original orbit, preserving the prescribed one-sigma uncertainties in each Cartesian component.

This procedure yields a statistically representative ensemble of clones around the nominal state, suitable for Monte Carlo propagation under the assumption of independent Gaussian errors.

As a result of the integrations, we indeed identified several relatively close approaches between comets and TNOs. Of particular interest is comet C/1969 P1, which, with high probability, approached the object 2003 VS_2 in 1951 at a distance of approximately 0.05–0.20 au. We also recorded two moderate encounters with Salacia — specifically involving comets C/1937 D1 and C/2024 V2 — at distances of $\approx$ 0.15–0.35 au.

Naturally, the orbital uncertainties of the TNOs themselves and the limitations of the numerical methods must be taken into account before drawing firm conclusions.

Nevertheless, the calculations demonstrate that close encounters between long-period comets and TNOs are plausible.

7 DISCUSSION

Our analysis indicates a statistically robust association between certain long-period comets and trans-Neptunian objects. In particular, 2003 VS_2 stands out: both the nodal-plane test ($N = 53$ comet passages, $t = 2.72$, confidence

Table 2. Number of LPC–2003 VS_2 pairs with MOID $\leqslant 0.1$ au

r [au]	0.006	0.007	0.008	0.009	0.01	0.02	0.03
N	1	1	1	1	2	4	5
r [au]	0.04	0.05	0.06	0.07	0.08	0.09	0.1
N	9	10	13	16	18	18	19

Table 3. List of integrated comets and transneptunian objects

Comet	MOID [au]	Comet	MOID [au]	Comet	MOID [au]
C/2002 J4	5.08×10^{-2}	C/1984 U1	1.16×10^{-2}	C/2005 G1	5.64×10^{-5}
C/2015 Y1	5.53×10^{-3}	C/2019 T3	2.19×10^{-2}	C/2006 A2	2.28×10^{-4}
C/2021 V1	9.79×10^{-3}	C/1942 C1	2.44×10^{-2}	C/2020 J1	3.15×10^{-2}
C/1997 P2	1.14×10^{-2}	C/1937 D1	4.07×10^{-2}	C/2004 P1	3.35×10^{-2}
C/2014 M3	2.41×10^{-2}	C/2021 A4	4.15×10^{-2}	C/2011 O1	3.38×10^{-2}
C/2010 H1	0.03280725	C/1992 B1	0.060198	C/2020 M5	4.67×10^{-2}
C/1906 E1	3.40×10^{-2}	C/2004 L1	6.52×10^{-2}	C/1981 H1	5.09×10^{-2}
C/1999 K4	0.03864269	C/1994 T1	7.46×10^{-2}	C/2021 D2	5.37×10^{-2}
C/2007 W1	4.09×10^{-2}	C/1996 J1-A	8.66×10^{-2}	C/1945 L1	0.065135
C/1998 T1	6.41×10^{-2}	C/1909 L1	8.91×10^{-2}		
C/2011 Q3	0.0643297	C/2024 V2	9.52×10^{-2}		
C/1969 P1	0.06669534	C/2024 V2	9.52×10^{-2}		
C/2019 K4	7.07×10^{-2}	C/2024 V2	9.52×10^{-2}		
C/1998 K2	7.34×10^{-2}				

99.6%) and the MOID count (19 comets within 0.1 au, $t = 3.28$, confidence 99.9%) show a highly significant clustering of LPC orbits near 2003 VS_2's orbital path.

We also detect weaker but notable signals for 2010 KZ_{39} and Salacia ($t \approx 2.0$), suggesting these bodies may similarly influence or align with the LPC population.

Importantly, our findings qualitatively confirm and extend earlier studies by Guliyev and colleagues. For example, Guliyev & Nabiyev (2014) and related works reported non-random clustering of LPC orbital elements near the orbits of large Kuiper-belt objects. The present, much larger dataset isolates 2003 VS_2 as the dominant case, providing stronger evidence that the long-standing hypothesis of an LPC–TNO connection has merit.

We note that obtaining $t > 2$ for two of 37 tested TNOs is well beyond the 5% significance threshold, making random coincidence highly unlikely.

If these statistical correlations reflect a physical connection, what mechanism could underlie them?

The large TNOs identified (2003 VS_2, 2010 KZ_{39}, Salacia) are massive ($\sim 10^{20}$–10^{21} kg) but still much smaller than planets. Their instantaneous action spheres at ~ 40 au are only a few thousand km in radius (~ 0.003–0.008 au), far smaller than the observed encounter distances (e.g. ~ 0.05–0.20 au for C/1969 P1–VS_2).

Notably, we found a few even closer encounters down to ≈ 0.005 au — formally within the estimated influence sphere of the TNO — but these are isolated cases amid several hundred recorded approaches and should be regarded as singular outliers, especially in light of the uncertainties in the orbital elements. Thus, a single "flyby" would impart only a minor impulse.

Instead, these alignments may stem from shared dynamical history. For example, recent models suggest the Oort cloud initially contained a flattened disk-like component of comets originating near the giant planets, possibly retaining a memory of its primordial plane (see, e.g., Zwart (2021), Fouchard (2019), Nesvorný (2024)).

