Formation and Evolution of Satellite Systems

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Selected Moons of the Solar System, with Earth for Scale

- Earth (Moon: Moon, Phobos, Deimos)
- Mars
- Asteroid Ida
- Jupiter (Satellites: Io, Europa, Ganymede, Callisto)
- Saturn (Satellites: Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, Phoebe)
- Uranus (Satellites: Puck, Miranda, Ariel, Umbriel, Titania, Oberon)
- Neptune (Satellite: Triton)
- Pluto (Satellite: Charon)
- Eris (Satellite: Dysnomia)

Scale: 1 pixel = 25 km

Galilean Satellites
Satellite Systems

- **Regular satellites** of Jupiter, Saturn, and Uranus:
  - Prograde orbits nearly coplanar with planet’s equator plane.
  - $a$ up to tens of $R_p$
  - $M_{\text{tot}}/M_p = 1.1 - 2.5 \times 10^{-4}$
  - Formation in circumplanetary disk

- **Earth-Moon and Pluto-Charon**:
  - $M_s/M_p \approx 1/80$ and $1/9$
  - $a/R_p = 60$ an $17$
  - Pluto-Charon dual synchronous
  - Giant impact origin
Formation of the Galilean Satellites

• Constraints:
  – Ganymede and Callisto about half rock and half ice.
  – Callisto only partially differentiated \( (I/MR^2 \approx 0.355; \) Anderson et al. 2001).

• Formation scenarios:
  – Gas poor planetesimal capture model (Safronov et al. 1986; Estrada & Mosqueira 2006).
  – Minimum mass subnebula model (Lunine & Stevenson 1982; Takata & Stevenson 1996; Mosqueira & Estrada 2003).
  – Gas-starved subnebula model (Canup & Ward 2002).
• Nature of mass and angular momentum transport in subnebula is a major uncertainty in modeling satellite origins.

• Turbulence driven by Magneto-Rotational Instability (MRI) provides transport if gas is sufficiently ionized to couple to the magnetic fields.
Origin of the Laplace Resonance: Tidal or Primordial?

- Orbits of Io, Europa, and Ganymede are in the Laplace resonance, with orbital periods nearly in the ratio 1:2:4.
- Resonances could be assembled inside-out long after the formation of the satellites by tidal expansion of orbits (Goldreich 1965, Yoder 1979, Yoder & Peale 1980).
• Alternatively, resonances could be assembled outside-in during satellite formation by the differential migration of satellites due to interactions with circumjovian disk (Peale & Lee 2002; Sasaki, Stewart & Ida 2009).

• Probability of capture into the observed Laplace resonance could be sensitive to circumjovian disk model.
Minimum Mass Subnebula Model

- Analogous to minimum mass solar nebula.
- Galilean satellites + enough volatiles for Solar abundance.

(Pollack & Consolmagno 1984)
• Very high gas surface density $\sigma_G \sim 1/r$.
• Sharp drop in $\sigma_G$ at $r/R_J \approx 23$ in the Mosqueira & Estrada (2003) model.
• Temperature $T \sim 1/r$ at $r/R_J < 30$ and $\sim$ constant at $r/R_J > 30$. 
Gas-starved Subnebula Model

- Not all mass needed to form the satellites in the disk all at once.
- Replenished by slow inflow of gas and solids from the solar nebula after Jupiter opens a gap.

(D’Angelo et al. 2003)

(Canup & Ward 2002)
We have constructed **Improved Gas-starved Subnebula models with**

- Improved treatment of low $\tau_c$ (optical depth to the midplane) regime and incoming radiation of Jupiter.
- Midplane temperature $T_c$ using
  - Analytic vertical structure model of Hubeny (1991) for viscous dissipation and isotropic solar nebula irradiation
  - Extension by Malbet et al. (2001) for irradiation by a central source (i.e. Jupiter).

$$T_c^4 = \frac{3}{4} \left[ \frac{\tau_c}{2} + \frac{1}{\sqrt{3}} + \frac{1}{3\tau_c} \right] T_d^4 + T_{\text{neb}}^4$$

$$+ \frac{3}{4} \left[ \mu_J \left(1 - e^{-\tau_c/\mu_J}\right) + \frac{1}{\sqrt{3}} + \frac{1}{3\mu_J} e^{-\tau_c/\mu_J} \right] \left(\frac{\mu_J}{2}\right) \left(\frac{R_J}{r}\right)^2 T_J^4,$$
• Opacity $\kappa = f_{\text{opac}} \kappa_P$, where $\kappa_P$ is the Pollack et al. (1994) temperature dependent opacity and $f_{\text{opac}} \leq 1$. 
- High opacity model:
  \( f_{\text{opac}} = 1 \)
  \( \alpha = 5 \times 10^{-3} \)
  \( \tau_G = 7 \times 10^7 \text{ yr} \)

