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Angular momentum of two collided rarefied preplanetesimals and formation of binaries

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Abstract. The mean angular momentum associated with the collision of two celestial objects moving in almost circular heliocentric orbits was studied. The results of these studies were used to develop models of the formation of binaries at the stage of rarefied preplanetesimals. The models can explain a greater fraction of binaries formed at greater distances from the Sun. Sometimes there could be two centers of contraction inside the rotating preplanetesimal formed as the result of a collision between two rarefied preplanetesimals. Such formation of binaries could result in binaries with almost the same masses of components separated by a large distance. Formation of a disk around the primary could result because the angular momentum that was obtained by a rarefied preplanetesimal formed by collision was greater than the critical angular momentum for a solid body. One or several satellites of the primary could be formed from the disk.

Keywords. Minor planets, asteroids; Kuiper Belt; solar system: formation

1. Introduction

In recent years, new arguments in favor of the model of rarefied preplanetesimals – clumps were made (e.g., Cuzzi *et al.* 2008, Johansen *et al.* 2007, Lyra *et al.* 2008). Even before new arguments in favor of formation of planetesimals from rarefied preplanetesimals were developed, Ipatov (2001, 2004) considered that some trans-Neptunian objects (TNOs), planetesimals, and asteroids with diameter $d > 100$ km could be formed directly by the compression of large rarefied preplanetesimals, but not by the accretion of smaller solid planetesimals. Some smaller objects (TNOs, planetesimals, asteroids) could be debris from larger objects, and other smaller objects could be formed directly by compression of preplanetesimals. There are several hypotheses of formation of binaries for a model of solid bodies (e.g., Petit *et al.* 2008, Richardson & Walsh 2006, Walsh *et al.* 2008). Ipatov (2004) supposed that a considerable fraction of trans-Neptunian binaries could be formed at the stage of compression of rarefied preplanetesimals moving in almost circular orbits. Based on analysis of the angular momentum of two collided rarefied preplanetesimals, Ipatov (2009a-b) studied models of the formation of binaries at the stage of the preplanetesimals.

2. Angular momentum of two collided rarefied preplanetesimals

Previous papers devoted to the formation of axial rotation of forming objects considered mainly a model of solid-body accumulation. Besides such model, Ipatov (1981a-b, 2000, 2009b) also studied the formation of axial rotation for a model of rarefied preplanetesimals. He presented the formulas for the angular momentum of two collided rarefied

Table 1. Angular momenta of several binaries.

binary	Pluto	(90842) Orcus	2000 CF_{105}	2001 QW_{322}	(90) Antiope
a, AU	39.48	39.3	43.8	43.94	3.156
d_p, km	2340	950	170	108?	88
d_s, km	1212	260	120	108?	84
m_p, kg	1.3×10^{22}	7.5×10^{20}	2.6×10^{18}?	6.5×10^{17}?	4.5×10^{17}
m_s, kg	1.52×10^{21}	1.4×10^{19} for $\rho = 1.5$	9×10^{17}?	6.5×10^{17}?	3.8×10^{17}
L, km	19,750	8700	23,000	120,000	171
L/r_H	0.0025	0.0029	0.04	0.3	0.007
T_{sp}, h	153.3	10			16.5
K_{scm}, kg km^2 s^{-1}	6×10^{24}	9×10^{21}	5×10^{19}	3.3×10^{19}	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	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}	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}	6.6×10^{18}
$(K_{scm} + K_{spin})/K_{s06ps}$	0.07	0.2	0.3	0.63	0.1
$(K_{scm} + K_{spin})/K_{s06eq}$	0.02	0.01	0.2	0.63	0.1

preplanetesimals – Hill spheres (with radii r_1 and r_2 and masses m_1 and m_2) moved in circular heliocentric orbits. At a difference in their semimajor axes a equaled to $\Theta(r_1+r_2)$, the angular momentum is $K_s = k_\Theta (G \cdot M_S)^{1/2}(r_1+r_2)^2 m_1 m_2 (m_1+m_2)^{-1} a^{-3/2}$, where G is the gravitational constant, and M_S is the mass of the Sun. At $r_a = (r_1+r_2)/a \ll \Theta$, one can obtain $k_\Theta \approx (1 - 1.5\Theta^2)$. The mean value of k_Θ equals to 0.6. Mean positive values of k_Θ and mean negative values of k_Θ are equal to 2/3 and -0.24, respectively. The values of K_s are positive at $0 < \Theta < 0.8165$ and are negative at $0.8165 < \Theta < 1$.

For homogeneous spheres at $k_\Theta = 0.6$, $a = 1$ AU, and $m_1 = m_2$, the period of axial rotation $T_s \approx 9 \cdot 10^3$ hours for the rarefied preplanetesimal formed as a result of the collision of two preplanetesimals – Hill spheres, and $T_s \approx 0.5$ h for the planetesimal of density $\rho = 1$ g cm^{-3} formed from the preplanetesimal. For greater a, the values of T_s are smaller (are proportional to $a^{-1/2}$). Such small periods of axial rotations cannot exist, especially if we consider bodies obtained by contraction of rotating rarefied preplanetesimals, which can lose material easier than solid bodies. For $\rho = 1$ g cm^{-3}, the velocity of a particle on a surface of a rotating spherical object at the equator is equal to the circular and the escape velocities at 3.3 and 2.3 h, respectively.