Likewise, secular or resonant perturbations in the early Solar System might have preferentially placed comets into orbital planes near those of large TNOs. The very high t-values for 2003 VS_2 and 2010 KZ_{39} indicate that random chance is unlikely, pointing to an underlying cause beyond statistical fluctuation.

Collisions among TNOs could also contribute. The Haumea collisional family in the Kuiper belt demonstrates that giant impacts can shatter large bodies, creating swarms of fragments (Brown 2007; Leinhardt & Stewart 2010; Carry 2012). If 2003 VS_2 or Salacia experienced such an event, debris could be injected onto nearly parabolic orbits and later appear as LPCs.

To date, no definitive "comet family" linked to 2003 VS_2 is known, but compositional similarities between some comets and TNOs might hint at a common origin. In any case, a collisional debris cloud would initially be planar, so fragments sharing 2003 VS_2's orbital plane could produce the observed clustering. Thus, while direct gravitational scattering by these TNOs is weak, collisional or collective dynamical effects in the Kuiper belt cannot be ruled out.

Our backward integrations provide further context. We generated 1000 clones for each of the 31 candidate comets and integrated them with the four giant planets and the three selected TNOs. Several relatively close approaches emerged. Notably, comet C/1969 P1 likely passed within ~ 0.05–0.20 au of 2003 VS_2 around 1951.

We also observed moderately close approaches to Salacia: comets C/1937 D1 and C/2024 V2 approached within ~ 0.15–0.35 au during their respective perihelion passages. While these distances remain larger than the TNOs' Hill spheres, they demonstrate that LPC and TNO orbits can indeed come into proximity.We stress that the clones carry orbital uncertainties (older comets and some TNOs have imprecise elements), so exact distances are uncertain, but the occurrence of such near-encounters lends credence to the statistical associations.

As with any statistical study, selection effects and uncer-

tainties warrant discussion. Our LPC sample excludes objects with very short observation arcs or known fragmentation, and our 37 TNOs are limited to the brightest ($H < 4.1$) to avoid spurious hits. Nevertheless, the orbital elements of some TNOs carry large uncertainties, and a few comets have poorly constrained orbits. We have attempted to mitigate these biases: for instance, a simulated "dummy" TNO produced no signal ($t = 0.73$) under the same nodal test, and the MOID results are qualitatively similar across reasonable encounter radii.

In particular, 2003 VS_2's excess encounters persist even at smaller radii (Table 2), always significantly above the mean. These consistency checks increase our confidence that the patterns for 2003 VS_2 (and to a lesser extent Salacia and 2010 KZ_{39}) are not artifacts of data selection or method.

Comparing with other research on outer Solar System dynamics, our findings fit a broader pattern: massive TNOs can shepherd smaller bodies. For example, Muñoz-Gutiérrez et al. (2025) showed that Pluto (the largest TNO) significantly affects the evolution of Neptune-resonant Kuiper belt objects. By analogy, a mid-sized dwarf planet like 2003 VS_2 ($\sim$ 520 km diameter) could exert a subtler influence on the comet population.

2003 VS_2 occupies an intermediate mass regime — not as dominant as Pluto but large enough to leave statistical traces — and our results suggest it does impact the LPC flux. While we did not directly test hypothetical distant planets (e.g. a "Planet Nine"), the methods used here could be extended to evaluate such scenarios in future work.

Looking forward, these results open new avenues for exploration. If large Kuiper belt bodies influence the delivery or perturbation of Oort-cloud comets, then models of comet flux and Solar System evolution will need revision. Upcoming surveys (e.g. the Vera Rubin Observatory's LSST) will greatly expand the LPC catalog, enhancing the statistical power of these tests. Likewise, continued searches and orbit refinement for distant TNOs may reveal additional massive bodies whose orbital planes correlate with comets.

Detailed N-body simulations including all known TNOs and planets should be performed to attempt to reproduce the observed associations. For now, our study provides the most extensive statistical evidence to date that some LPC orbital elements are not randomly distributed with respect to the orbits of the largest trans-Neptunian objects, hinting at a subtle interplay between these distant populations.

8 CONCLUSION

In summary, our analysis of 1,495 long-period comets and 37 large trans-Neptunian objects reveals statistically significant correlations. Both the nodal-plane test and the MOID encounter statistics identify 2003 VS_2 as having an anomalously high number of comet interactions, well above random expectation. Salacia and 2010 KZ_{39} also show moderate excesses.

Our numerical integrations further suggest that these comets did indeed have relatively close approaches to their respective TNOs (e.g. C/1969 P1 with 2003 VS_2), lending dynamical support to the statistical findings. These results corroborate and extend earlier proposals of an LPC–TNO association.

These findings have important implications. If the largest Kuiper belt bodies influence the orbits of some Oort-cloud comets, models of comet delivery and Solar System evolution may need revision. Possible mechanisms could include collisional fragmentation of TNOs that produces cometary fragments, or long-range perturbations via resonances aligned with the planes of these TNOs.

Distinguishing among these scenarios will require additional study. In light of these results, our analyses provide substantial statistical evidence that the orbital distributions of long-period comets correlate with several major trans-Neptunian objects, motivating targeted dynamical and observational follow-ups to clarify the causal mechanisms.

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