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Probabilistic evolution of pairs of trans-Neptunian objects in close orbits

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Abstract. We have studied the probabilistic evolution of four candidates for young pairs of trans-Neptunian objects: 2003 QL_{91} – 2015 VA_{173}, 1999 HV_{11} – 2015 VF_{172}, 2002 CY_{154} – 2005 EW_{318} and 2013 SD_{101} – 2015 VY_{170} over 10 Myr in the past. All pairs belong to cold Classical Kuiper Belt objects. We concluded that the age of the considered pairs exceeds 10 Myr.

Keywords. Celestial mechanics, methods: numerical, Kuiper Belt.

1. Introduction

Apart from Pluto and Charon, the first trans-Neptunian object (TNOs) was found in 1992. Although many TNOs were found on quite elliptic orbits, some of them had roughly circular orbits on a plane near the ecliptic (or the invariant solar system plane), today about 3 500 objects have been recognized and indexed. The distribution of the orbits of asteroids in the Solar system is the result of various processes that affect for a long time.

A candidate collisional family in the outer Solar system was proposed by Chiang (2002). The first asteroid family identified in the outer Solar system was the one associated with dwarf planet Haumea (Brown et al. 2007). The subject of finding collisional families of trans-Neptunian objects has been studied by Chiang et al. (2003) and Marcus et al. (2011). de la Fuente Marcos & de la Fuente Marcos (2018) perform a systematic search for statistically significant pairs and groups of dynamically correlated objects through those with a semi-major axis greater than 25 au, applying a technique that uses the angular separations of orbital poles and perihelia together with the differences in time of perihelion passage to single out pairs of relevant objects from which groupings can eventually be uncovered. They confirm the reality of the candidate collisional family of TNOs associated with the pair 2000 FC_8 – 2000 GX_{146} and initially proposed by Chiang (2002). They find four new possible collisional families of TNOs associated with the pairs (134860) 2000 OJ_{67} – 2001 UP_{18}, 2003 UT_{291} – 2004 VB_{131}, 2002 CU_{154} – 2005 CE_{81} and 2003 HF_{57} – 2013 GG_{137}. They find several unbound TNOs that may have a common origin, the most significant ones are (135571) 2002 GG_{32} – (160148) 2001 KV_{76} and 2005 GX_{206} – 2015 BD_{519}.

Kuznetsov et al. (2021) performed a search for statistically significant pairs and groups of dynamically correlated objects through those with a semi-major axis greater than 30 au, applying a novel technique that uses Kholshevnikov metrics (Kholshevnikov et al. 2016, 2020) in the space of Keplerian orbits. Found 27 pairs of TNOs in close orbits, 22 pairs in which one of the TNO is binary, and 11 pairs of binary trans-Neptunian objects. All pairs belong to cold classical Kuiper belt objects. Among the dynamically

Table 1. Candidates for young TNO pairs.

TNO pair	ϱ_2 [au$^{1/2}$]	ϱ_5 [au$^{1/2}$]	$\varrho_2 - \varrho_5$ [au$^{1/2}$]
2003 QL_{91} – 2015 VA_{173}	0.0412	0.0368	0.0044
1999 HV_{11} – 2015 VF_{172}	0.0432	0.0409	0.0023
2002 CY_{154} – 2005 EW_{318}	0.0484	0.0391	0.0093
2013 SD_{101} – 2015 VY_{170}	0.0496	0.0434	0.0062

cold population of the classical Kuiper belt, during the evolution of the protoplanetary disk and the migration of planets, conditions are implemented for the preservation of close binary or contact TNOs with components of approximately equal masses (Nesvorný & Vokrouhlický 2019). On the other hand, the evolution of wide binary trans-Neptunian objects turns out to be unstable due to frequent encounters with other TNOs, which lead to the decay of binary systems (Campbell 2021) and the formation of TNO pairs in close orbits.

