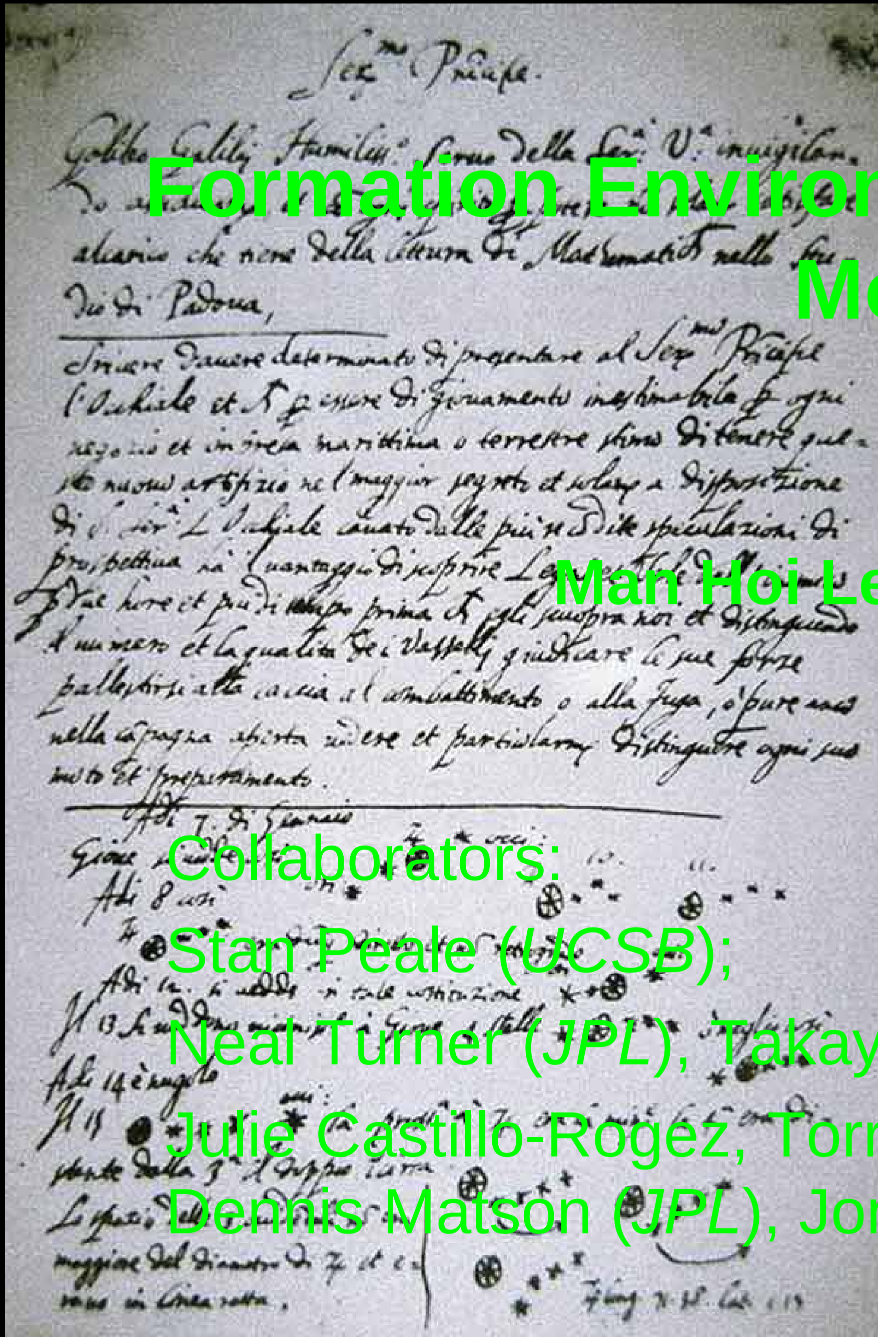
Formation Environment of the Galilean Moons



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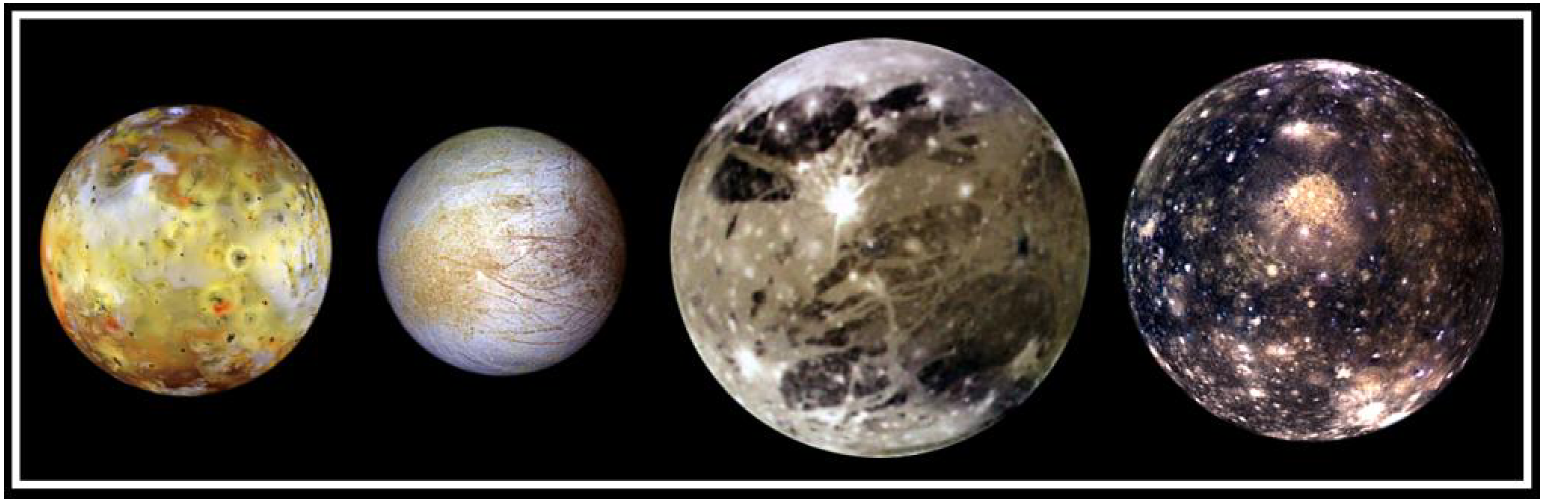
Neal Turner (*JPL*), Takayoshi Sano (*Osaka*);

Julie Castillo-Rogez, Torrence Johnson, Neal Turner, Dennis Matson (*JPL*), Jonathan Lunine (*Arizona*)

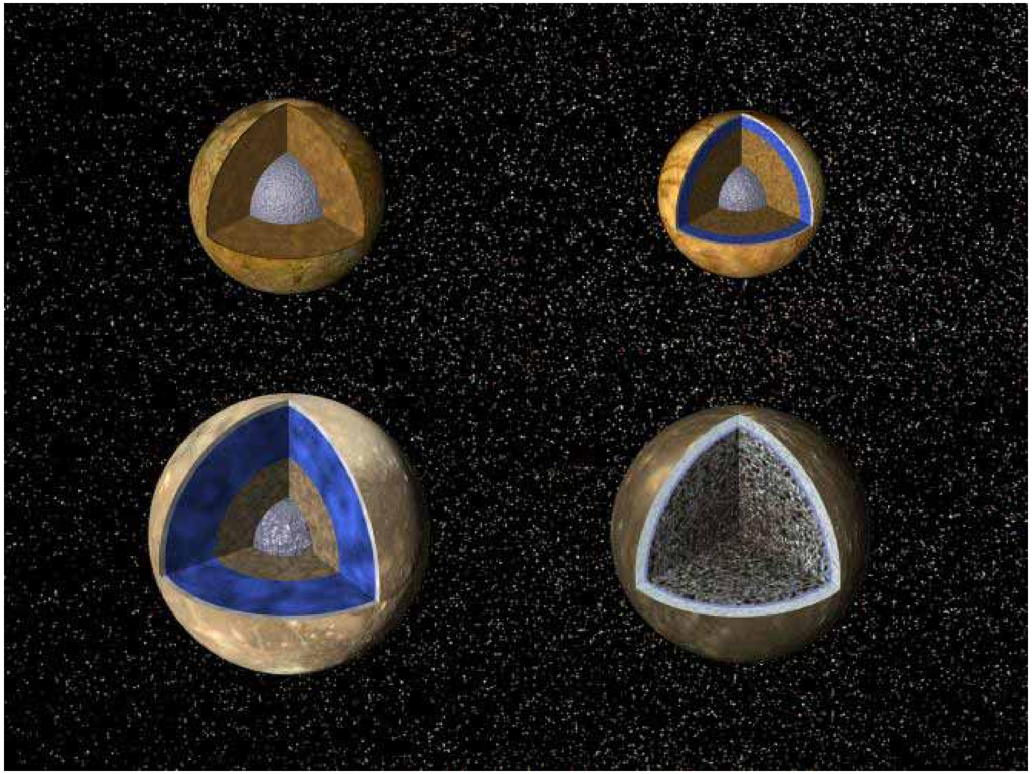
Properties of the Galilean Moons



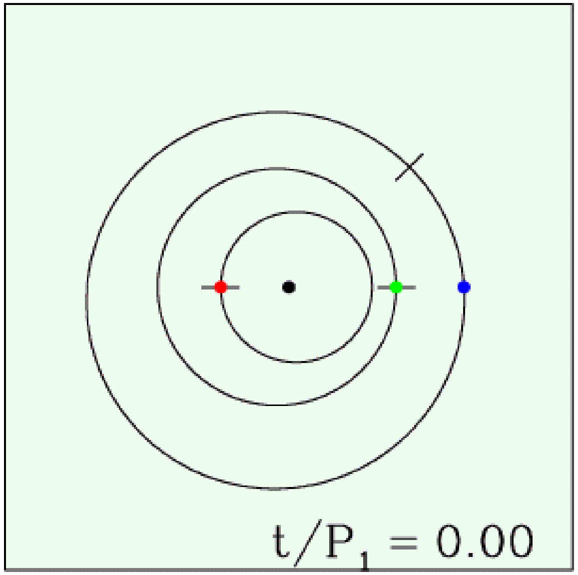
Io Europa Ganymede Callisto

- Masses: $M_G/M_J = 7.8\times10^{-5}$, $M_{tot}/M_J = 2.1\times10^{-4}$.
- 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 ($I/MR^2 \approx 0.355$; Anderson et al. 2001).
  - Require accretion time > 10^5 yr.
  - Finished accreting > 4 Myr after CAIs (Barr & Canup 2008).



