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The Galilean satellites' evolution toward a 4-body mean motion resonance

Giacomo Lari (1), Melaine Saillenfest (2) and Marco Fenucci (1)
(1) Dipartimento di Matematica, Università di Pisa, Italy, (2) IMCCE, Observatoire de Paris, France

Abstract

The three inner Galilean satellites (Io (1), Europa (2) and Ganymede (3)) are locked in the well-know Laplace resonance; however, their orbits suffer significant changes because of the tidal dissipation acting in the system. Taking the values of the dissipative parameters k_2/Q as computed from astrometric observations, we investigate the evolution of the system, focusing on the possible capture in resonance of Callisto (4). We find that after almost 2 Gy, Ganymede and Callisto have a resonant encounter, which can drive to a 4-body mean motion resonance (MMR) and/or disrupt the current Laplace resonance. We observe two main different behaviors of the 4-body resonant lock: the libration of the corresponding angle can be a pure geometric effect or have a dynamical evolution.

1. Introduction

The Galilean satellites of Jupiter have many fascinating characteristics, that make them ones of the most interesting bodies of the Solar System. Volcanoes on Io and hidden oceans under the crust of Europa and Ganymede are the results of a very peculiar dynamics. On the one hand, the MMRs involved in the system force the eccentricities of the bodies to non-zero values; on the other, the tides of Jupiter on the moons produce a strong friction that dissipates energy. Apart from geophysical events, tidal dissipation causes the migration of the satellites. Although Io suffers the main effects, they are redistributed to the other two moons involved in the Laplace resonance, leading to a change of their semi-major axes, too. The amount of the energy dissipation due to the tides is proportional to the bodies' parameters k_2/Q, which were computed in [3] fitting 100 years of astrometric observations.

Our aim is to study the evolution of the system. In particular, we focus on the possible capture in resonance of Callisto. Since the closest MMR between Ganymede and Callisto has ratio 2:1, we investigate the eventual formation of the 4-body MMR 8:4:2:1.

2. Methods

As we are interested in the long-term dynamics of the satellites, we need a model that manages to reproduce the resonant and secular variation of their orbits and their migration due to the tides. Such a model must contain the main forces acting on the system: the gravity acceleration of Jupiter, the mutual perturbations between the satellites, the oblateness of the planet (J_2 and J_4), the third-body perturbation of the Sun and the tidal dissipation between Io and Jupiter. We start from a recent semi-secular Hamiltonian model ([4]), based on analytical expansions of the perturbations and their averaging over the fast angles. Since we are exploring a possible insertion of Callisto into the resonance, we must include also the 2:1 resonant terms between Ganymede and Callisto. For the tidal dissipation we use the classic formulas ([2] and [6]) that describe the variation of the semi-major axis a_1 and eccentricity e_1 of Io

$$\frac{da_1}{dt} = \frac{2}{3}c\Big(1 - \Big(7D - \frac{51}{4}\Big)e_1^2\Big)a_1,$$
$$\frac{de_1}{dt} = -\frac{1}{3}c\Big(7D - \frac{19}{4}\Big)e_1;$$

with $c \propto (k_2/Q)_{Jup}$ and $cD \propto (k_2/Q)_{Io}$. In this study, we keep the dissipative parameters constant.

We take initial conditions at J2000 from the Jup310 ephemerides, appropriately filtered to eliminate the short period signals. We propagate forward until the first signs of the resonant encounter between Ganymede and Callisto, which produces abrupt variations of their orbital elements. As the time scale of the tidal evolution and the capture in resonance is largely greater than the characteristic time of the Galilean satellites' motion, we use the adiabatic approximation and we increase the values of the parameters k_2/Q of a factor α (see [5]). The dissipative effects are linearly proportional to these coefficients, then we have a reduction of the propagation time of a factor $1/\alpha$. For our simulations, we use $\alpha = 100$.

As the resonant encounter is chaotic, we perform a statistic investigation, taking different initial conditions. In particular, we stop the propagation just before Ganymede enters in the 2:1 resonant region with Callisto and we change the slow angle $2\lambda_4 - \lambda_3$ (combination of the mean longitudes λ_i) over the interval $[0, 2\pi)$, taking hundreds of sampling values. Then we run simulations with these new initial conditions and we look at the different evolutions of the system.

3. Results

For a preliminary analysis, we focus on the behavior of the 4-body angle $\gamma = \lambda_1 - 2\lambda_2 - \lambda_3 + 2\lambda_4$, associated with the linear combination of the mean motions

$$n_1 - 2n_2 - n_3 + 2n_4 = 0.$$

We find that it can start to librate around 0 (with a probability of almost 90%) or continue to circulate (almost 10%). The first case indicates the formation of a 4-body MMR, from Io to Callisto. However, we have two qualitatively different situations: in the first, the observed libration of γ is the result of the sum of four 2-body MMRs (Figure 1, on the top):

$$\begin{aligned}\gamma = \lambda_1 - 2\lambda_2 + \varpi_2 - (\lambda_2 - 2\lambda_3 + \varpi_2) \\ - (\lambda_2 - 2\lambda_3 + \varpi_3) + \lambda_3 - 2\lambda_4 + \varpi_3;\end{aligned}$$

in the other, we have a dynamical lock of γ (Figure 1, on the bottom). It is interesting to note that, although in this second scenario the satellites exit from most of the resonances (including the Laplace one), γ librates around a resonant center, which moves because of the tidal migration, until the angle reaches the value 0. In this evolution, it can happens that γ jumps to a symmetric center, because of the occurrence of a separatrix crossing.

When Callisto is captured in resonance, it begins to migrate as well as the other satellites, because the tidal effects on Io manage to reach it. Instead, the eccentricities show different behaviors: in the case of the geometric libration of γ, they stabilize on new values which remain almost constant for the rest of the integration; in the other, the eccentricities of Ganymede and Callisto increase up to reach values near to 0.1, making the system unstable.

4. Summary and Conclusions

Using the dissipative parameters estimated in [3], we found that Ganymede and Callisto will have a resonant encounter in almost 2 Gy. The chaotic nature of this event does not allow to be sure of its outcome; running hundreds of simulations, we observed that the system have a high probability to enter into a 4-body MMR. This event comprehends two different scenarios, characterized by a geometric or a dynamical libration of the resonant angle $\lambda_1 - 2\lambda_2 - \lambda_3 + 2\lambda_4$.

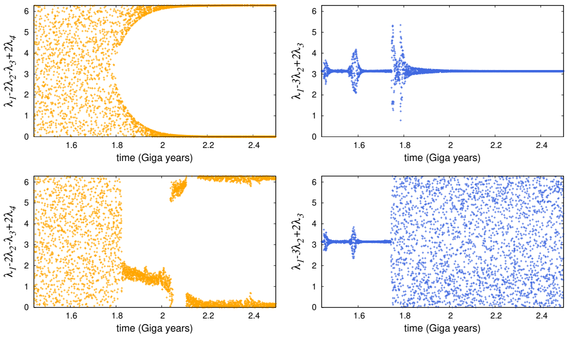

Figure 1: 4-body and Laplace resonant angles

Although, this study concerns a forward evolution of the Galilean satellites, it can reveal some clues of their past and the origin of the Laplace resonance. Further details on the evolution of orbital elements and resonant angles will be presented in a future paper, where we will consider also dissipative effects on the other moons and frequency-dependent dissipative parameters of Jupiter, as described in [1].

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