We perform a study of the dynamical evolution of pairs of TNOs in which one of the component is binary. This paper is organized as follows. Section 2 reviews the methods which we used to studied the probabilistic evolution of the TNO pairs. The results of the probabilistic evolution study are presented in Section 3. In Section 4, we discuss the results and summarize our conclusions.

2. Method

To search for candidates for young TNO pairs, we used the metrics $\varrho(\mathcal{E}_1, \mathcal{E}_2)$ in the space of Keplerian orbits (Kholshevnikov et al. 2016, 2020). The metric ϱ_2 defines the distance between two orbits in the five-dimensional space of Keplerian orbits $\mathcal{E} = (a,\ e,\ i,\ \omega,\ \Omega)$ (where a, e, i, ω, Ω are the semi-major axis, eccentricity, inclination, argument of the pericentre and longitude of the ascending node of the orbit, respectively) and shows the current distance between the Keplerian orbits. The metric ϱ_5 defines the distance in the three-dimensional factor-space of the positional elements $\mathcal{E}' = (a,\ e,\ i)$ and gives the minimum metric ϱ_2 among all possible positions of the nodes and pericenter of the orbits and therefore $\varrho_5 \leq \varrho_2$. Analyzing the metrics will help identify candidates for young pairs. The positions of the lines of nodes and apses of the TNO orbits in young pairs should be close because the orientation of the orbits has changed slightly since the formation of the pair due to the secular drift of nodes and pericenter. If the metrics ϱ_2 and ϱ_5 are small (for TNO pair, one can limit ourselves to 0.05 au$^{1/2}$) and have close values (e.g. $\varrho_2 - \varrho_5 < 0.01$ au$^{1/2}$), then such a pair of TNOs can be considered a candidate for young pair. The criteria for the metrics ϱ_2 and ϱ_5 correspond to two or three values of the Hill sphere radius for TNO. However, this is only a necessary condition for the youth of the pairs because the precession of the nodes and pericenter of the orbits has a conditionally periodic type.

We have used both numbered and multiopposition objects from the Asteroids Dynamic Site (AstDyS, https://newton.spacedys.com/astdys/). We calculated the Kholshevnikov metrics ϱ_2 and ϱ_5 using the osculating orbital elements for the epoch MJD 59000 (00^h 00^m 00.000^s BDT 31.05.2020). We selected four pairs of TNOs satisfying the conditions: $\varrho_2 < 0.05$ au$^{1/2}$, $\varrho_5 < 0.05$ au$^{1/2}$ ($\varrho^2 < 0.0025$ au $= 3.7 \cdot 10^5$ km) and $\varrho_2 - \varrho_5 < 0.01$ au$^{1/2}$ ($(\varrho_2 - \varrho_5)^2 < 0.0001$ au $= 1.5 \cdot 10^4$ km) (see Tab. 1). Tab. 2 gives orbital elements and absolute magnitude H for TNOs in pairs.

To model the dynamical evolution of TNOs, we have performed numerical integrations of the orbits of TNOs in pairs backward in time (a period of 10 Myr) with the code known as Orbit9 (the OrbFit Software Package, http://adams.dm.unipi.it/orbfit/). The four giant planets were integrated consistently. The mean ecliptic of J2000.0 was taken as reference plane for the output. We used heliocentric coordinates.

Table 2. Orbital elements of TNOs in pairs.

TNO	a [au]	e	i [deg]	Ω [deg]	ω [deg]	H [mag]
2003 QL_{91}	43.246	0.01397	1.540	164.595	186.171	6.87
2015 VA_{173}	42.923	0.01091	1.689	169.363	184.498	8.41
1999 HV_{11}	43.114	0.02100	3.158	160.952	275.115	7.61
2015 VF_{172}	43.319	0.01866	2.924	162.939	276.482	8.87
2002 CY_{154}	44.229	0.07940	0.978	120.902	235.871	6.68
2005 EW_{318}	44.407	0.07423	1.060	128.503	225.712	6.35
2013 SD_{101}	43.430	0.02450	1.585	44.632	302.693	7.43
2015 VY_{170}	43.064	0.02097	1.765	43.830	311.497	7.73

We used two methods to estimate the age of TNO pairs in close orbits: 1) search for low relative-velocity close encounters of TNOs (e.g., Pravec et al. (2019)), 2) search for the minimum distances between the orbits of TNOs (e.g., Kuznetsov et al. (2020)).