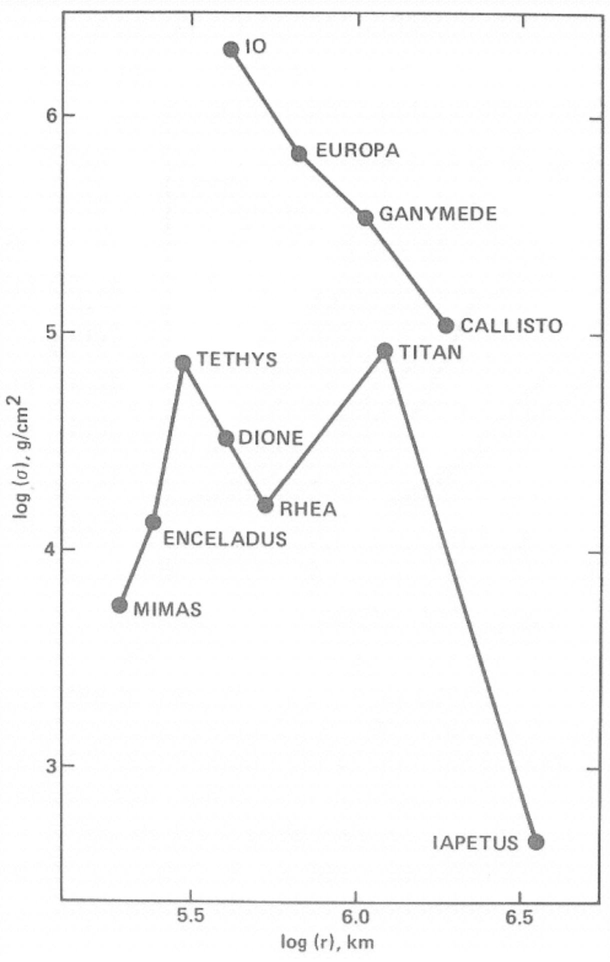
- The orbits of Io, Europa, and Ganymede are in the Laplace resonance, with orbital periods nearly in the ratio 1:2:4.
- The orbital eccentricities maintained by the resonances lead to
  - sustained dissipation of tidal energy
  - active volcanism on Io and probably liquid ocean on Europa.
- Primordial or tidal origin of the resonance?



Formation Scenarios

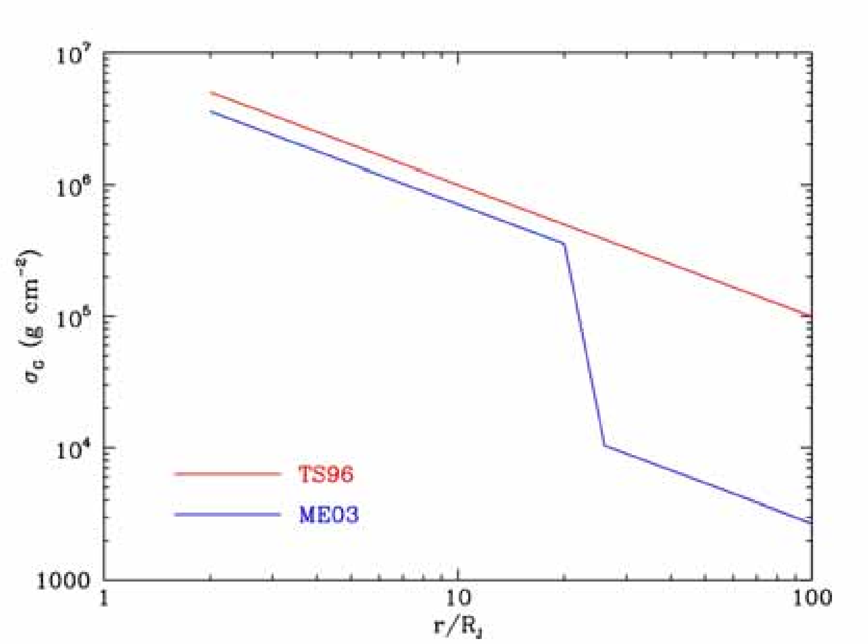
- Gas poor planetesimal capture model (Safronov et al. 1986; Estrada & Mosqueira 2006).
- Minimum mass subnebula model (Lunine & Stevenson 1982; Takata & Stevenson 1996; Mosqueira & Estrada 2003).
- Gas-starved subnebula model (Canup & Ward 2002).
- Nature of mass and angular momentum transport in subnebula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

Minimum Mass Subnebula Model

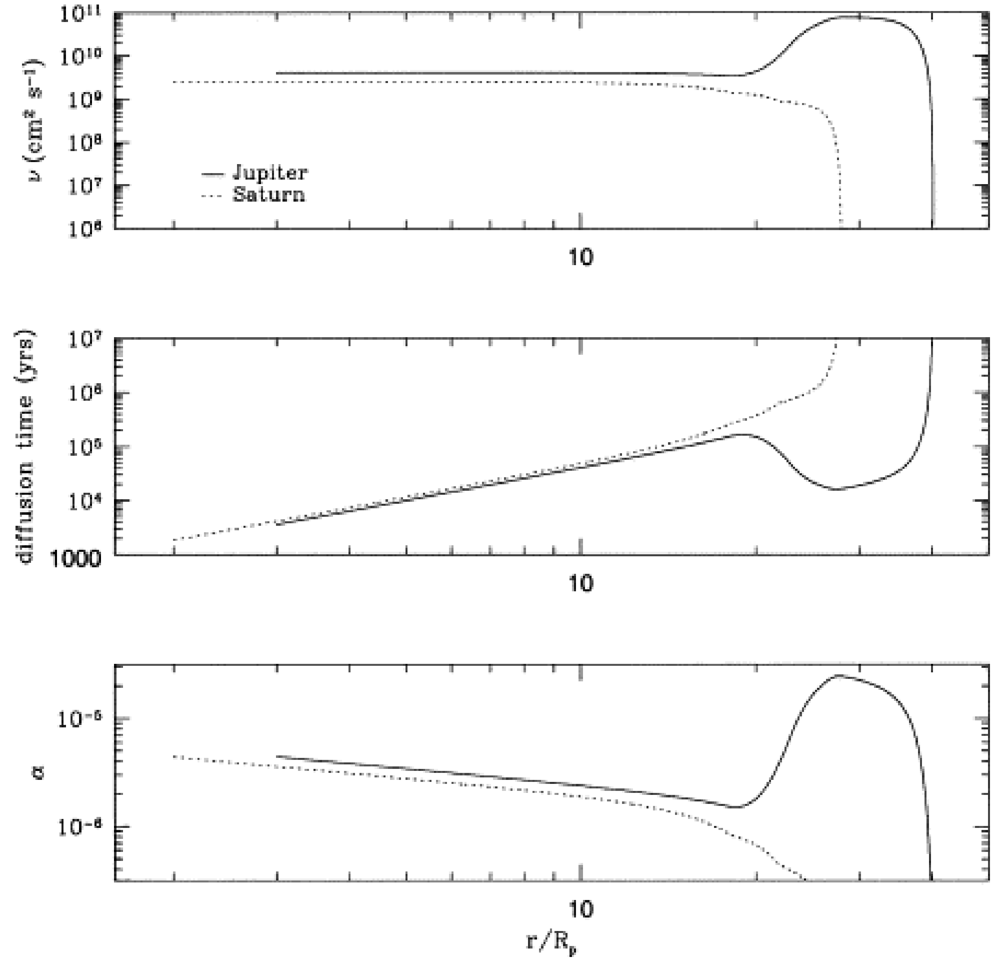


(Pollack & Consolmagno 1984)

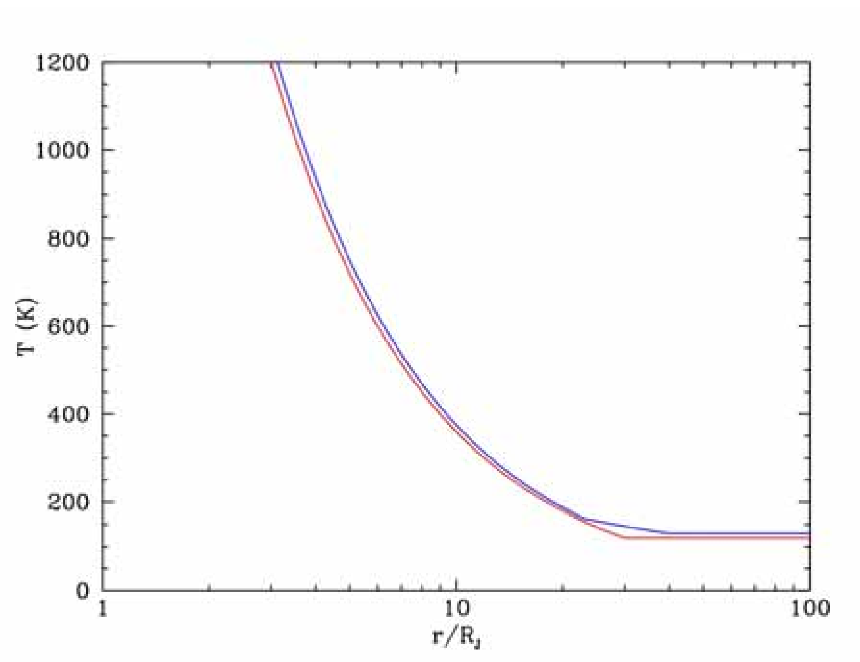
- Analogous to minimum mass solar nebula.
- Callisto accretion time too fast unless surface density drops sharply at $r/R_J \approx 23$ as in Mosqueira & Estrada (2003).



- Temperature too high unless $\alpha \sim 10^{-6}$ to 10^{-5}.
- Is required α below that from e.g. damping of satellitesimal density wave wakes? (Goodman & Rafikov 2001)



(Mosqueira & Estrada 2003)



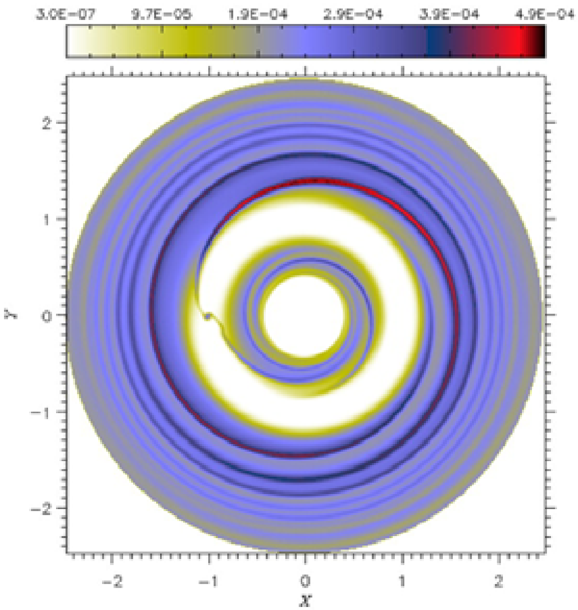
- Type I migration timescale (Ward 1997; Tanaka et al. 2002)

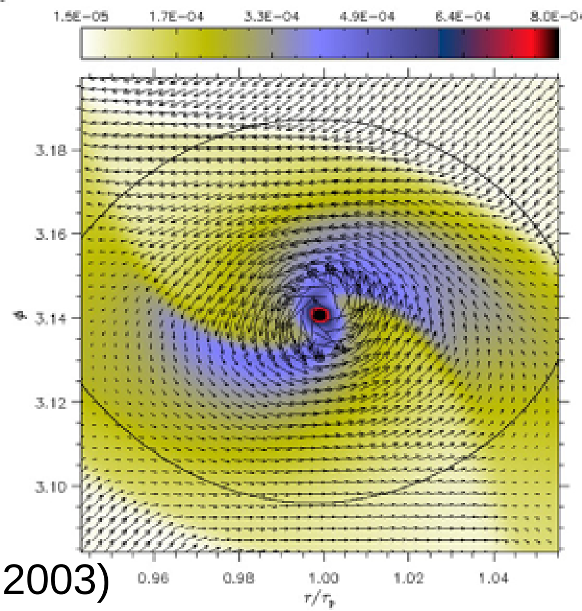
$$\tau_{\rm I} = (C_{\rm a}\,\Omega)^{-1}\,(M_{\rm p}/M_{\rm s})\,(M_{\rm p}/\sigma_{\rm G}a^2)\,(H/a)^2$$

  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 α.

