ORIGIN OF ORBITS OF SECONDARIES IN DISCOVERED TRANS-NEPTUNIAN BINARIES. S. I. Ipatov[1,2], [1]Vernadsky Institute of Geochemistry and Analytical Chemistry of Russian Academy of Sciences, Kosygina 19, 119991, Moscow, Russia; [2]Space Research Institute of Russian Academy of Sciences, Profsoyuznaya st. 84/32, Moscow, Russia. Contact: siipatov@hotmail.com.

Introduction: Ipatov [1-2] and Nesvorny et al. [3] supposed that trans-Neptunian binaries were formed by contraction of rarefied preplanetesimals (RPPs). Ipatov supposed that a considerable fraction of trans-Neptunian satellite systems could get the main fraction of their angular momenta due to collisions of RPPs.

Prograde and Retrograde Rotation of Trans-Neptunian Binaries: Based on the data from http://www.johnstonsarchive.net/astro/astmoons/, below we study inclinations i_s of orbits of secondaries around 32 objects moving in the trans-Neptunian belt (Fig. 1) and discuss how such inclinations could form. Note that i_s is considered relative to the ecliptic and differs from the inclination relative to the plane which is perpendicular to the axis of rotation of a primary. For example, i_s=96^o for Pluto, though Charon is moving in the plane perpendicular to the Pluto's rotational axis. Besides the 32 considered objects with known values of i_s, the above website contains also information about many binaries with unknown i_s. The fraction of objects with i_s>90^o equals 13/32≈0.406 at all values of eccentricity e of a heliocentric orbit of a binary, and it is 13/28≈0.464 for e<0.3. The distribution of i_s is in the wide range almost from 0 to 180^o (Fig. 1a). It shows that a considerable fraction of the angular momentum of the RPPs that contracted to form satellite trans-Neptunian systems was not due to initial rotation of RPPs or to collisions of RPPs with small objects (e.g., boulders and dust), but it was acquired at collisions of the RPPs which masses did not differ much, because else the angular momentum would be positive. Ipatov [1] noted that the angular momentum of collided RPPs could be positive or negative depending on heliocentric orbits of the RPPs. Some excess of the number of discovered binaries with positive angular momentum compared with the number of discovered binaries with negative angular momentum was caused in particular by the contribution of initial positive angular momentum of RPPs and by the contribution of collisions of RPPs with small objects to the angular momentum of the final RPP that produced the binary. Also there could be some excess of positive angular momentum at mutual collisions of RPPs of similar sizes.

Orbits of Binaries at Different Separation Distances: All four secondaries of the considered binaries with e>0.3 move in prograde orbits (i.e., i_s<90^o). For e>0.3 the ratio a_s/r_H of the separation between the primary and the secondary to the Hill radius of the binary was smaller than 0.024, while a_s/r_H can exceed 0.225 at e<0.3 (Fig. 1a). Note that the trans-Neptunian objects with e>0.3 could form in the feeding zone of the giant planets (see, e.g., [4]), i.e., closer to the Sun than the objects with e<0.3. Maximum values of a_s/r_H (and also of a_s) are greater for greater semi-major axis a of a heliocentric orbit of an object at 38<a<46 AU (there is no place in the abstract for all analyzed figures). We suppose that for smaller distances a from the Sun the mean sizes of collided RPPs could be smaller, and so the mean values of a_s for the formed binaries could be smaller. The smaller sizes of the collided RPPs at smaller distances from the Sun could be due to their smaller Hill radii (which are proportional to a) at the collisions and may be also due to faster contraction.

For a_s/r_H<0.008, except one object, the values of i_s are between 60^o and 105^o, i.e., are in some vicinity of 90^o. Probably, such i_s were originated because for smaller sizes of collided RPPs (that produce binaries with smaller a_s/r_H) the ratio of their sizes to the height of the disk where RPPs moved was smaller, and collided RPPs often moved one above another, but not in almost the same plane as in the case when the sizes of RPPs were about the height.

Fig. 1c shows that i_s is between 60^o and 130^o for e_s<0.1, but i_s can take any values for greater eccentricities e_s of orbits of secondaries around objects moving in the trans-Neptunian belt. For objects with e_s<0.1, a_s/r_H<0.011; e_s<0.15 at a_s/r_H<0.008. Eccentricities e_s are typically greater than 0.2 at a_s/r_H>0.011. The values of e_s are usually in the range of 0.3-0.7 at 0.009<a_s/r_H<0.035 and can be in a wider range (from 0.15 to 0.9) for a_s/r_H>0.035. The greater maximum values of e_s at greater values of a_s/r_H are in accordance with the formation of satellites from a disk of material (e.g., if the disk formed as a result of contraction of a rarefied condensation). Orbits of satellites of planets are also almost circular for small distances from planets.

Inclinations of Orbits of Secondaries at Different Diameters of Components of Binaries: No dependence has been found for the plot of i_s vs. the diameter of the primary. The absence of such dependence can be a result of the evolution of the disk of RPPs, if the height of the disk of collided RPPs is greater than radii of collided RPPs.

For the ratio d_s/d_p of diameters of the secondary to the primary greater than 0.7, i_s can take any values, but there are no objects with $130^o<i_s<180^o$ and $d_s/d_p<0.7$, and there is only one binary with $i_s<50^o$ and $d_s/d_p<0.5$ (Fig. 1c). The absence of binaries with $i_s>130^o$ at $d_s/d_p<0.7$ may be caused by that the contribution of initial positive angular momentum of RPPs to the final angular momentum of the RPP that contacted to form the considered binary was greater (and the angular momentum acquired at the collision of RPPs of similar masses that produced the final RPP was smaller) at $d_s/d_p<0.7$ than at $d_s/d_p>0.7$. The smaller contribution of the angular momentum acquired at the collision at smaller ratio d_s/d_p could be caused by that in this case the masses of collided RPPs differed more than at greater d_s/d_p. The fraction of binaries with $d_s/d_p>0.7$ is $20/32\approx0.625$. A considerable (about 0.8) fraction of binaries with $d_s/d_p>0.7$ was also obtained in the computer models considered by Nesvorny et al. [3].

