Icy Bodies of the Solar System
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On the Origin of Retrograde Orbit Satellites around Saturn and Jupiter

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Abstract. Many Retrograde Orbit Satellites around Jupiter and Saturn have been found recently. Most of them are small with irregular shapes. They are farther from the planet than regular satellites. Their orbits have big eccetricities.

We tested their dynamical origin and found:

1. The small bodies can be captured by normal satellites and form retrograde orbits. But these orbits are not stable. Sooner or later, they would escape from planetary region or fall down into the planets.

2. Another way is that they have formed by collisions just after regular moons formed. We studied the mechanism and obtained good results.

Keywords. Solar System, planets and satellites: formation.

1. Introduction

Jupiter and Saturn have 63 (R = 48) and 61 (R = 29) moons, respectively (Figure 1, or http://ssd.jpl.nasa.gov). "R" is the number of retrograde orbits (dark colour in Figure).

We list retrograde irregular moons of Saturn on table 1 and put a photo of Phoebe - biggest irregular moon (Figure 1, right side) here. We also list prograde irregular moons on the table since they have irregular shapes and big i and e.

From the table and Figures we can see:

(1) Normal moons are very close to their planets and with regular orbits (small i, e). They have regular shapes (ball).

(2) Irregular moons are far from their planets with irregular shapes.

(3) Retrograde irregular moons mostly are far from their planet. They are located about half of the radius of planetary activity sphere and their orbits are near planetary orbital plane (few near 145°, most > 165°).

(4) Prograde irregular moons are closer than retrograde irregular moons, about 25% of radius of planetary activity sphere. Their inclinations are big, mostly about 45°.

Normal moons have formed by accretion. This is why they have regular shapes and regular orbits. Irregular moons cannot form by normal process as normal moons. We suppose that they were from outer solar system.

2. Test and problems of capture process

In an early work (Zheng 1994), we proved that short period comets were captured when they came from Oort cloud (or Kuiper belt) by close encounters with planets. The capture process of moons can be similar when small bodies come into planetary activity sphere (see Figure 2).

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Table 1. Irregular moons of Saturn

Name	$a(km)$	$i(°)$	e	**size(km)**					
Kiviuq	11111000	45.71	0.334	16	Jarnsaxa	18811000	163.3	0.216	6
Ijiraq	11124000	46.44	0.316	12	Narvi	19007000	145.8	0.431	7
Phoebe	12944300	174.8	0.164	240	Bergelmir	1933800	158.5	0.142	6
Paaliaq	15200000	45.13	0.364	22	Suttungr	19459000	175.8	0.114	7
Skathi	15541000	152.6	0.270	8	Hati	19856000	165.8	0.372	6
Albiorix	16182000	33.98	0.478	32	Bestla	20129000	145.2	0.521	7
Bebhionn	17119000	35.01	0.469	6	Farbauti	20390000	156.4	0.206	5
Erriapo	17343000	34.62	0.474	10	Thrymr	20474000	176.0	0.470	7
Siarnaq	17531000	45.56	0.295	40	Aegir	20735000	166.7	0.252	6
Skoll	17665000	161.2	0.464	6	Kari	22118000	156.3	0.478	7
Tarvos	17983000	33.82	0.531	15	Fenrir	22453000	164.9	0.136	4
Tarqeq	18009000	46.09	0.160	7	Surtur	22707000	177.5	0.451	6
Greip	18206000	179.8	0.326	6	Ymir	23040000	173.1	0.335	18
Hyrrokkin	18437000	151.4	0.333	8	Loge	23065000	167.9	0.187	6
Mundilfari	18685000	167.3	0.210	7	Fornjot	25108000	170.4	0.206	6
Unnamed	Irregular	moons							
S/2004 S07	19800000	165.1	0.580	6	S/2006 S1	18981135	154.2	0.130	6
S/2004 S12	19650000	164.0	0.401	5	S/2006 S3	21132000	150.8	0.471	6
e S/2004 S13	18450000	167.4	0.273	6	S/2007 S2	16560000	176.7	0.218	6
e S/2004 S17	18600000	166.6	0.259	4	S/2007 S3	20518500	177.2	0.130	5

Notes: We put some prograde orbit moons on the table since they are also "Irregular" by shapes and big e.

Retrograde orbit moons can be captured by normal moons of the planets, but these orbits always cross the orbits of normal moons, then sooner or later, they would have new close encounters which could cause them to escape. These orbits are not stable. In other words, if retrograde orbit moons were captured by inner moons of Saturn, they can be the transfer source of short period comets, but they may not become into stable orbits as current retrograde moons we see now.