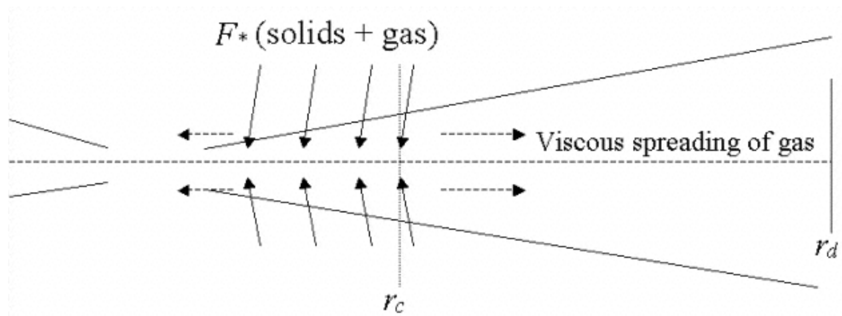
Gas-starved Subnebula Model



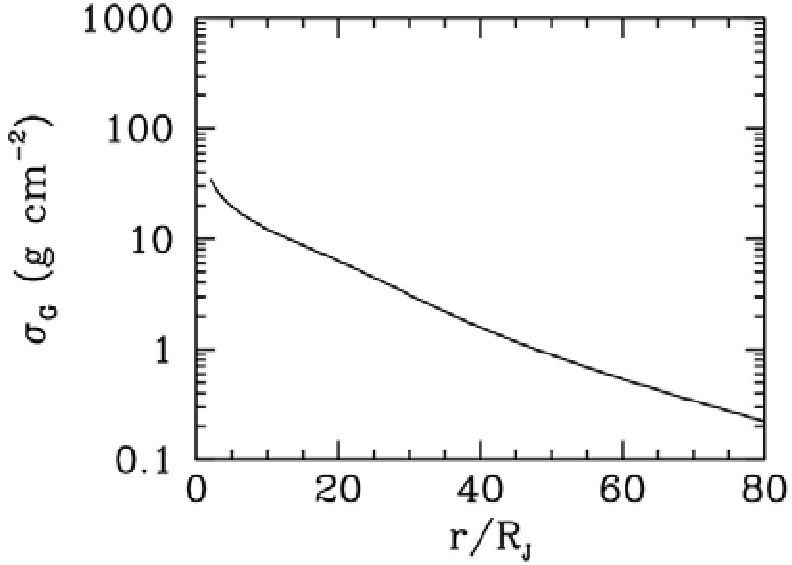


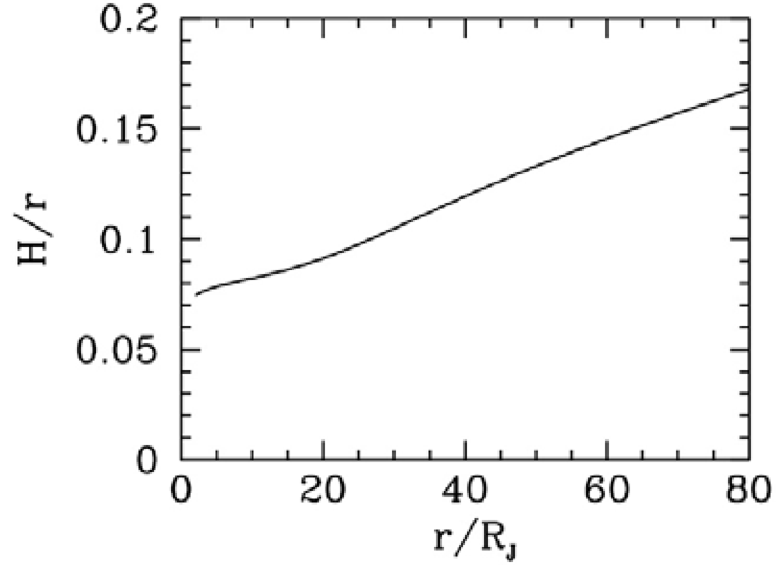
(D'Angelo et al. 2003)

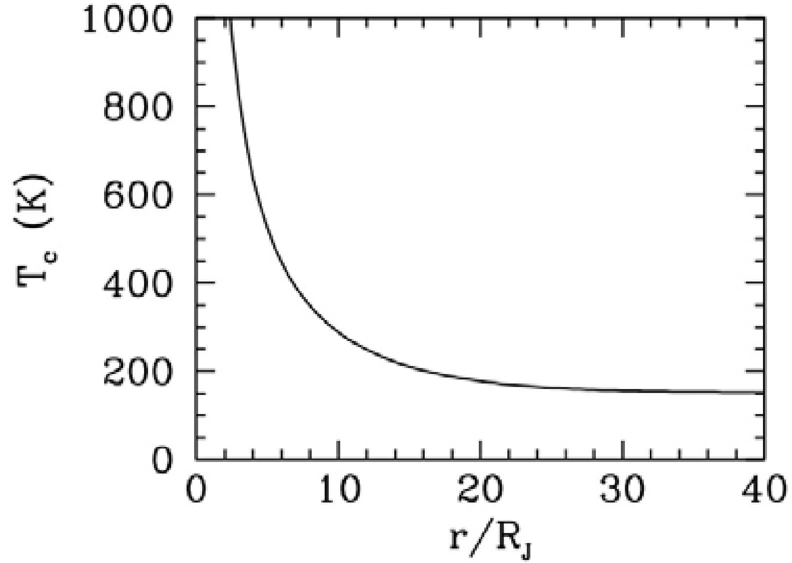
- Not all mass needed to form the satellites in the disk all at once.
- Replenished by slow inflow of gas and solids from the solar nebula after Jupiter opens a gap.



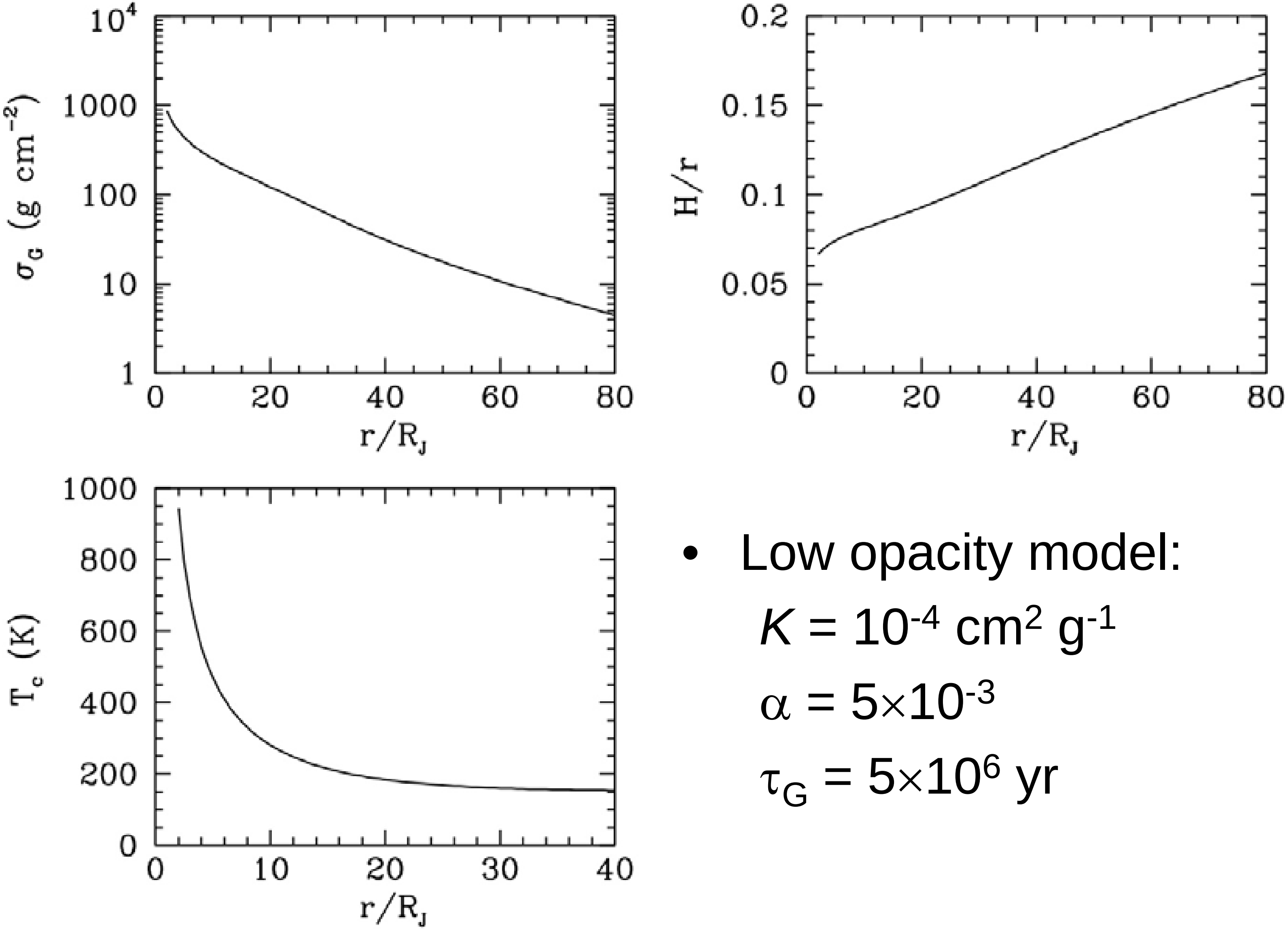
(Canup & Ward 2002)





