Formation of the Jovian and Saturnian satellite systems

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ABSTRACT

The Jovian satellite system consists of four Galilean satellites with similar masses that are trapped in mutual mean motion resonances with negligibly small other satellites, while the Saturnian satellite system has only one big body, Titan, with other satellites of two order of magnitude smaller mass. Here we explain the origin of the difference by simulating growth and orbital evolution of proto-satellites in an accreting proto-satellite disk model that is combined with the idea of different termination timescales of gas infall between Jupiter and Saturn based on a planet formation model. We show that in the case of the Jovian system, a few similar-mass satellites are likely to remain in mean motion resonances, the configuration of which is formed by type-I migration, temporal stopping of the migration near the disk inner edge, and quick truncation of gas infall by gap opening in the Solar nebula. The Saturnian system tends to end up with one dominant body in the outer regions caused by the slower decay of gas infall associated with global depletion of the Solar nebula. The compositional zoning of the predicted satellite systems is consistent with the observed satellite systems.

1. Jovian/Saturnian Satellite Systems

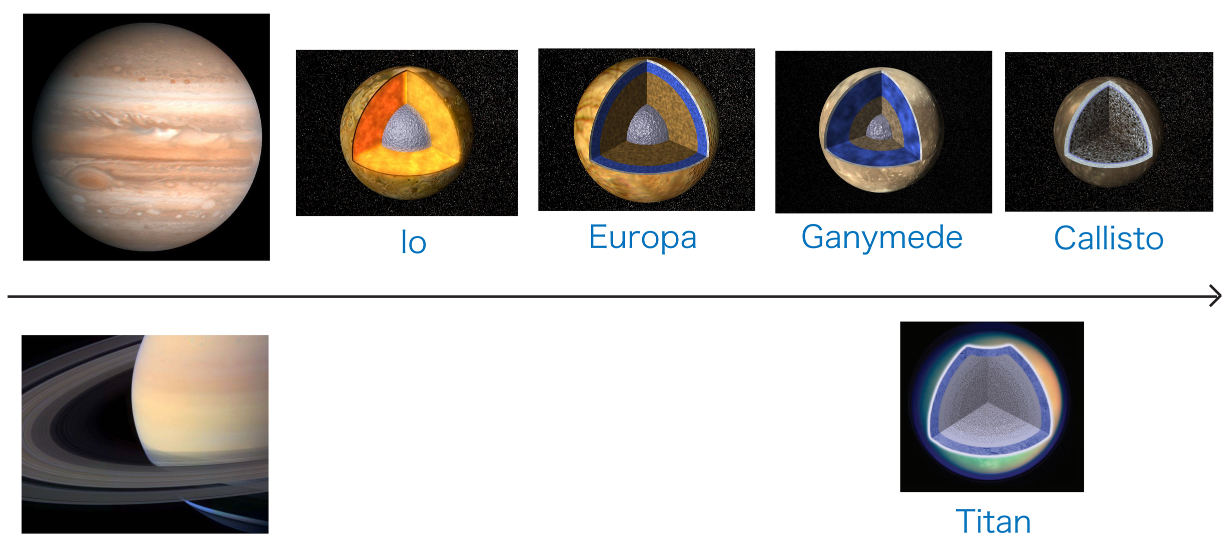


Table 1
Satellite Properties

Satellite	a/R_p	M/M_p (10^{-5})	ρ (g cm^{-3})	C/MR^2
Io	5.9	4.70	3.53	0.378
Europa	9.4	2.53	2.99	0.346
Ganymede	15.0	7.80	1.94	0.312
Callisto	26.4	5.69	1.83	0.355
Titan	20.3	23.7	1.88	0.34

Note. Source: Schubert et al. (2004); Iess et al. (2010).

From left to right, semimajor axis, mass, density and axial moments inertia are shown.

- The difference of the mean density:
  Io, Europa are rocky satellites, Ganymede and Callisto are icy satellites.
- The difference of the axial moments of inertial:
  Io, Europa and Ganymede are differentiated,
  Callisto and Titan are undifferentiated.
- Galilean satellites are trapped in mutual mean motion resonances (MMR).
- Saturn has only one big icy satellite, while Jupiter has four.

