Resonant Planets and Satellites

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Introduction

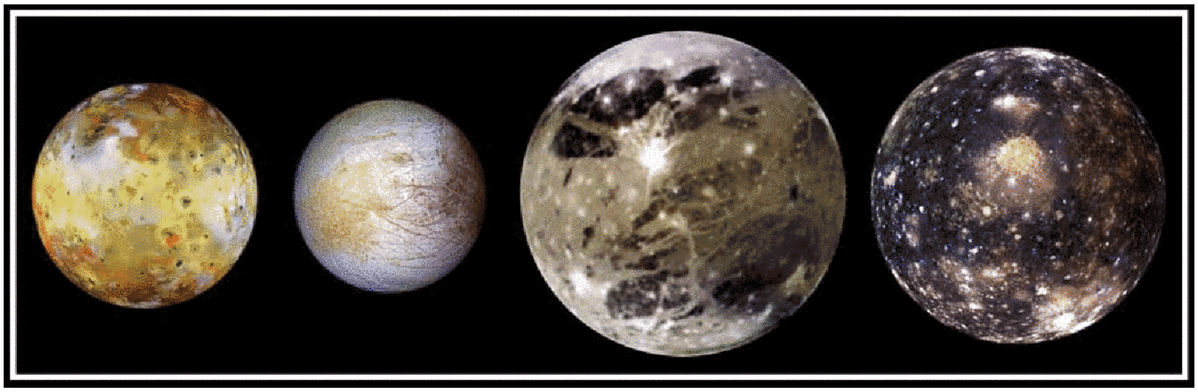
- The two planets about GJ 876 discovered by Marcy et al. (2001) are in 2:1 mean-motion resonance, with both lowest order eccentricity-type mean-motion resonance variables $\theta_1 = \lambda_1 - 2\lambda_2 + \varpi_1$ and $\theta_2 = \lambda_1 - 2\lambda_2 + \varpi_2$ librating about 0° (Laughlin & Chambers 2001; Rivera & Lissauer 2001; Lee & Peale 2002).

- There are possibly two other systems with mean-motion resonances:
  - 2:1 resonance for the two planets about HD 82943 (Mayor et al. 2004).
  - 3:1 resonance for the inner two planets about 55 Cnc (Marcy et al. 2002).
- Mean-motion resonances can be easily established during planet formation by the differential migration of planets due to planet-disk interaction (Kley's talk).
- Mean-motion resonances can also be established by multiple-planet scattering in crowded planetary systems (Levison et al. 1998; Adams & Laughlin 2003).

- Mean-motion resonances may be ubiquitous in extrasolar planetary systems.
  - What are the 2:1 resonance configurations that we can expect to find in the future?
  - What do these resonances tell us about the evolution of orbits during planet formation?

(Lee 2004)

(see also Lee & Peale 2003; Beaugé et al. 2003; Ferraz-Mello et al. 2003; Hadjidemetriou & Psychoyos 2003; Ji et al. 2003; Thommes & Lissauer 2003)



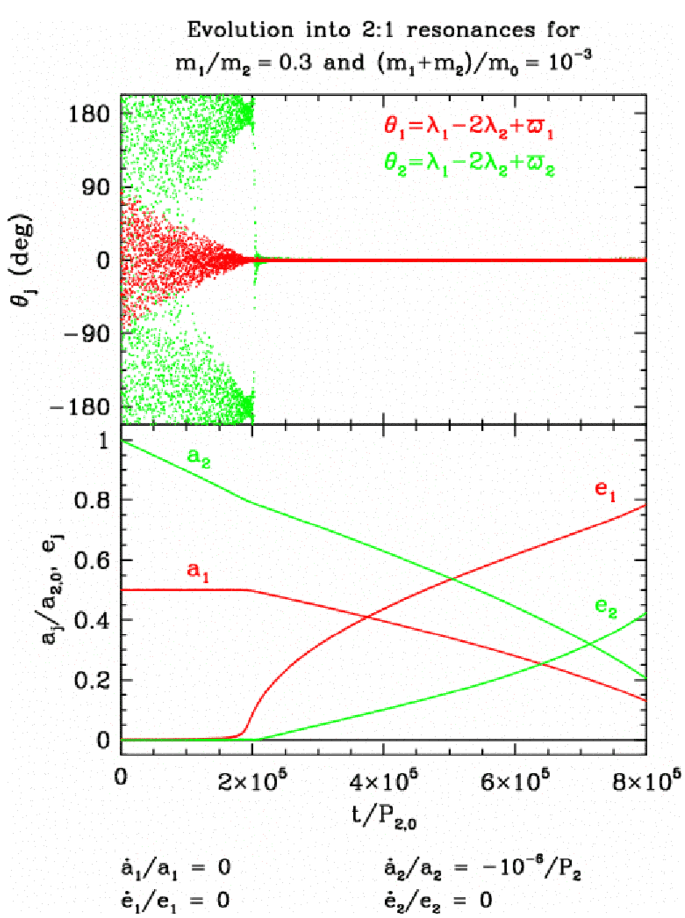
- The orbits of the inner three Galilean satellites of Jupiter, Io, Europa, and Ganymede, are in a set of resonances (including the Laplace relation), with orbital periods nearly in the ratio 1:2:4.
- The orbital eccentricities maintained by the resonances have led to sustained dissipation of tidal energy to produce the active volcanism on Io and, probably, to maintain a liquid ocean on Europa.

