Formation of trans-Neptunian satellite systems at the stage of rarefied condensations

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Formation of small body binaries

- **The binary fractions in the minor planet population are about 2 % for main-belt asteroids, 30 % for cold classical TNOs, and 10 % for all other TNOs (Noll 2006, 2008).**
- There are **several hypotheses of the formation of binaries for a model of solid objects**. For example, Goldreich et al. (2002) considered the capture of a secondary component inside Hill sphere due to dynamical friction from surrounding small bodies, or through the gravitational scattering of a third large body. Weidenschilling (2002) studied collision of two planetesimals within the sphere of influence of a third body. Funato et al. (2004) considered a model for which the low mass secondary component is ejected and replaced by the third body in a wide but eccentric orbit. Studies by Astakhov et al. (2005) were based on four-body simulations and included solar tidal effects. Gorkavyi (2008) proposed multi-impact model. Ćuk, M. (2007), Pravec et al. (2007) and Walsh et al. (2008) concluded that the main mechanism of formation of binaries with a small primary (such as near-Earth objects) could be rotational breakup of 'rubble piles'. More references can be found in the papers by Richardson and Walsh (2006), Petit et al. (2008), and Scheeres (2009).

Introduction

In recent years, new arguments in favor of the model of rarefied condensations (preplanetesimals, clumps) have been found (e.g. Makalkin and Ziglina 2004, Johansen et al. 2007, 2011, Cuzzi et al. 2008, Lyra et al. 2008). These clumps could include meter sized boulders in contrast to dust condensations earlier considered (e.g., Johansen, A., et al., Science Advances, 2015, Vol. 1, N 3, id. 1500109). Sizes of preplanetesimals could be up to their Hill radii.

In particular, Lyra et al. (2008) showed that in the vortices launched by the Rossby wave instability in the borders of the dead zone, the solids quickly achieve critical densities and undergo gravitational collapse into protoplanetary embryos in the mass range $0.1M_E$-$0.6M_E$ (where M_E is the mass of the Earth).

Introduction. Planetesimals/TNOs

Ipatov (MNRAS, 2010, 403, 405-414) and **Nesvorny et al**. (AJ, 2010, 140, 785-793) **supposed that trans-Neptunian binaries have been formed as a result of contraction of some rarefied condensations** (preplanetesimals). In my opinion, formation of some binaries, especially those with primaries with *d*<100 km, e.g., most of binaries in the asteroid belt and in the near-Earth population, can be explained by other models.

The angular momenta acquired at collisions of condensations that were moving in circular heliocentric orbits could have the same values as the angular momenta of discovered trans-Neptunian and asteroid binaries with masses equal to the sum of masses of two collided condensations (Ipatov 2010).

Some trans-Neptunian binaries have negative rotation, but condensations initially formed in a protoplanet disk had only positive rotation. Ipatov (2010a-b) concluded that TNO satellite systems formed from those rarefied condensations that got the necessary angular momentum as a result of a collision of two condensations. My estimates of the angular momentum obtained at a collision is in accordance with that needed for formation of a satellite system.

Nesvorny et al. (AJ, 2010, 140, 785-793) calculated contraction of rarefied condensations in the trans-Neptunian region and found the angular velocities of condensations at which the contraction ends in formation of binaries (or triples).

Angular momenta needed for formation of binaries

Ipatov (2014, Proc. IAU Symp. No. 293, 285-288) showed that **the angular momenta used by Nesvorny et al. (2010,** Astron. J. 140, 785-793**) as initial data in their calculations of contraction of condensations leading to formation of satellite systems could be obtained at collisions of two condensations that were moving before collisions in circular heliocentric orbits.** My estimates showed that the typical angular momentum obtained at a collision of two identical uniform condensations can be greater by an order of magnitude than the sum of initial angular momenta of the collided condensations. **Initial angular momenta of condensations (Safronov, 1972) were not enough for formation of binaries** (Ipatov S.I. Solar System Research, 2017, 51. N 4, 321-343).

However, if *radii* of two uniform condensations *decreased before their collision* from their initial radii by a factor of more than 3, then the angular momentum due to a typical collision is smaller than that due to initial rotation of condensations. For condensations more dense to their centers this factor is greater.

At the *ratio of radii of collided* uniform *condensations* of different masses greater than 3, the role of initial rotation in the angular momentum of the formed condensation is greater than that of the collision.

For the considered model at which the parental condensation that formed at a collision contracted to form a solid binary system, more chances to form a binary were for greater distances from the Sun.