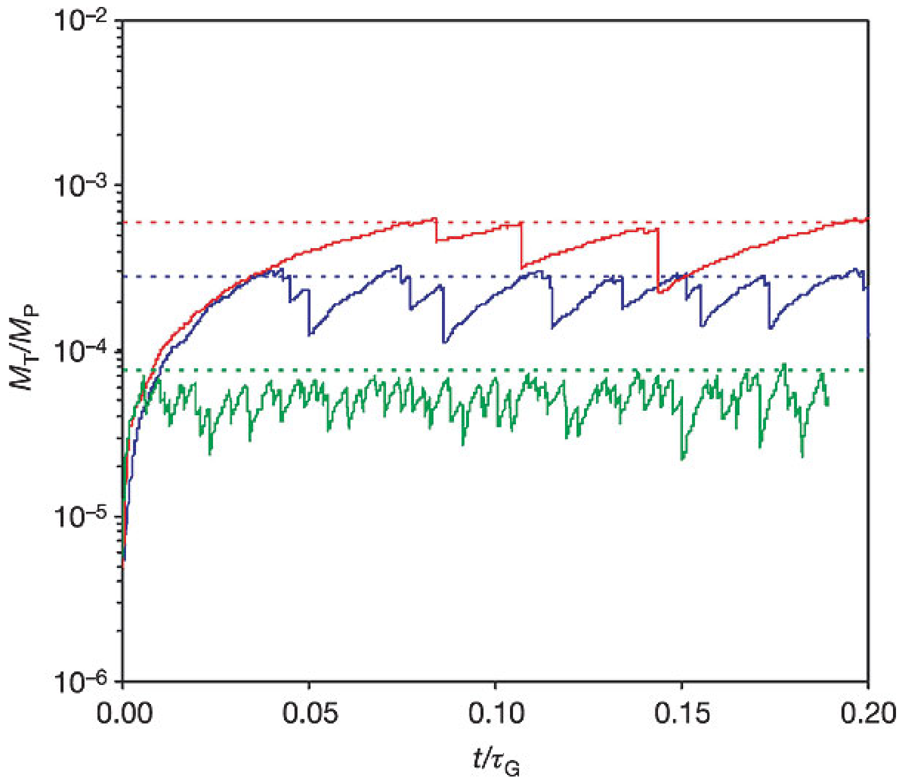


- High opacity model:
  $K = 1$ cm^2 g^{-1}
  $\alpha = 5\times10^{-3}$
  $\tau_G = 10^8$ yr



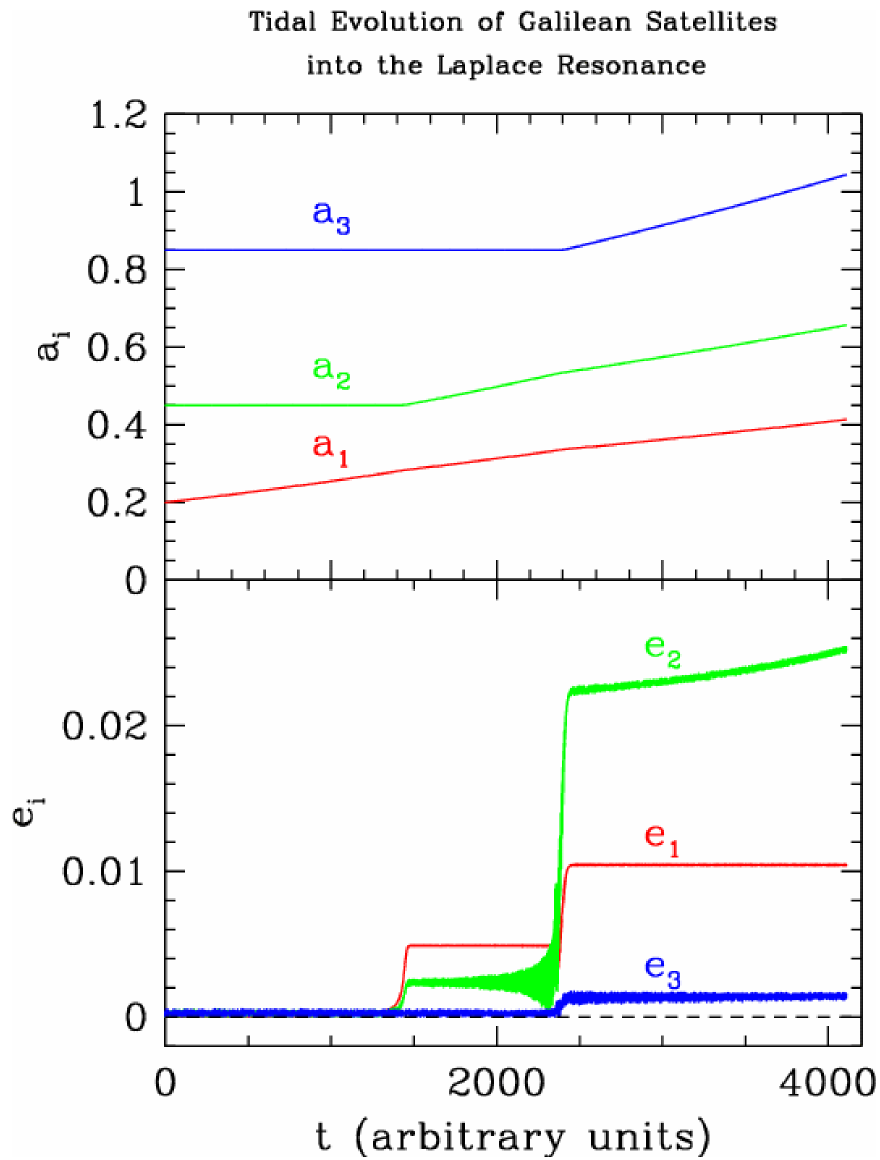
- Low opacity model:
  $K = 10^{-4}$ cm^2 g^{-1}
  $\alpha = 5\times10^{-3}$
  $\tau_G = 5\times10^6$ yr

- Balance of supply of inflowing material to satellites and satellite loss due to migration regulates mass fraction of satellite systems to ~ 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.

Nebula Induced Evolution of Galilean Satellites into Laplace Resonance

QuickTime™ and a
BMP decompressor
are needed to see this picture.

Nebula Induced Evolution of Galilean Satellites into Laplace Resonance

- We used a simple model with:
  - Full satellite masses throughout migration
  - Type I migration with $a^{-1} da/dt \sim M_s$ (i.e. we assumed the *a*-dependence is weak)
  - Eccentricity damping with $|e^{-1} de/dt| \sim 30 |a^{-1} da/dt|$ (Artymowicz 1993).

QuickTime™ and a
BMP decompressor
are needed to see this picture.

- But capture into 1:2:4 is probabilistic.
- In a more complex model with:
  - Satellite masses growing linearly with time
  - $a^{-1} da/dt \propto M_s\, a^{-n}$
    (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 $n = 0$

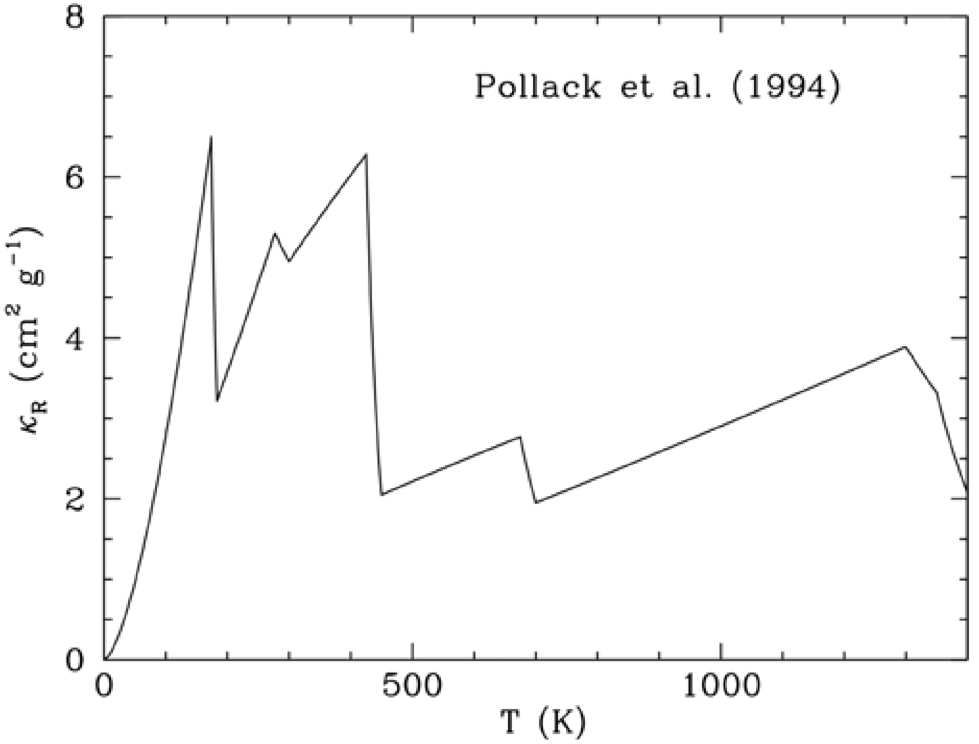
  $P_{1:2:4} \approx 0.29$ for $n = 1/5$
- To determine the likelihood of capture into the observed Laplace resonance, we need a more realistic circumjovian disk model.