Dependencies of Inclination of a Secondary on Orbital Elements of a Heliocentric Orbit of a Binary: Below we discuss dependencies of i_s on orbital elements (a, e, i) of a heliocentric orbit of a binary object (or an object with several satellites) moving in the trans-Neptunian belt. At $38<a<44$ AU the maximum values of i_s are greater for greater values of a semi-major axis a of a heliocentric orbit of an object (Fig. 1d). The values of i_s exceed 134^o only at $44<a<46$ AU, and $i_s<110^o$ at $38<a<40$ AU. Initial semi-major axes of objects with $e>0.3$, probably, were less than 38 AU [4]. Smaller maximum values of i_s at smaller a can be caused by that the maximum values of the contribution of the angular momentum at a collision of two RPPs to the final angular momentum of the formed RPP were smaller (i.e., the role of initial positive angular momentum of RPPs was greater) at smaller a (as maximum values of a separation a_s are smaller at smaller a).

The maximum value of i_s typically is smaller at greater eccentricity e of a heliocentric orbit. It is close to 180^o at $e<0.1$, is about 128^o at $e\approx0.2$, and is less than 90^o at $e>0.37$.

At $i>13^o$ the values of i_s are in some region around 90^o ($61^o\le i_s\le126^o$) and $e\ge0.219$; in particular, $68^o<i_s<110^o$ at $13^o<i<24^o$. May be some of the binaries with $i>13^o$ originated at a smaller distance than most of other considered TNO binaries. The discussion of dependence of i_s on a is presented above.

Conclusions: The model at which a considerable fraction of the angular momentum of the rarefied condensation that contracted to form a satellite system was acquired at a collision of two condensations is in accordance with observations of trans-Neptunian binaries. For any other theory of formation of trans-Neptunian binaries, it is needed to explain the observations of the binaries, e.g., a considerable fraction of binaries with negative rotation.

This study was supported by Program no. 22 of the Presidium of the Russian Academy of Sciences and by the RFBR grant no. 14-02-00319.

References: [1] Ipatov S. I. (2010) *Mon. Not. R. Astron. Soc.*, *403*, 405-414. [2] Ipatov S. I. (2014) In *Proc. IAU Symp. No. 293* "*Formation, detection, and characterization of extrasolar habitable planets*", 285-288. [3] Nesvorny D., Youdin A. N., Richardson D. C. (2010) *Astron. J.*, *140*, 785-793. [4] Ipatov S. I. (1987) *Earth, Moon, & Planets*, 39, 101-128.

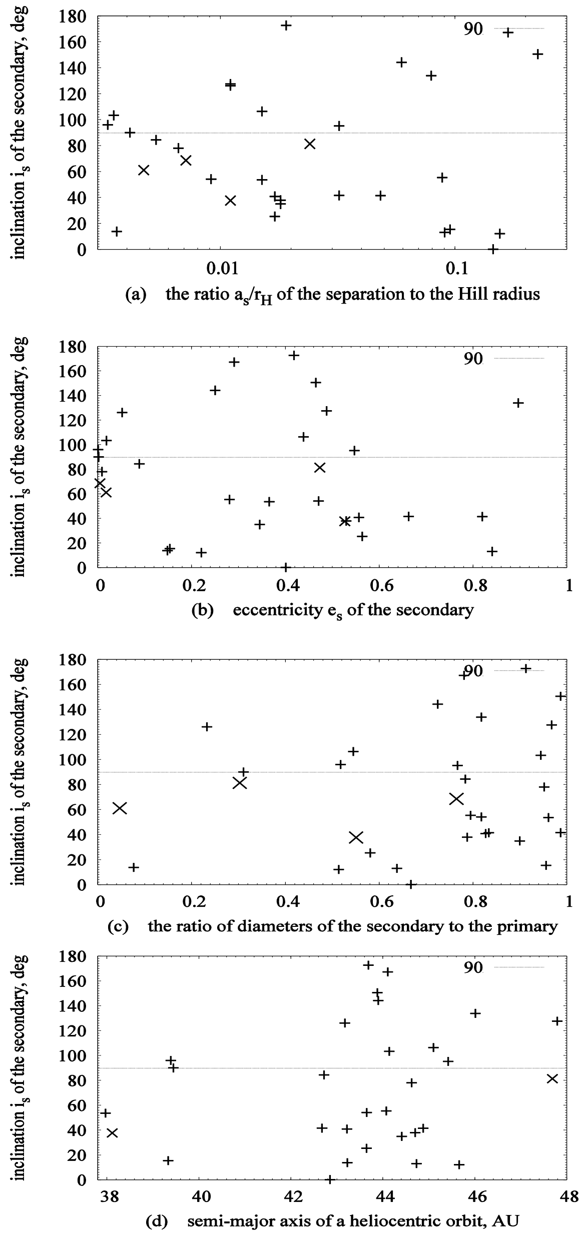

Fig. 1. The inclination i_s of the orbit of the secondary around the primary moving in the trans-Neptunian belt vs. (a) a_s/r_H, (b) e_s, (c) d_s/d_p, (d) a. Data for objects with $e<0.3$ are marked by plusses '+', and those at $e>0.3$ are marked by '×'.