Growth of a condensation by accumulation of smaller objects

- Formulas for the angular momentum were obtained in (Ipatov S.I. Solar System Research, 2017, 51. N 4, 294-314) for several models of a growth of a condensation by accumulation of smaller objects. **The parental condensation with radius close to its Hill radius that *grew by accumulation of small objects* could get the angular momentum at which a satellite system of a trans-Neptunian object could form.**
- **However, in the case of growth of a condensation by accumulation of smaller objects, *the angular momentum* of all satellite systems (e.g., binaries) formed from such condensations *would be positive* and perpendicular to the ecliptic. Actually about 40% of observed trans-Neptunian binaries have negative angular momentum. Depending on heliocentric orbits of two colliding condensations, the angular momentum at their collision can be positive or negative.**
- **Therefore in most cases the greater fraction of the angular momentum of a parental condensation that contracted to form a trans-Neptunian binary was acquired at a collision of condensations, but not by accumulation of small objects. However, some fraction of the angular momentum of parental condensations could be delivered by small objects.**
- **I suppose that the fraction of condensations collided (with a necessary angular momentum) with other condensations during their contraction can be about the initial fraction of small bodies of diameter *d*>100 km with satellites (among all such small bodies), i.e., it can be about 0.45 in the trans-Neptunian belt.**
- In (Ipatov S.I. Solar System Research, 2017, 51. N 4, 294-314) I also consider mergers of condensations and the frequency of their collisions.

Origin of orbits of secondaries in discovered trans-Neptunian binaries

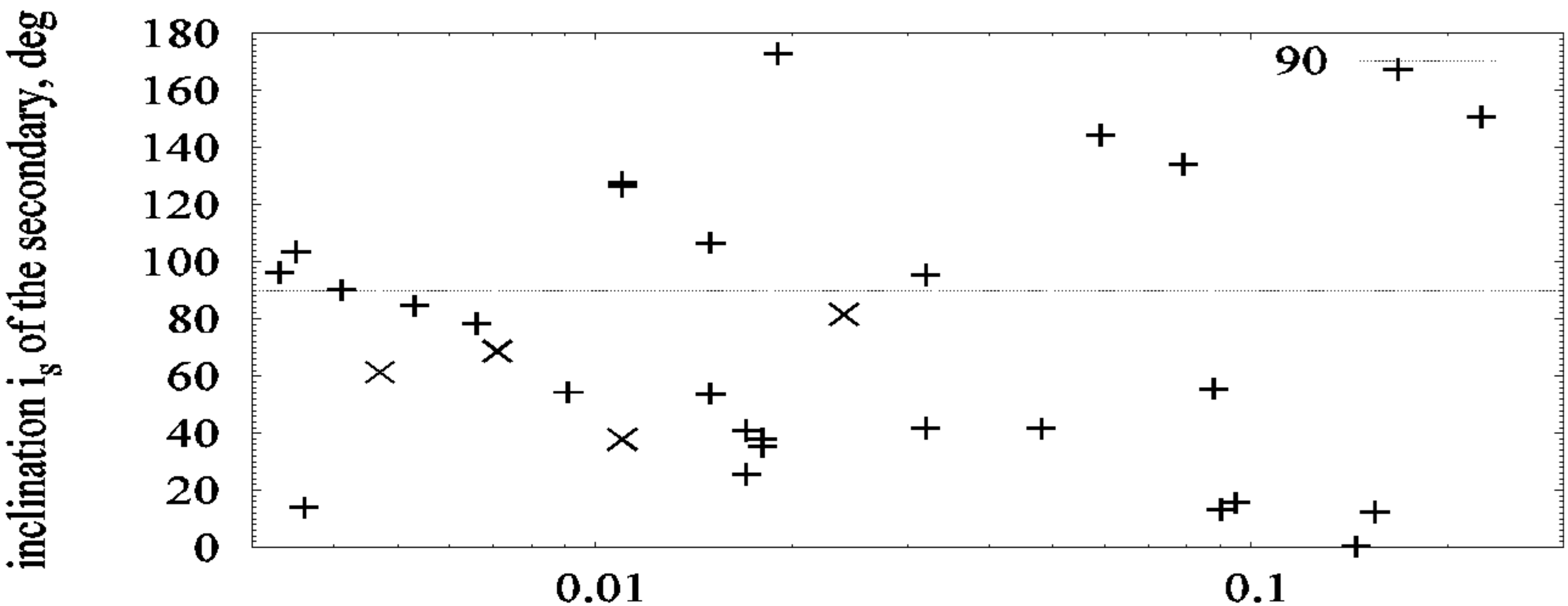
Based on the observational data presented in http://www.johnstonsarchive.net/astro/astmoons/, **I studied** (Ipatov S.I. Solar System Research, 2017, 51, N 5, 409-416) **different interrelationships between elements of an orbit of the secondary around the primary, elements of a heliocentric orbit of the binary, and the ratio of diameters of the secondary and primary** (e.g., prograde and retrograde rotation of discovered trans-Neptunian binaries, the inclinations of orbits of secondaries at different ratios of diameters of the secondary to the primary and at different orbital elements of heliocentric orbits of binaries, the separation distances at different semi-major axes of heliocentric orbits, the eccentricities and inclinations of orbits of secondaries at different separation distances). **It was shown that all these dependences can be explained for the model of formation of binaries at the stage of rarefied condensations**. A few of figures are presented and discussed below.