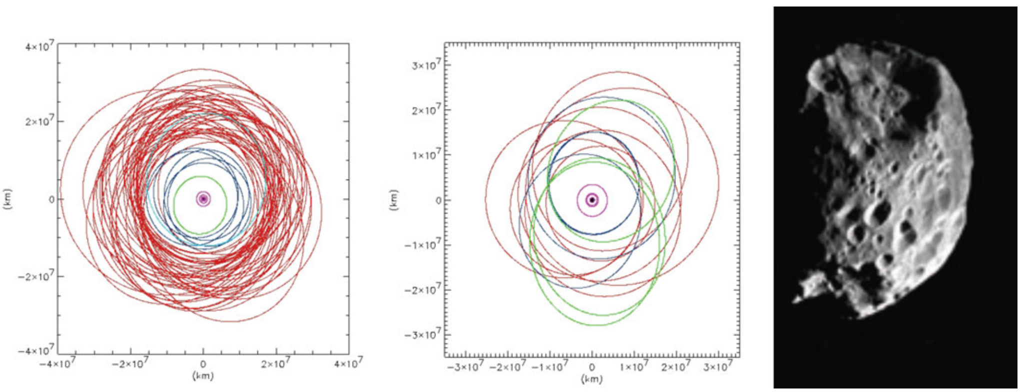

Figure 1. Jupiter and Saturn's Known Satellites Phoebe (by Cassini)

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3. Collision process – formation of retrograde orbits

Now, we study retrograde moons of Saturn (similar for Jupiter). Since current orbits of retrograde moons are stable, they might form by another way at early time after Saturn formed. At that time, around Saturn's orbit, still there were some planetesimals, and around Saturn, after normal moons formed, many small bodies remained also. When these two kinds bodies met in Saturn's activity area, the relative motion between them were opposite: planetesimals were 'retrograde" and small bodies around Saturn were prograde, when they collided or combined with each other, some retrograde moons could form.

Let's consider a small body moves with a planet, the planet moves on a circular orbit and small body has eccentricity 0.1:$a_p = 1, e_p = 0, a_s = 1, e_s = 0.1$.

In Figure 3, left side is the orbits of planet and the small body in a fixed coordinate, right side is the orbits on a rotating coordinate. In a rotating coordinate, the small body moves around the planet looks like a satellite but moves on a retrograde direction.

The activity sphere of Saturn is

$$m_s^{0.4} * a_s = 0.0382 * 9.555AU = 0.365AU = 5.5 * 10^7 km$$

Most retrograde orbits are located about half of this value.

Suppose a prograde moon moves in a circular orbit with $a = 0.2AU$, the orbital velocity is

$$V_m = \sqrt{m_s/0.2} * V_e = 1.13km/sec$$

.

A particle with $a = a_s$ and $e < 0.038$ moves on saturn's orbital plane would come into the activity sphere. Saturn's orbital velocity is $9.65km/sec$, an orbit with $e = 0.02$ at perihelion ($q = a_s - 0.2AU$) would have a relative velocity (to Saturn) about $0.2km/sec$. When this particle arrives into activity sphere at $r = 0.2AU$, its velocity is about $1.15km/sec$. A little more than the circular orbital velocity but on a retrograde direction.

If this "retrograde" body collided by the prograde satellite (in different orientations), their relative velocity can be reduced, and one of them could become a retrograde satellite.

4. Collision probability

Suppose we have two particles with r = 10km. One particle moves in Saturn's activity sphere and another moves as a quasi-satellite around Saturn. When a quasi-satellite comes into Saturn's activity sphere, in one revolution, the collision probability is

$$p_{revo} = (2r)^3/R_{act}^3 = 5 * 10^{-19}$$

where $R_{act} = 0.365AU = 5.5 * 10^7 km$

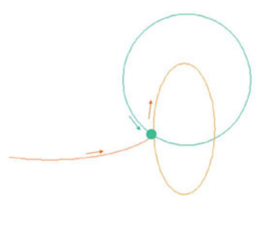

Figure 2. Sketch of a capture process

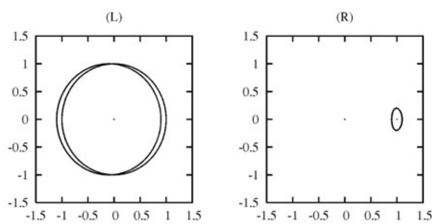

Figure 3. Quasi-satellite

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Table 2. First results from simulation

Test	c	$a(10^7 km)$	$i(°)$	e
1	0.2	1.895	171.3	0.159
1	0.2	2.121	176.3	0.122
1	0.2	2.154	170.6	0.085
1	0.2	2.429	179.5	0.198
2	0.5	2.620	169.0	0.419
2	0.5	2.936	167.1	0.405

At the planetary and satellite system formation time, there are billions small bodies (Titan is about 1.3E8 greater than a r = 10km small body) .

The number of collisions should be multiplied by

$$N_{particle1} * N_{particle2} * N_{revolution}.$$

Let't put

$N_{particle1} = 1 * 10^8$, $N_{particle2} = 1 * 10^9$, $N_{revolution} = T/30yr = 3 * 10^7/30 = 1 * 10^6$,
Then

$$N_{collision} = p * N_{particle1} * N_{particle2} * N_{revolution} = 5 * 10^4$$

Of course this is not very accurate, but not very far from real process.

5. Simulation

In simulation, we set a planet as Saturn revolves around the Sun. Put 10^n $(n=5)$ particles around Saturn with random orbital elements (small i, e in Saturn's activity sphere, put $10 \cdot 10^n$ particles (quasi-satellites) move in similar orbits as Saturn but with $0 < e < 0.038$. We check the condition for impacts (collision coefficient $c = 0.2 - 0.5$, $\Delta V_{new} = c \cdot \Delta V_{old}$ along the centers of two bodies) and obtain a few retrograde satellite orbits (They are all from quasi-satellites). We will simulate Large N in order to obtain more results.

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