# Les satellites galiléens de Jupiter, une longue histoire – Part II

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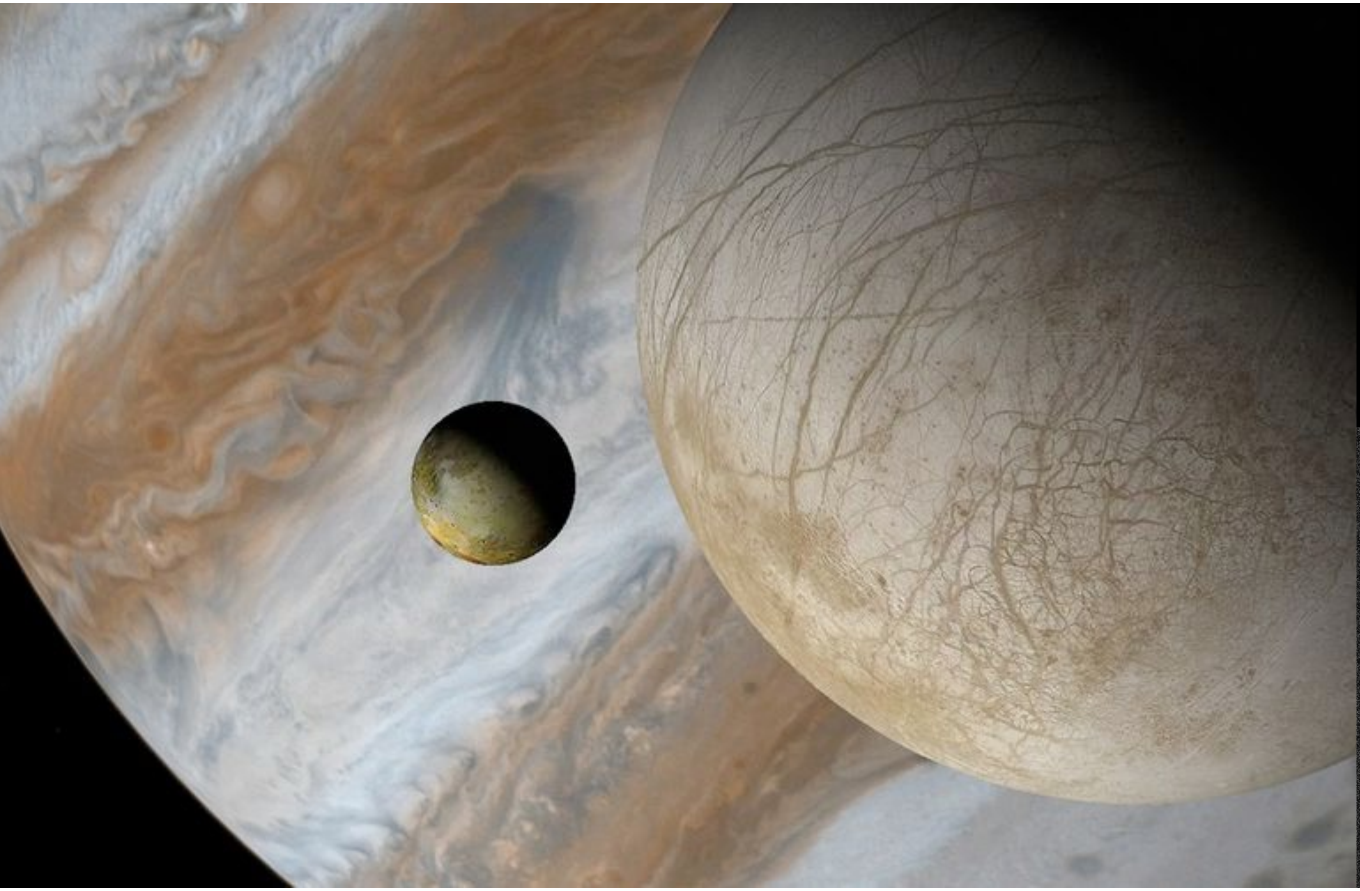
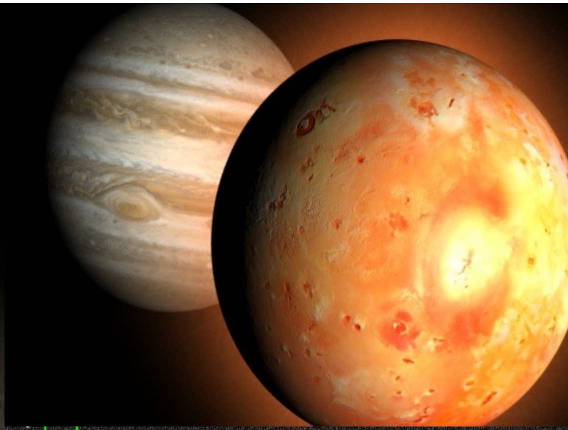
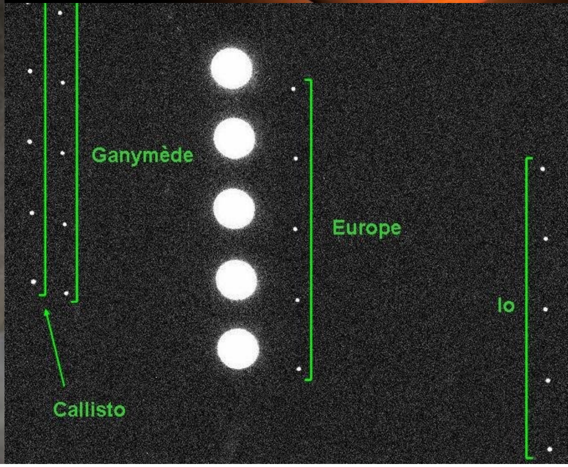







