THE ORIGIN AND ROTATION OF BINARY ASTEROIDS

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Binary asteroids were detected in a variety of dynamical populations, including Near-Earth Asteroids (NEAs), the main belt (MB), Trojans, and transneptunian objects (TNO). We discuss a new "multi-impact" model for origin of all classes of binary objects, including binary asteroids, Pluto–Charon, and the Earth–Moon systems. Basic elements of the model is the effective accumulation of multi-impact meteoritic ejecta in satellite orbits due to the collisional interaction between impact debris and initial low-massive ring around the primary body. The origin of satellites of all small planets in the Solar System is a result of numerous meteoritic impacts on a rotated small planet and accumulation of meteoritic ejecta around the primary body. An important prediction from the new model is that asteroids with satellites rotate faster than single asteroids. The model is confirmed by comparisons of spin rates of binary asteroids and single objects. Average spin rate for main-belt asteroid is 2.45 ± 0.05 rev/d (single objects) and 4.51 ± 0.21 rev/d (13 binary objects); direction of rotation of satellites is prograde only (three samples). Average spin rate for NEAs is 2.72 ± 0.26 rev/d (single objects) and 9.28 ± 0.25 rev/d (19 binary objects).

INTRODUCTION

Pioneering observations of several binary asteroids were conducted by Prokof'eva's team in the Crimean Astrophysical Observatory (see review by Prokof'eva *et al.* [9]). Understanding how binary asteroids are formed is essential because models of their formation may also provide important clues to the origin of the Moon and other planetary satellites. There are several theories seeking to explain the origin of binary systems: binary encounters in dissipative media [10], mega-impacts [5]; tidal breakup for binary NEAs [1]; triple encounters [15] or dynamical friction and three-body encounters [3] for binary TNO. All these theoretical models are not universal. The transneptunian binaries cannot be a result of binary catastrophic collisions in the present dynamical environment of the Kuiper belt. The origin of satellites of main-belt asteroids cannot depend on tidal splitting during a close encounter with a planet. The triple encounters cannot create the binary NEAs.

As discussed by Prokof'eva *et al.* [9], the formation of asteroid satellites should be considered from the point of view of a general theory of satellite system formation. Also, the presence of protosatellite discs around the smallest asteroids is not excluded. The formation of asteroid satellites to revolve mainly in the prograde direction can be expected due to possible cosmogonical connection between the central body rotation and satellites.

The "multi-impact" universal mechanism for the origin of satellites of all planets with solid surfaces, including binary asteroids was discussed by Gorkavyi [4].

MULTI-IMPACT MODEL FOR THE ORIGIN OF BINARIES

From our point of view, we cannot consider the origin of satellites of giant planets and small planets within a single model. The critical parameter for splitting population of planets into two different groups is a ratio of the orbital velocity of a planet and the escape velocity from a planet. This ratio is much smaller than 1 for giant planets (Jupiter, Saturn, Uranus, and Neptune) and much larger than 1 for all other smaller planets, TNO, and asteroids. Our new model considers the existence of double planets (the Earth–Moon, Pluto–Charon) and binary asteroids as a general rule. The basic elements of the model are:

1. Initial low-mass protosatellite swarm or disc was formed around an Earth-like planet (or an asteroid) due to collisions of particles from heliocentric orbits [11]. The volume of prograde meteoritic ejecta from planetary surface is larger than retrograde debris volume due to rotation of the planet and strong dominance of initial prograde discs can be expected (in specific circumstances, initial retrograde discs can not be excluded).

2. Incoming meteoroidal flux has the velocity higher than the escape velocity from the planetary surface and the large part of meteoritic ejecta has highly eccentric or hyperbolic orbits.
3. Collisions of meteoritic ejecta with particles of initial low-mass protosatellite disc or a swarm are a key factor for collection of debris in stable orbits. It is easy to show that meteoritic ejecta effectively joined to protosatellite disc after collisions with small particles that have similar direction of rotation. Ejecta with opposite rotation fall into primary body or transit to heliocentric orbits. As a result of such dynamical mechanism, a protosatellite disc accumulates mass and angular momentum of ejecta with same direction of rotation and a planet collects ejecta with opposite rotation. An asteroid with a large prograde satellite can decrease initial angular momentum up to reverse rotation. A planet with a retrograde satellite will increase speed of rotation.
4. Calculations of ballistic transfer of angular momentum show that protosatellite ring must have the optimal radius that is close to average semi-major axis of ejecta orbits: impact ejecta push away the ring with radius smaller than semi-major axis of ejecta and decrease momentum of the ring with radius larger than semi-major axis of orbits of meteoritic ejecta (such ballistic drift for Uranian rings was studied by Fridman and Gorkavyi [2]).
5. Effective accumulation of meteoritic ejecta around an asteroid lead to formation of a massive disc and following accretional origin of a satellite in a near-circular orbit.
6. After formation, a satellite experienced long-term ejecta bombardment and origin of craters.
7. The origin of a triple asteroidal system by this mechanism is also possible.