The distribution of inclinations i_s of orbits of secondaries in the wide range almost from 0 to 180^o shows that a considerable fraction of the angular momentum of the rarefied condensations that contracted to form trans-Neptunian satellite systems was not due to initial rotation of condensations, but was acquired at collisions of condensations. Some excess of positive angular momenta compared with negative angular momenta for all binaries was, in particular, caused by the contribution of initial positive angular momenta of condensations and by accumulation of small objects. Data for objects with the eccentricity of the heliocentric orbit e<0.3 are marked in figures by plusses '+', and those at e>0.3 are marked by '×'.

Inclinations of orbits of secondaries vs. separation

The model at which a considerable fraction of angular momentum of the preplanetesimal that contracted to form a satellite system is in accordance with observations of TNO binaries. *Based on the data from* http://www.johnstonsarchive.net/astro/astmoons/, **I studied inclinations i_s of orbits of secondaries around 32 objects moving in the trans-Neptunian belt. Note that i_s is considered relative to the ecliptic** and does not depend on the axis of rotation of a primary.

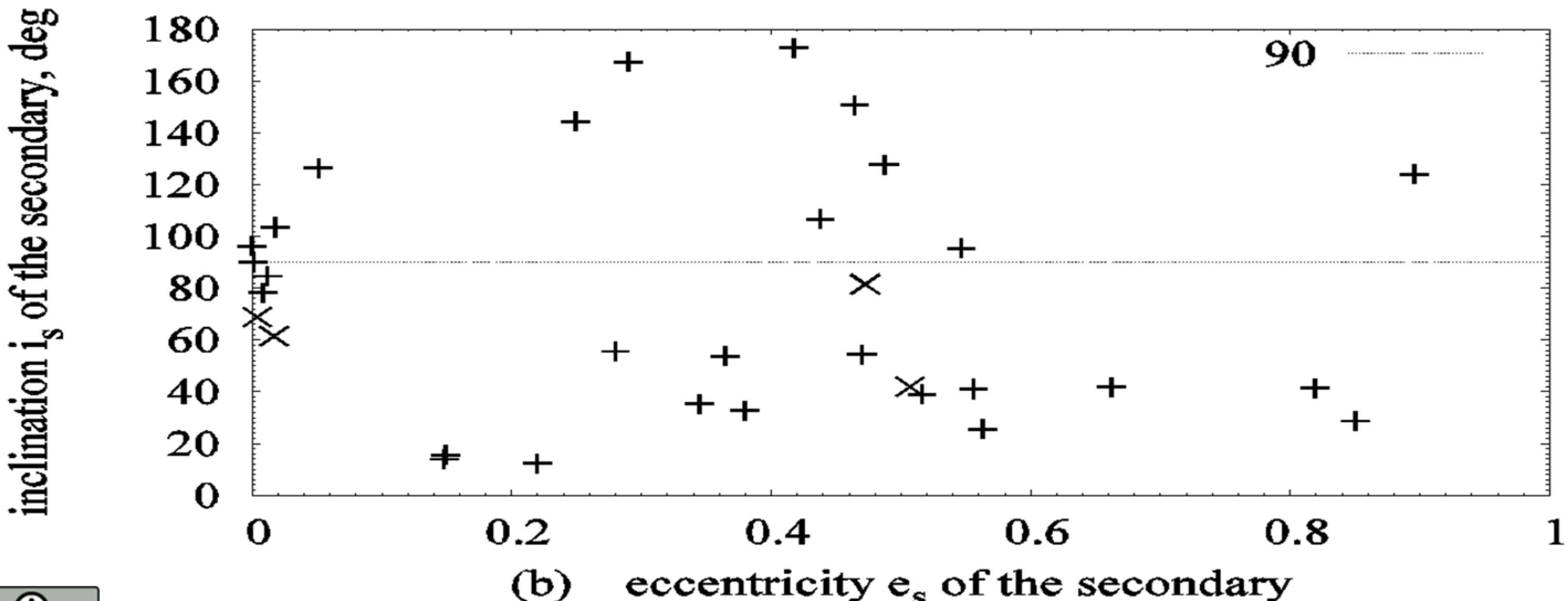
The fraction of objects with i_s>90º is equal to 13/32≈**0.4,** and it is 13/28≈0.464 for objects with eccentricity of a heliocentric orbit e<0.3**. The distribution of i_s in the wide range almost from 0 to 180º** (Fig. 1a) **shows that a considerable fraction of the angular momentum of the rarefied condensations that contracted to form satellite TNO systems was not due to initial rotation of condensations or due to accumulation of small objects, but was acquired at collisions of condensations**. Some excess of positive angular momenta compared with negative angular momenta for all binaries was, in particular, caused by the contribution of initial positive angular momenta of RPPs.