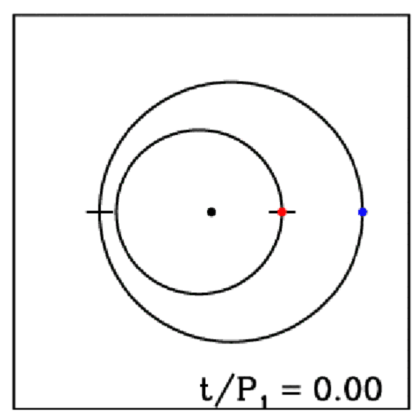
- Can the resonances be assembled primordially by satellite-disk interaction?

  (Peale & Lee 2002)

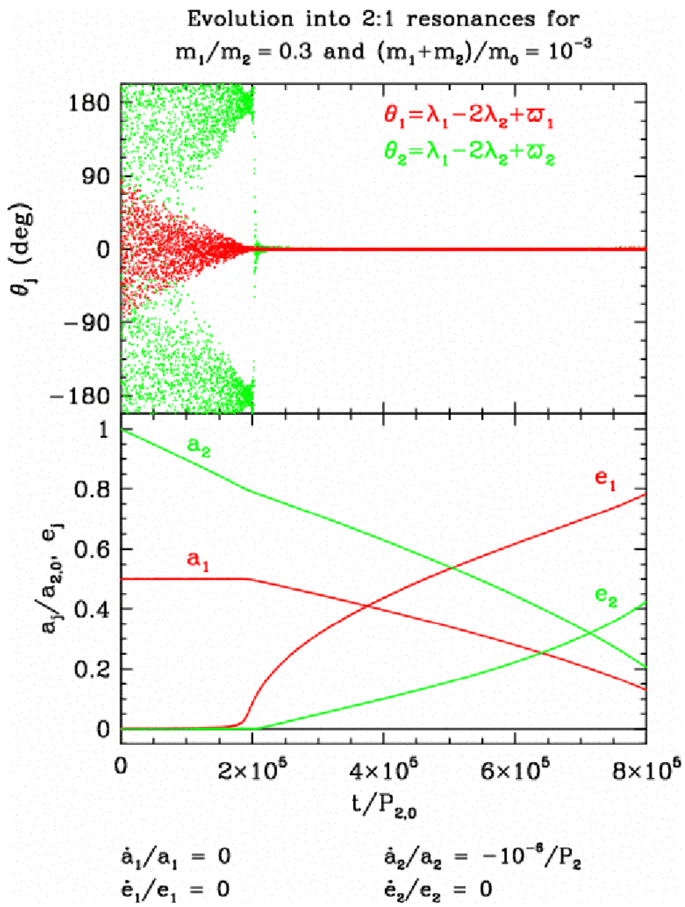
Diversity and Origin of 2:1 Orbital Resonances in Extrasolar Planetary Systems

- Direct numerical orbit integrations of planar 2-planet systems.
- First series:
  - Constant planetary masses
  - Forced inward migration of outer planet
  - No eccentricity damping.

