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Formation Environment of the Galilean Moons

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- Julie Castillo-Rogez, Torrence Johnson, Neal Turner, Dennis Matson (JPL), Jonathan Lunine (Arizona)
Properties of the Galilean Moons

- Masses: $M_G/M_J = 7.8 \times 10^{-5}$, $M_{\text{tot}}/M_J = 2.1 \times 10^{-4}$.
- Orbital radii: $a/R_J = 5.9$ to 26.
- Compositional gradient:
  - Io and Europa mostly rocky material.
  - Ganymede and Callisto about half rock and half ice.
  - Temperature in outer region of circumjovian disk must be cold enough to have water ice.
• Callisto only partially differentiated \( (I/MR^2 \approx 0.355; \text{ Anderson et al. 2001}) \).
  – Require accretion time > \( 10^5 \text{ yr.} \)
  – Finished accreting > 4 Myr after CAIs (Barr & Canup 2008).
• The orbits of Io, Europa, and Ganymede are in the Laplace resonance, with orbital periods nearly in the ratio 1:2:4.

• The orbital eccentricities maintained by the resonances lead to
  – sustained dissipation of tidal energy
  – active volcanism on Io and probably liquid ocean on Europa.

• Primordial or tidal origin of the resonance?
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.
Minimum Mass Subnebula Model

- Analogous to minimum mass solar nebula.
- Callisto accretion time too fast unless surface density drops sharply at $r/R_J \approx 23$ as in Mosqueira & Estrada (2003).

(Pollack & Consolmagno 1984)
• Temperature too high unless $\alpha \sim 10^{-6}$ to $10^{-5}$.

• Is required $\alpha$ below that from e.g. damping of satellitesimal density wave wakes? (Goodman & Rafikov 2001)

(Mosqueira & Estrada 2003)
• **Type I migration timescale** (Ward 1997; Tanaka et al. 2002)
  \[
  \tau_I = (C_a \Omega)^{-1} \left( \frac{M_p}{M_s} \right) \left( \frac{M_p}{\sigma G a^2} \right) (H/a)^2
  \]
  due to satellite-disk interaction very short (but see Paardekooper & Mellema; Bareteau & Masset 2008).

• Mosqueira & Estrada invoke a gap opening criterion where the forming Galilean satellites are big enough to open gaps: slow type II migration with low \( \alpha \).
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)
- High opacity model:
  \[ K = 1 \text{ cm}^2 \text{ g}^{-1} \]
  \[ \alpha = 5 \times 10^{-3} \]
  \[ \tau_G = 10^8 \text{ yr} \]
- Low opacity model:
  \[ K = 10^{-4} \text{ cm}^2 \text{ g}^{-1} \]
  \[ \alpha = 5 \times 10^{-3} \]
  \[ \tau_G = 5 \times 10^6 \text{ yr} \]
• Balance of supply of inflowing material to satellites and satellite loss due to migration regulates mass fraction of satellite systems to $\sim 10^{-4}$ (Canup & Ward 2006).
Origin of the Laplace Resonance: Tidal or Primordial?

- It has been widely assumed that the 1:2:4 resonances were assembled from initially non-resonant orbits by the differential orbital expansion due to torques from dissipation of tides raised on Jupiter (Goldreich 1965, Yoder 1979, Yoder & Peale 1980).

- Resonances were assembled inside-out long after the formation of the satellites.
• Peale & Lee (2002) demonstrated that resonances could be assembled outside-in during satellite formation in the gas-starved subnebula model.

• Differential migration of satellites due to interactions with circumjovian disk.
• We used a simple model with:
  • Full satellite masses throughout migration
  • Type I migration with \( a^{-1} \frac{da}{dt} \sim M_s \)
    (i.e. we assumed the \( a \)-dependence is weak)
  • Eccentricity damping with
    \[ |e^{-1} \frac{de}{dt}| \sim 30 \]
    \[ |a^{-1} \frac{da}{dt}| \] (Artymowicz 1993).
• But capture into 1:2:4 is probabilistic.
• In a more complex model with:
  • Satellite masses growing linearly with time
  • $a^{-1} \frac{da}{dt} \propto M_s a^{-n}$
    (e.g., $n = (1-2\beta)/(5-\beta)$ for an optically thick, steady state disk with constant mass flux and $\kappa \propto T^\beta$).
• In two sets of simulations,
  $P_{1:2:4} \approx 0.67$ for $n = 0$
  $P_{1:2:4} \approx 0.29$ for $n = 1/5$
• To determine the likelihood of capture into the observed Laplace resonance, we need a more realistic circumjovian disk model.
Improved Gas-starved Subnebula Model

• 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).

\[
T_c^4 = \frac{3}{4} \left[ \frac{\tau_c}{2} + \frac{1}{\sqrt{3}} + \frac{1}{3\tau_c} \right] T_d^4 + T_{\text{neb}}^4
+ \frac{3}{4} \left[ \mu_J \left( 1 - e^{-\tau_c/\mu_J} \right) + \frac{1}{\sqrt{3}} + \frac{1}{3\mu_J} e^{-\tau_c/\mu_J} \right] \left( \frac{\mu_J}{2} \right) \left( \frac{R_J}{r} \right)^2 T_J^4,
\]
• Pollack et al. (1994) temperature dependent opacity $\kappa$. 
• High opacity model:
  \[ f_{\text{opac}} = 1 \]
  \[ \alpha = 5 \times 10^{-3} \]
  \[ \tau_G = 6 \times 10^7 \text{ yr} \]