(a) the ratio a_s/r_H of the separation to the Hill radius

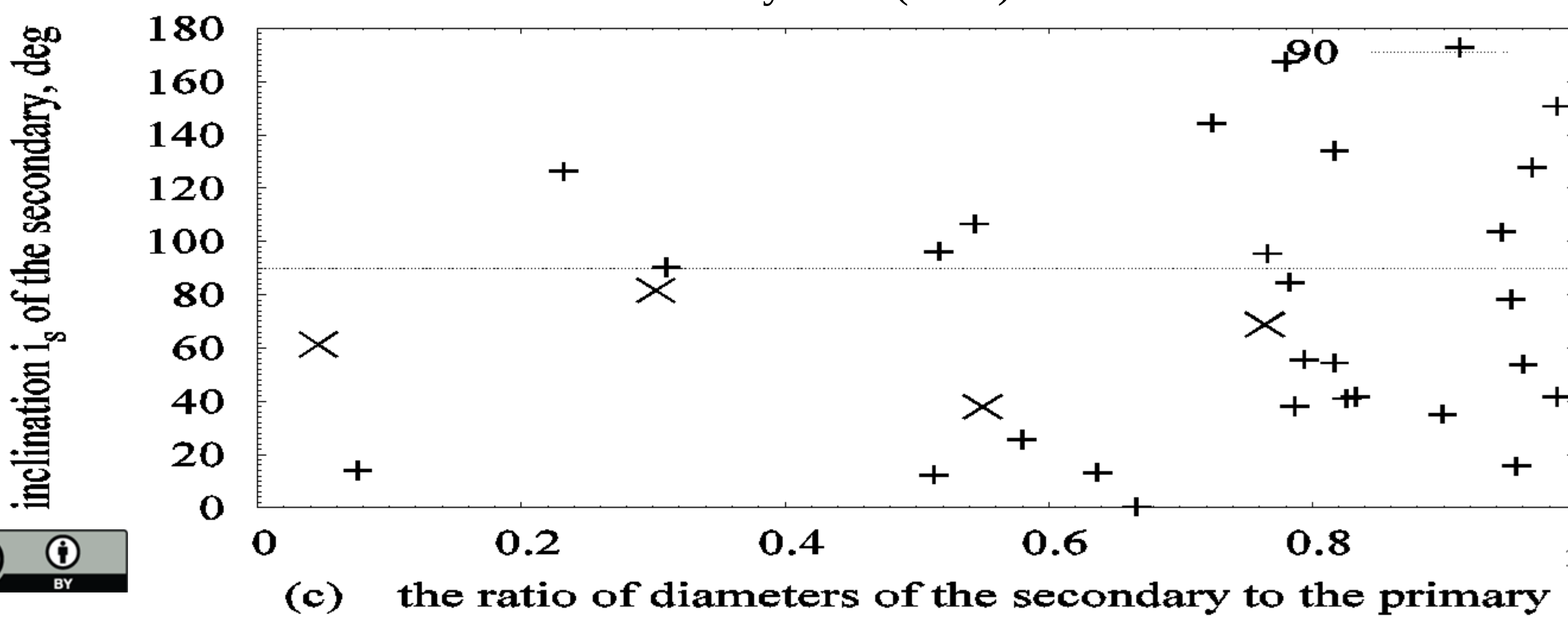
Inclinations i_s of orbits of secondaries vs. their eccentricities

