

Strong tidal dissipation in Io and Jupiter from astrometric observations

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Io is the volcanically most active body in the Solar System and has a large surface heat flux^{1–3}. The geological activity is thought to be the result of tides raised by Jupiter⁴, but it is not known whether the current tidal heat production is sufficiently high to generate the observed surface heat flow^{5,6}. Io's tidal heat comes from the orbital energy of the Io–Jupiter system (resulting in orbital acceleration), whereas dissipation of energy in Jupiter causes Io's orbital motion to decelerate. Here we report a determination of the tidal dissipation in Io and Jupiter through its effect on the orbital motions of the Galilean moons. Our results show that the rate of internal energy dissipation in Io ($k_2/Q = 0.015 \pm 0.003$, where k_2 is the Love number and Q is the quality factor) is in good agreement with the observed surface heat flow^{5,6}, and suggest that Io is close to thermal equilibrium. Dissipation in Jupiter ($k_2/Q = (1.102 \pm 0.203) \times 10^{-5}$) is close to the upper bound of its average value expected from the long-term evolution of the system⁷, and dissipation in extrasolar planets may be higher than presently assumed⁸. The measured secular accelerations indicate that Io is evolving inwards, towards Jupiter, and that the three innermost Galilean moons (Io, Europa and Ganymede) are evolving out of the exact Laplace resonance.

The orbital evolution of the Galilean system due to tidal dissipation can be determined from astrometrically observed positions of the Galilean satellites over an extended period of time^{9,10} by using an accurate model of the orbital motion. Most orbital models are based on elaborate analytical methods and include the complex dynamics induced by the interactions of the Galilean moons. In particular, because the three innermost Galilean moons are in the Laplace resonance characterized by the relation

$$L_1 - 3L_2 + 2L_3 \approx \pi$$

where L_1 , L_2 and L_3 denote the mean longitudes of Io, Europa and Ganymede, respectively, changes in orbital energy and angular momentum are distributed between the three moons. Unfortunately, some long-period terms are lacking in such models, which explains why previous studies show large and widely different, even contradictory, results (see Table 1 and Supplementary Information for details). Here we use a method that numerically integrates the full equations of motion (Supplementary Information) for the satellite centres of mass instead of using an approximate analytical solution. Moreover, the tidal effects are directly included in the orbital model through the appearance of the Love number, k_2 , and the quality factor, Q , in the combination k_2/Q for Io and Jupiter. The orbital effects due to the dissipation in the Galilean satellites other than Io are neglected, but we take into account the tidal bulges raised by each moon on Jupiter using a constant Jupiter quality factor (Supplementary Information).

An extensive set of astrometric observations starting in 1891 and ending in 2007 has been considered in the fitting process. A long,

detailed set of observations such as this is necessary to reveal the long-term effects of dissipation on the orbits. We use a weighted least-squares inversion procedure and minimize the differences between the observed and computed positions of the satellites to determine the parameters of the model, in particular the respective dissipation ratios, k_2/Q , of Io and Jupiter. Our solution for the tidal dissipation yields $k_2/Q = 0.015 \pm 0.003$ (formal error bar, 1σ) for Io and $k_2/Q = (1.102 \pm 0.203) \times 10^{-5}$ for Jupiter. The Io–Jupiter interaction dominates the orbital evolution and is responsible for a large correlation coefficient of 0.983 between the dissipation ratios of Io and Jupiter. The almost 2% difference with respect to unity is due to the evolution of the Laplace resonance and is sufficient to separate the dissipation in Io from that in Jupiter (see Supplementary Information for a complete analysis of this correlation).

The dissipation values correspond to orbital acceleration values, \dot{n}/n (a dot denoting differentiation with respect to time), of $(0.14 \pm 0.01) \times 10^{-10} \text{ yr}^{-1}$, $-(0.43 \pm 0.10) \times 10^{-10} \text{ yr}^{-1}$ and $-(1.57 \pm 0.27) \times 10^{-10} \text{ yr}^{-1}$ (formal error bars, 1σ) for Io, Europa and Ganymede, respectively. These accelerations represent a shift in the satellite orbital positions of respectively 55 km, -125 km and -365 km over the 116 years considered. Surprisingly, the most external moon Ganymede shows the largest drift, as a consequence of the Laplace resonance. The 1σ post-fit astrometric residuals range essentially between 0.02 and 0.15 arcsec (Fig. 1, Supplementary Table 2 and Supplementary Table 3), which corresponds to 60 to 450 km at the distance of Jupiter. Owing to the long time span considered, such accuracy is enough to allow the tidal accelerations to be discerned from the observations.