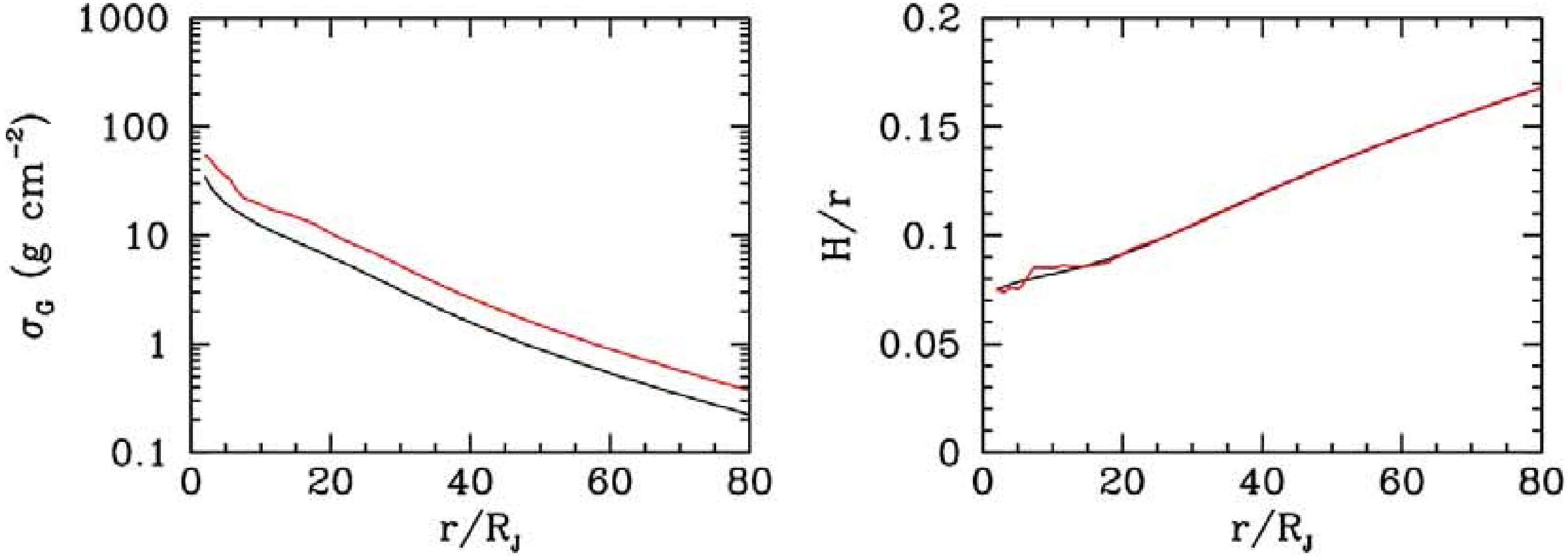
Improved Gas-starved Subnebula Model

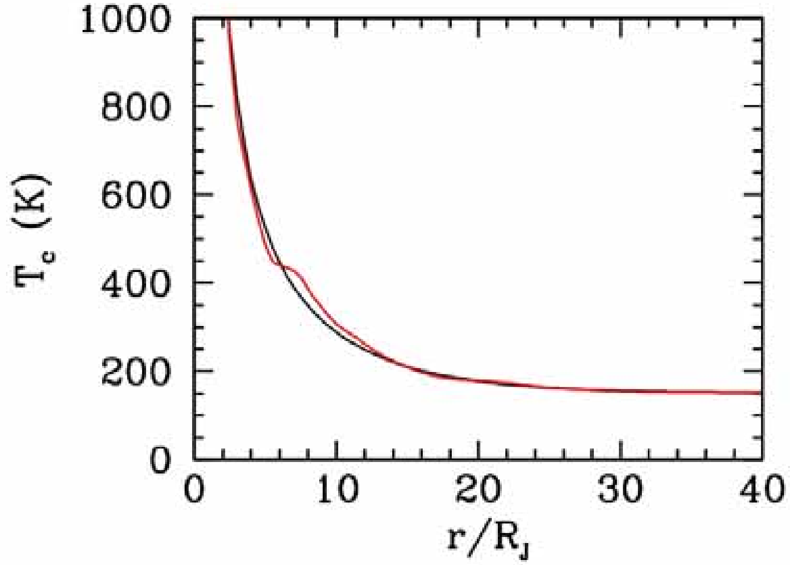
- Improved treatment of low τ_c (optical depth to the midplane) regime and incoming radiation of Jupiter.
- Midplane temperature T_c using
  - Analytic vertical structure model of Hubeny (1991) for viscous dissipation and isotropic solar nebula irradiation
  - Extension by Malbet et al. (2001) for irradiation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

$$
\begin{aligned}
T_c^4 &= \frac{3}{4}\left[\frac{\tau_c}{2}+\frac{1}{\sqrt{3}}+\frac{1}{3\tau_c}\right]T_d^4+T_{\rm neb}^4 \\
&+\frac{3}{4}\left[\mu_J\left(1-e^{-\tau_c/\mu_J}\right)+\frac{1}{\sqrt{3}}+\frac{1}{3\mu_J}e^{-\tau_c/\mu_J}\right]\left(\frac{\mu_J}{2}\right)\left(\frac{R_J}{r}\right)^2 T_J^4,
\end{aligned}
$$

- Pollack et al. (1994) temperature dependent opacity κ.







- High opacity model:

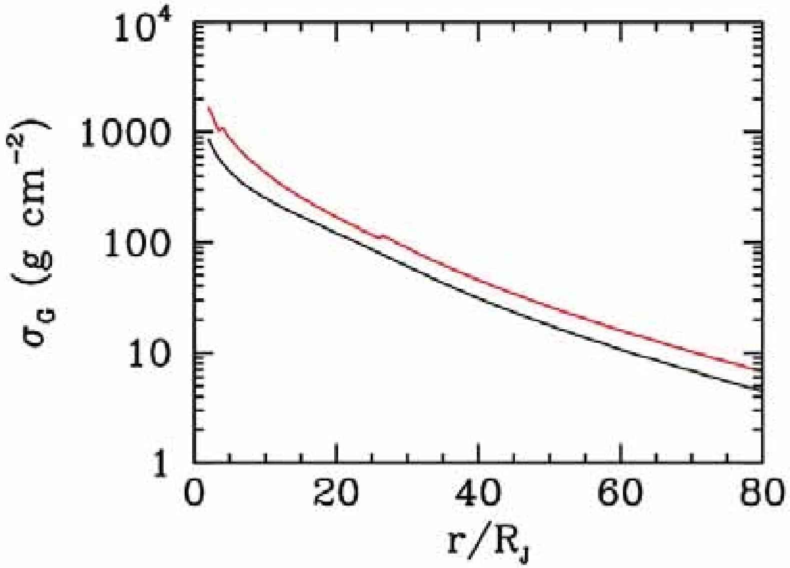
  $f_{opac} = 1$

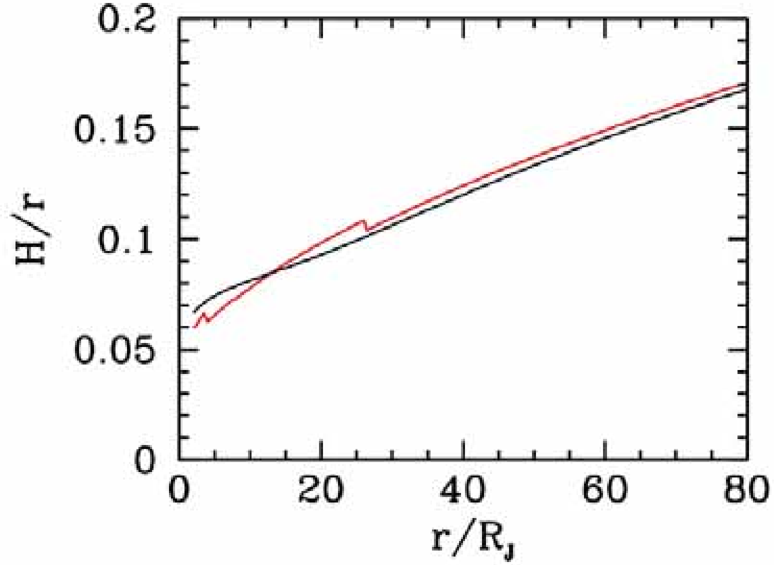
  $\alpha = 5\times10^{-3}$

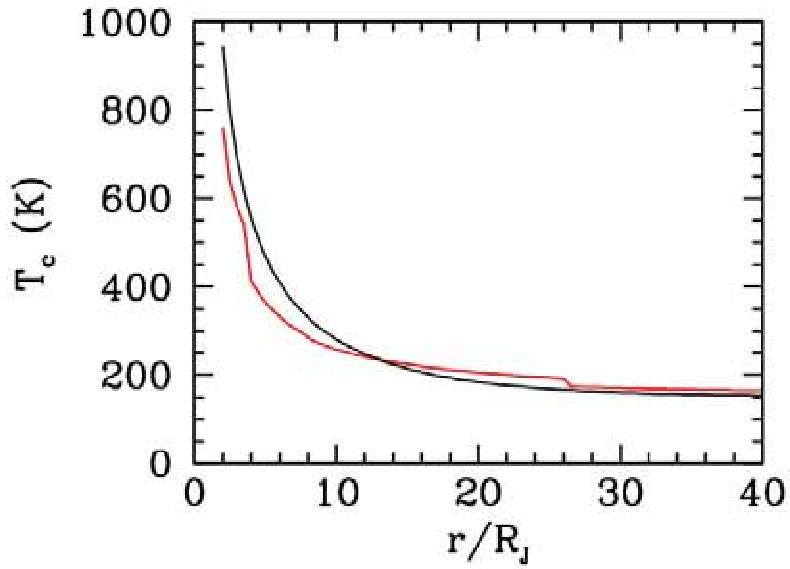
  $\tau_G = 6\times10^{7}$ yr

Red: Improved gas-starved disk model

Black: CW02 model with $K = f_{opac}$







- Low opacity model:

  $f_{opac} = 10^{-4}$

  $\alpha = 8\times10^{-4}$

  $\tau_G = 2\times10^{7}$ yr

Red: Improved gas-starved disk model

Black: CW02 model with $K = f_{opac}$

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

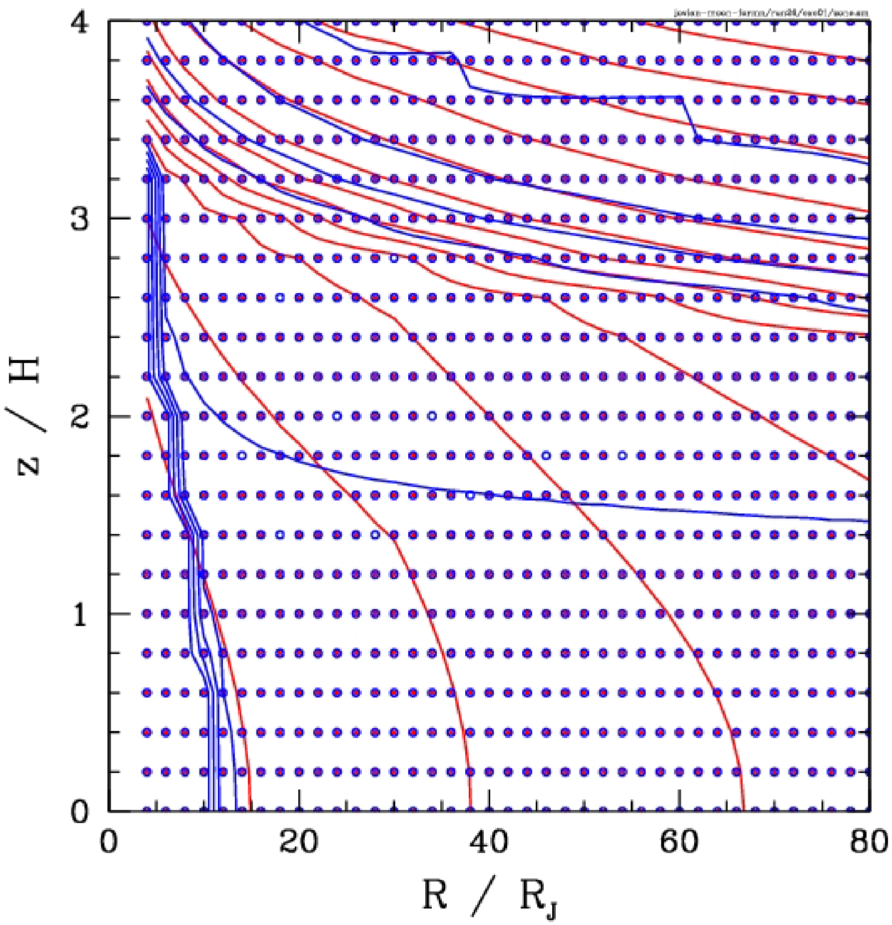
- Seven species added to reaction network: charged grains G^0, $G^{\pm}$, $G^{\pm 2}$ and adsorbed neutrals $H_2(G)$ and $Mg(G)$.
- Thermal adsorption and desorption of neutrals and ions.
- Grain charging and neutralization in collisions with ions and electrons.
- Charge exchange in grain-grain collisions.
- 1 micron grain size.