The condition of convergence of orbits does not yet guarantee the convergence of objects moving in these orbits. Therefore, to estimate the age of pairs, it is also necessary to analyze the possibility of the onset of low relative-velocity close encounters, at which the distance between objects r_{rel} is comparable to the radius of the Hill sphere R_H of a more massive body, and the relative velocity v_{rel} is of the order of the escape velocity V_{esc} relative to a more massive body. Pravec et al. (2019) used follow the criteria for low-speed encounters for asteroids in the main belt are: $r_{rel} < (5 \text{ or } 10)R_H$, $v_{rel} < (2 \text{ or } 4)V_{esc}$, where V_{esc} is the escape velocity on the surface of a more massive body.

For each close approach of TNOs in pair we determined the relative distance r_{rel} between TNOs and relative velocity v_{rel}, as well as the Hill sphere radius R_H and escape velocity V_{esc} of the primary body. The radius of the Hill sphere was estimated as:

$$R_H = \frac{1}{2} r_1 D_1 \left(\frac{4\pi}{9} \frac{G\rho_1}{\mu} \right)^{1/3}, \tag{2.1}$$

where r_1 is the heliocentric distance of the primary's TNO, D_1 is its diameter, ρ_1 is its bulk density, G is the gravitational constant and μ is the gravitational parameter of the Sun. The escape velocity of primary body for relative distance r_{rel} was estimated as:

$$V_{esc} = \sqrt{\frac{\pi}{3} \frac{G D_1^3 \rho_1}{r_{rel}}}. \tag{2.2}$$

The diameter D of the TNO can be estimated from the absolute magnitude H and the geometric albedo p_v (Bowell et al. 1989):

$$D = 1329 \,\text{km}\, 10^{-H/5} \frac{1}{\sqrt{p_v}}. \tag{2.3}$$

We need to know the physical parameters of the TNO to estimate the radius of the Hill sphere R_H (2.1) and the escape velocity V_{esc} (2.2). Since the objects included in the studied TNO pairs belong to the dynamically cold population of the classical Kuiper belt and have dimensions not exceeding several hundred km, we used the same density values $\rho = 0.5$ g cm^{-3} and geometric albedo $p_v = 0.13$ for all TNOs (Müller et al. 2020).

Estimates of the single TNO density range from 0.5 to 2 g cm^{-3} (Lacerda & Jewitt 2007; Grundy et al. 2008; Fernández 2020) and grow with an increase in the TNO diameter. For TNOs several hundred km in size, the density estimates are $0.5 - 0.6$ g cm^{-3} (Lacerda & Jewitt 2007; Grundy et al. 2008; Fernández 2020). We used the minimum density value $\rho = 0.5$ g cm^{-3}, which will give the minimum estimates for the radius of the Hill sphere R_H (2.1) and the escape velocity V_{esc} (2.2). If the density value is 2 g cm^{-3}, the value of the radius of the Hill sphere R_H will be underestimated by $4^{1/3} \approx 1.6$ times,

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and the value of the escape velocity V_{esc} by $4^{1/2} = 2$ times. This can be taken into account when establishing the criteria for close encounters of the TNO pair.