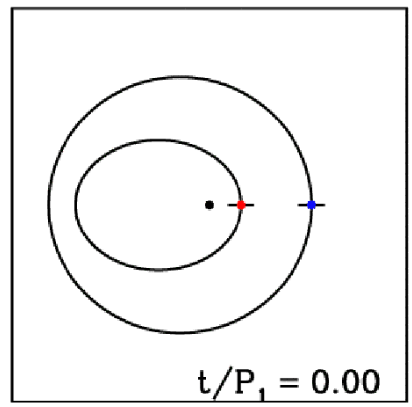


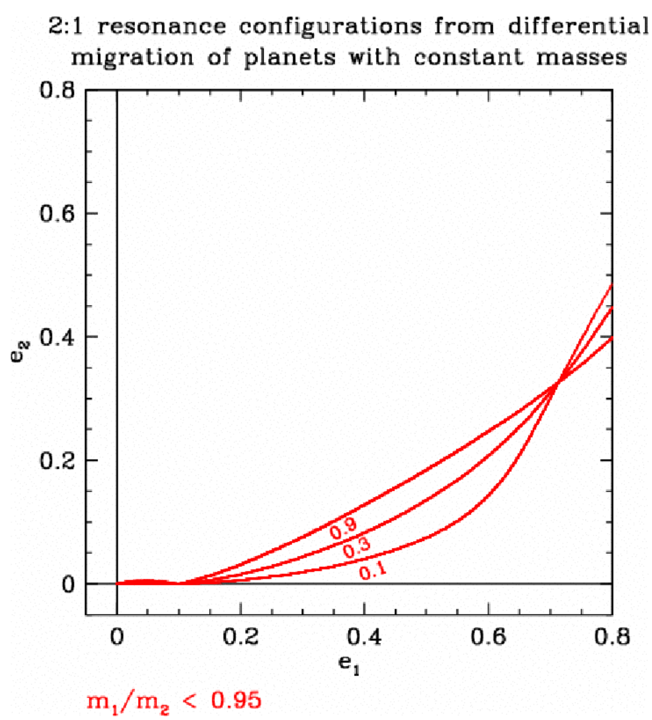


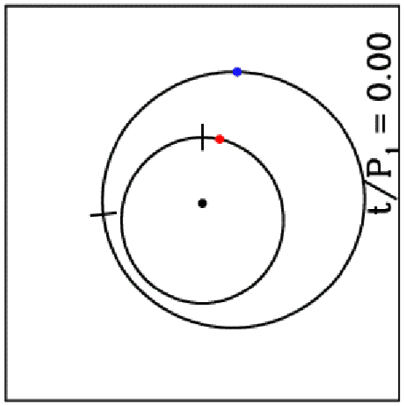
When the e_j are small as in Io-Europa, the only stable 2:1 resonance configuration is the anti-symmetric
$\theta_1 \approx 0^o$ and
$\theta_2 \approx 180^o$ configuration.

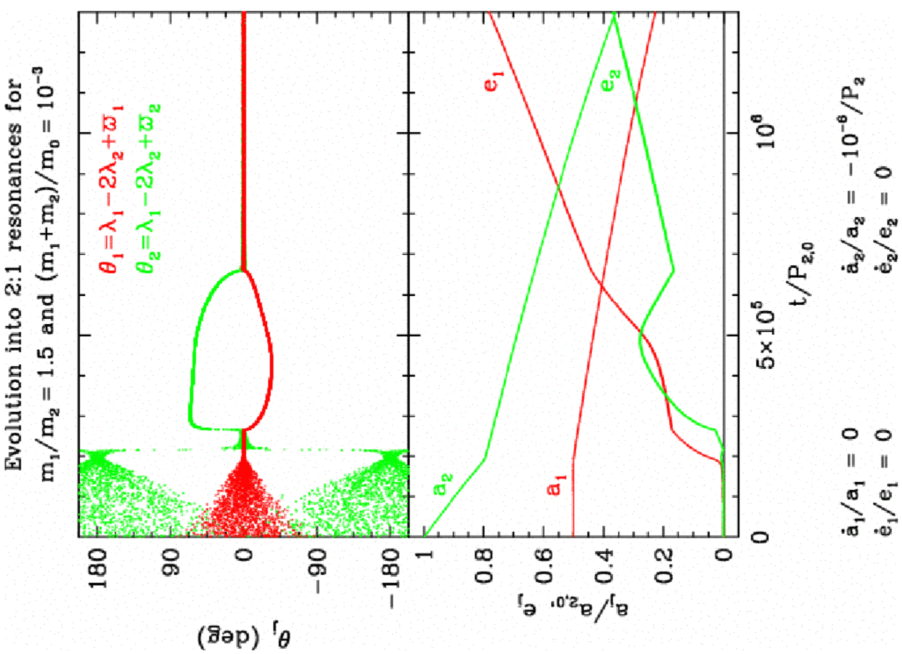


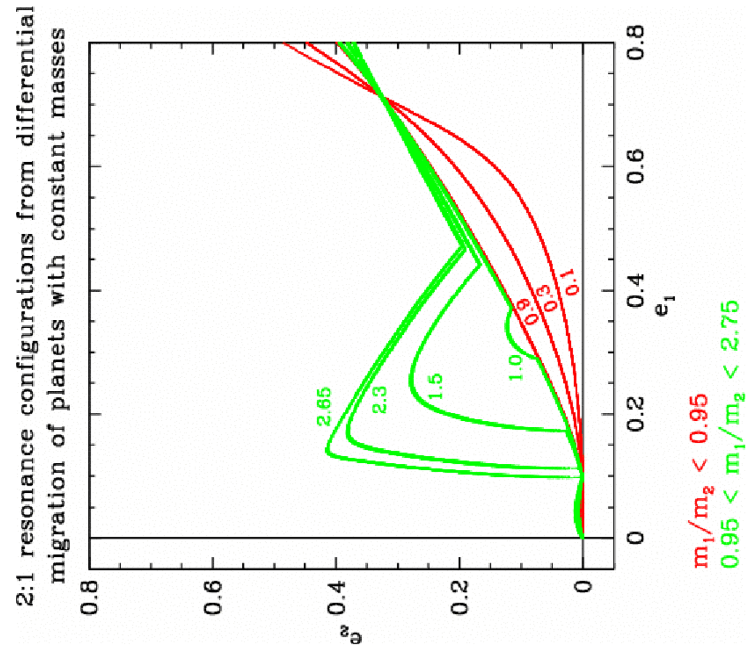
When the e_j are large, both θ_1 and $\theta_2 \approx 0^o$ as in GJ 876.