Dead Zone Criterion

MRI turbulence is absent if both

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

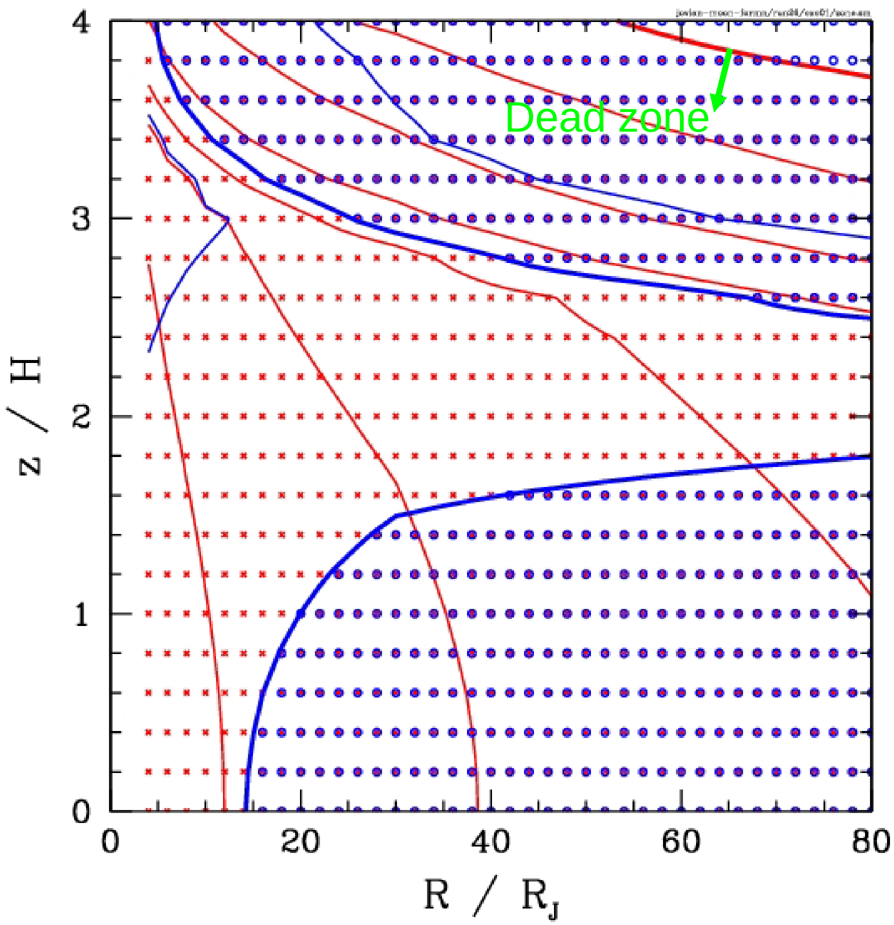
Takata & Stevenson MMSN with dust



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

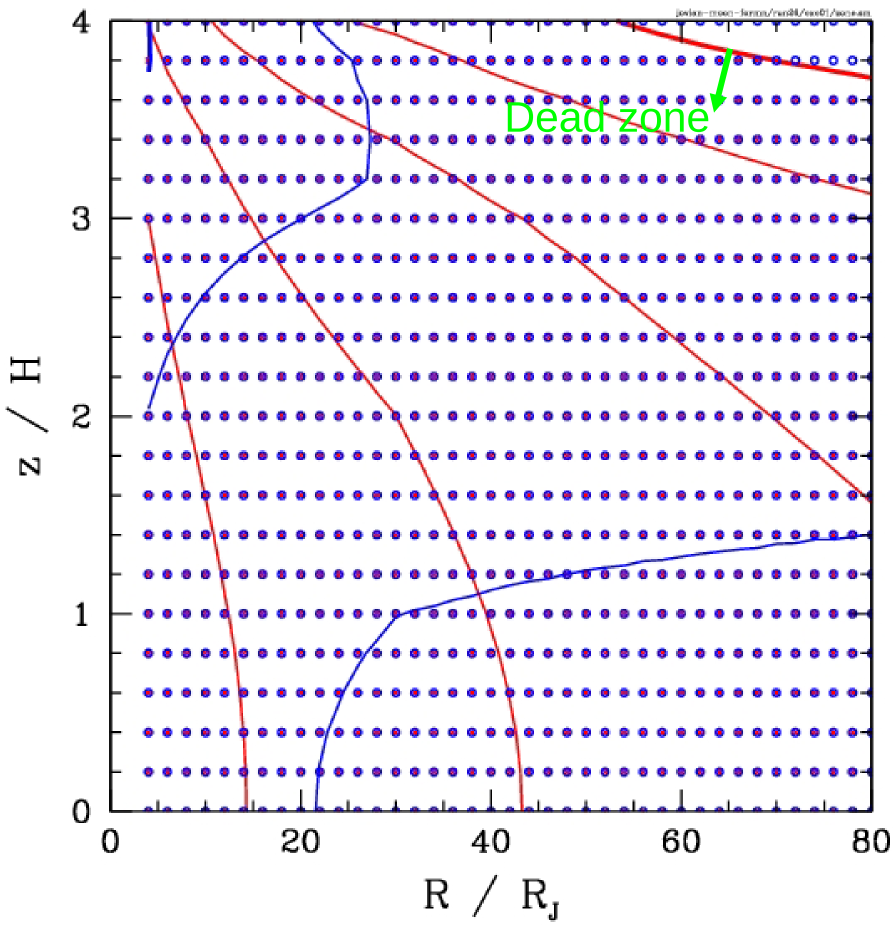
Takata & Stevenson MMSN without dust



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

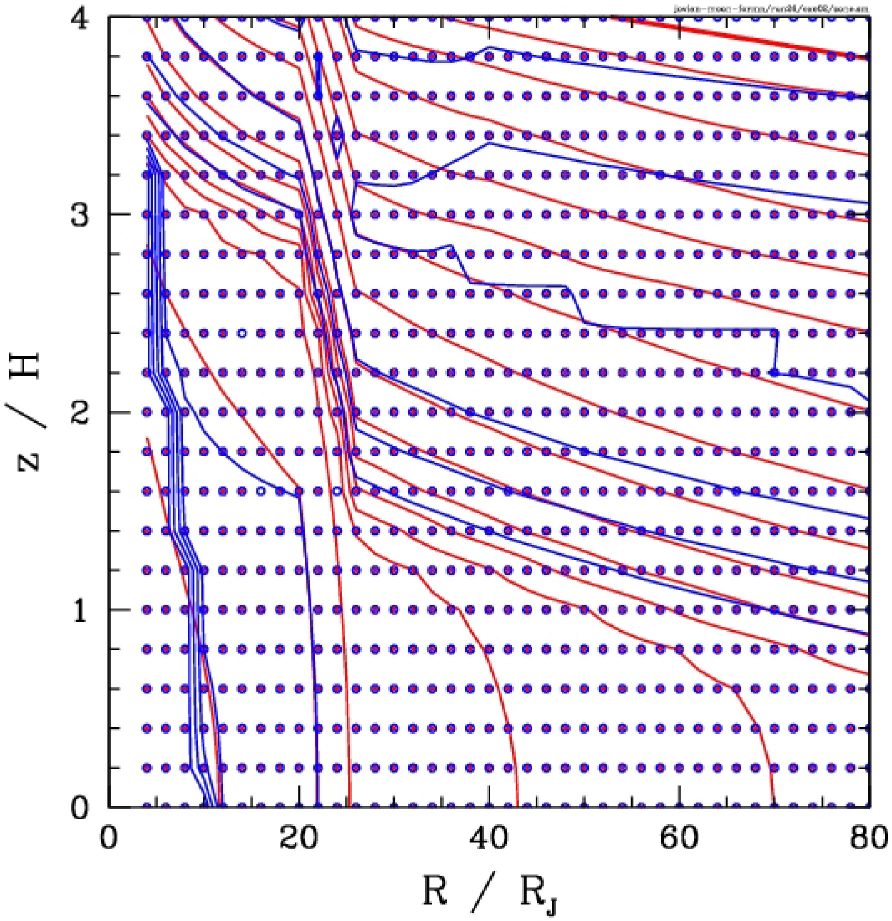
Takata & Stevenson MMSN without dust and with ^{26}Al