Conclusion from this scenario for the Earth–Moon system is the following: most of the Moon's material was delivered from the Earth's mantle by many impacts of about ∼1–100-km asteroids. This explains low-iron chemical composition of the Moon as in the Hartmann–Davis giant impact model. Our multi-impact model can solve many the outstanding difficulties that remain with the giant impact scenario for the formation of the Moon, including problematic predictions of a completely molten Moon and the existence of a magma ocean on the Earth (Stewart [14]; Spudis [12]). Also, a flux of asteroidal ejecta from the Earth to the new-born Moon can explain mysterious dichotomy of terrain: dark maria dominant on the visible side of the Moon and the Moon's far side lacks maria almost completely [13].

Testable predictions from the universal multi-impact model under consideration are:

a. Most of asteroids with satellites must have a faster rotation than single asteroids;
b. Most satellites of asteroids must have circular orbits that close to equator of central body or to ecliptic plane (for enough large planet like the Earth). Prograde orbits must dominate over retrograde. Three samples of prograde satellites from the main belt of asteroids and three planetary systems with prograde satellites like the Moon–Earth and Charon–Pluto support the prediction on dominance of prograde orbits. Besides, circular orbits were determined for several asteroidal satellites.
c. Craters' dichotomy (larger number of craters on near sides of bodies) must be typical for Charon, Pluto, and components of minor planets with the rotation that synchronized with the mutual orbital motions.
d. The Moon must have chemical, isotopic and geological signatures of many different ejecta from the Earth's mantle.

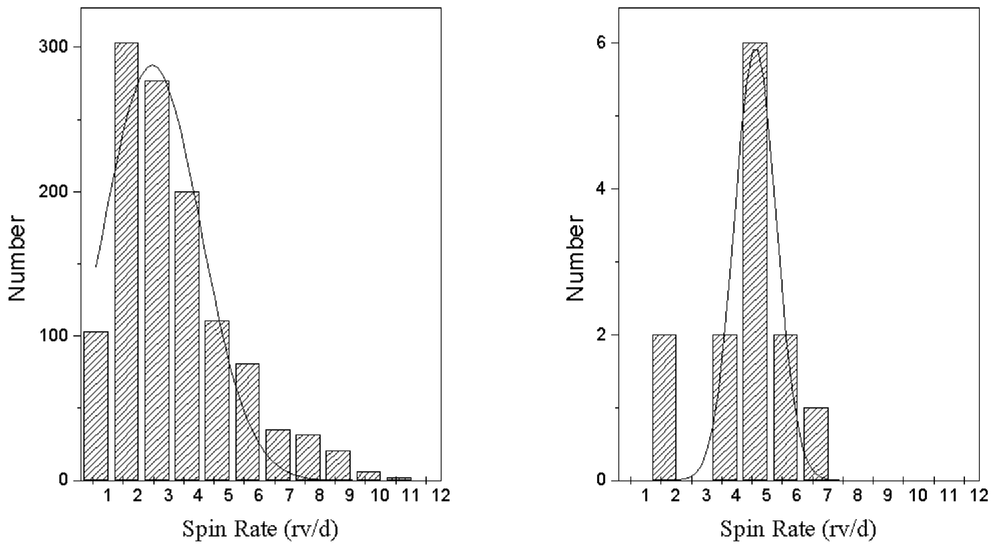
OBSERVATIONAL TEST OF MULTI-IMPACT MODEL

Average spin rates of single asteroids and binary systems from populations of the main belt and NEAs were compared for testing the first point of predictions of proposed multi-impact model. We used the data on 57 binary asteroids from the site by Wm. Robert Johnston ([`http://www.johnstonsarchive.net/astro`], updated September 8, 2004). They include the following: 21 main-belt asteroids, 22 NEAs, 12 TNOs, one Mars-crosser (asteroid 5407) and one Trojan asteroid (asteroid 617). We considered Mars-crosser 5407 together with population of binary NEAs, and Trojan 617 with binary MB asteroids.

Periods of rotation of primary bodies were determined for 13 binary MB asteroids with enough high accuracy, periods for two MB binaries can be wrong (the code is 1), and for other seven objects are unknown. Rotation periods of larger bodies from population of binary NEAs were not determined for three asteroids and asteroid 1998 ST27 has the code 1. Spin rates for binary asteroids from TNO population are almost unknown (periods were determined for two TNO binaries only). TNOs were not used for test of the multi-impact model.