- *Tides and motions in planetary systems Workshop* (in honour of Prof. Ferraz-Mello) - April 8th 2026

# The Galilean satellites: the tidal acceleration in question

Acceleration or deceleration?

| References | $\dot{n}_1/n_1$ | $\dot{n}_2/n_2$ | $\dot{n}_3/n_3$ | Units in $10^{-10}yr^{-1}$ |
|---|---|---|---|---|
| de Sitter (1928) | 3.3+/-0.5 | 2.7+/-0.7 | 1.5+/-0.6 | |
| Lieske (1987) | -0.074+/-0.087 | -0.082+/-0.097 | -0.098+/-0.153 | |
| Vasundhara et al. (1996) | 2.46+/-0.73 | -1.27+/-0.84 | -0.022+/-1.07 | |
| Aksnes & Franklin (2001) | 3.6+/-1.0 | | | |

# One step forward…

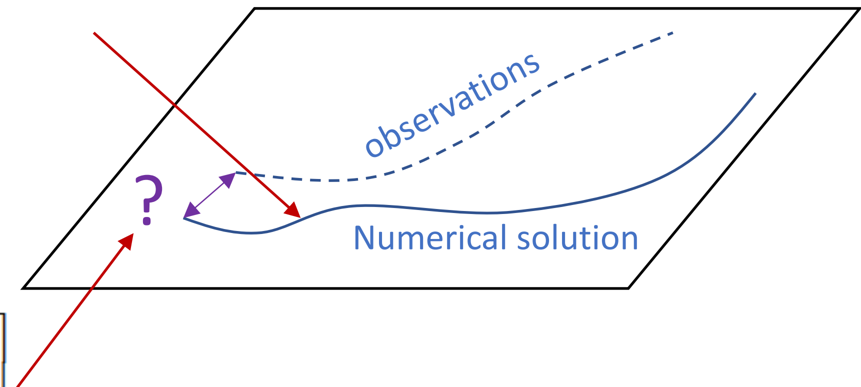
Integration of equations of motion

$$\ddot{\vec r}_i = -G(m_0+m_i)\left(\frac{\vec r_i}{r_i^3} - \nabla_i U_{\bar i\hat 0} + \nabla_0 U_{\bar 0\hat i}\right) + \sum_{j=1,\, j\neq i}^{N} G m_j\left(\frac{\vec r_j-\vec r_i}{r_{ij}^3} - \frac{\vec r_j}{r_j^3} - \nabla_j U_{\bar j\hat i} + \nabla_i U_{\bar i\hat j} + \nabla_j U_{\bar j\hat 0} - \nabla_0 U_{\bar 0\hat j}\right)$$

$$+\frac{(m_0+m_i)}{m_i m_0}\left(\vec F_{\bar i\hat 0}{}^T - \vec F_{\bar 0\hat i}{}^T\right) - \frac{1}{m_0}\sum_{j=1,\, j\neq i}^{N}\left(\vec F_{\bar j\hat 0}{}^T - \vec F_{\bar 0\hat j}{}^T\right) \; + GR$$

Simultaneously with the variationnal equations

$$\frac{\partial}{\partial c_l}\left(\frac{d^2\vec r_i}{dt^2}\right) = \frac{1}{m_i}\left[\sum_j\left(\frac{\partial\vec F_i}{\partial\vec r_j}\frac{\partial\vec r_j}{\partial c_l} + \frac{\partial\vec F_i}{\partial\dot{\vec r}_j}\frac{\partial\dot{\vec r}_j}{\partial c_l}\right) + \frac{\partial\vec F_i}{\partial c_l}\right]$$