The origin of the differences should be explained

2.1. Cirumplanetary Disk Model

Actively-supplied accretion disk [Canup & Ward, 2002, 2006]

- Satellites are formed in the circum-planetary disk
- Gas and small solids from heliocentric orbits flow into the disk across a region ~30 Rp
- The temperature of the proto-satellite disk is determined by a balance between viscous heating and blackbody radiation from the photosurface
- The surface density of solid materials is determined by a balance between infall and removal due to accretion by proto-satellites and their migration

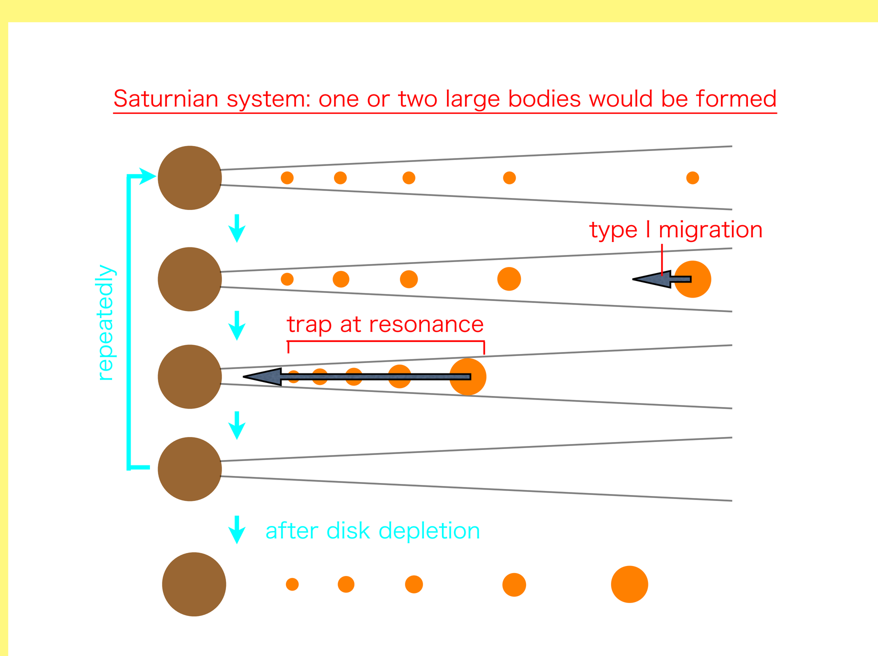
2.2. Satellite Formation Model

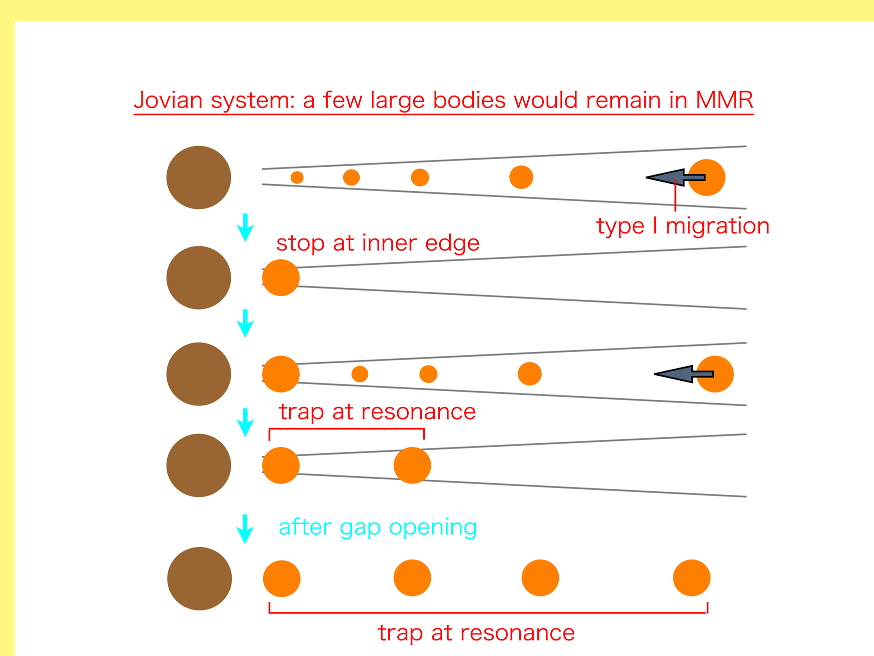
Accretion and migration [Ida & Lin, 2004, 2008]

- Type I migration and re-generation of proto-satellites in the regions out of which preceding runaway bodies have migrated leaving many small bodies
- Resonant trapping for migrating proto-satellites, and migrating together keeping the ratio of semimajor axes of mutual mean motion resonances
- (For Jovian system)The total mass of the trapped satellites at inner edge cannot exceed the mass of the disk in the range in which density waves carry angular momentum

Infall to Saturn would continue until the proto-planetary disk was globally depleted. The global proto-planetary disk depletion timescale is 1~10 Myr.
→ Saturnian satellite system must be the survivors against type I migration in the final less massive disk.