Red: Improved gas-starved disk model
Black: CW02 model with \( \kappa = f_{\text{opac}} \)
- Low opacity model:
  \[ f_{\text{opac}} = 10^{-4} \]
  \[ \alpha = 9 \times 10^{-4} \]
  \[ \tau_G = 2 \times 10^7 \text{ yr} \]

Red: Improved gas-starved disk model
Black: CW02 model with \( \kappa = f_{\text{opac}} \)
Chemical Network Calculations

• Ionization state from chemical network with gas-phase species \( \text{H}_2, \text{H}_2^+, \text{Mg}, \text{Mg}^+, \) and \( \text{e}^- \) after Ilgner & Nelson (2006).

Gas Phase Reactions:

• Ionization by interstellar cosmic ray (Umebayashi & Nakano 2009), solar x-ray, and radioisotope decay: \( \text{H}_2 \rightarrow \text{H}_2^+ + \text{e}^- \)

• Dissociative Recombination: \( \text{H}_2^+ + \text{e}^- \rightarrow \text{H}_2 \)

• Radiative Recombination: \( \text{Mg}^+ + \text{e}^- \rightarrow \text{Mg} + h\nu \)

• Charge Exchange: \( \text{H}_2^+ + \text{Mg} \rightarrow \text{H}_2 + \text{Mg}^+ \)

• The cosmic ray absorbing column \( \approx 96 \text{ g cm}^{-2} \) and x-ray absorbing column \( \approx 8 \text{ g cm}^{-2} \).
Grain Surface Reactions:

- Seven species added to reaction network if dust grains are present: Charged grains $G^0$, $G^\pm$, $G^{\pm 2}$ and adsorbed neutrals $H_2(G)$ and Mg(G).
- Thermal adsorption and desorption of neutrals and ions.
- Grain charging and neutralization in collisions with ions and elections.
- Charge exchange in grain-grain collisions.
Criteria for Dead Zone

MRI turbulence is absent if both

1. The equilibrium ionization is too small (Elsasser number $\Lambda = \nu_{A,z}^2/(\eta \Omega) < 1$) and
2. The recombination is too fast for ionized gas transported from regions of lower column depth to affect ionization fraction ($t_{\text{rec}} < 0.1 \ t_{\text{mix}}$).

• The $\Lambda < 1$ criterion was established by previous analytic and numerical results (Jin 1996; Sano & Miyama 1999; Sano & Inutsuka 2001; Sano & Stone 2002).
• The \( t_{\text{rec}} < 0.1 \ t_{\text{mix}} \) criterion from existing MHD+chemistry simulations of the Solar nebula.

- **Green** contours: \( \Lambda > 1 \) for equilibrium ionization fraction.
- **Red** contours: \( \Lambda < 1 \) for equilibrium ionization fraction.
- **Large blue dots**: \( t_{\text{rec}} > t_{\text{mix}} \)
- **Medium blue dots**: \( t_{\text{mix}} > t_{\text{rec}} > 0.1 \ t_{\text{mix}} \)
Dead Zone of Minimum Mass Subnebula

- Mixing can slightly reduce the size of the dead zone if there is no dust.
Dead Zone of Minimum Mass Subnebula

Even with the sharp drop in surface density at $r/R_J \approx 23$ in the Mosqueira & Estrada models, MMSN models are magnetically dead everywhere, except very high in the upper layers.
Dead Zone of Gas-Starved Subnebula

Opacity = $f_{\text{opac}} \kappa_P$

- $f_{\text{opac}} = 1$
- $f_{\text{opac}} = 10^{-2}$
- $f_{\text{opac}} = 10^{-4}$

- Mixing does not significantly affect the size of the dead zone.
Dead Zone of Gas-Starved Subnebula

Opacity = \( f_{\text{opac}} \kappa_P \)

\( f_{\text{opac}} = 1 \)

\( f_{\text{opac}} = 10^{-2} \)

\( f_{\text{opac}} = 10^{-4} \)

- No dead zone in the outer regions.
- Dead zone plus active upper layers in the inner regions.
Pluto Satellite System

- Charon was discovered in 1978.
- Two small satellites, Nix and Hydra, were discovered in 2005 by Weaver et al.
• Orbits of Nix and Hydra nearly circular and nearly coplanar with that of Pluto-Charon (Buie et al. 2006).
• Orbital periods of Charon, Nix and Hydra nearly in the ratio 1:4:6.
• Orbits of Nix and Hydra significantly non-Keplerian due to
  – large mass ratio of Charon-Pluto
  – proximity of Nix and Hydra to 3:2 commensurability
    (Lee & Peale 2006).
Giant Impact Origin of the Moon

- Moon accreted from impact generated disk.

