Origin of the Difference of the Jovian and Saturnian Satellite Systems

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Jovian System v.s. Saturnian System

rocky

Io

mutual mean motion resonances (MMR)

rocky

Europa

icy

Ganymede

icy, undiff.

Callisto

only one big body

icy, undiff.

Titan

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### Satellite Properties

<table>
<thead>
<tr>
<th></th>
<th>$a/R_p$</th>
<th>$M/M_p \times 10^{-5}$</th>
<th>$\rho \text{ [g/cm}^3\text{]}$</th>
<th>$C/\text{MR}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Io</td>
<td>5.9</td>
<td>4.70</td>
<td>3.53</td>
<td>0.378</td>
</tr>
<tr>
<td>Europa</td>
<td>9.4</td>
<td>2.53</td>
<td>2.99</td>
<td>0.346</td>
</tr>
<tr>
<td>Ganymede</td>
<td>15.0</td>
<td>7.80</td>
<td>1.94</td>
<td>0.312</td>
</tr>
<tr>
<td>Callisto</td>
<td>26.4</td>
<td>5.69</td>
<td>1.83</td>
<td>0.355</td>
</tr>
<tr>
<td>Titan</td>
<td>20.3</td>
<td>23.7</td>
<td>1.88</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Callisto and Titan’s undifferentiated interiors → accretion timescale $> 5 \times 10^5$ years [Barr & Canup, 2008]
Questions; Motivation of this study

Satellites’ size, number, and location

Jovian: 4 similar mass satellites in MMR
Saturnian: only 1 large satellite far from Saturn

Among Galilean satellites

Io & Europa: rocky satellite
Ganymede & Callisto: icy satellite
Callisto: undifferentiated

What is the origin of the different architecture?

What is the origin of the satellites’ diversity?
Overview of this study

Circum-Planetary Disk
  - Satellites formed in c.-p. disk
  - Actively-supplied accretion disk
  - Supplied from circum-stellar disk
    → Analytical solution for $T, \Sigma$

Satellite Formation
  - Analytical solution for accretion timescale
  - type I migration timescale
  - trapping condition in MMR
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Adding New Ideas

Disk boundary conditions

Difference of Jovian/Saturnian systems is naturally reproduced?
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**Actively-Supplied Accretion Disk**

Uniform mass infall $F_{\text{in}}$ from the circum-stellar disk

Infall regions: $r_{\text{in}} < r < r_{c}$ ($r_{c} \sim 30R_{p}$)

Diffuse out at outer edge: $r_{d} \sim 150R_{p}$

Infall rate decays exponentially with time

Temperature: balance of viscous heating and blackbody radiation

Viscosity: $\alpha$ model
Canup & Ward (2002, 2006) $+\alpha$

Inflow flux $F_{in} = F_{in}(t = 0) \exp(-t/\tau_{in})$ [g/s]

Temperature $T_d \approx 160 \left( \frac{M_p}{M_J} \right)^{1/2} \left( \frac{\tau_G}{5 \times 10^6 \text{ yrs}} \right)^{-1/4} \left( \frac{r}{20R_J} \right)^{-3/4}$ [K]

Gas density $\Sigma_g \approx 100 f_g \left( \frac{M_p}{M_J} \right) \left( \frac{r}{20R_J} \right)^{-3/4}$ [g/cm$^2$] $f_g \equiv \left( \frac{\alpha}{5 \times 10^{-3}} \right)^{-1} \left( \frac{\tau_G}{5 \times 10^6 \text{ yrs}} \right)^{-3/4}$

Dust density $\Sigma_d = \eta_{ice} f_d \left( \frac{M_p}{M_J} \right) \left( \frac{r}{20R_J} \right)^{-3/4}$ [g/cm$^2$]