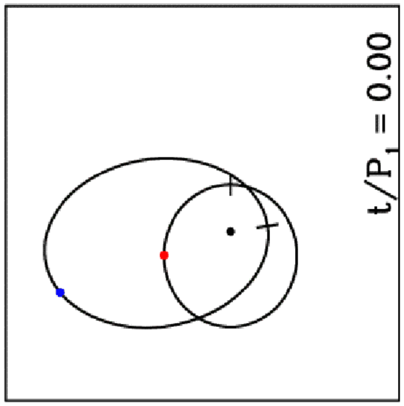


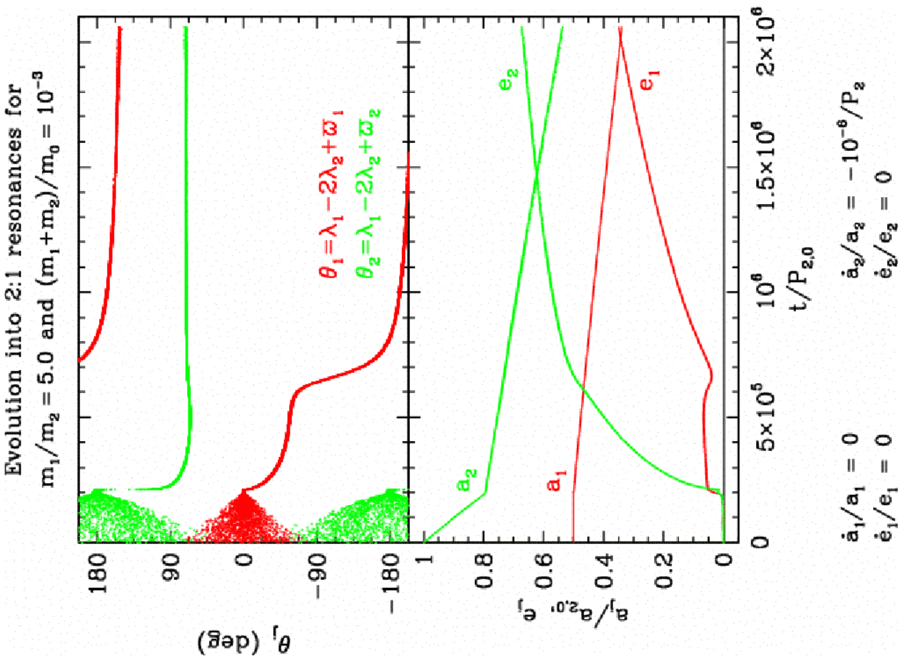


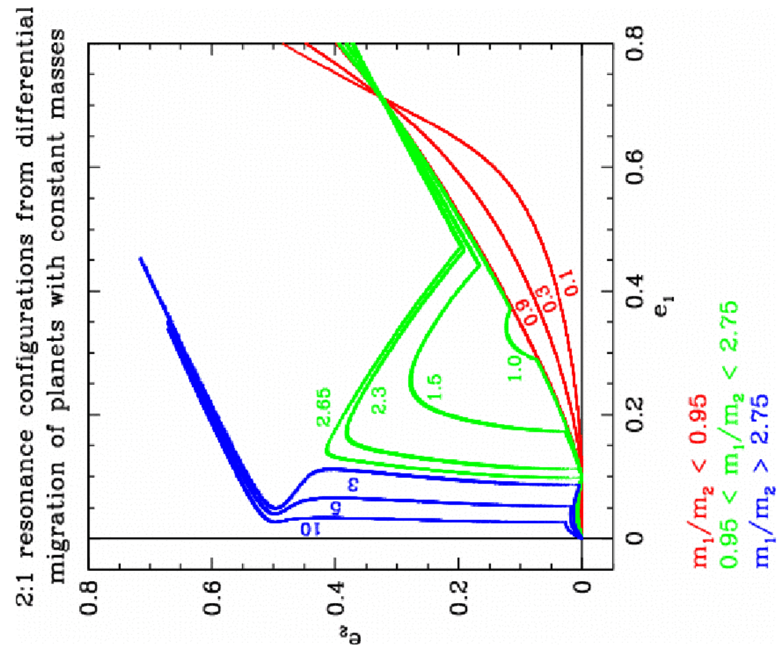

t/P1 = 0.00

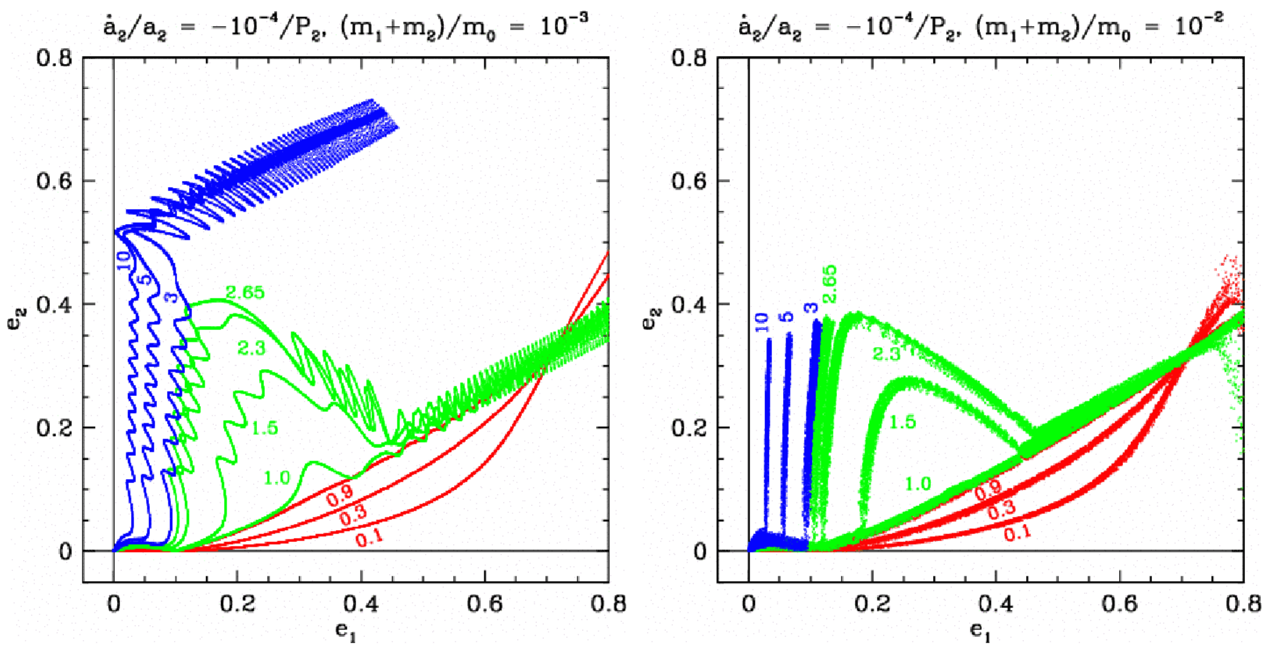

Evolution into 2:1 resonances for
m1/m2 = 1.5 and (m1+m2)/m0 = 10^-3
θ1=λ1−2λ2+ϖ1
θ2=λ1−2λ2+ϖ2
θj (deg)
aj/a2,0, ej
t/P2,0
ȧ1/a1 = 0
ė1/e1 = 0
ȧ2/a2 = −10^-6/P2
ė2/e2 = 0


2:1 resonance configurations from differential
migration of planets with constant masses