In late stages with a less massive disk, non-truncated boundary without cavity would be formed at the inner boundary.





Infall to Jupiter would be truncated by a gap opening in the proto-planetary gas disk by perturbations of Jupiter. After the gap opening, the proto-satellite disk would be depleted on their viscous diffusion timescale (~1000 yr).
→ Jovian satellite system must be the frozen configuration formed in a relatively massive disk at the sudden disk depletion.

In early stages with a massive disk and high accretion rate, truncated boundary with cavity due to coupling between a disk and planetary magnetic field would be formed at the inner boundary.

Migrating satellites from outer regions would shepherd inner ones to sweep them up to the host planet. This process repeats until disk gas is so depleted that type I migration becomes no more effective. Consequently, one or two bodies would remain in relatively outer regions.

Type I migration would be halted near the inner edge. So, several large bodies would be trapped in mutual mean motion resonances (MMR), and the configuration would remain after the disk depletion.

3. Results - Monte Carlo Simulations

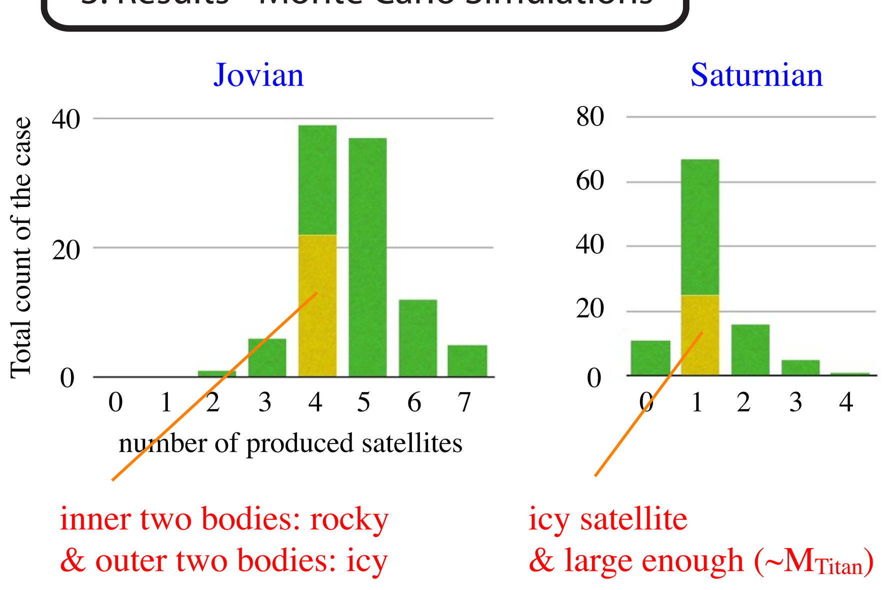


Fig 1. Produced large satellites numbers resulted from100 simulations for each system. Yellow parts show the runs that the produced satellite systems are analogous to the real one.