For five binaries, the angular momentum 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} of two collided preplanetesimals with masses of the binary components moved in circular heliocentric orbits at $k_\Theta = 0.6$, and the momentum K_{s06eq} of two identical collided preplanetesimals with masses equal to a half of the total mass of the binary components 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. K_{spin} is the spin momentum of the primary. L is the distance between the primary and the secondary, r_H is the radius of the Hill sphere, and T_{sp} is the period of spin rotation of the primary.

3. Models of formation of binaries

For circular heliocentric orbits, two objects that entered inside the Hill sphere could move there for a longer time than those entered the sphere from eccentric heliocentric orbits. The diameters of preplanetesimals were greater than the diameters of solid planetesimals of the same masses. Therefore, 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 studied by several authors for solid objects, could be more effective for rarefied preplanetesimals.

We suppose that 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 with velocity greater than the circular velocity could have formed a cloud (that transformed into a disk) of material that moved around the primary. One or several satellites of the primary could be formed from this cloud. Some material could leave the Hill sphere of a rotating contracting planetesimal, and the mass of an initial rotating preplanetesimal could exceed the mass of a corresponding present binary system. Due to tidal interactions, the distance between binary components could increase with time, and their spin rotation could become slower. For the discussed model of formation of binaries, the vector of the original spin momentum of the primary was approximately perpendicular to the plane where the secondary component (and all other satellites of the primary) moved. It is not necessary that this plane was close to the ecliptic if the difference between the distances from centers of masses of collided preplanetesimals to the middle plane of the disk of preplanetesimals was comparable with sizes of preplanetesimals. Eccentricities of orbits of satellites of the primary formed in such a way are usually small. As it was shown by Ipatov (2009b), the critical angular momentum could be attained as a result of a collision of two identical asteroids of any radii ($<$6000 km). At the same eccentricities of heliocentric orbits and $m_1/m_2 = \text{const}$, the probability to attain the critical momentum at a collision is greater for smaller values of m_1 ($m_1 \geqslant m_2$) and a.

Some collided rarefied preplanetesimals had a greater density at distances closer to their centers. It might be possible that sometimes there were two centers of contraction inside the rotating preplanetesimal formed as a result of a collision of two rarefied preplanetesimals. Such formation of binaries could result in binaries with almost the same masses of components separated by a large distance. It could be also possible that the primary had partly contracted when a smaller object (objects) entered into the Hill sphere, and then the object was captured due to collisions with the material of the outer part of the contracted primary. For such a scenario, a satellite can be formed at any distance (inside the Hill sphere) from the primary. The eccentricity of the mutual orbit of components can be any (small or large) for the model of two centers of contraction.

For the binaries presented in the Table, the ratio $r_K = (K_{scm} + K_{spin})/K_{s06eq}$ is smaller than 1. Small values of r_K for most discovered binaries can be due to that preplanetesimals already had been partly compressed at the moment of collision.

At $K_s = \text{const}$, T_s is proportional to $a^{-1/2}\rho^{-2/3}$. Therefore, for greater a, more material of a contracting rotating preplanetesimal was not able to contract into a primary and could form a cloud surrounding the primary (or there were more chances that there were two centers of contraction). This can explain why binaries are more frequent among TNOs than among large main-belt asteroids, and why the typical mass ratio of the secondary to the primary is greater for TNOs than for asteroids. Longer time of contraction of rotating preplanetesimals at greater a (for dust condensations, this was shown by several authors, e.g. by Safronov) could also testify in favor of the above conclusion. Spin and form of an object could change during evolution of the Solar System.

Ipatov (2009b) discussed the possibility of a merger of two rarefied preplanetesimals and the formation of highly elongated small bodies by the merger of two (or several) partly compressed components.

4. Conclusions

Some trans-Neptunian objects could have acquired their primordial axial momenta and/or satellites at the stage when they were rarefied preplanetesimals. Most rarefied preasteroids could have become solid asteroids before they collided with other preasteroids. Some collided rarefied preplanetesimals could have greater densities at locations that are closer to their centers. In this case, there sometimes could be two centers of contraction inside the rotating preplanetesimal formed as a result of the collision of two rarefied preplanetesimals. Such contraction could result in binaries with similar masses separated by any distance inside the Hill sphere and with any value of the eccentricity of the orbit of the secondary component relative to the primary component. The observed separation distance can characterize the radius of a greater encountered preplanetesimal.

The formation of some binaries could have resulted because the angular momentum of a binary that was obtained at the stage of rarefied preplanetesimals was greater than the angular momentum that can exist for solid bodies. Material that left a contracted preplanetesimal formed as a result of a collision of two preplanetesimals could form a disk around the primary. One or more satellites of the primary could be grown in the disk at any distance from the primary inside the Hill sphere, but typical separation distance is much smaller than the radius of the sphere. The satellites moved mainly in low eccentric orbits. Both of the above scenarios could have taken place at the same time. In this case, it is possible that, besides massive primary and secondary components, smaller satellites could be moving around the primary and/or the secondary.

For discovered trans-Neptunian binaries, the angular momentum is usually considerably 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 conclusion is also true for preplanetesimals with masses of components of considered trans-Neptunian binaries. The above difference in momenta and the separation distances, which usually are much smaller than the radii of Hill spheres, support the hypothesis that most preplanetesimals already had been partly compressed at the moment of collision, i.e. were smaller than their Hill spheres and/or were denser at distances closer to the center of a preplanetesimal. The contraction of preplanetesimals could be slower farther from the Sun, which can explain the greater fraction of binaries formed at greater distances from the Sun.

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