e1
e2
m1/m2 < 0.95
0.95 < m1/m2 < 2.75


t/P1 = 0.00

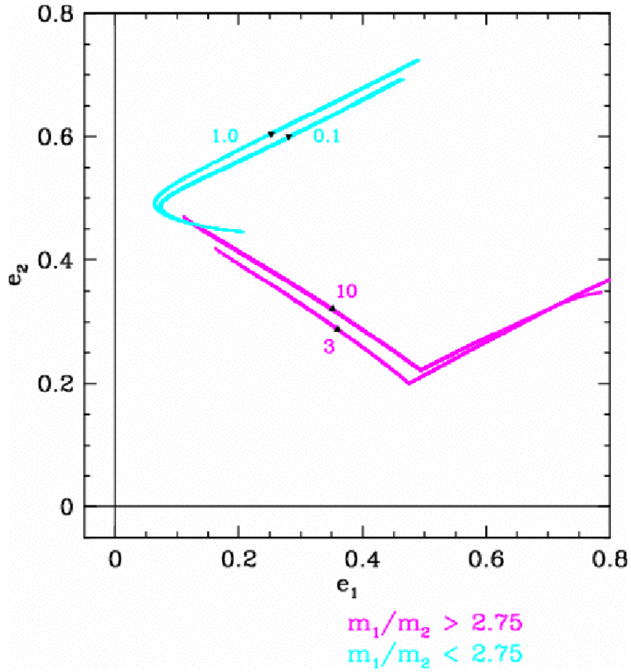

Evolution into 2:1 resonances for
m1/m2 = 5.0 and (m1+m2)/m0 = 10^-3
θ1=λ1−2λ2+ϖ1
θ2=λ1−2λ2+ϖ2
θj (deg)
aj/a2,0, ej
t/P2,0
ȧ1/a1 = 0
ė1/e1 = 0
ȧ2/a2 = −10^-6/P2
ė2/e2 = 0


2:1 resonance configurations from differential
migration of planets with constant masses
e1
e2
m1/m2 < 0.95
0.95 < m1/m2 < 2.75
m1/m2 > 2.75