To study the probabilistic evolution and estimate the ages of the TNO pairs, we consider 1000 clones for each TNO in pair. Using the Monte Carlo method, it is possible to generate distributions of clones' equivalent to those of observational results. Consequently, the simulated distribution represents the actual propagation of errors. Covariance matrix values and element errors were taken from AstDyS database. Based on this data, 1000 clones with a $\pm 3\sigma$ dispersion were generated for each nominal orbit. Such a strategy allows relatively good coverage of the whole probability space. Clones covering a 6-dimensional error ellipsoid were generated using a random number generator, with the following assumptions: the dispersion of each element has a normal distribution, the distribution coverage limit is $\pm 3\sigma$, the errors of each element are the same for clones as for real observational ones, and the distribution of all clones reproduces the original covariance matrix.

3. Results

2003 QL_{91} – 2015 VA_{173} Analysis of the results of probabilistic evolution shows that in the considered interval of 10 Myr, there is no noticeable concentration of close approaches to any selected time interval. The distribution of minimum distances Δr_{min} for close encounters up to a distance of less than 4 R_H is also uniform and does not allow identifying time intervals with prevailing close encounters. The relative velocity at close encounters exceeds 15.5 V_{esc}. All this allows us to conclude that the age of the pair 2003 QL_{91} – 2015 VA_{173} exceeds 10 Myr.

1999 HV_{11} – 2015 VF_{172} There is no noticeable concentration of close approaches to any selected time in the considered interval of 10 Myr. The distribution of minimum distances Δr_{min} for close encounters up to a distance of less than 4 R_H is also uniform and does not allow identifying time intervals with prevailing close encounters. The relative velocity at close encounters exceeds 59 V_{esc}. We conclude that the age of the pair 1999 HV_{11} – 2015 VF_{172} exceeds 10 Myr.

2002 CY_{154} – 2005 EW_{318} There is no noticeable concentration of close approaches to any selected time in the considered interval of 10 Myr. The distribution of minimum distances Δr_{min} for close encounters up to a distance of less than 4 R_H is also uniform and does not allow identifying time intervals with prevailing close encounters. The relative velocity at close encounters exceeds 16.1 V_{esc}. The minima of the metric $\varrho_{2\min}$ are concentrated in the intervals from 0 to 0.25 and from 0.75 to 1.5 Myr in the past (see Fig. 1). The minimum metric $\varrho_{2\min}$ values are 0.01 $\mathrm{au}^{1/2}$, which exceeds the expected metric value near the moment of pair formation 0.001 $\mathrm{au}^{1/2}$. We conclude that the age of the pair 2002 CY_{154} – 2005 EW_{318} exceeds 10 Myr.

2013 SD_{101} – 2015 VY_{170} There is no noticeable concentration of close approaches to any selected time in the considered interval of 10 Myr. The distribution of minimum distances Δr_{min} for close encounters up to a distance of less than 4 R_H is also uniform and does not allow identifying time intervals with prevailing close encounters. The relative velocity at close encounters exceeds 22 V_{esc}. The minima of the metric $\varrho_{2\min}$ are concentrated to the present (see Fig. 2). The minimum metric $\varrho_{2\min}$ values are 0.019 $\mathrm{au}^{1/2}$. We conclude that the age of the pair 2013 SD_{101} – 2015 VY_{170} exceeds 10 Myr.

4. Discussion and Conclusions

The pairs studied belong to the dynamically cold population of the classical Kuiper belt. This region has favorable conditions for the preservation of close binary TNO systems (Nesvorný & Vokrouhlický 2019). However, at the same time, wide TNO binary