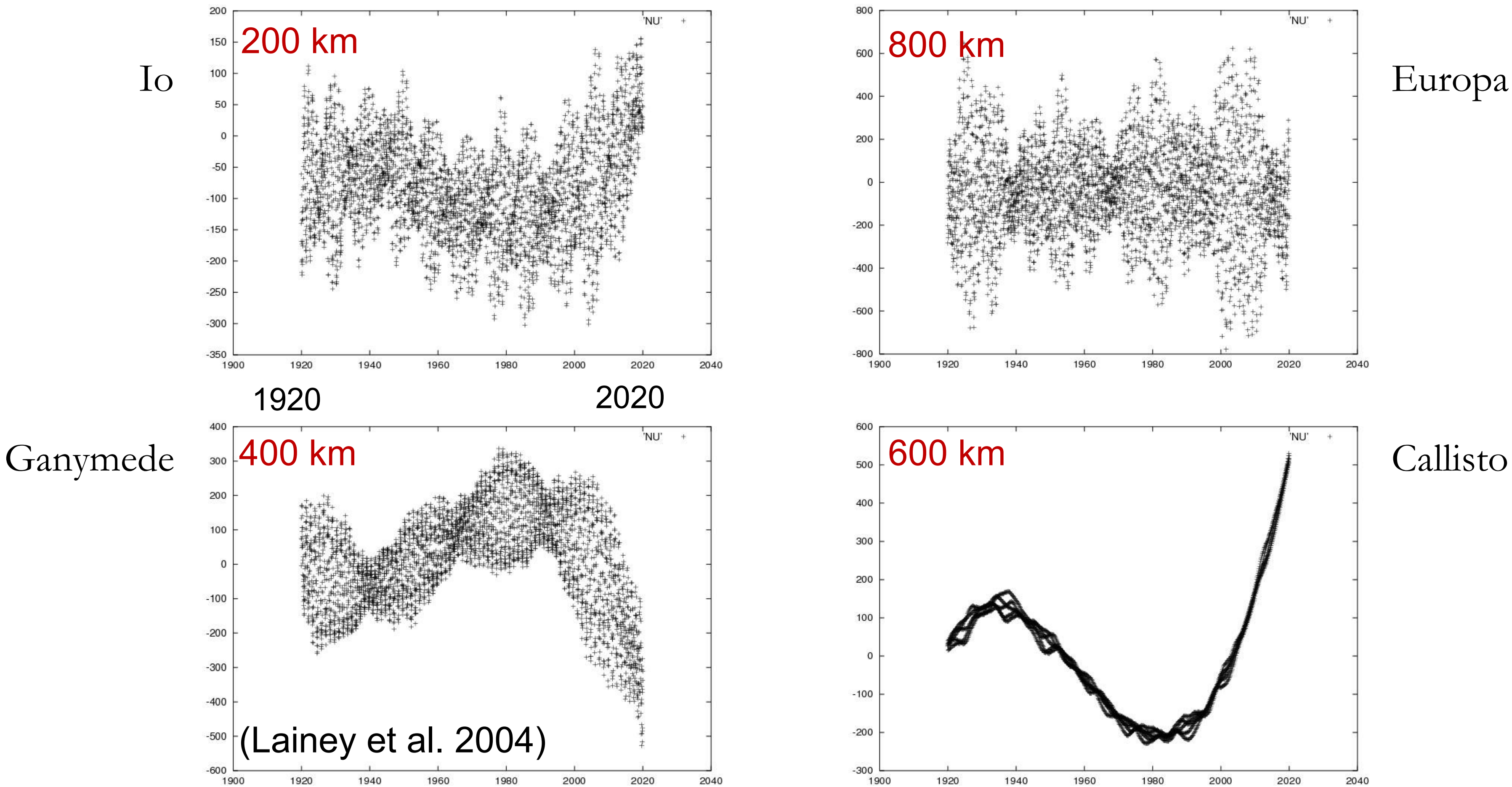



Integration of the variational system is much more tricky and computing time consuming than equations of motion.

