Angular momenta of rarefied preplanetesimals and formation of small-body binaries

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Abstract

- In recent years, several scientists found new arguments in favor of the formation of rarefied preplanetesimals - clumps in the protoplanetary disk. Some preplanetesimals could collide with each other before they became solid bodies. We found that the angular momentum of two identical rarefied preplanetesimals encountering to their Hill sphere from circular heliocentric orbits exceeded the angular momentum of any observed trans-Neptunian and asteroidal binary which mass equals to the sum of masses of the two preplanetesimals. At the stage of rarefied preplanetesimals, satellites of a small-body could form in two ways: (1) a merger between rarefied preplanetesimals could have two centers of contraction or (2) the formation of satellites from a disk around the primary. The result of the first way would be a binary with two roughly equal masses, which could be separated by any distance up to the Hill radius. For the second scenario, formation of the disk could be caused by that the angular momentum of the rarefied preplanetesimal formed as a result of a collision of two preplanetesimals was greater than the critical angular momentum for a solid body. Material that left the contracted preplanetesimal formed at the collision could form a disk around the primary. One or several satellites of the primary (moving mainly in low-eccentricity orbits) could be formed from this disk at any separation less than the Hill radius. Radii of most collided preplanetesimals in the trans-Neptunian region probably were smaller by at least a factor of several than their Hill radii. The contraction of preplanetesimals could be slower farther from the Sun, which would explain the greater fraction of binaries formed at greater distances from the Sun. Most of rarefied preasteroids could contract into solid asteroids before they collided with other preasteroids.

Introduction

- The binary fractions in the minor planet population are about 2 % for main-belt asteroids, 22 % for cold classical TNOs, and 5.5 % for all other TNOs (Noll 2006).
- 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).
- **In recent years, new arguments in favor of the model of rarefied preplanetesimals - clumps have been found** (e.g. Makalkin and Ziglina 2004, Johansen et al. 2007, Cuzzi et al. 2008, Lyra et al. 2008). These clumps could include meter sized boulders in contrast to dust condensations earlier considered. Sizes of preplanetesimals could be up to their Hill radii.
- **Our studies presented below testify in favor of existence of rarefied preplanetesimals and can allow one to estimate their sizes.**

Scenarios of formation of binaries at the stage of rarefied preplanetesimals

- ***Application of previous solid-body scenarios to preplanetesimals****.* The models of binary formation due to the gravitational interactions or collisions of future binary components with an object (or objects) that were inside their Hill sphere, which were considered by several authors for solid objects, could be more effective for rarefied preplanetesimals. For example, due to almost circular heliocentric orbits, duration of the motion of preplanetesimals inside the Hill sphere could be longer and the minimum distance between centers of masses of preplanetesimals could be smaller than for solid bodies, which usually moved in more eccentric orbits.
- ***Two centers of contraction****.* Some collided rarefied preplanetesimals had a greater density at distances closer to their centers, and **sometimes there could be two centers of contraction inside the preplanetesimal formed as a result of a collision of two rarefied preplanetesimals.**
- For such model**, binaries with close masses separated by a large distance** (up to a radius of a Hill sphere) **and with any value of the eccentricity** of the orbit of the secondary component relative to the primary component **could be formed**. The observed separation distance can characterize sizes of encountered preplanetesimals. *Most of rarefied preasteroids could contract into solid asteroids before they collided with other preasteroids*.