For eccentricity of a secondary e_s<0.1, inclinations i_s of orbits of secondaries are between 60° and 130°, but i_s can take any values for greater eccentricities e_s of orbits of secondaries around objects moving in the trans-Neptunian belt. **The values of i_s close to 90° could be produced in the case when two condensations that formed the parental condensation for a binary moved one above another at the collision.** Probably, **small eccentricities of orbits of secondaries could form only at some of the collisions, when *relative velocities were smaller* than for typical collisions**. **At close values of semi-major axes of heliocentric orbits of collided condensations the above two necessary conditions for the inclination and the eccentricity are fulfilled.** E.g., velocity of a collision could be smaller than for typical collisions, and small relative velocity of a collision could lead to small eccentricity of a secondary.



Inclinations of orbits of secondaries vs. the ratio of diameters

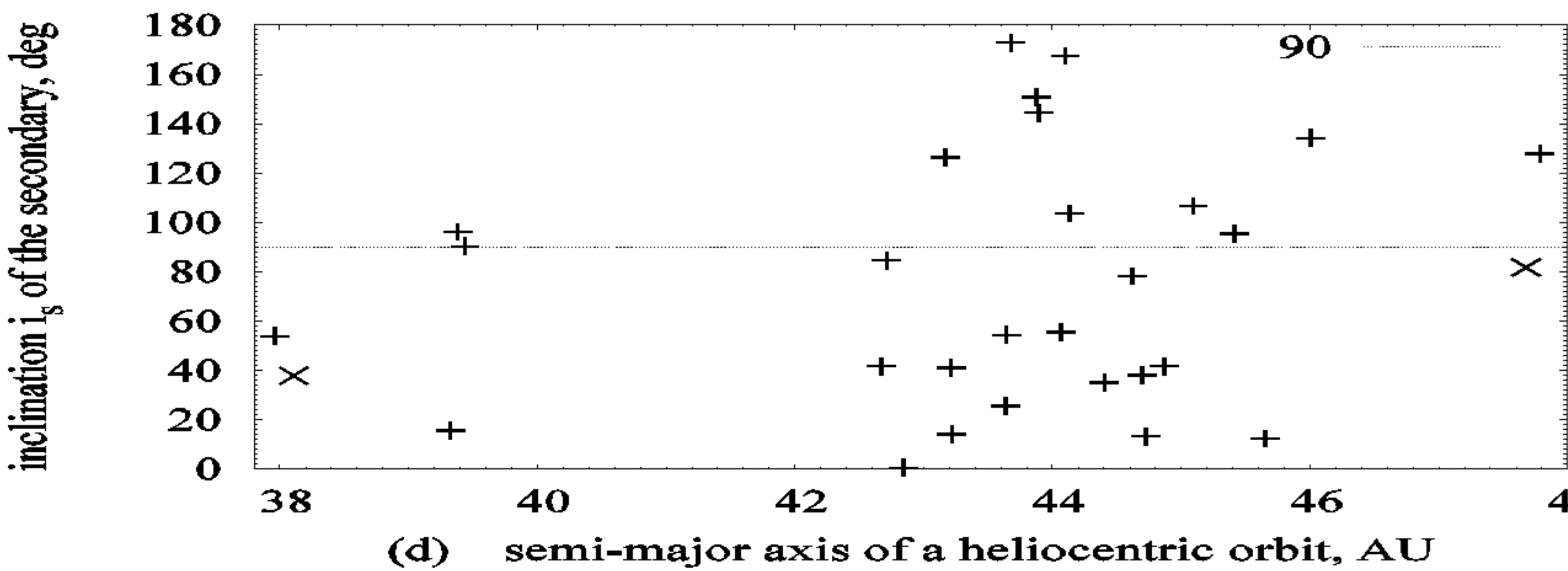
For the ratio d_s/d_p of diameters of the secondary to the primary greater than 0.7, i_s can take any values, but there are no objects with $130^o<i_s<180^o$ and $d_s/d_p<0.7$, and there is only one binary with $i_s<50^o$ and $d_s/d_p<0.5$ (Fig. 1c). **The absence of binaries with $i_s>130^o$ at $d_s/d_p<0.7$ may be caused by that the contribution of positive angular momentum of condensations caused by initial rotation or collisions with small objects to the final angular momentum of the parental condensation** that contacted to form the considered binary **was greater** (and the angular momentum acquired at the collision that produced the 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 to the total momentum at smaller ratio d_s/d_p could be caused by that in this case the masses of collided condensations 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. (2010).