# Comparing numerical solution to Sampson-Lieske

Internal precision of Sampson-Lieske's theory over 1 century:

**→ few hundreds of kilometers on the longitudes!**



# Comparing numerical solution to Sampson-Lieske

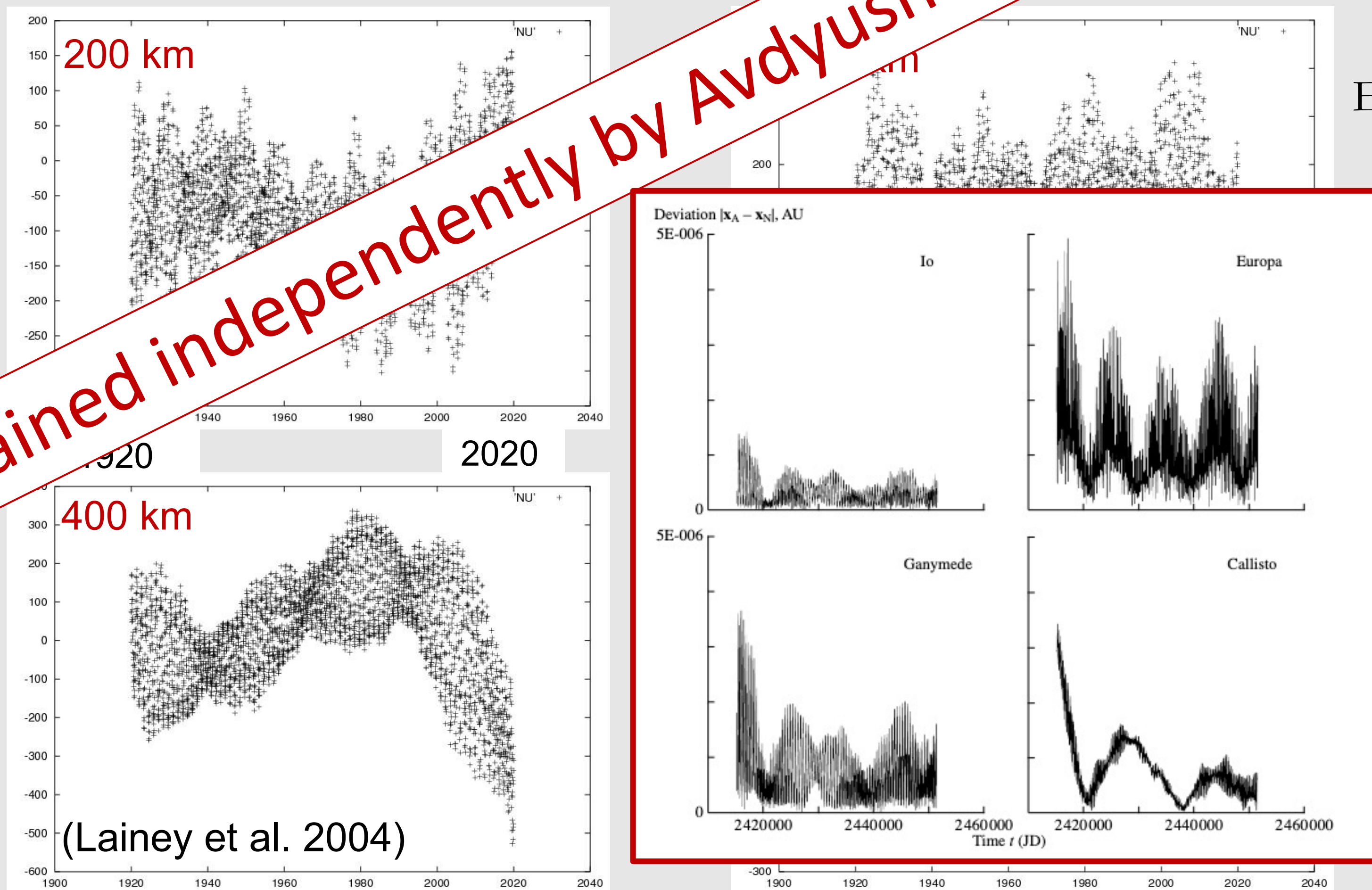
Internal precision of Sampson-Lieske's theory over 1 cent

→ **few hundreds of kilometers on the longitud**

**Obtained independently by Avdyushev 2004**

Io Europa

Ga de allisto



# Comparing numerical solution to Sampson-Lieske

Report from Sylvio Ferraz-Mello
Lainey 's PhD thesis

Report on the doctor thesis "Théorie Dynamique des Satellites Galiléens" by Valéry Lainey

The main contribution of this thesis is a new theory of the motion of the Galilean Satellites of Jupiter. It lies in the tradition of the Bureau des Longitudes (IMCCE) where, since Andoyer, efforts were done to construct theories and algorithms able to produce good ephemerides for these satellites. The difference is that, now, we may use the decades of progress done in the improvement of computing machines which allowed, for the first time, the construction of a numerical theory able to be extended over one century or more.