Increasing rate of dust density $\frac{df_d}{dt} = 0.029 \left( \frac{M_p}{M_J} \right)^{-2/3} \left( \frac{f}{100} \right)^{-1} \left( \frac{\tau_G}{5 \times 10^6 \text{ yrs}} \right)^{-1} \left( \frac{r}{20R_J} \right)^{3/4}$ [/years]
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Timescales of satellite’s accretion & type I migration

\[ \tau_{\text{acc}} = \frac{M}{\dot{M}} \approx 10^6 \frac{f_d^{-1} \eta_{ice}^{-1}}{\rho} \left( \frac{\rho}{\rho_p} \right)^{1/3} \left( \frac{M}{10^{-4} M_p} \right)^{1/3} \left( \frac{M_p}{M_J} \right)^{-5/6} \left( \frac{\beta}{10} \right)^2 \left( \frac{r}{20 R_J} \right)^{5/4} \text{ [years]} \]

\[ \tau_{\text{mig}} = \frac{\frac{r}{\dot{r}}}{f_g} \approx 10^5 \frac{1}{f_g} \left( \frac{M}{10^{-4} M_p} \right)^{-1} \left( \frac{M_p}{M_J} \right)^{-1} \left( \frac{r}{20 R_J} \right)^{1/2} \left( \frac{\tau_G}{5 \times 10^6} \right)^{-1/4} \text{ [years]} \]

Resonant trapping width of migrating proto-satellites

\[ b_{\text{trap}} = 0.16 \left( \frac{m_i + m_j}{M_\oplus} \right)^{1/6} \left( \frac{v_{\text{mig}}}{v_K} \right)^{-1/4} r_H \text{ [m]} \]

These approximate analytical solutions are based on the results of N-body simulations.
Comparison with N-body simulation

Time evolution of total mass of satellites (time-constant inflow)

\[ \alpha = 10^{-4}, 5 \times 10^{-3}, 5 \times 10^{-2} \]
Comparison with N-body simulation

Time evolution of total mass of satellites (time-constant inflow)

\[ \alpha = 10^{-4}, \, 5 \times 10^{-3}, \, 5 \times 10^{-2} \]

Excellent agreement with N-body simulation!
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The Ideas

Jupiter

inner cavity
opened up gap in c.-s. disk
→ infall to c.-p. disk stop abruptly

Saturn

no cavity
did not open up gap in c.-s. disk
→ c.-p. disk decay with c.-s. disk

Difference of “inner cavity” is from Königl (1991) and Stevenson (1974)
Difference of gap conditions is from Ida & Lin (2004)
Inner Cavity (Analogy with T-Tauri stars)
Inner Cavity (Analogy with T-Tauri stars)

weak magnetic field

strong magnetic field → coupling with disk

If the magnetic torque is stronger than the viscous torque, the disk would be truncated at the corotation radius

Herbst & Mundt (2005)
Inner Cavity (Analogy with T-Tauri stars)

weak magnetic field

No Cavity

Saturnian

strong magnetic field → coupling with disk

Cavity

Jovian

The rotation period distribution for the 173 stars in NGC 2264 is shown in Figure 6. The 142 stars with spectral types (K4–M2) range of 3.54–3.67. Periods are based on the work of Lamm et al. (2004) and appropriate values of the period distribution for stars in the same color range chosen by Lamm et al. (2004) shows, their period distribution in NGC 2264 does differ from that in the ONC at the 99% confidence limit when a K-S test is applied. Other features of this distribution have been discussed by Lamm et al. (2005) and include its bimodality, with peaks near 1 and 4 days and the extended tail of slowly rotating stars.

Kolmogorov-Smirnov (K-S) test shows that there is no significant difference between the clusters, or by some other selection effect. It is easier to explore these issues in the rotation properties and a difference in the mass distributions for all stars. This is a more robust value than the mean (2 ± 0.09). Since there is no clear trend of visible in the data, we adopt the median radius of R = 0.78

to the log radii. The combined period distribution shown in the bottom panel than in the

to the greater Orion association. In fact, as Figure 7 combined, there are 148 stars, enough to reasonably postpone the task of combining the data until after a discussion of the figures and confirmed by a K-S test. Clearly, the period distribution for stars in this mass range are not drawn from the same parent population. A K-S test indicates that they are different at the 99.7% confidence limit. While this contradicts the statement in Makidon et al. (2004) that there is no significant difference between ''Orion'' and NGC 2264, it should be kept in mind that by adopting a single value of P

eq C11

e→

eff

strong magnetic field

Saturnian

weak magnetic field

No Cavity

strong magnetic field → coupling with disk

Cavity

Jovian

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Estimates of Cavity Opening

Stevenson (1974)
proto-Jovian magnetic field $\sim 1000$ Gauss
(Jovian system should be correspond to the stage)

$\checkmark$

Königl (1991)
magnetic field for the magnetic coupling
accretion rate $10^{-6}M_J/yr \rightarrow \sim$ a few hundred Gauss