Inclinations of orbits of secondaries vs. the semimajor axis of a heliocentric orbit

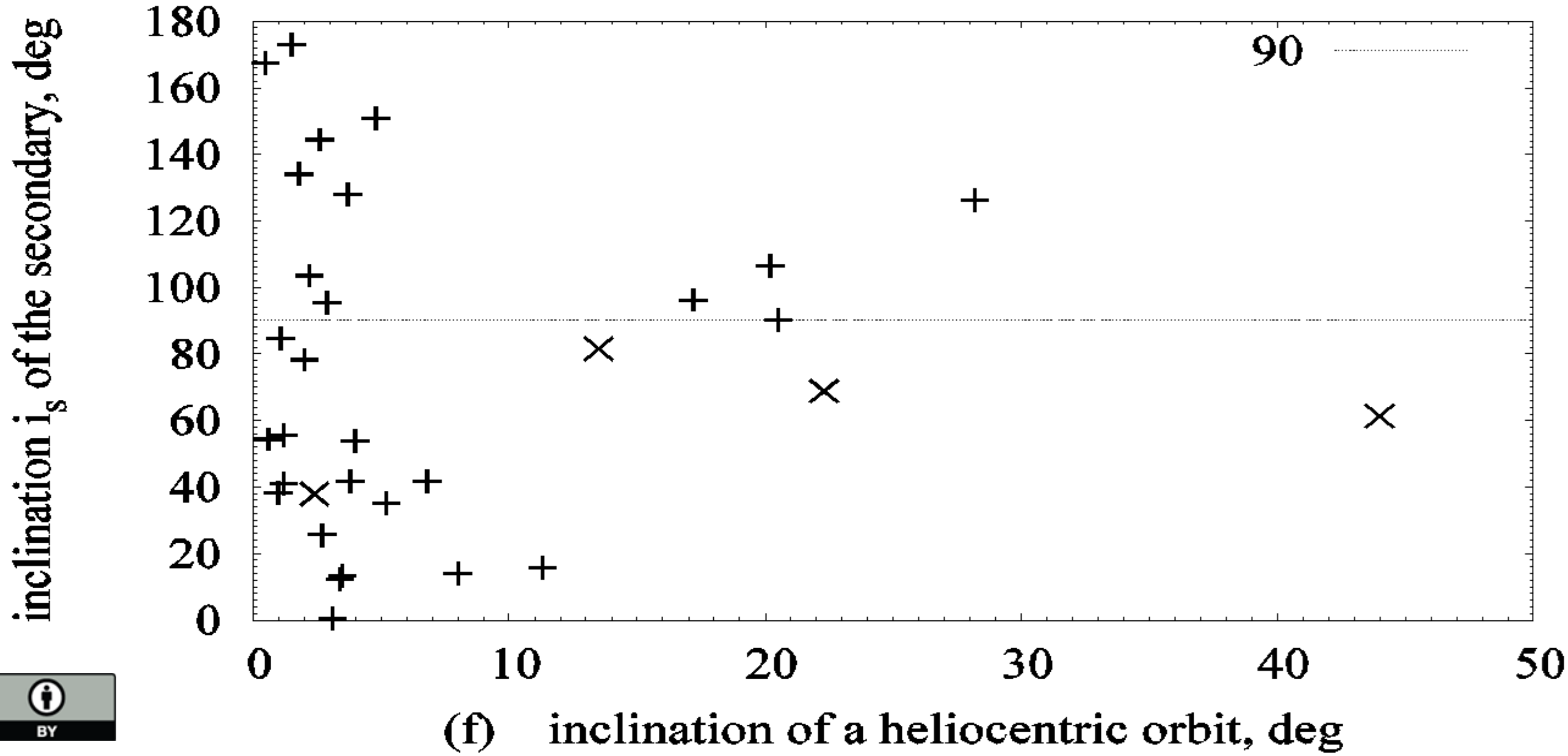
In Fig. 1d **at 38<*a*<44 AU** one can see that the **maximum values of i_s are greater for greater values of a semi-major axis *a* of a heliocentric orbit** of an object. The values of i_s exceed 134º only at 44<*a*<46 AU, and i_s<110º at 38<*a*<40 AU. Initial semi-major axes of objects with *e*>0.3, probably, were less than 38 AU. **Greater maximum values of i_s at greater *a* can be caused by that the maximum values of the contribution of the angular momentum at a collision of two condensations to the final angular momentum of the formed condensation were greater for some reasons** (i.e., the role of initial positive angular momentum of condensations was greater) **at greater *a***.