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

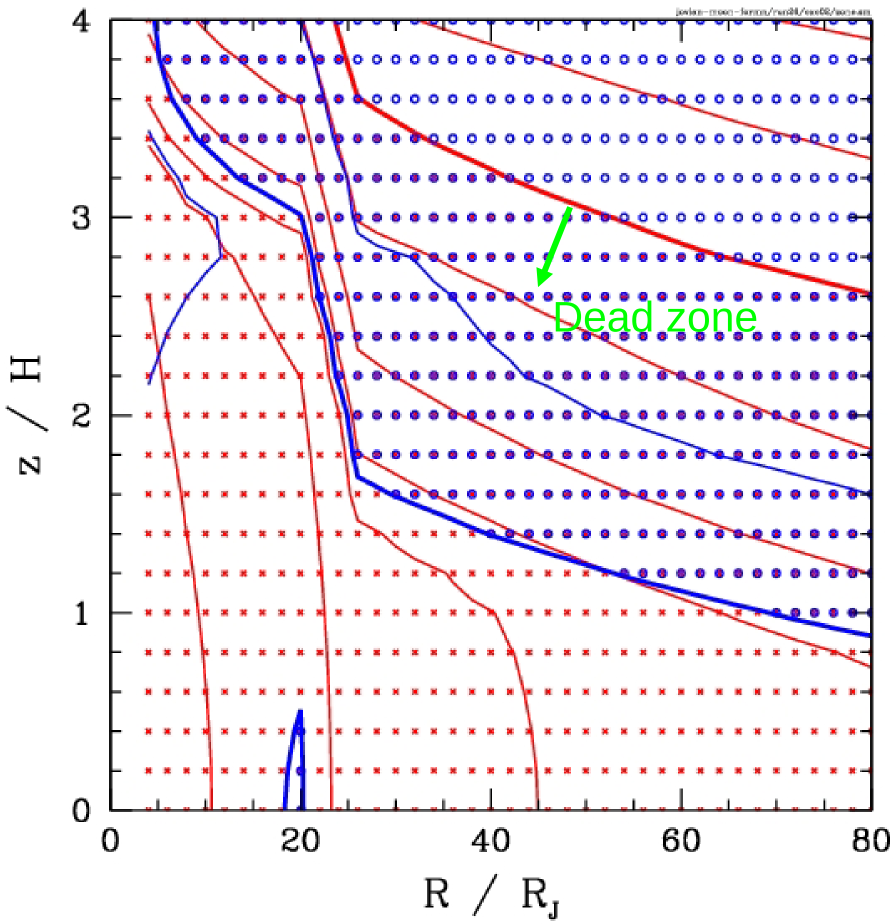
Mosqueira & Estrada MMSN with dust



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

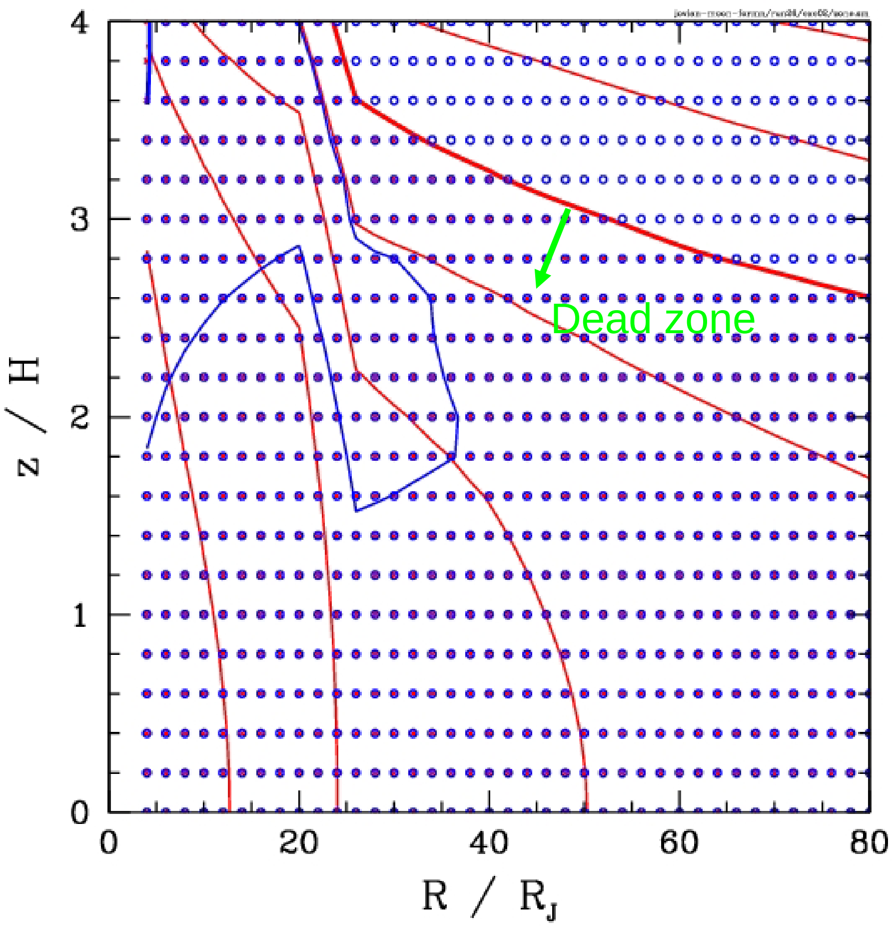
Mosqueira & Estrada MMSN without dust



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

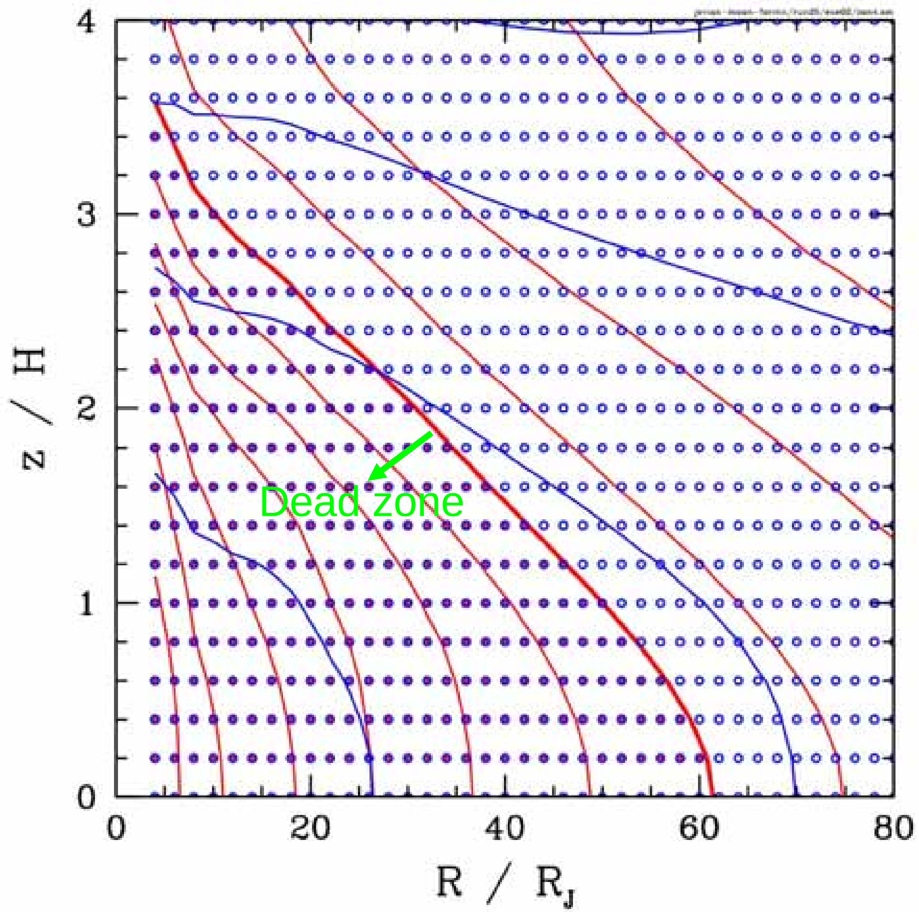
Mosqueira & Estrada MMSN without dust and with ^{26}Al



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

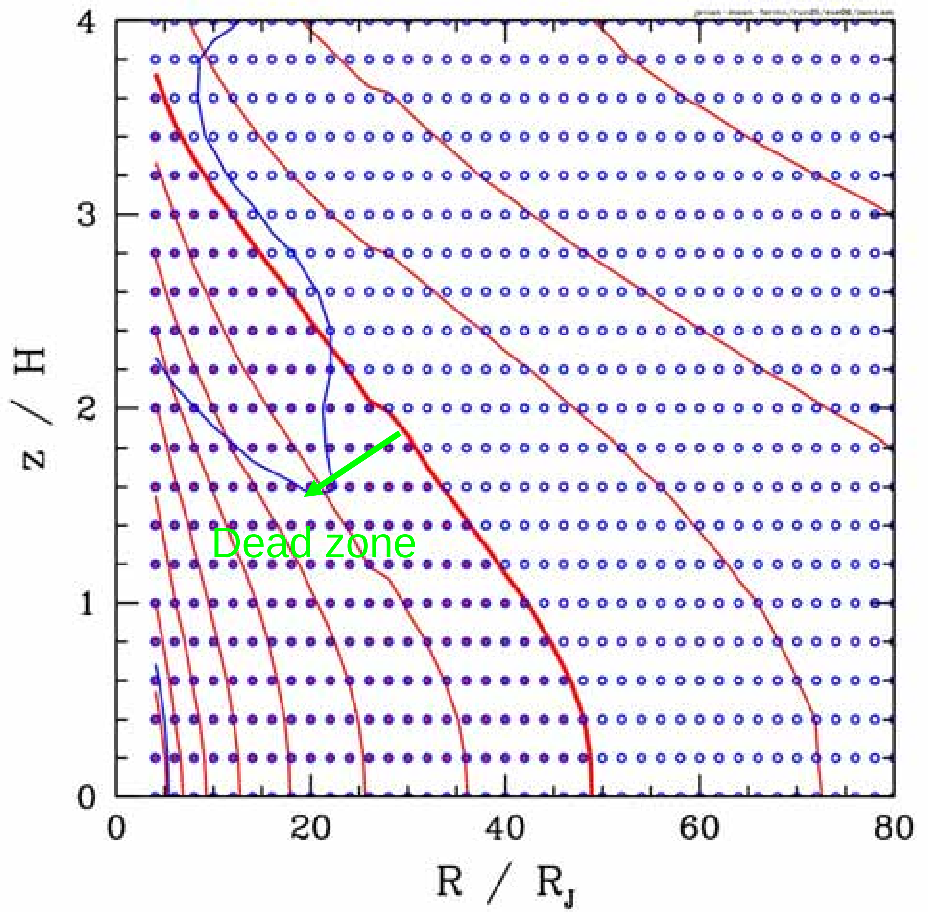
Improved Gas-starved Subnebula with $f_{opac} = 1$



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

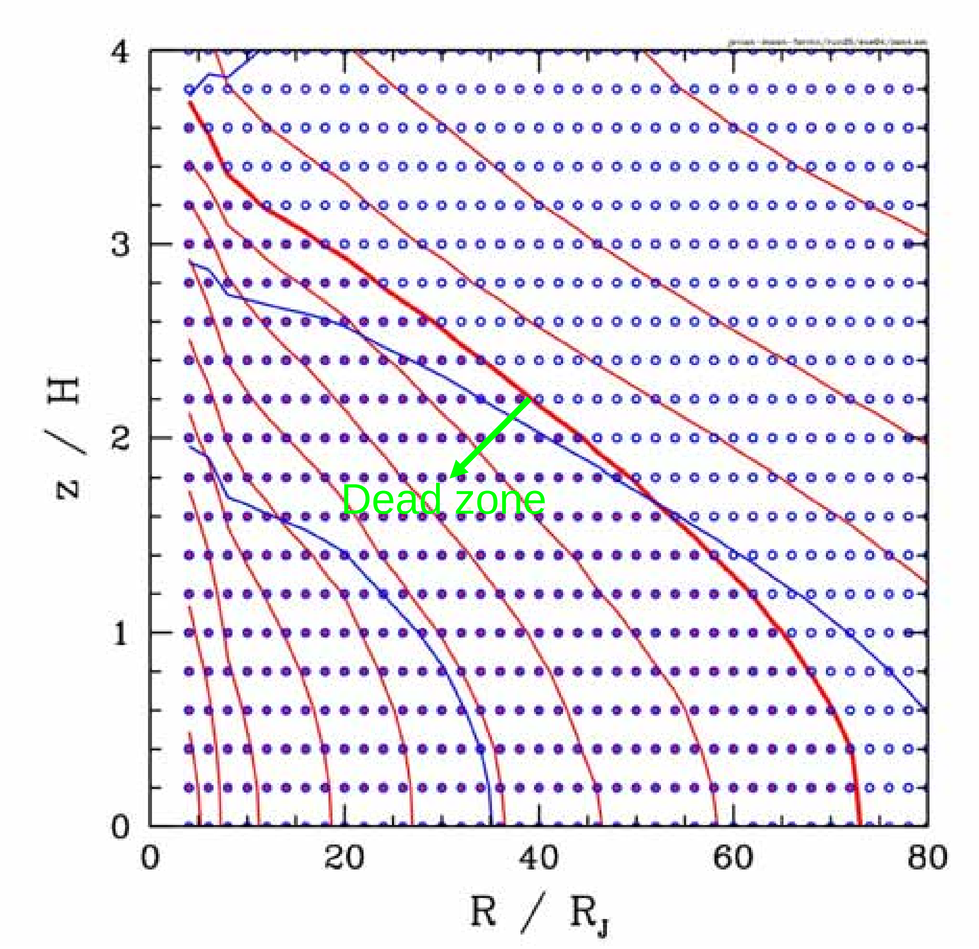
Improved Gas-starved Subnebula with $f_{opac} = 10^{-4}$