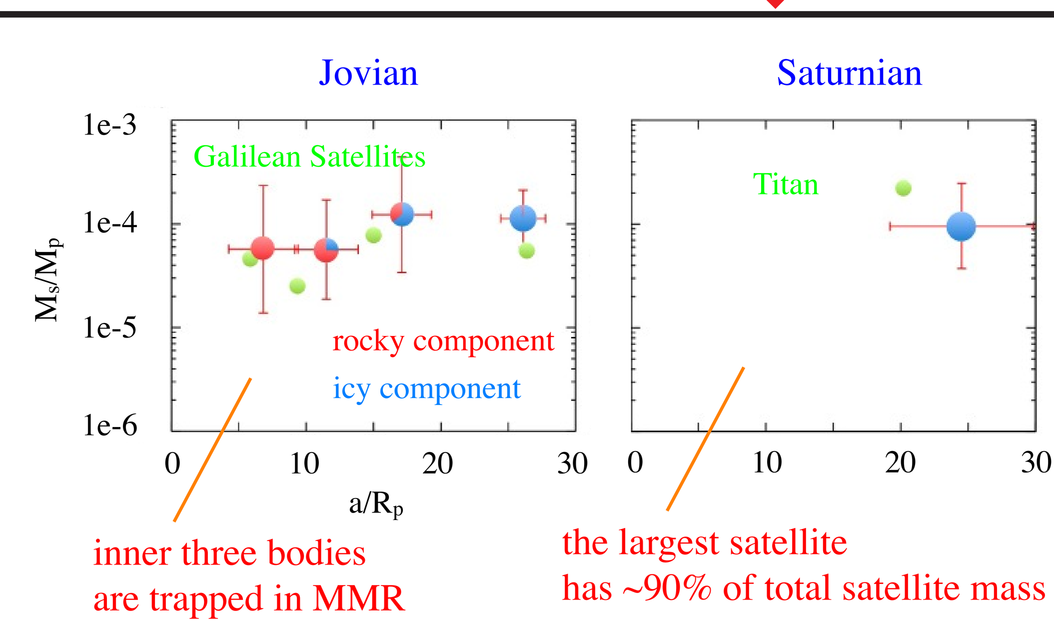


Fig 2. Theoretically predicted satellte systems. The average mass-semimajor axis distributions of the large satellites are plotted with real satellites (green). Error-bars show the standard deviation (1σ). The colors show the fraction of rocky (red) and icy (blue) satellites.

RESULTS

Saturnian System:

Since the infall flux is larger in outer regions, the accretion timescale is shorter and satellites grow and migrate faster in outer regions. Then, the satellites formed in outer regions repeatedly sweep up inner ones to remain one or two large bodies in relatively outer regions at last.

Jovian System:

Because type I migration is halted near the inner edge, several large bodies are trapped in MMR to reproduce the current configuration of Galilean satellites. The inner large bodies tend to be composed of rocky materials while outer bodies are composed mostly of icy materials.

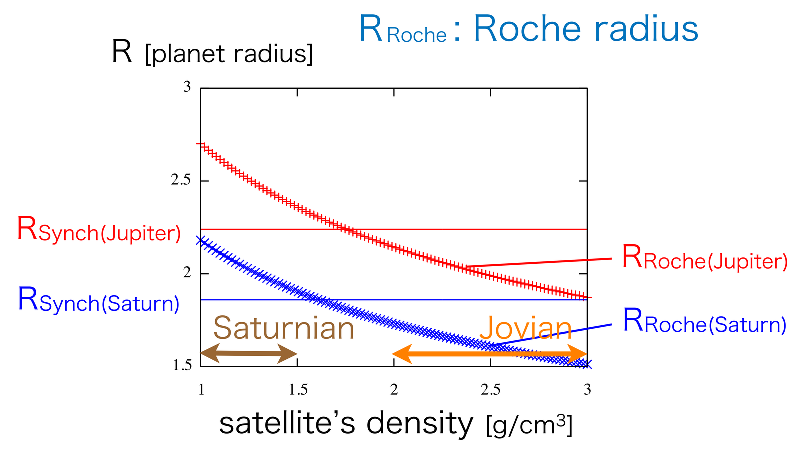
The formation timescales of produced satellites corresponding to Callisto and Titan are long enough for the satellites not to be differentiated.

4. Formation of Saturn's Rings

The ring may be formed from an ancient satellite which was originally in the planet's Roche zone and was destroyed by a passing comet. [Charnoz et al., 2009]

key parameters
$R_{Synch} > R_{Roche}$: satellite migrate to the planet
$R_{Synch} < R_{Roche}$: satellite survive near the RZ

R_{Synch} : Synchronous radius
R_{Roche} : Roche radius



Our results indicate that the inner satellite, which can be the seed of the ring, should be mixture of ice and rock for Saturnian system, while it may be rocky for Jovian system. Therefore, Saturn is more plausible planet to maintain a satellite inside the R_{Roche}. This is consistent with the fact that Saturn has a massive ring while Jupiter does not.

CONCLUSION

We simulated growth and orbital evolution of proto-satellites following accreting circumplanetary disk model and planet formation model for the satellite formation problem. Based on the hypotheses for the proto-planetary disks such as difference of gap opening and inner boundary condition, we explained the origin of the difference between Jovian and Saturnian satellite systems. The zoning and thermal conditions of our produced satellite systems are consistent with observed satellite systems.