

PROBABILISTIC EVOLUTION OF PAIRS OF TRANS-NEPTUNIAN OBJECTS. Eduard Kuznetsov¹, Omar Al-Shiblawi², and Vladislav Gusev³, ¹Ural Federal University, Lenina Avenue, 51, Yekaterinburg, 620000, Russia, eduard.kuznetsov@urfu.ru, ²Ural Federal University, Lenina Avenue, 51, Yekaterinburg, 620000, Russia, themyth_24@yahoo.com, ³Ural Federal University, Lenina Avenue, 51, Yekaterinburg, 620000, Russia, vlad06gusev@gmail.com.

Introduction: A candidate collisional family in the outer Solar system was proposed by Chiang [1]. The first asteroid family identified in the outer Solar system was the one associated with dwarf planet Haumea [2]. The subject of finding collisional families of trans-Neptunian objects has been studied by Chiang et al. [3] and Marcus et al. [4]. de la Fuente Marcos C. and de la Fuente Marcos R. [5] 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 FC8 – 2000 GX146 and initially proposed by Chiang [1]. They find four new possible collisional families of TNOs and several unbound TNOs that may have a common origin.

Kuznetsov et al. [6] 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 Kholoshevnikov metrics [7], [8] in the space of Keplerian orbits. Found 26 pairs of TNOs in close orbits, 20 pairs in which one of the TNO is binary, and 13 pairs of binary trans-Neptunian objects. All pairs belong to cold classical Kuiper belt objects. Among the dynamically 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 [9]. 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 [10] and the formation of TNO pairs in close orbits.

We consider the probabilistic evolution of ten TNO pairs in close orbits for 10 Myr.

Methods: To find close approaches of TNOs in pairs in the past and, therefore, estimate the age of the pairs, we have performed numerical integrations of the orbits of TNOs in pairs backward in time for 10 Myr with the code known as Orbit9 (the OrbFit Software

Package (<http://adams.dm.unipi.it/orbfit/>). For each close approach of TNOs in pair, we determined the relative distance r_{rel} between TNOs and relative velocity v_{rel} and the Hill sphere radius R_H and escape velocity v_{esc} of the primary body. Thus, to find low relative-velocity close encounters between TNOs in pairs, we chose the following limits on the relative distance and relative velocity between the TNOs in pairs: $r_{\text{rel}} < 10 R_H$ and $v_{\text{rel}} < 4 v_{\text{esc}}$ [11]. To get more information for each TNO, like albedo or diameter, we rely on the site JPL Small-Body Database (<https://ssd.jpl.nasa.gov/sbdb.cgi#top>).

We have used natural metric ρ_2 in the space of Keplerian orbits [7], [8] to calculate the distance between two orbits in the five-dimensional space of Keplerian orbits (the position on the orbit is omitted).

We studied the probabilistic evolution for 10 Myr. The Orbit9 integrated the four giant planets and the dwarf planet Pluto consistently. We considered 1000 clones for each TNO in pair. Using the Monte Carlo method, it is possible to generate distributions of clone's equivalent to those of observational results. Consequently, the simulated distribution represents the actual propagation of errors. We took covariance matrix values and element errors from the Asteroids Dynamic Site AstDyS database (<https://newton.spacedys.com/astdys/index.php?pc=4>). Based on this data, one thousand 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.

Results: We have estimated of the mean intervals (from the initial epoch MJD 59000 to the past) for the minimum distances between the TNOs and their orbits. The interval t_{r4} is the mean of the moments when the TNOs approaches less than four radii of the Hill spheres. The intervals t_r and t_p are the mean overall approach moments of the TNOs and their orbits, respectively. Table 1 gives the mean intervals t_{r4} , t_r , t_p and their standard deviations for ten TNO pairs.