Red: Improved gas-starved disk model
Black: CW02 model with \( K = f_{\text{opac}} \)
- Low opacity model:
  \( f_{\text{opac}} = 10^{-4} \)
  \( \alpha = 8 \times 10^{-4} \)
  \( \tau_G = 2 \times 10^7 \) yr

Red: Improved gas-starved disk model
Black: CW02 model with \( K = f_{\text{opac}} \)
Ionization and Recombination

- Ionization from chemical network with gas-phase species $H_2$, $H_2^+$, Mg, $Mg^+$, and $e^-$ after Ilgner & Nelson (2006).
- Ionization by interstellar cosmic ray (Umebayashi & Nakano 2009), solar x-ray, and radioisotope decay: $H_2 \rightarrow H_2^+ + e^-$
- Dissociative Recombination: $H_2^+ + e^- \rightarrow H_2$
- Radiative Recombination: $Mg^+ + e^- \rightarrow Mg + h\nu$
- Charge Exchange: $H_2^+ + Mg \rightarrow H_2 + Mg^+$
- Cosmic ray absorbing column $\approx 96$ g cm$^{-2}$.
- X ray absorbing column $\approx 8$ g cm$^{-2}$. 
Grain Surface Reactions

- Seven species added to reaction network: 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.
- 1 micron grain size.
Dead Zone Criterion

MRI turbulence is absent if both

1. The equilibrium ionization is too small (Elsasser number $\nu_{A,z}^2/(\eta\Omega) < 1$) and

2. The recombination is too fast for ionized gas to be transported from regions of lower column depth ($t_{\text{recomb}} < t_{\text{mix}} \approx c_s^2/(2\nu_{A,z}^2)$ orbits).
* Elsasser number < 1

- $t_{\text{recomb}} < t_{\text{mix}}$
* Elsasser number < 1

○ $t_{\text{recomb}} < t_{\text{mix}}$
Takata & Stevenson MMSN without dust and with $^{26}\text{Al}$

* Elsasser number $< 1$

$ t_{\text{recomb}} < t_{\text{mix}} $
* Elsasser number < 1

$\circ t_{\text{recomb}} < t_{\text{mix}}$
Mosqueira & Estrada MMSN without dust

* Elsasser number < 1

\[ t_{\text{recomb}} < t_{\text{mix}} \]
* Elsasser number < 1

$ t_{\text{recomb}} < t_{\text{mix}} $
Improved Gas-starved Subnebula with $f_{\text{opac}} = 1$

* Elsasser number $< 1$

- $t_{\text{recomb}} < t_{\text{mix}}$
Improved Gas-starved Subnebula with $f_{\text{opac}} = 10^{-4}$

* Elsasser number < 1

$ t_{\text{recomb}} < t_{\text{mix}} $
Improved Gas-starved Subnebula with $f_{\text{opac}} = 10^{-2}$

* Elsasser number < 1

$0 \ t_{\text{recomb}} < t_{\text{mix}}$
26Al Decay: Heat Production

(Castillo-Rogez et al. 2009)

• 26Al decay to 26Mg (half-life = 0.72 Myr) can be a major heat source in the early Solar System.
• Wide range of different values for heat production per 26Al decay used in the literature.
• Factor of 3.3 ranging from 1.2 to 4 MeV per decay.
• $^{26}\text{Al}$ decays 82% of the time by $\beta^+$ emission and 18% of the time by $e^-$ capture.

• Some energy is lost by neutrino emission in both branches.

• 4 MeV: mass energy difference between ground states of $^{26}\text{Al}$ and $^{26}\text{Mg}$.
  – does not account for energy lost by neutrino emission.

• 1.2 MeV: close to max. $\beta^+$ kinetic energy.
  – does not account for absorption of $\gamma$ rays or the $e^-$ capture branch.

• Approach of Schramm et al. (1970) with updated nuclear data gives 3.12 MeV per decay.
IAPETUS: TWO DYNAMICAL PUZZLES

SHAPE:
OBLATE SPHEROID

(A-C) = 33 KM

PERIOD:
16 HRS

79 DAY EQUILIBRIUM
(A-C) = 10 M

SPIN STATE:
MOST DISTANT SYNCHRONOUS MOON IN THE SOLAR SYSTEM

\( a = 60 R_s \)

PERIOD:
79.33 DAYS

(AND A CONUNDRUM:
EQUATORIAL RIDGE)
26Al Decay: Revised Age for Iapetus

• Short-lived radioactive isotopes (26Al and 60Fe) provide heat needed to
  – decrease porosity
  – preserve 16-hr rotational shape and equatorial ridge
  – increase tidal dissipation to despin to synchronous rotation.

• Using 1.28 MeV per decay, Castillo-Rogez et al. (2007) constrained formation of Iapetus to 2.5-5 Myr after CAIs.
Age of Iapetus is delayed by about 1 Myr to between 3.4 and 5.4 Myr after CAIs.
Summary (I)

• Differential migration of newly formed Galilean satellites due to interactions with the circumjovian disk can lead to the primordial formation of the Laplace resonance.

• Minimum Mass Subnebula models are magnetically dead everywhere, except very high up in the outer regions if there is no dust.

• Constructed improved Gas-starved Subnebula models.
Summary (II)

• 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.

• Recommended heating rate of $^{26}\text{Al}$: $3.12$ MeV per decay.

• Age of Iapetus is revised to be between 3.4 and 5.4 My after CAIs.