The database by A. Harris [`http://cfa-www.harvard.edu/iau/lists`] was used for study of the distribution of spin rates of single asteroids. For analysis, 1171 objects of the main belt and 203 of NEAs were selected. These subsets contain asteroids with different diameters. We excluded objects, whose periods have the code less than 2, as well as very slow (the periods $T \geq 100$ hr) and very fast (the periods $T < 2$ hr) rotators, which usually have a very small diameter ($D < 0.15$ km).

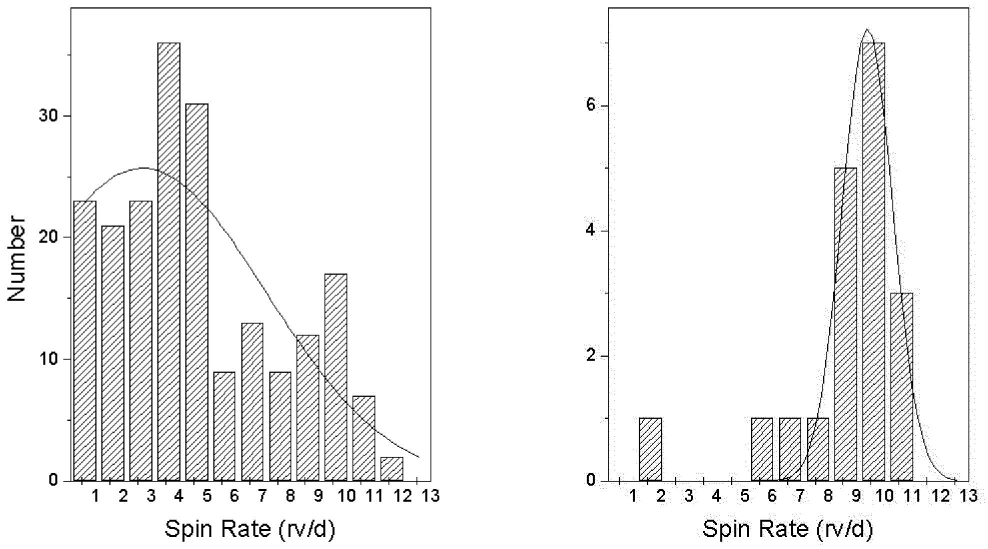
The histograms of spin rates for single and binary asteroids from the main belt and NEAs are shown in Fig. 1 and Fig. 2, respectively. Mean spin rates were found by fitting these histograms to Gaussian curves.



a) single asteroids

b) binary asteroids

Figure 1. Histograms of spin rates for main-belt asteroids: (a) single asteroids (1171), average spin rate is 2.45 ± 0.05 rev/d; (b) binary asteroids (13), average spin rate is 4.51 ± 0.21 rev/d



a) single asteroids

b) binary asteroids

Figure 2. Histograms of spin rates for NEAs: (a) single asteroids (203), average spin rate is 2.72 ± 0.26 rev/d; (b) binary asteroids (13), average spin rate is 9.28 ± 0.25 rev/d

The comparison of the histograms for single and for binary asteroids shows their drastic differences. Binary asteroids have vastly greater rotation rates, than single. Single asteroids of the main belt have a mean spin rate of 2.45 ± 0.05 rev/d and primary body of MB binary systems of 4.51 ± 0.21 rev/d. Mean spin rate for single asteroids in NEAs population is 2.72 ± 0.26 rev/d and for binaries 9.28 ± 0.25 rev/d.

The values of differences of the mean rotation rates of single asteroids and primary bodies of binary systems are 2.05 rev/d and 6.56 rev/d for asteroids from MB and NEAs, respectively. These differences are nine times or more as great as the standard deviation, *i.e.*, they are noticeably higher than standard 3 confidence level. We suppose that such significant differences between spin rates can not be explained by any effects of observational selection. For example, it is well known that small asteroids rotate faster than large asteroids [6] but known binary asteroids from the main belt are large bodies with diameter $D \geq 100$ km and not belong to the population of fast small rotators. It is interesting that in populations of binary asteroids of MB and NEAs slow rotators with period longer than a day are not found.

In the large review on rotation of asteroids, Pravec *et al.* [6] note that binary systems in inner-planet-crossing orbits are characterized by fast spin of their primaries with diameter $0.15 < D < 10$ km. Fast rotation of binaries in NEAs is discussed by Pravec *et al.* [7, 8] as well.

CONCLUSION

From comparison of the rotation periods for single asteroids and binaries of the main belt and NEAs, we can make a conclusion that binary asteroids have considerably greater spin rates than single minor planets. This observational fact confirms multi-impact mechanism for the origin of binary asteroids discussed by Gorkavyi [4] and imposes serious restrictions on other possible theoretical models for the formation of asteroid satellites.

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