PAIRS OF TRANS-NEPTUNIAN OBJECTS WITH CLOSE ORBITS. E. D. Kuznetsov[1] O. M. Al-Shiblawi[2], V. D. Gusev[3], and D. S. Ustinov[4], [1]Ural Federal University, Lenina Avenue, 51, Yekaterinburg, 620000, Russia, eduard.kuznetsov@urfu.ru, [2]Ural Federal University, themyth_24@yahoo.com, [3]Ural Federal University, vlad06gusev@gmail.com, [4]Ural Federal University, denisusti@gmail.com.

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 3500 objects have been recognized and indexed. As was shown in [1], in the main belt of asteroids, there are a large number of pairs of asteroids with close orbits that have a common origin. A study of these pairs [2] proved their statistical significance. Unbound pairs of asteroids have also been identified in [3–5]. One candidate pair resides in the scattered disc [6]. Groups of pairs define young asteroid clusters [7, 8].

Different processes can lead to the formation of pairs or groups of minor bodies with close orbits. It is collisional break-ups, rotational or thermal-stress-induced splittings, tidal disruptions, and binary dissociations (see e.g., [4, 9–16]. Mean motion and secular resonances can also induce orbital coherence (see e.g., [17]).

A candidate collisional family in the outer Solar system was proposed by [18]. The first asteroid family identified in the outer Solar system was the one associated with dwarf planet Haumea [19]. The subject of finding collisional families of trans-Neptunian objects has been studied by [20] and [21]. de la Fuente Marcos C. and de la Fuente Marcos R. [22] perform a systematic search for statistically significant pairs and groups of dynamically correlated objects through those with a semimajor 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 [18]. They find four new possible collisional families of TNOs associated with the pairs (134860) 2000 OJ67 – 2001 UP18, 2003 UT291 – 2004 VB131, 2002 CU154 – 2005 CE81 and 2003 HF57 – 2013 GG137. They find several unbound TNOs that may have a common origin, the most significant ones are (135571) 2002 GG32 – (160148) 2001 KV76 and 2005 GX206 – 2015 BD519.

Here we perform a search for statistically significant pairs and groups of dynamically correlated objects through those with a semimajor axis greater than 30 au, applying a novel technique that uses Kholshevnikov metrics [23, 24] in the space of Keplerian orbits.

Methods: We have used natural metrics $\rho(E_1, E_2)$ in the space of Keplerian orbits [23, 24] to search for TNOs with close orbits. Here Keplerian orbits E_s are points in a five-dimensional space of orbits (the position on the orbit is omitted). Let us denote by a, p, e, i, ω, Ω the semimajor axis, semi-latus rectum, eccentricity, inclination, argument of the pericentre and longitude of the ascending node of the orbit of an asteroid, respectively. The metric ρ_2 defines the distance between two orbits in the five-dimensional space of Keplerian orbits. The metric ρ_5 defines the distance in the three-dimensional factor-space of the positional elements. Its elements are classes of orbits with fixed p, e, i and all possible values of ω and Ω.

The metric ρ_2 shows the current distance between the Keplerian orbits. The metric ρ_5 gives the minimum distance between the orbits among all possible positions of the nodes and pericenter of the orbits. 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, one can limit ourselves to 0.07 au$^{1/2}$) and have close values (e.g., $\rho_2 - \rho_5 <$ 0.014 au$^{1/2}$), then such a pair of TNOs can be considered a candidate for young pair [25].

We have used both numbered and multiopposition objects from the Asteroids Dynamic Site – AstDyS (https://newton.spacedys.com/astdys/). Epoch of the orbital elements is MJD58800. The metrics ρ_2 and ρ_5 have been calculated to search for TNOs pairs with close orbits.

The dynamic evolution of TNO pairs was studied in two stages. In the first step, 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 (a time span of 10 Myr) with the code known as Orbit9 (the OrbFit Software Package (http://adams.dm.unipi.it/orbfit/). The numerical integrations were made taking the nominal orbits given by AstDyS database as initial conditions. The eight giant planets and the dwarf planet Pluto were integrated consistently. The mean ecliptic of J2000.0 was taken as reference plane for the output. We used heliocentric coordinates. Mercury software [26] was used to follow the close encounters to the TNOs.

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. To find low relative-velocity close encounters between TNOs in pair we chose following limits on the relative distance and relative velocity between the TNOs in pairs: $r_{\mathrm{rel}} < 10\ R_{\mathrm{H}}$ and $v_{\mathrm{rel}} < 4\ v_{\mathrm{esc}}$ [27]. To get the more information for each TNO like albedo or diameter we rely on data from the site JPL Small-Body Database (https://ssd.jpl.nasa.gov/sbdb.cgi\#top).

In the second step, if the nominal orbits allow low relative-velocity close encounters between TNOs in pair, to refine the estimate of the age of the pair, 1000 clones were considered 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 ±3σ 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 ±3σ, 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 found 27 pairs with metrics less than 0.07 au$^{1/2}$ (e.g., 2004 VA131 – 2004 VU131), 22 pairs in which one of the components is binary, for metrics less than 0.12 au$^{1/2}$ (e.g., 2001 OG109 – 2005 GD187), and 11 pairs of binary trans-Neptunian objects with metrics less than 0.3 au$^{1/2}$ (e.g., 2003 QY90 – 2005 CE81). All pairs belong to cold classical Kuiper Belt Objects.

The pair 2004 VA131 – 2004 VU131 may be the youngest pair of Kuiper Belt Objects known today. The age estimate of this pair is several hundred years based on the analysis of the results of probabilistic evolution. It is possible that 2004 VA131 and 2004 VU131 are the same TNO. To solve this puzzle, additional observations of these TNOs are required.

Discussions and Conclusion: According to modern concepts, most of the cool classical objects of the Kuiper belt were formed in the form of binary objects. The observed pairs of TNOs in close orbits may result from the decay of these binary systems due to the instability that develops under the influence of disturbing external factors.

This study is the initial stage of studying the dynamic properties of TNO pairs in close orbits. In the future, it is planned to study the probabilistic evolution of TNO pairs to clarify their age. Pairs containing binary TNOs will be investigated separately. These pairs are of particular interest because they could have formed due to the decay of multiple TNOs.

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