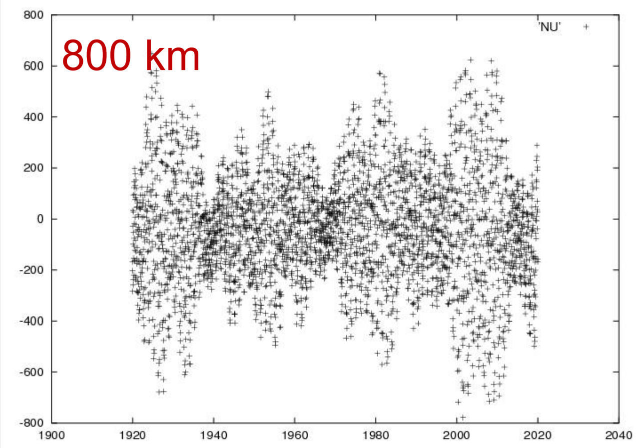
To contribute with this work, I would like to make some comments.

My first comment concerns the analysis of the perturbations usually neglected. In chapter I-2.3, a comment is done concerning the absorption of secular terms, but this very comment is not properly taken into account in Chapter I-3. Let us take, for instance, the largest of the perturbations listed in section I-3.7.1, which amounts to 9.000 km in one century. It is certainly due, mainly, to a difference in longitude of about 1.2 degrees, which corresponds to a contribution of only 1.6E-7 to the constant perturbation sigma (see Tisserand, vol.IV, p.17 or reference [18], p. 65). This value means, indeed, a correction to the mean motion much larger than the current precision of its determination, Nevertheless, because of the lack of precision in the measurements of the distance scale, the mean-motion plays, actually, the role of constant of the motion, and a correction as small as the one obtained will disappear when translated into semi-major axis. Therefore, it seems to me that the relevant contribution of the considered perturbations is not given by the bulk variation in one century, but by the oscillations seen along that time. Their amplitude should be the quantity to be listed in Table 3.1. Looking at the figures, I would dare to say that the most important of the listed effects is that coming from the motion of Jupiter's equator.

I have been puzzled by the big deviations between the given theory and Lieske's theory shown in sec II-2.2. The explanation considering the problems arising by the variables used by Sampson is not very convincing, given the progressive aspect

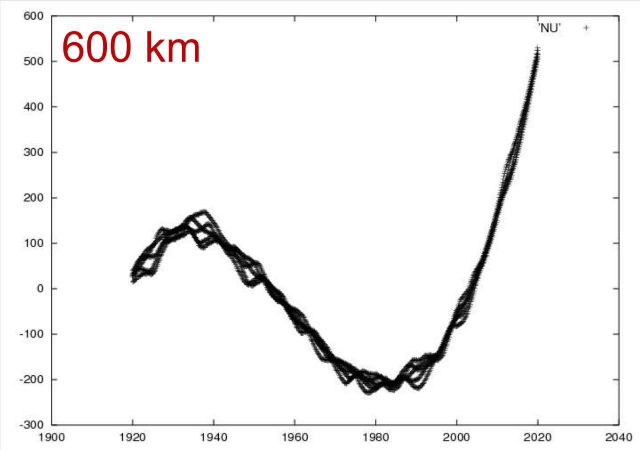
heory over 1 century:

**longitudes!**




Europa

Ga




Callisto

# Evolution of physical modeling

Sampson 1921

- The four Galilean moons
- Jupiter with its $J_2$ and $J_4$
- Jupiter's precession
- The Sun

Lainey (NOE-5-2010-GAL)

- The four Galilean moons with their $J_2$ and $c_{22}$
- Jupiter with its $J_2$,$J_3$, $J_4$, $J_6$,$c_{22}$,$s_{22}$
- Jupiter's precession
- The Sun and Saturn
- Tides inside Io and Jupiter (constant $k_2/Q$)

Lieske 1970s/1998

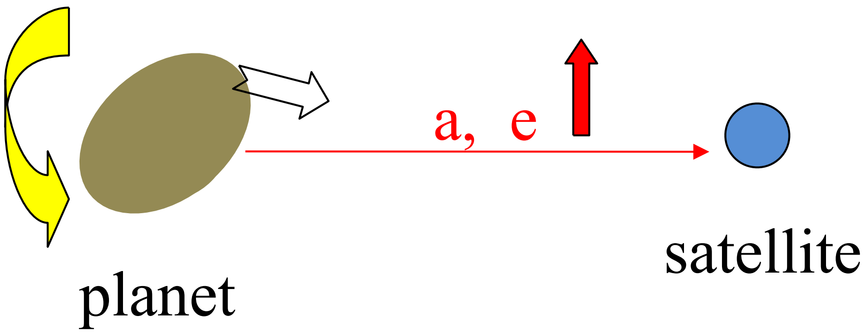
Same as Sampson but corrected for:

Calculus error, De Haerdtl inequality, extra solar terms, Laplace resonance libration,

Jacobson (JUP310)

- The four Galilean moons and Amalthea
- Jupiter with its $J_2$,$J_4$,$J_6$
- Jupiter's precession
- The Sun (inner planets in Solar mass), Saturn, Uranus, Neptune

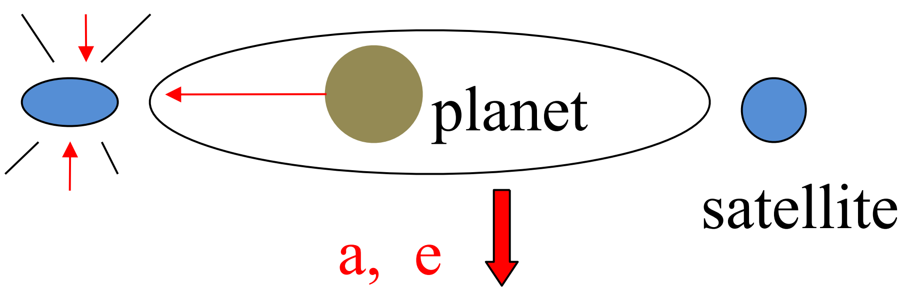
# Implication of tidal dissipation on orbital motion




Secular deceleration on the mean motion

**Jovian $k_2/Q$**

***Competition between tidal dissipation effects***




Secular acceleration on the mean motion

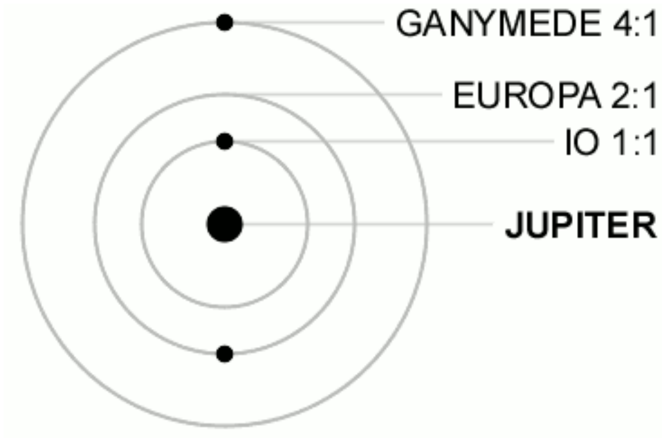
**Moon's $k_2/Q$**

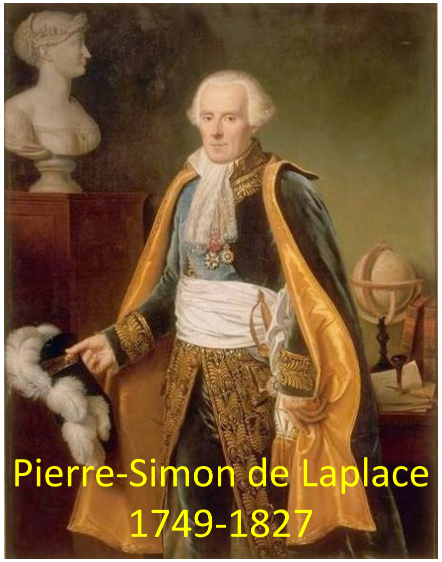
# Implication of tidal dissipation on orbital motion