* Elsasser number < 1

o $t_{recomb} < t_{mix}$

Improved Gas-starved Subnebula with $f_{opac} = 10^{-2}$



* Elsasser number < 1

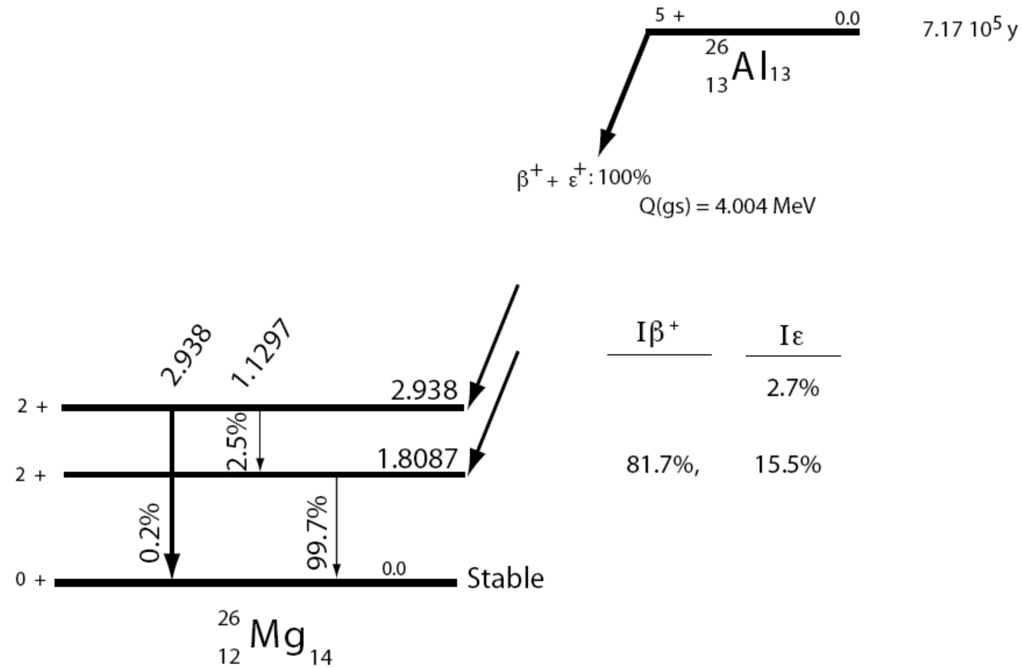
o $t_{recomb} < t_{mix}$

^{26}Al Decay: Heat Production

(Castillo-Rogez et al. 2009)

- ^{26}Al decay to ^{26}Mg (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 ^{26}Al decay used in the literature.
- Factor of 3.3 ranging from 1.2 to 4 MeV per decay.

- ^{26}Al decays 82% of the time by β^+ 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}Al and ^{26}Mg.
  - does not account for energy lost by neutrino emission.
- 1.2 MeV: close to max. β^+ kinetic energy.
  - does not account for absorption of γ 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

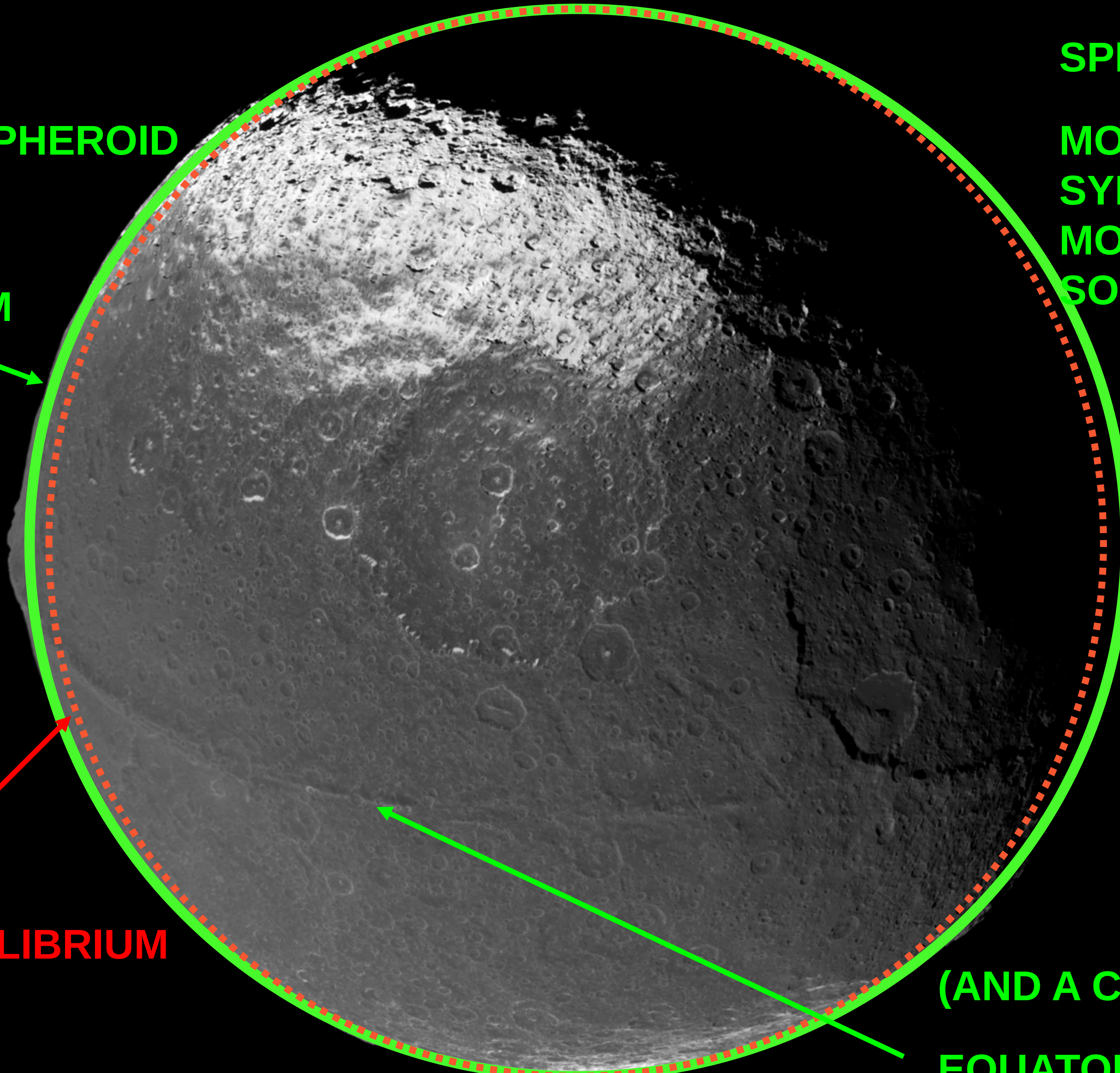
SHAPE:

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

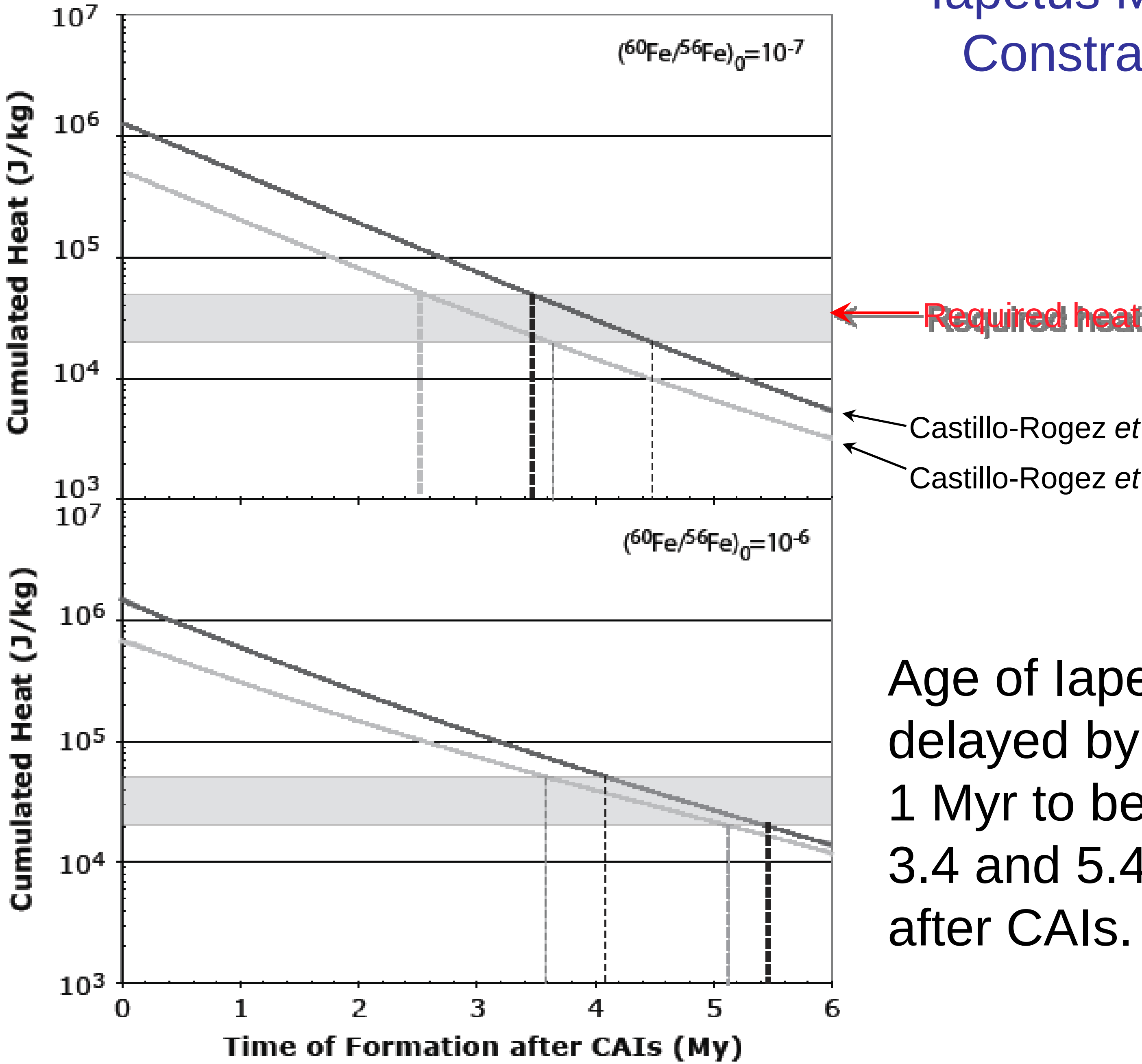
(AND A CONUNDRUM:

EQUATORIAL RIDGE)

^{26}Al Decay: Revised Age for Iapetus

- Short-lived radioactive isotopes (^{26}Al and ^{60}Fe) 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.

Iapetus Model Constraints



Age of Iapetus is delayed by about 1 Myr to between 3.4 and 5.4 My 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}Al: 3.12 MeV per decay.
- Age of Iapetus is revised to be between 3.4 and 5.4 My after CAIs.