# ORIGIN OF ORBITS OF SECONDARIES IN DISCOVERED TRANS-NEPTUNIAN BINARIES

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**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. The estimates presented in [2] showed that the angular velocities used by Nesvorny et al. [3] as initial data for simulations of the contraction of rarefied preplanetesimals that leads to formation of trans-Neptunian binaries can be acquired at collisions of the preplanetesimals which sizes did not differ much from their initial sizes. The fraction of rarefied preplanetesimals collided with other preplanetesimals of similar sizes in the forming region of small solid bodies can be about or a little greater than the fraction of small bodies with diameter $d$>100 km having satellites (among all such bodies with and without satellites). Such fraction of preplanetesimals could be about (or exceed) 0.3 for preplanetesimals that were parents for classical trans-Neptunian objects.

**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° 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° 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° (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 for all binaries. Ipatov [1] noted that the angular momentum of two 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 considered binaries with $e$>0.3 move in prograde orbits (i.e., $i_s$<90°). For $e$>0.3 the ratio $a_s/r_H$ of the separation $a_s$ between the primary and the secondary to the Hill radius $r_H$ of the binary is smaller than 0.024, while $a_s/r_H$ can exceed 0.225 at $e$<0.3 (Fig. 1a). Note that the TNOs 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. Fig. 2 shows that maximum values of $a_s/r_H$ (and also of $a_s$) are greater for a greater semi-major axis $a$ of a heliocentric orbit of an object at 38<$a$<46 AU. We suppose that for smaller distances from the Sun, the mean sizes of collided RPPs could be smaller, and so the mean value of $a_s$ for the formed objects 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 to faster contraction.

For $a_s/r_H$<0.008, except one object, the values of $i_s$ are between 60° and 105°, i.e., are in some vicinity of 90°. Probably, such values of $i_s$ 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 disc where RPPs moved were 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. Eccentricities $e_s$ of orbits of secondaries around objects moving in the trans-Neptunian belt were less than 0.15 at $a_s/r_H$<0.008 (Fig. 3), i.e., orbits close to primaries have small eccentricities.

**Inclinations of Orbits of Secondaries at Different Diameters of Components of Binaries**

Fig. 1c shows that $i_s$ is between 60° and 130° 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, also $e_s$<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 (Fig. 3). 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 disc of material (e.g., if the disc have formed as a result of contraction of a rarefied condensation). Orbits of satellites of planets are also almost circular for small distances from planets.

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 disc of RPPs, if the height of the disc 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°<$i_s$<180° and $d_s/d_p$<0.7, and there is only one binary with $i_s$<50° and $d_s/d_p$<0.5 (Fig. 1c). The absence of binaries with $i_s$>130° 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≈0.625. 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**

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 are presented in Figs. 1d-1f. 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° only at 44<$a$<46 AU, and $i_s$<110° 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 $a$; see the above discussion on Fig. 2).

The maximum value of $i_s$ typically is smaller at greater eccentricity $e$ of a heliocentric orbit (Fig. 1e). It is close to 180° at $e$<0.1, is about 128° at $e$≈0.2, and is less than 90° at $e$>0.37.

At $i$>13° the values of $i_s$ are in some region around 90° (61°≤$i_s$≤126°, Fig. 1f) and $e$≥0.219; in particular, 68°<$i_s$<110° at 13°<$i$<24°. May be some of the binaries with $i$>13° originated at a smaller distance than most of other considered trans-Neptunian binaries. The discussion of dependence of $i_s$ on $a$ is presented above.

The above discussion shows that the model at which a considerable fraction of angular momentum of the parental preplanetesimal that contracted to form a satellite system has been acquired at a collision of two preplanetesimals 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 presented in Figs. 1-3, e.g., a considerable fraction of binaries with negative rotation.

**Conclusions**

Trans-Neptunian objects, including those with satellites, could form as a result of contraction of rarefied preplanetesimals. The model of formation of a trans-Neptunian binary as a result of contraction of the parent preplanetesimal formed at a collision of two preplanetesimals is in accordance with that about 40% of discovered objects moving in the trans-Neptunian belt have negative angular momentum.

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**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.