A matter of dynamics…

$n_1$-2$n_2$=$v$
$n_2$-2$n_3$=$v$
$n_1$-3$n_2$+2$n_3$=0

$< L_1 - 3L_2 + 2L_3 > = 180°$




The Laplace resonance is dynamically stable

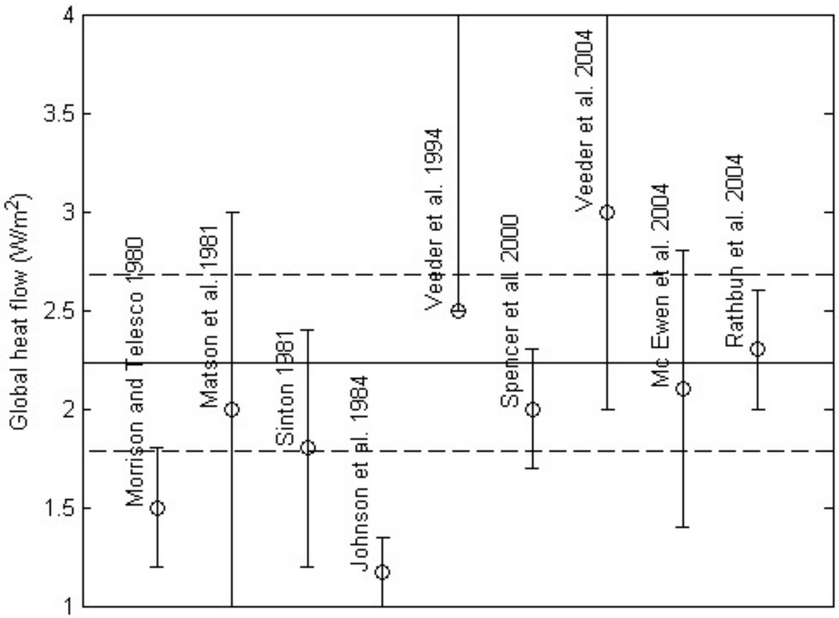
The three moons *share* their **orbital energy** and **angular momentum**

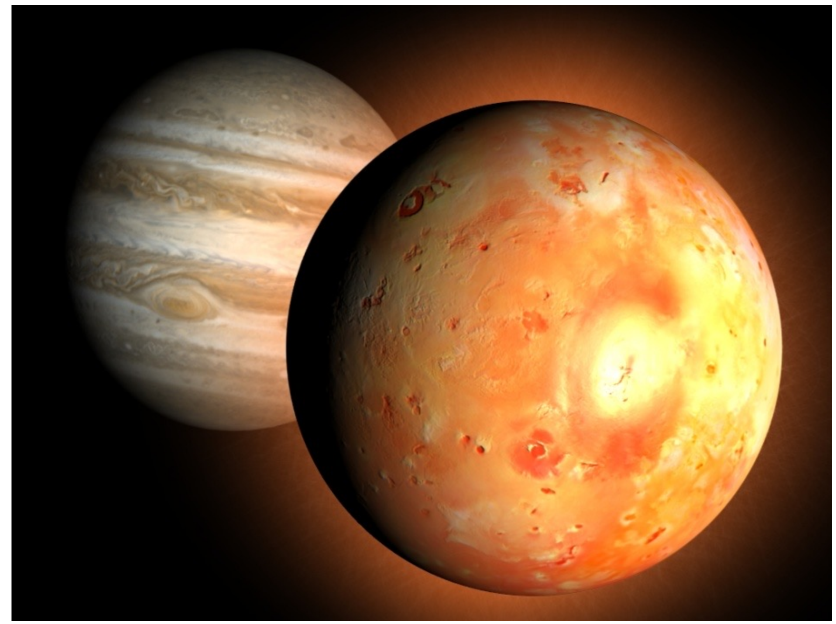
**IMPORTANT:**
Any perturbation affecting one of the moons will affect immediately the two others!

# Estimations of tides in the Galilean system: XXI$^{th}$ century

Fit of Io's tidal dissipation provides $k_2/Q$ =0.015 ± 0.003 (Lainey et al. 2009)

One can compare our value with the ones derived from IR emission



Lainey et al. (2009) obtained a very good agreement and confirmed the values derived from heat flux observations.

Those values were confirmed recently by Park et al. (2025)

