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Formation and Evolution of Satellite Systems

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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:
  \( f_{\text{opac}} = 1 \)
  \( \alpha = 5 \times 10^{-3} \)
  \( \tau_G = 7 \times 10^7 \) 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 $\text{H}_2$, $\text{H}_2^+$, Mg, Mg$^+$, and 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 electrons.
- 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 $\Lambda = \frac{v_{A,z}^2}{(\eta \Omega)} < 1$) and
2. The recombination is too fast for ionized gas transported from regions of lower column depth to affect ionization fraction ($t_{rec} < 0.1 t_{mix}$).

• 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: $t_{\text{mix}} > t_{\text{rec}} > 0.1 \ t_{\text{mix}}$
• 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.

$0.1\mu m$ dust with gas-to-dust ratio = $100/f_{\text{opac}}$

No dust
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 $a = 17, 42,$ 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, $e_c <~ 0.024$
    To transport Hydra, $e_c >~ 0.8 \frac{R_p}{a_c}$
    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
\[ \frac{1}{n} \left\langle \frac{d\psi_i}{dt} \right\rangle = \frac{3G}{C_i a^8} k_{2i} \Delta t_i M_j^2 R_i^5 \left[ f_1(e^2) - f_2(e^2) \frac{\psi_i}{n} \right], \]

\[ \frac{1}{a} \left\langle \frac{da}{dt} \right\rangle = \frac{6G}{\mu a^8} k_{2p} \Delta t_P M_C^2 R_P^5 \left\{ \left[ \frac{\psi_P}{n} f_1(e^2) - f_3(e^2) \right] + A \left[ \frac{\psi_C}{n} f_1(e^2) - f_3(e^2) \right] \right\}, \]

\[ \frac{1}{e} \left\langle \frac{de}{dt} \right\rangle = \frac{27G}{\mu a^8} k_{2p} \Delta t_P M_C^2 R_P^5 \left\{ \left[ \frac{11}{18} \frac{\psi_P}{n} f_4(e^2) - f_5(e^2) \right] + A \left[ \frac{11}{18} \frac{\psi_C}{n} f_4(e^2) - f_5(e^2) \right] \right\}; \]

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.
\[ k_{2p} = 0.058, \Delta t_p = 10 \text{ mins} \]
$k_{2p} = 0.058, \ Q = 100$
$k_{2p} = 0.058$, $\Delta t_p = 10$ 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?