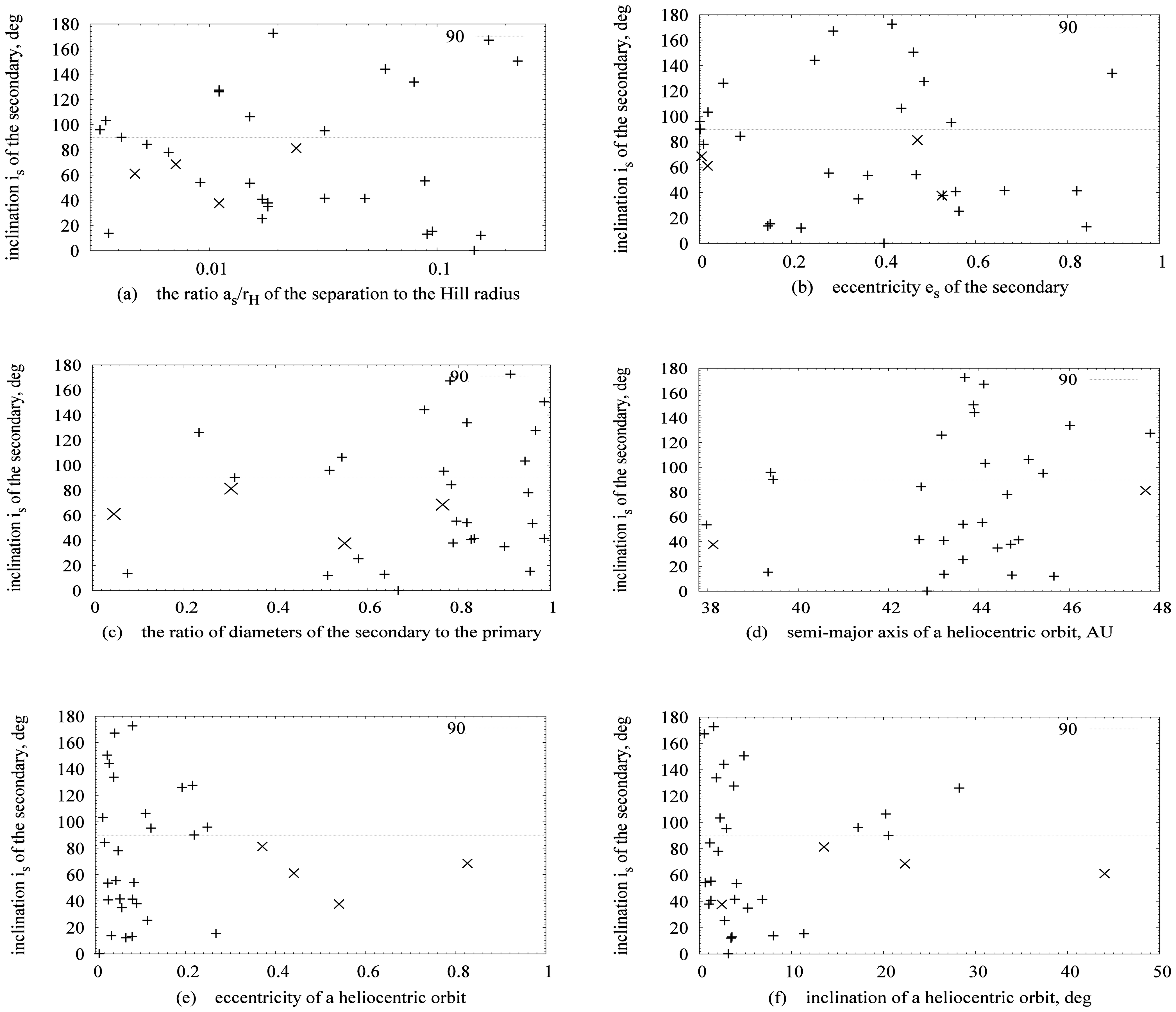


Fig. 1. The inclination $i_s$ of the orbit of the secondary around the primary moving in the trans-Neptunian belt vs. (a) the ratio $a_s/r_H$ of the separation between the primary and the secondary to the Hill radius of the binary; (b) the eccentricity $e_s$ of the orbit of the secondary around the primary; (c) the ratio $d_s/d_p$ of diameters of the secondary to the primary; (d) the semi-major axis $a$ of the heliocentric orbit of the binary; (e) the eccentricity $e$ of the heliocentric orbit of the binary; (f) the inclination $i$ of the heliocentric orbit of the binary. Data for objects with $e$<0.3 are marked by plusses '+', and those at $e$>0.3 are marked by '×'.