# Io’s volcanism and tides

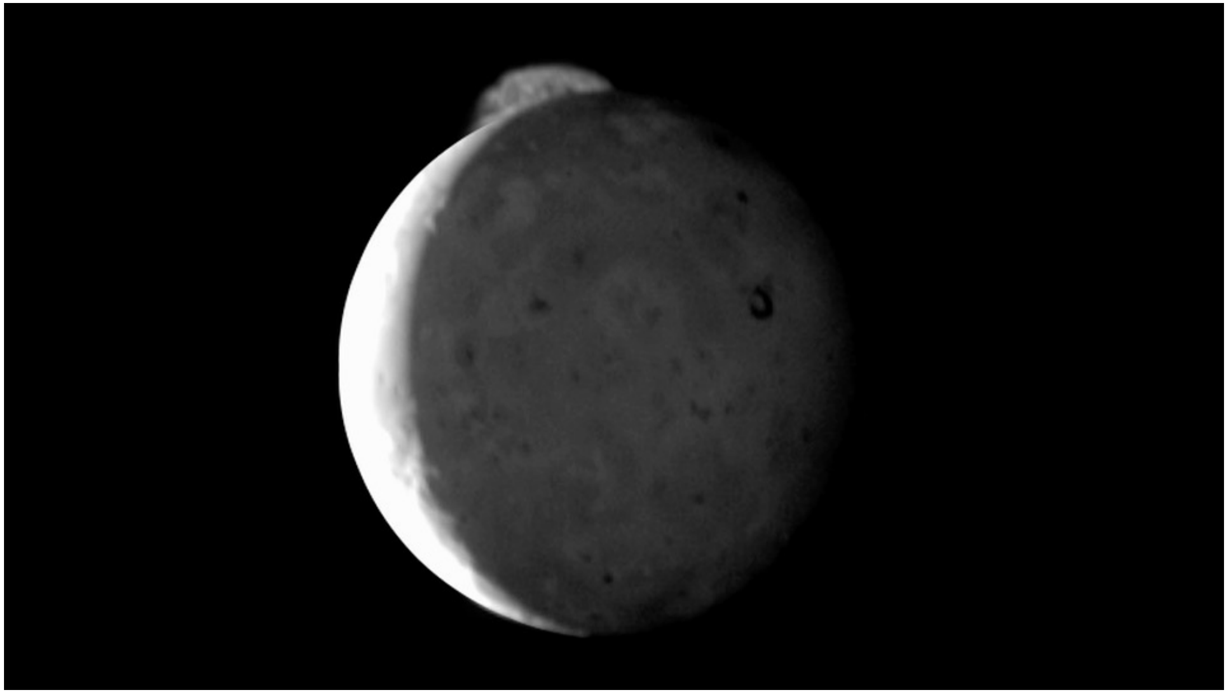
The orbital energy reservoir of the whole system involved in the Laplace resonance is

$$E = -2.672 \times 10^{31} \text{ J}$$

The orbital energy loss from Io’s internal tide activity is

$$\dot{E} = (9.33 \pm 1.87) \times 10^{13}\,\text{W}$$ Lainey et al. (2009)

There is enough energy in the orbits to still power Io’s volcanism over about 9Byr



# XXI$^{st}$ century: a new problem arises

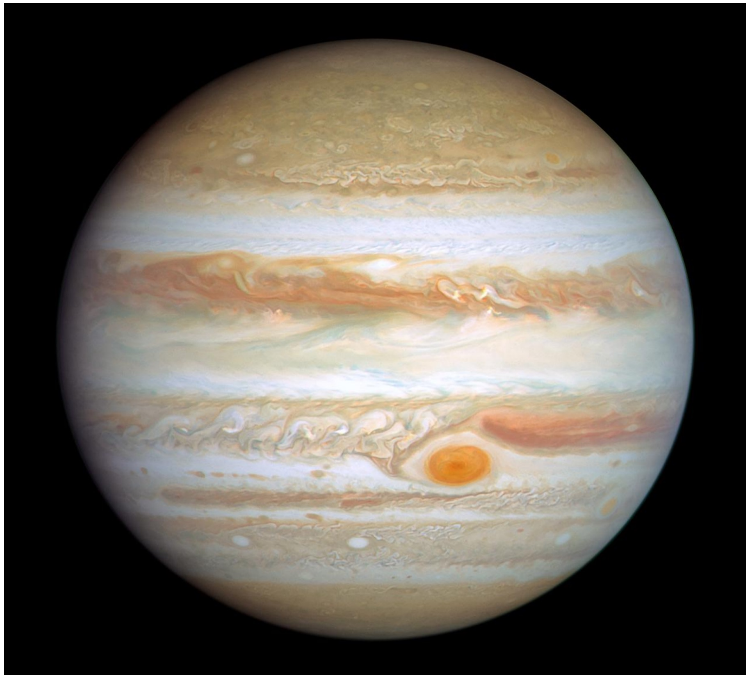
## What physical mechanism triggers tides in giant planets ?

Equilibrium Tides:

- Viscoelastic deformation of core (Dermott 1979, Remus et al. 2015)
- Convective viscosity in envelope (Terquem (2024))

Dynamical Tides:

- G-modes in stably stratified layers (Morales et al. 2009, Fuller et al. 2016)
- Inertial waves in convective envelope (Ogilvie & Lin 2007, Guenel et al. 2014)



Sensitivity to tidal frequency

$Q(\,X\,)$ ?

NB: Most (all?) dynamical studies of the Galilean system assume a constant Jovian $k_2/Q$

# Conclusion

Our comprehension of the Galilean system is going to radically improve in the coming decade