Scenarios of formation of binaries at the stage of rarefied preplanetesimals

- *Excessive angular momentum.* **Formation of some binaries could be caused by that the angular momentum that they obtained at the stage of rarefied preplanetesimals was greater than that could exist for solid bodies. During contraction of a rotating rarefied preplanetesimal, some material could form a** cloud (that transformed into **a disk) of material moved around the primary**. **One or several satellites of the primary could be formed from this cloud*.***
- *The angular momentum of any discovered trans-Neptunian binary is smaller than the typical angular momentum of two identical rarefied preplanetesimals* having the same total mass and encountering up to the Hill sphere from circular heliocentric orbits.
- ***Hybrid scenario.*** Both above scenarios could work at the same time. In this case, it is possible that **besides massive primary and secondary components, there could be smaller satellites moving around the primary** (and/or the secondary) at smaller distances. For binaries formed in such a way, separation distance between main components can be different (e.g. large or small).
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Data presented in the Table

- For six binaries, the angular momentum $\boldsymbol{K_{scm}}$ of the present primary and secondary components (with diameters d_p and d_s and masses m_p and m_s), **the momentum** $K_{s06ps}=\boldsymbol{K_{s\Theta}}=v_\tau\cdot(r_p+r_s)\cdot m_p\cdot m_s/(m_p+m_s)=k_\Theta\cdot(G\cdot M_{Sun})^{1/2}\cdot(r_p+r_s)^2\cdot m_p\cdot m_s\cdot(m_p+m_s)^{-1}\cdot a^{-3/2}$ ($\boldsymbol{v_\tau}$ is the tangential component of velocity v_{col} of collision) **of two collided Hill spheres -preplanetesimals** with masses m_p and m_s ***moved in circular heliocentric orbits*** at $\boldsymbol{k_\Theta}\approx(1-1.5\cdot\Theta^2)=0.6$ (this value of $|k_\Theta|$ characterizes the mean momentum; the difference in semimajor axes equaled to $\boldsymbol{\Theta}\cdot(r_p+r_s)$, r_p+r_s was the sum of radii of the spheres), and the momentum $\boldsymbol{K_{s06eq}}$ of two identical collided preplanetesimals with masses equal to a half of the total mass of the binary components (i.e. to $0.5m_{ps}$, where $m_{ps}=m_p+m_s$) at $k_\Theta=0.6$ are presented in the Table. All these three momenta are considered relative to the center of mass of the system. The resulting momentum of two colliding spheres ***is positive at*** $0<\Theta<(2/3)^{1/2}\approx0.8165$ and ***is negative at*** $0.8165<\Theta<1$. Formulas and other details of calculation of momenta can be found in Ipatov (2010a).
- $\boldsymbol{K_{spin}}=0.2\pi\cdot\chi\cdot m_p\cdot d_p^{\,2}\cdot T_{sp}^{\,-1}$ is the spin momentum of the primary ($\chi=1$ for a homogeneous sphere; $\boldsymbol{T_{sp}}$ is the period of spin rotation of the primary). ***L*** is the distance between the primary and the secondary. In this Table we also present the values of $2L/d_p$ and L/r_{Htm}, where $\boldsymbol{r_{Htm}}$ is the radius of the Hill sphere for the total mass m_{ps} of the binary.
- Three velocities are presented in the last lines of the Table, where $\boldsymbol{v_{\tau pr06}}$ is the **tangential velocity $\boldsymbol{v_\tau}$ of encounter of Hill spheres** at present masses of components of the binary, $\boldsymbol{v_{\tau eq06}}$ is the value of v_τ for encounter of Hill spheres at masses equal to $0.5m_{ps}$ each, and $\boldsymbol{v_{esc\text{-}pr}}$ is the **escape velocity on the edge of the Hill sphere** of the primary.