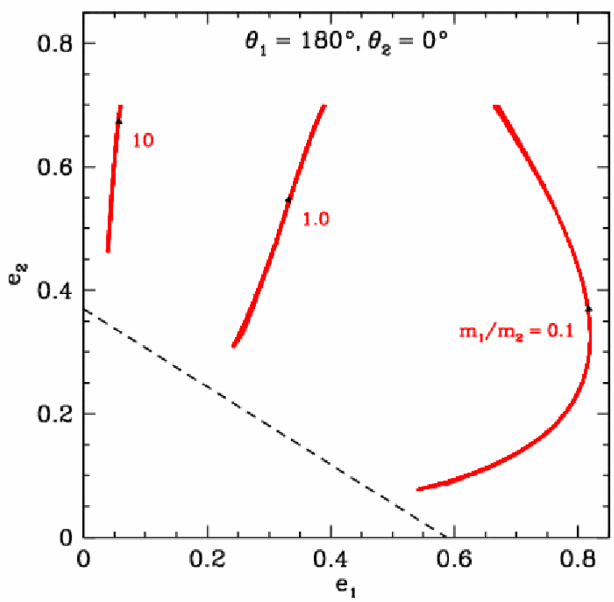


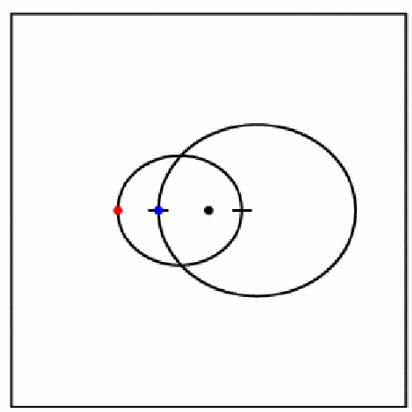
BUT

There are stable 2:1 resonance configurations that cannot be reached by differential migration of planets with constant masses and initially coplanar orbits.



These configurations can be reached if the planets continue to grow at different rates and m_1/m_2 changes during migration.





These configurations can be reached by a migration scenario involving non-coplanar orbits and inclination resonances (Thommes & Lissauer 2003).

The Laplace Relation Among the Galilean Satellites of Jupiter

- For Io (1) and Europa (2),

  $\theta_1 = \lambda_1 - 2\,\lambda\ + \varpi_1 \approx 0^\circ$ and $\theta_2 = \lambda_1 - 2\,\lambda_2 + \varpi_2 \approx 180^\circ$.

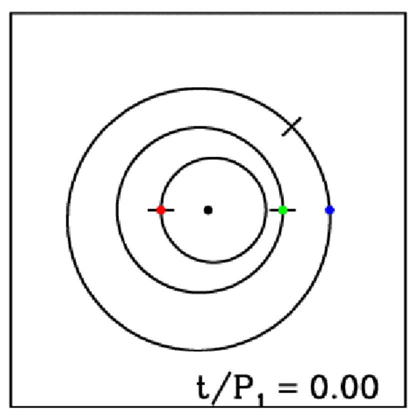
- For Europa (2) and Ganymede (3),

  $\theta_3 = \lambda_2 - 2\,\lambda_3 + \varpi_2 \approx 0^\circ$ but $\theta_4 = \lambda_2 - 2\,\lambda_3 + \varpi_3$ circulates.

- Simultaneous libration of θ_2 and θ_3 means the Laplace Angle

  $\theta_5 = \theta_2 - \theta_3 = \lambda_1 - 3\,\lambda_2 + 2\,\lambda_3 \approx 180^\circ$.

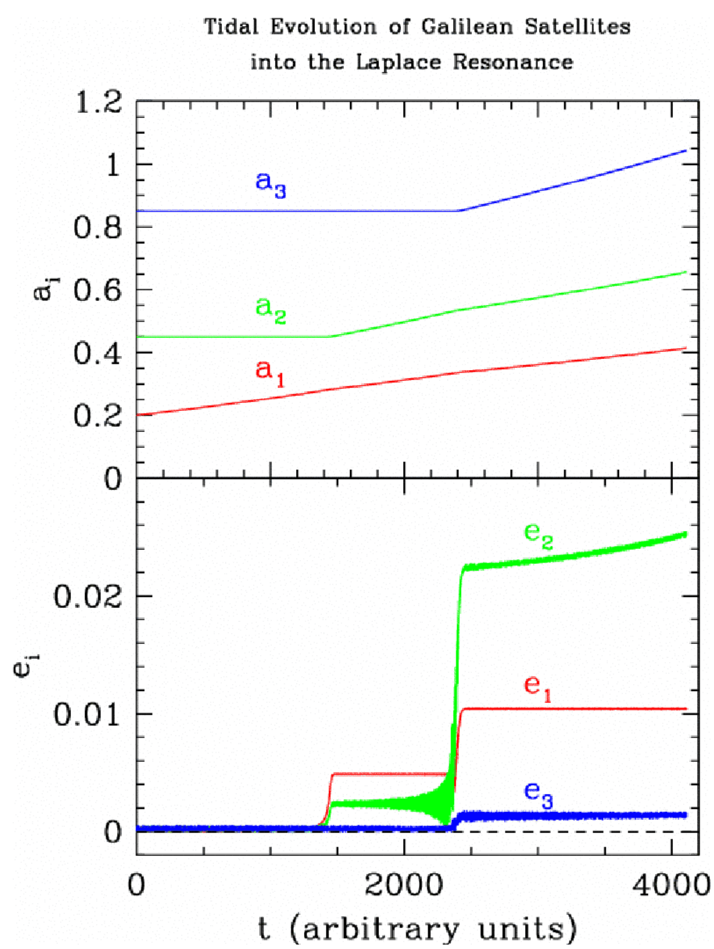
- Periapses of Io and Europa are nearly anti-aligned.
- Conjunctions of Io and Europa occur when Io is near periapse and Europa is near apoapse.
- Conjunctions of Europa and Ganymede occur when Europa is near periapse and Io is on opposite side of Jupiter. Ganymede can be anywhere in its orbit.



Tidal Origin of the Laplace Relation

- The currently popular means of assembling the resonances from initially random orbits is by differential orbital expansion due to torques from tides raised on Jupiter (Goldreich 1965, Yoder 1979, Yoder & Peale 1980).
- Resonances were assembled long after the formation of the satellites.