(Canup 2004)
Impact Origin of the Pluto Satellite System

• Impact captured Charon nearly intact into eccentric orbit with $a_c \sim 4 R_p$.
• Coplanarity: Nix and Hydra were debris from the same impact.
• But debris did not extend beyond $\sim 15 R_p$.
• Current $a = 17, 42, \text{ and } 56 R_p$ for Charon, Nix, and Hydra.

(Canup 2005)
Resonant Migration of Nix and Hydra

- Nix and Hydra not in 4:1 and 6:1 resonances with Charon at present.
- But Nix and Hydra could once be in these resonances and were pushed out as Charon's orbit expanded due to tidal evolution (Ward & Canup 2006).
Stable transport of Nix and Hydra in 4:1 and 6:1 as $a_c$ increases by a factor of ~ 4 is difficult:
- Ward & Canup (2006): Nix and Hydra trapped in corotation resonance only, which does not excite eccentricity.
- Charon's eccentricity $e_c$ must be maintained during most of the orbital expansion to maintain stability of resonance.
- Lithwick & Wu (2007):
  - To transport Nix, $e_c \leq 0.024$
  - To transport Hydra, $e_c \geq 0.8 \frac{R_p}{a_c}$
  - Both cannot be satisfied at the same time.
Tidal Evolution of Pluto-Charon

- Need evolution of Charon’s orbit (in particular $e_c$) for resonant migration problem.
- Previous study of tidal evolution of Charon’s orbit assumed circular orbit (Dobrovolskis et al. 1997).
- Tidal Models:
  - Constant time lag $\Delta t$: closed expressions valid for large $e$ (Mignard 1980; Hut 1981).
  - Constant dissipation function $Q$ (Goldreich & Soter 1966)
  - Tides on both Pluto and Charon
  - Non-zero $C_{22} = (B-A)/(4MR^2)$: Permanent non-axisymmetric deformation
\[
\begin{align*}
\frac{1}{n} \left\langle \frac{d\psi_i}{dt} \right\rangle &= \frac{3G}{C_i a_i^8} k_{2i} \Delta t_i M_j^2 R_i^5 \left[ f_1(e^2) - f_2(e^2) \frac{\psi_i}{n} \right], \\
\frac{1}{a} \left\langle \frac{da}{dt} \right\rangle &= \frac{6G}{\mu a_i^8} k_{2P} \Delta t_P M_C^2 R_P^5 \left\{ \left[ \frac{\psi_P}{n} f_1(e^2) - f_3(e^2) \right] + A \left[ \frac{\psi_C}{n} f_1(e^2) - f_3(e^2) \right] \right\}, \\
\frac{1}{e} \left\langle \frac{de}{dt} \right\rangle &= \frac{27G}{\mu a_i^8} k_{2P} \Delta t_P M_C^2 R_P^5 \left\{ \left[ \frac{11}{18} \frac{\psi_P}{n} f_4(e^2) - f_5(e^2) \right] + A \left[ \frac{11}{18} \frac{\psi_C}{n} f_4(e^2) - f_5(e^2) \right] \right\};
\end{align*}
\]

where

\[
A = \frac{k_{2C} \Delta t_C}{k_{2P} \Delta t_P} \left( \frac{M_P}{M_C} \right)^2 \left( \frac{R_C}{R_P} \right)^5
\]

- \( A \approx (\mu_p \Delta t_c R_c)/(\mu_c \Delta t_p R_p) \) is a measure of relative rates of tidal dissipation.
$k_{2p} = 0.058$, $\Delta t_p = 10$ mins
$k_{2p} = 0.058, \ Q = 100$
\( k_{2p} = 0.058, \Delta t_p = 10 \text{ mins}, A = 10 \)
$k_{2p} = 0.058, \Delta t_p = 10$ mins, $A = 9$
Summary (I)

• We have developed criteria for estimating the size of the dead zone from chemical network calculations.

• Minimum Mass Subnebula models of the circumjovian disk are magnetically dead everywhere, except very high in the upper layers.

• Gas-starved Subnebula models are similar to solar nebula models:
  – No dead zone in the outer regions
  – Dead zone plus active upper layers in the inner regions.
Summary (II)

• Tidal evolution of Pluto-Charon shows complex behaviors: pseudo-synchronous rotation, 3:2 spin-orbit resonance, semimajor axis overshooting

• Can a consistent history of the Pluto satellite system be constructed based on intact capture of Charon and resonant migration of Nix and Hydra?