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 '×'.



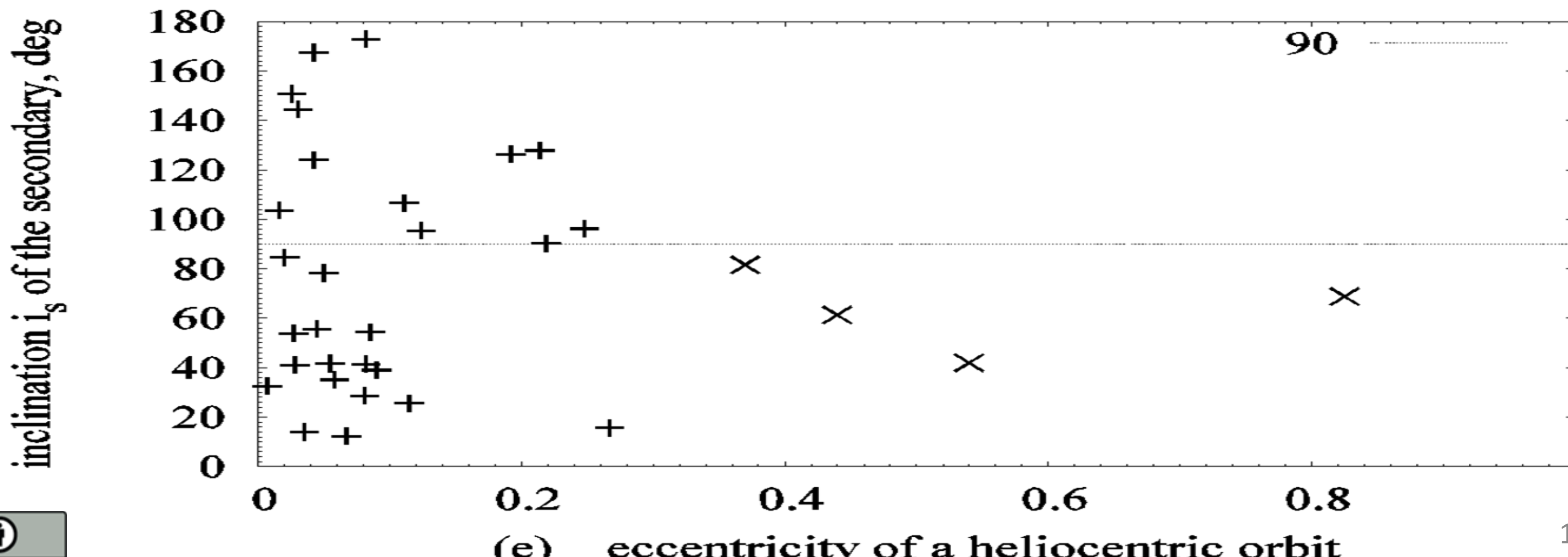
Inclination of a secondary vs. inclination of a heliocentric orbit

At inclination of a heliocentric orbit i>13^o the values of inclination of a secondary i_s are in some region around 90^o (61^o≤i_s≤126^o, Fig. 1f) **and e≥0.219**; in particular, 68^o< i_s<110^o at 13^o<i<24^o. **May be the condensations that formed the parental condensations for binaries with i>13^o moved farther from the middle disk plane than the condensations that formed parental condensations for other binaries, i.e. they could move one above another, that caused the inclinations of secondaries close to 90^o**. 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 ‘×’.