Table 1. The mean intervals of reaching the minimum distances between the TNOs and their orbits

TNO pair	t_{r4} [Myr]	t_r [Myr]	t_p [Myr]
(88268) 2001 KK76 – 2013 UL17	5.3 ± 2.7	5.2 ± 2.7	6.5 ± 0.6
(88268) 2001 KK76 – 2015 GV58	4.7 ± 2.9	4.8 ± 2.9	0.57 ± 1.50
(468422) 2000 FA8 – 2000 YV1	4.4 ± 2.7	4.2 ± 2.7	3.1 ± 2.7
1999 HV11 – 2015 VF172	2.9 ± 1.9	2.8 ± 2.0	0.39 ± 0.13
2000 PW29 – 2015 GL58	4.5 ± 2.9	3.9 ± 2.9	2.2 ± 3.5
2002 CY154 – 2005 EW318	3.5 ± 4.4	3.1 ± 4.2	0.56 ± 0.59
2002 FW36 – 2015 VF170	4.5 ± 2.9	4.3 ± 2.9	0.85 ± 2.4
2003 QD91 – 2015 VC173	3.9 ± 2.6	3.7 ± 2.6	3.3 ± 1.9
2003 QL91 – 2015 VA173	4.6 ± 2.9	4.5 ± 2.9	2.1 ± 2.1
2013 SD101 – 2015 VY170	3.6 ± 2.7	3.7 ± 2.9	0.43 ± 0.87

Table 2. Minimum values of relative distance r_{rel} , corresponding velocity v_{rel} , and metric ρ_2

TNO pair	r_{rel} [R_H]	v_{rel} [v_{esc}]	ρ_2 [$au^{1/2}$]
(88268) 2001 KK76 – 2013 UL17	0.24	24	0.012
(88268) 2001 KK76 – 2015 GV58	0.27	42	0.030
(468422) 2000 FA8 – 2000 YV1	0.15	34	0.013
1999 HV11 – 2015 VF172	0.76	561	0.019
2000 PW29 – 2015 GL58	1.6	108	0.014
2002 CY154 – 2005 EW318	0.24	13	0.0096
2002 FW36 – 2015 VF170	0.26	34	0.015
2003 QD91 – 2015 VC173	0.16	23	0.0044
2003 QL91 – 2015 VA173	0.15	15	0.019
2013 SD101 – 2015 VY170	0.21	22	0.019

We have obtained the minimum values of the distances r_{rel} between TNOs in pairs and the corresponding relative velocities v_{rel} and the minimum values of the metric ρ_2 for 10^6 variants (see Table 2). Note that the minimum values of the distance r_{rel} and metric ρ_2 are reached at different moments for all pairs.

Discussion and Conclusions: To estimate the age of pairs, we require that the intervals t_{r4} , t_r , t_p obtained by different methods must be close at the moment of pair formation. As can be seen from Table 1, only a pair 2003 QD91 – 2015 VC173 satisfies this requirement. Note that the moments t_p are concentrated to 6.5 Myr for pair (88268) 2001 KK76 – 2013 UL17.

The second requirement is the fulfillment of the conditions of low relative-velocity close encounters and smallness of the orbital metric. Table 2 shows that for all pairs, close approaches of TNOs are possible up to distances of the order of the radius of the Hill sphere. However, the relative speeds v_{rel} are significantly higher than those corresponding to low relative-velocity close encounters. So, we obtained the lowest relative velocities for pairs 2002 CY154 – 2005 EW318 and 2003 QL91 – 2015 VA173, but they are more than three times higher than the value corresponding to the low relative-velocity close encounters. The minimum values of the metric ρ_2 are obtained for pairs 2002 CY154 – 2005 EW318 and 2003 QD91 – 2015 VC173.

To conclude, we can estimate the age of the pair 2003 QD91 – 2015 VC173 from 1.1 to 6.5 Myr or more, the pair (88268) 2001 KK76 – 2013 UL17 from 5.9 to 7.1 Myr or more. The age of the other eight TNO pairs is more than 10 Myr.

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