Table. Angular momenta of several small-body binaries

binary	Pluto	(90842) Orcus	2000 CF_{105}	2001 QW_{322}	(87) Sylvia	(90) Antiope
a, AU	39.48	39.3	43.8	43.94	3.49	3.156
d_p, km	2340	950	170	108?	286	88
d_s, km	1212	260	120	108?	18	84
m_p, kg	1.3×10^{22}	7.5×10^{20}	2.6×10^{18} ?	6.5×10^{17} ?	1.478×10^{19}	4.5×10^{17}
m_s, kg	1.52×10^{21}	1.4×10^{19} for ρ=1.5 g cm^{-3}	9×10^{19} ?	6.5×10^{17} ?	3×10^{15} for ρ=1 g cm^{-3}	3.8×10^{17}
L, km	19,570	8700	23,000	120,000	1356	171
L/r_{Htm}	0.0025	0.0029	0.04	0.3	0.019	0.007
$2L/d_p$	16.9	18.3	271	2200	9.5	3.9
T_{sp}, h	153.3	10			5.18	16.5
K_{scm}, kg·km^2·s^{-1}	6×10^{24}	9×10^{21}	5×10^{19}	3.3×10^{19}	10^{17}	6.4×10^{17}
K_{spin}, kg·km^2·s^{-1}	10^{23}	10^{22}	1.6×10^{18} at T_s=8^h	2×10^{17} at T_s=8^h	4×10^{19}	3.6×10^{16}
K_{s06ps}, kg·km^2·s^{-1}	8.4×10^{25}	9×10^{22}	1.5×10^{20}	5.2×10^{19}	3×10^{17}	6.6×10^{18}
K_{s06eq}, kg·km^2·s^{-1}	2.8×10^{26}	2×10^{24}	2.7×10^{20}	5.2×10^{19}	8×10^{20}	6.6×10^{18}
$(K_{scm}+K_{spin})/K_{s06eq}$	**0.02**	**0.01**	**0.2**	**0.63**	**0.05**	**0.1**
$v_{\tau eq06}$, m·s^{-1}	6.1	2.2	0.36	0.26	2.0	0.82
$v_{\tau pr06}$, m·s^{-1}	**5.5**	**1.8**	**0.3**	**0.26**	**1.3**	**0.82**
$v_{esc\text{-}pr}$, m·s^{-1}	**15.0**	**5.8**	**0.8**	**0.53**	**5.3**	**1.7**

Comparison of angular momenta of present binaries with model angular momenta

- For the binaries presented in the Table, the ratio $\boldsymbol{r_K}=(K_{scm}+K_{spin})/K_{s06eq}$ (i.e., the ratio of the angular momentum of the present binary to the typical angular momentum of two colliding preplanetesimals – Hill spheres moving in circular heliocentric orbits) does not exceed 1. For most of observed binaries, this ratio is smaller than for the binaries considered in the Table. Small values of r_K for most discovered binaries can be due to that **preplanetesimals had already been partly compressed at the moment of collision** (could be smaller than their Hill spheres and/or could be denser for distances closer to the center of a preplanetesimal).
- Petit et al. (2008) noted that most other models of formation of binaries cannot explain the formation of the trans-Neptunian binary **2001 QW$_{322}$**. For this binary we obtained that the equality $K_{s\Theta}=K_{scm}$ is fulfilled at $k_\Theta\approx0.4$ and $v_\tau\approx0.16$ m/s. Therefore in our approach this binary **can be explained** even for circular heliocentric orbits of two collided preplanetesimals.
- *The angular momentum obtained at collisions of two preplanetesimals was of the same order same as that used by D. Nesvorny et al*. (AJ, 2010, 785-793) in their model of gravitational collapse that caused formation of binaries. In their model, momentum must be only positive, though there are observed binaries with negative momentum.

Formation of axial rotation of Pluto and inclined mutual orbits of components

Pluto has three satellites, but the contribution of two satellites (other than Charon) to the total angular momentum of the system is small. To explain Pluto's tilt of 120° and inclined mutual orbit of 2001 QW_{322} components (124° to ecliptic), we need to consider that thickness of a disk of preplanetesimals was at least of the order of sizes of preplanetesimals that formed these systems.

Inclined mutual orbits of many trans-Neptunian binaries testify in favor of that momenta of such binaries were acquired mainly at single collisions of rarefied preplanetesimals, but not due to accretion of much smaller objects (else primordial inclinations of mutual orbits relative to the ecliptic would be small).