- Io's orbit expanded more rapidly than Europa's, and the convergence of the orbits resulted in capture into the 2:1 orbital resonances.
- Io and Europa then moved out together locked in the resonances, and Europa eventually captured Ganymede into a 2:1 orbital resonance.



Primordial Origin of the Laplace Relation

- Greenberg (1982, 1987) proposed a primordial origin of the Laplace relation and considered evolution from much deeper in the resonances, but there was no mechanism for placing the system in the resonances at the time of satellite formation.
- Peale & Lee (2002) demonstrated that the differential migration of the newly formed Galilean satellites due to interactions with a circumjovian disk can lead to the primordial formation of the Laplace relation.

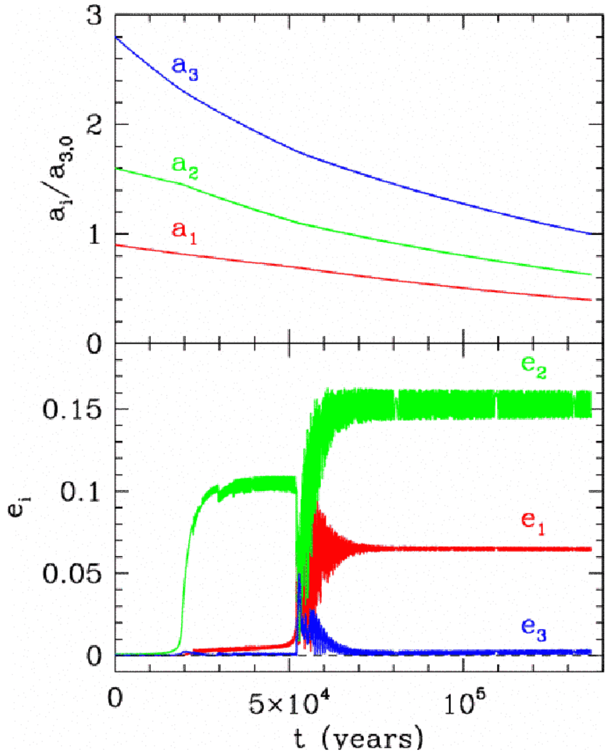
Canup & Ward (2002; see also Stevenson 2001) have found that:

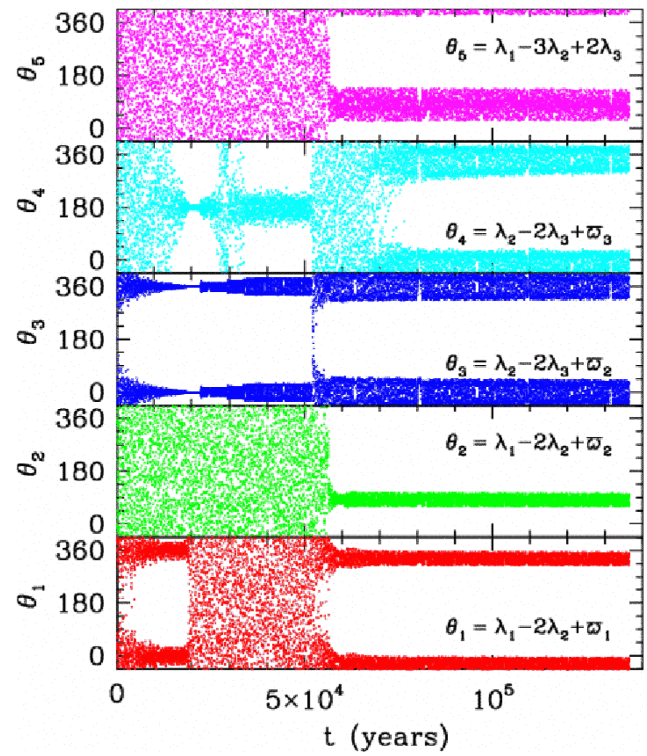
- In a Minimum Mass Sub-Nebula analogous to the Minimum Mass Solar Nebula, temperatures too high and accretion rates too fast to allow formation of satellites with their observed properties (Ganymede and Callisto ~ 50% ice by mass; Callisto may not be fully differentiated).
- Constraints imposed by the Galilean satellites' current physical properties can be satisfied if the satellites formed near the end of Jupiter's formation.
  - Flux of material into Jupiter through an accretion disk was greatly reduced by Jupiter opening a gap in the solar nebula.
  - Surface mass density of the circumjovian disk Σ_d was low.

- The satellites are not sufficiently massive to open gaps in the disk and migrated toward Jupiter via Type I Migration.
  - $(a^{-1} da/dt)_{\mathrm{I}} = C_a \, \Omega \, (M_{\mathrm{s}}/M_{\mathrm{p}}) \, (\Sigma_d a^2/M_{\mathrm{p}}) \, (H/a)^{-2}$
  - If the a dependence is weak, $(a^{-1} da/dt)_{\mathrm{I}} \sim M_{\mathrm{s}}$.
  - Since Ganymede is the most massive of the Galilean satellites, Ganymede's orbit converged on those of Europa and Io, and Callisto was left behind.