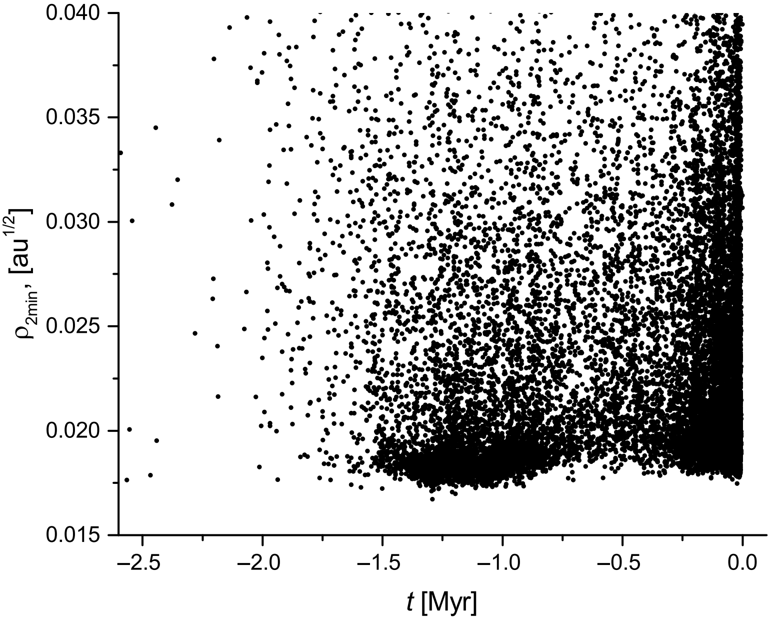

Figure 1. Minimum metric $\varrho_{2\min}$ vs time t for pair 2002 CY_{154} – 2005 EW_{318}.

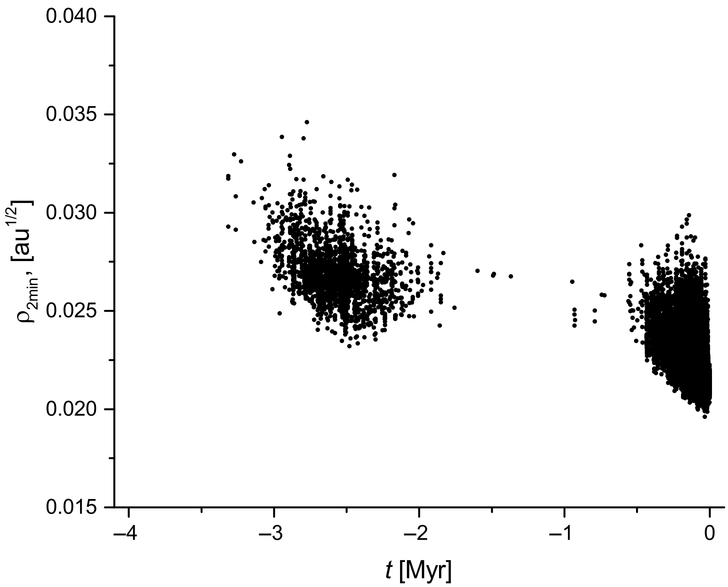

Figure 2. Minimum metric $\varrho_{2\min}$ vs time t for pair 2013 SD_{101} – 2015 VY_{170}.

systems disintegrate due to encounters with other objects (Campbell 2021). The most probable source of TNO pairs in the cold classical Kuiper belt is the decay of binary TNO systems.

Analysis of the results of probabilistic evolution shows the absence of low relative-velocity close encounters of TNO in pairs. Approaches to distances less than 4 R_H occur, but the relative velocities exceed 15.5 V_{esc}. We cannot estimate the moments of formation

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of pairs of TNO because the distribution of the minimum distances Δr_{min} in time is close to uniform.

The interval of 10 Myr is relatively short for study the dynamic evolution of the young TNO pairs because, during this time, objects of the Classical Kuiper Belt make only $33-36$ thousand periods in orbit. For comparison, young pairs in the main asteroid belt are pairs with an age of up to 2 Myr. During this time, asteroids make $400-600$ thousand the orbital periods. In the future, it is planned to increase the integration interval to 200 Myr. On such a long interval, the manifestation of stochastic properties of the TNO dynamic evolution is inevitable; therefore, the main methods used to estimate the age of pairs should be methods that estimate the distance between orbits.

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