It is not possible to obtain reverse rotation if the angular momentum was caused by a great number of collisions of small objects with a larger preplanetesimal (for such model, the angular momentum K_s and period T_s of axial rotation of the formed preplanetesimal were studied by Ipatov 1981a-b, 2000).

Discussion

- In the considered model, **sizes of preplanetesimals comparable with their Hill spheres are needed only for formation of binaries at a separation distance *L* close to the radius r_{Htm} of the Hill sphere (such as 2001 QW_{322})**. **For other binaries** presented in the Table (and for most discovered binaries), the ratio L/r_{Htm} does not exceed 0.04. To form such binaries, **sizes of preplanetesimals much smaller (at least by an order of magnitude) than the Hill radius r_{Htm} are enough**. The observed separation distance *L* can characterize the sizes of contracted preplanetesimals.
- Density of rarefied preplanetesimals was very low, but **relative velocities v_{rel} of their encounters up to Hill spheres** were also very small, and they **were smaller than escape velocities on the edge of the Hill sphere of the primary** (see Table). It is not needed that all encounters up to the Hill sphere resulted in collision of preplanetesimals. It is enough that there were such encounters only once during lifetimes of some preplanetesimals.

Discussion

- For a primary of mass m_p and a much smaller object, both in circular heliocentric orbits,
- $\boldsymbol{v_\tau/v_{esc\text{-}pr}}=k_\Theta\cdot 3^{-1/6}\cdot(M_{Sun}/\boldsymbol{m_p})^{\mathbf{1/3}}\cdot\boldsymbol{a}^{\mathbf{-1}}$ (designations are presented on page 7 in "Data presented in the Table"). This ratio is smaller for greater a and m_p. Therefore, **the capture was easier for more massive preplanetesimals and for preplanetesimals in the trans-Neptunian region than in the asteroid belt.**
- **The ratio of the time needed for contraction of preplanetesimals to the period of rotation around the Sun**, and/or the total mass of preplanetesimals **could be greater for the trans-Neptunian region** than for the initial asteroid belt. **It may be one of the reasons of a larger fraction of trans-Neptunian binaries than of binaries in the main asteroid belt.**
- At greater eccentricities of heliocentric orbits, the probability of that the encountering objects form a new object is smaller (as collision velocity and the minimum distance between centers of mass are greater and the time of motion inside the Hill sphere is smaller) and the typical angular momentum of encounter up to the Hill sphere is greater.
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Conclusions

- The models of binary formation due to the gravitational interactions or collisions of future binary components with an object (or objects) that were inside their Hill sphere, which were considered by several authors for solid objects, could be more effective for rarefied preplanetesimals.
- Some collided rarefied preplanetesimals had a greater density at distances closer to their centers, and sometimes there could be two centers of contraction inside the rotating preplanetesimal formed as a result of a collision of two rarefied preplanetesimals. In particular, binaries with close masses separated by a large distance and with any value of the eccentricity of the orbit of the secondary component relative to the primary component could be formed. The observed separation distance can characterize the sizes of contracted preplanetesimals. Most of rarefied preasteroids could contract into solid asteroids before they collided with other preasteroids.
- Formation of some binaries could have resulted because the angular momentum that they obtained at the stage of rarefied preplanetesimals was greater than that could exist for solid bodies. During contraction of a rotating rarefied preplanetesimal, some material could form a disk of material moving around the primary. One or several satellites of the primary could be formed from this cloud.

Conclusions

Both above scenarios could take place at the same time. In this case, it is possible that besides massive primary and secondary components, there could be smaller satellites moving around the primary (and/or secondary).

The angular momentum of any discovered trans-Neptunian binary is smaller than the typical angular momentum of two identical rarefied preplanetesimals having the same total mass and encountering up to the Hill sphere from circular heliocentric orbits. This difference and the separation distances, which are usually much smaller than radii of Hill spheres, testify in favor of that **most of preplanetesimals had already been partly compressed at the moment of collision.**

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