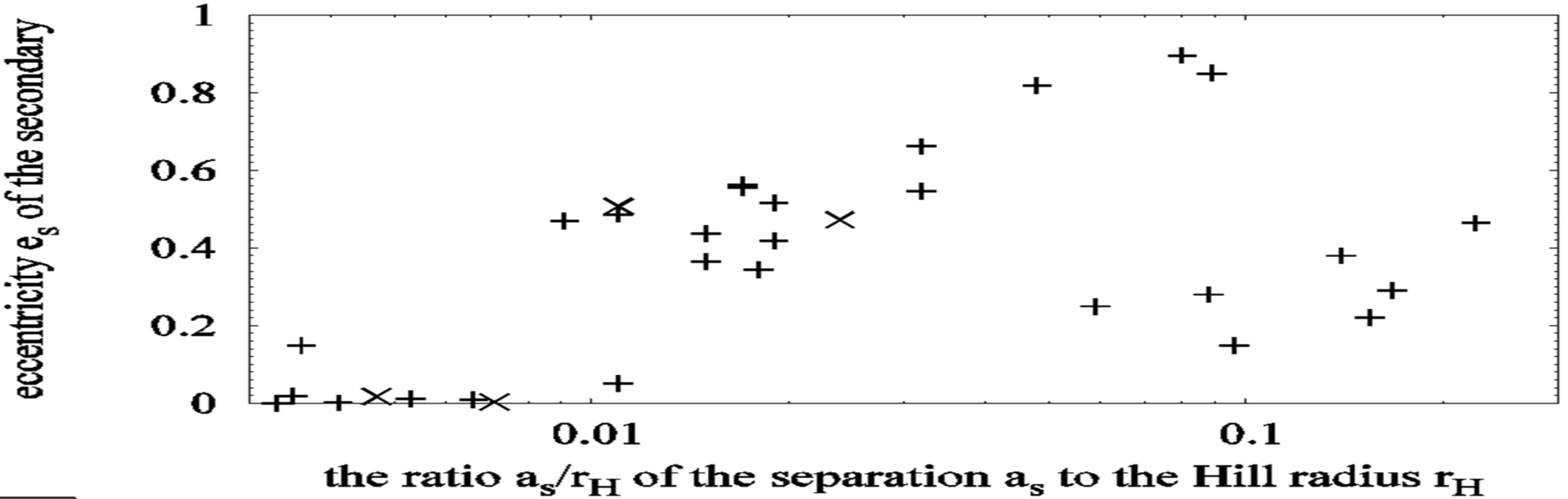
Inclination of a secondary vs. eccentricity of a heliocentric orbit

The maximum value of i_s typically is smaller at greater eccentricity e of a heliocentric orbit of a binary. It is close to 180º at e<0.1, is about 128º at e≈0.2, and is less than 90º at e>0.37. **The trans-Neptunian objects with e>0.3 could form** [Ipatov S.I. Earth, Moon, & Planets, 1987, 39, 101-128] **closer to the Sun, where for some reasons the role of initial positive rotation and/or the role of small objects in the final angular momentum could be greater than at greater distances a from the Sun**, and the ratio of sizes of collided condensations to a could be greater than at greater a.



Eccentricity of the secondary vs. separation

The greater maximum values of eccentricity e_s of the secondary at greater values of the ratio a_s/r_H of the separation to the Hill radius are in accordance with the formation of satellites from a disc of material (e.g. if the disc has formed as a result of contraction of a rarefied condensation). Formation of satellites of planets from a disc is a popular model. Orbits of satellites of planets are also almost circular for small distances from planets, and can be eccentric for greater distances. So there could be similar mechanisms of formation of satellites of large planets and trans-Neptunian objects.



Formation of the Moon

- I suppose that formation of the Earth-Moon system could be similar to the formation of trans-Neptunian binaries, discussed above.
- The embryos of the Earth and the Moon could form as a result of contraction of the same parental rarefied condensation. A considerable fraction of the angular momentum of such condensation could be acquired at a collision of two rarefied condensation.
- The solid Moon embryo could get more material ejected from the solid Earth embryo than the material that fell directly on the Moon embryo.
- Such model of the formation of the Earth-Moon system was discussed in the Poster P125.

Conclusions

Trans-Neptunian objects, including those with satellites, could form as a result of contraction of rarefied preplanetesimals.

The angular velocities used by Nesvorny et al. (AJ, 2010, 140, 785-793) as initial data for simulations of contraction of rarefied preplanetesimals are compared with the angular velocities obtained at a collision of two such preplanetesimals moving in circular orbits. The comparison showed that **the angular momenta of rarefied preplanetesimals needed for formation of trans-Neptunian binaries can be acquired at collisions of preplanetesimals.**

The initial fraction of small bodies with *d*>100 km having satellites can be about or a little greater than the fraction of rarefied preplanetesimals collided with other preplanetesimals of similar masses in the forming region of the small bodies. Such fraction can be about 0.45 for classical trans-Neptunian objects.

The model of formation of a TNO binary at a collision of two preplanetesimals is in accordance with various observations of TNO binaries, e.g. with that about 40% of discovered binaries in the trans-Neptunian belt have negative angular momentum.

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Thank you for attention