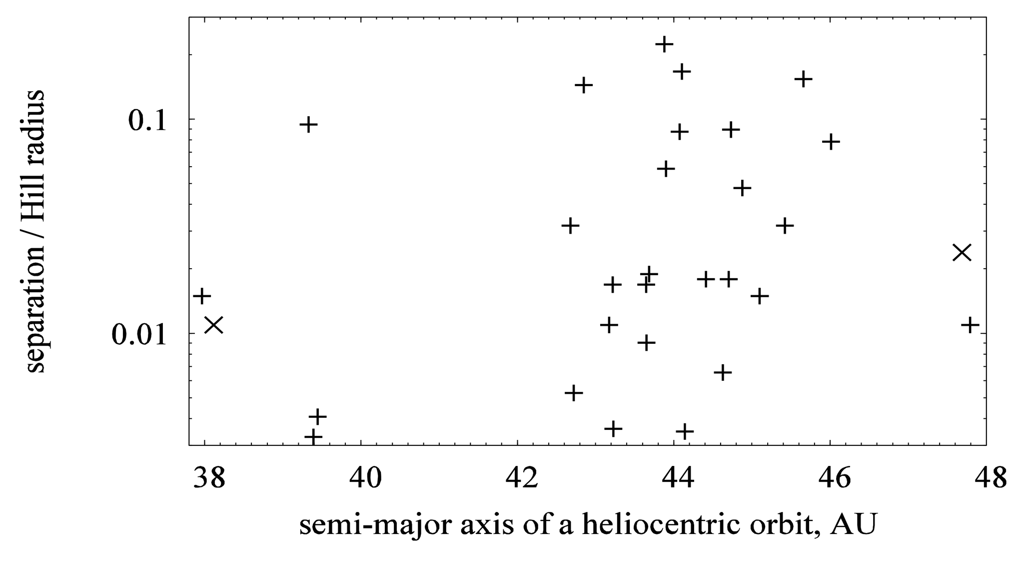


Fig. 2. The ratio $a_s/r_H$ of the separation distance between the primary and the secondary to the Hill radius of the binary vs. the semi-major axis $a$ of the heliocentric orbit of the binary. Data for objects with the eccentricity of the heliocentric orbit of the binary $e$<0.3 are marked by plusses '+', and those at $e$>0.3 are marked by '×'.

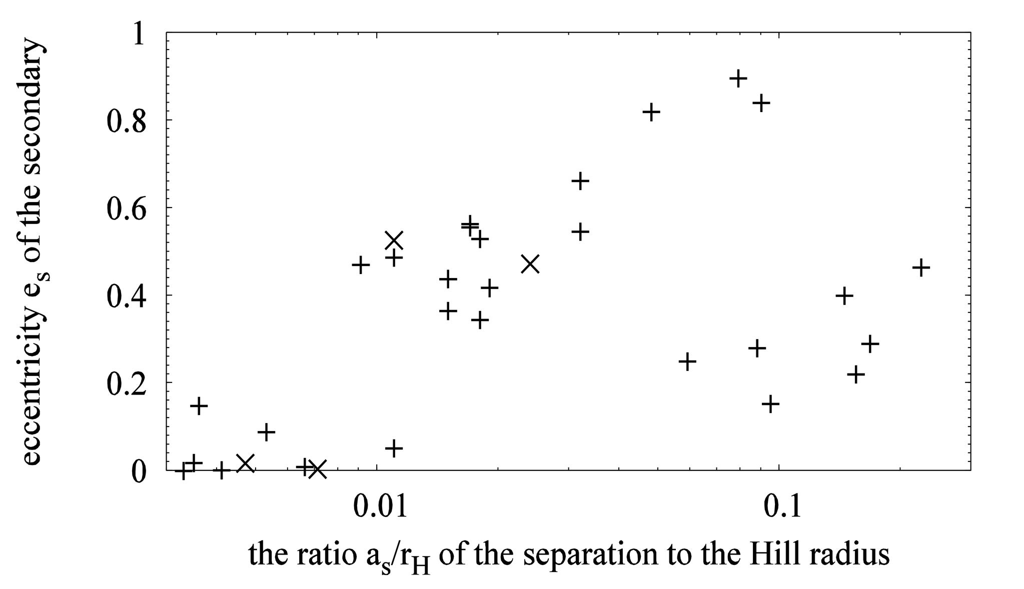


Fig. 3. The eccentricity $e_s$ of the orbit of the secondary around the primary moving in the trans-Neptunian belt vs. the ratio $a_s/r_H$ of the separation between the primary and the secondary to the Hill radius of the binary. Data for objects with the eccentricity of the heliocentric orbit $e$<0.3 are marked by plusses '+', and those at $e$>0.3 are marked by '×'.

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**Poster Location #363**. Abstract No 1512