$\checkmark$

Present Saturnian magnetic field $< 1$ Gauss
≡ late stage of Saturnian satellite formation
THE IDEAS

Jupiter: open up gap in circum-stellar disk
  → infall to circum-planetary disk stop
  → c.-p. disk quickly depleted
  → frozen satellite system with “inner cavity”

Saturn: did not open up the gap
  → c.-p. disk decay with c.-s. disk decay
  → c.-p. disk slowly depleted
  → satellite system without “inner cavity”

difference of gap conditions are from Ida & Lin (2004)
Because the infall mass flux per unit area is constant, the total mass flux to satellite feeding zones is larger in outer regions.
Type I migration is halted near the inner edge.

The outermost satellite migrates and sweeps up the inner small satellites.
Proto-satellites grow & migrate repeatedly. They are trapped in MMR with the innermost satellite.
Jovian System

Total mass of the trapped satellites > Disk mass
→ the halting mechanism is not effective
→ innermost satellite is released to the host planet
Jovian System

after the gap opening → c.-p. disk deplete quickly
Saturnian System

- No inner cavity
- Outer proto-satellite grow faster & migrate earlier
Saturnian System

Large proto-satellites migrate from the outer regions and fall to the host planet with inner smaller satellites.
Saturnian System

c.-p. disk depleted slowly with the decay of c.-s. disk
Monte Carlo Simulation (n=100)

Parameters:
- Disk viscosity (\(\alpha\) model) \(\alpha = 10^{-3} - 10^{-2}\)
- Disk decay timescale \(\tau_{in} = 3 \times 10^6 - 5 \times 10^6\) yr
- Number of “satellite seeds” \(N = 10 - 20\)
Results: Distribution of the number of large satellites

<table>
<thead>
<tr>
<th>Number of Produced Satellites</th>
<th>Jovian</th>
<th>Saturnian</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
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<td>5</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Number of produced satellites: 0, 1, 2, 3, 4, 5, 6, 7
Total count of the case: Jovian 6, Saturnian 3
Results: Distribution of the number of large satellites

<table>
<thead>
<tr>
<th>Total count of the case</th>
<th>Jovian</th>
<th>Saturnian</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>![Bar Chart of Jovian]</td>
<td>![Bar Chart of Saturnian]</td>
</tr>
<tr>
<td>20</td>
<td>![Bar Chart of Jovian]</td>
<td>![Bar Chart of Saturnian]</td>
</tr>
<tr>
<td>10</td>
<td>![Bar Chart of Jovian]</td>
<td>![Bar Chart of Saturnian]</td>
</tr>
<tr>
<td>inner two bodies: rocky &amp; outer two bodies: icy</td>
<td>icy satellite &amp; large enough ($\sim M_{\text{Titan}}$)</td>
<td></td>
</tr>
</tbody>
</table>
Results: Properties of produced satellite systems

Galilean Satellites

- rocky component
- icy component

Saturnian

- Titan
Results: Properties of produced satellite systems

- Saturnian
- Jovian
- icy component
- rocky component
- Galilean Satellites

- Inner three bodies are trapped in MMR
- The largest satellite has ~90% of total satellite mass
Results: Other features of produced satellite systems

Callisto and Titan’s undifferentiated interior
→ accretion timescales > $5 \times 10^5$ years [Barr & Canup, 2008]

Saturn’s ring formed from an ancient satellite at Roche Zone
→ $R_{\text{Roche}} > R_{\text{Synch}}$ is required [Charnoz et al., 2009]

Jovian: $R_{\text{Roche}} < R_{\text{Synch}}$
Saturnian: $R_{\text{Roche}} > R_{\text{Synch}}$
Uranian, Neptunian: $R_{\text{Roche}} < R_{\text{Synch}}$

Accretion timescales in our simulations
Callisto: $10^5$-$10^6$ years
Titan: $\sim 10^6$ years
Summary

• **Jovian Satellite System v.s. Saturnian Satellite System**
  Difference of size, number, location, and compositions

• **Satellite Accretion/Migration in Circum-Planetary Disk**

• **The Ideas of Disk Boundary Conditions**
  Difference of inner cavity opening and gap opening conditions

• **Monte Carlo Simulations**
  Difference of Jovian/Saturnian system are naturally reproduced