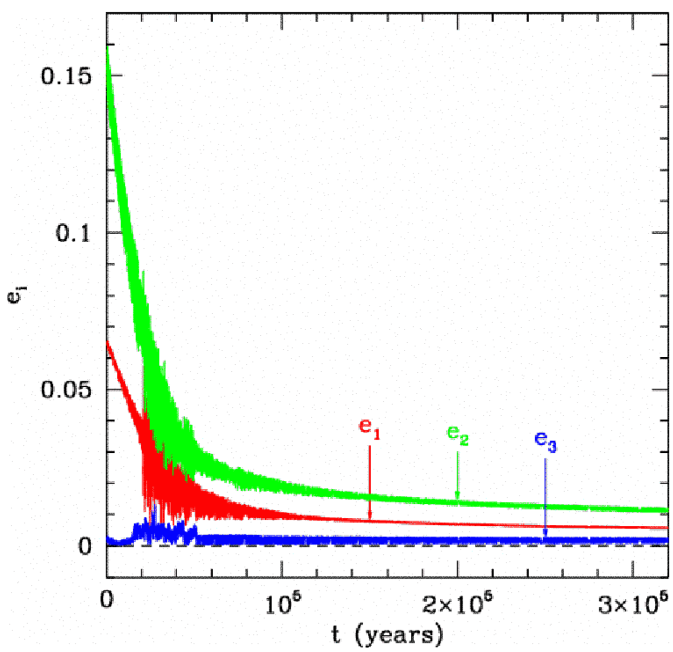
- Peale & Lee (2002) demonstrated capture of Io, Europa, and Ganymede into resonances with period ratios 1:2:4 in a simple model with:
  - Full satellite masses throughout migration
  - $a^{-1} da/dt \sim M_{\mathrm{s}}$
  - Eccentricity damping with $| e^{-1} de/dt | \sim 30 | a^{-1} da/dt |$ (Artymowicz 1993).

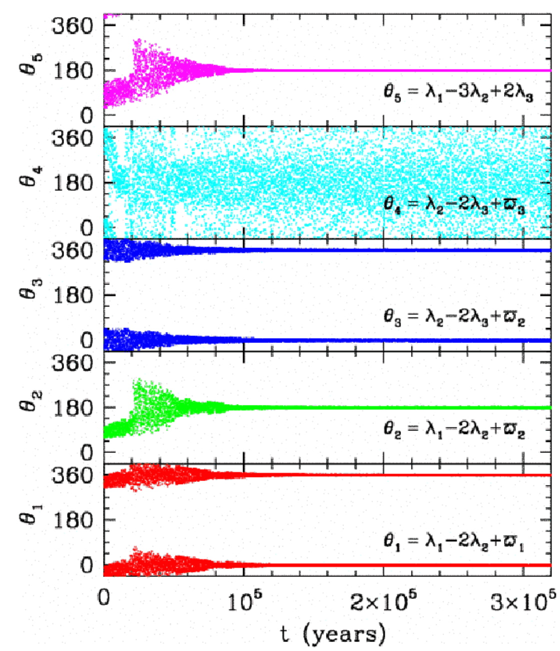
Nebula Induced Evolution of Galilean Satellites into Laplace Resonance





Relaxation of Galilean Satellite System to the Current Configuration





- After the dispersal of the disk, migration essentially stopped and orbital eccentricities were damped by tidal dissipation in the satellites.

Probability of Capture into the Observed Laplace Relation

- 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 $\kappa \propto T^{\beta}$)
- Can deduce the range of initial conditions that can lead to capture into 1:2:4.

- But capture into 1:2:4 is probabilistic.
- In two sets of simulations,

  $P_{1:2:4} \approx 0.67$ for $n = 0$

  $P_{1:2:4} \approx 0.29$ for $n = 1/5$
- Other possible outcomes include:
  - Capture into other Laplace-like resonance such as 2:4:9
  - Only one pair of satellites in resonance
  - No resonance
- Future work:
  - Determine probability of capture using a more realistic disk model that takes into account the changing opacity due to the ice line.

Conclusions

- A wide variety of 2:1 (and 3:1) resonance configurations and, in particular, asymmetric librations can be expected among future discoveries.
- Discovery of systems with certain resonance geometries would indicate a change in the planetary mass ratio during migration or a migration scenario involving inclination resonances.
- The differential migration of the newly formed Galilean satellites due to interactions with a circumjovian disk can lead to the primordial formation of the Laplace relation.
- A primordial origin of the Laplace relation among the Galilean satellites, with the help of tidal dissipation, reproduces every detail of the current configuration.

- Observed eccentricities of the GJ 876 system require either resonance capture occurring just before nebula dispersal or significant eccentricity damping from planet-disk interaction

  or ...
- Orbital eccentricities in a larger sample of resonant pairs may constrain eccentricity damping vs. nebula dispersal.
- How does the material from the solar nebula accrete onto the circumjovian disk?
- Either primordial or tidal origin of the Laplace relation leads to similar constraint on $Q_J \sim 10^5$ -10^6.
- Is there a characteristic of Io's surface or of its inventory of volatiles that could constrain the longevity and possible episodic nature of the volcanism?