Table 1 | A selection of secular mean-motion accelerations published for the three inner Galilean moons

| Ref. | Secular mean-motion acceleration (\dot{n}/n) (10^{-10} yr^{-1}) | | |
|------------|---|--------------------|--------------------|
| | Io | Europa | Ganymede |
| 9 | $+3.3 \pm 0.5$ | $+2.7 \pm 0.7$ | $+1.5 \pm 0.6$ |
| 10 | -0.074 ± 0.087 | -0.082 ± 0.097 | -0.098 ± 0.153 |
| 24 | $+4.54 \pm 0.95$ | $+5.6 \pm 5.7$ | $+2.8 \pm 2.0$ |
| 25 | $+2.27 \pm 0.70$ | -0.67 ± 0.80 | $+1.06 \pm 1.00$ |
| 26 | $+3.6 \pm 1.0$ | — | — |
| This paper | $+0.14 \pm 0.01$ | -0.43 ± 0.10 | -1.57 ± 0.27 |

Refs 9, 24 used a simple orbital model, whereas refs 10, 25, 26 used the much more accurate Sampson–Lieske theory. Nevertheless, this orbital model has internal errors on the order of a few hundred kilometres (Supplementary Information), explaining the lack of agreement between all acceleration values. In particular, most of the tidal acceleration values found (see also Supplementary Table 1) are quite large except for those of ref. 10, in which data from over a very long time span (old eclipses) were used, partly averaging the missing long-period terms. Because our dynamical model fits the k_2/Q ratios, our solution uncertainties in \dot{n} have been derived for each satellite from the comparison of the two simulations that produced the minimum and maximum values of k_2/Q , respectively. As the k_2/Q ratios of Io and Jupiter are highly correlated, we could assume the minimum bound for Io's ratio when introducing the minimum bound of Jupiter's ratio, and vice versa.

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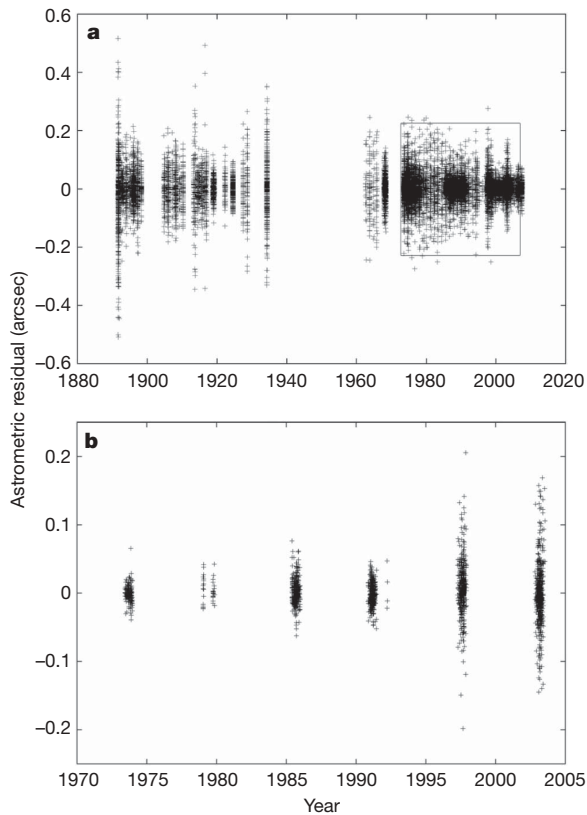


Figure 1 | Astrometric residuals. Residuals between the astrometric observations and our numerical model, after fitting the initial state vectors of each moon and the k_2/Q ratios of Jupiter and Io. We used an extensive set of astrometric observations that started in 1891, with heliometer measurements and the first photographic plates, and continued until 2007, with the most recent observations from the FASTT survey²⁷. **b**, Observations of the mutual events (occultation or eclipse of one satellite by another occurring every six years) from 1973 to 2003 (Supplementary Information; boxed region in **a**). The global 1σ accuracy is better than 0.1 arcsec (Supplementary Tables 2 and 3) at the Jovian distance (1 arcsec corresponds to about 3,000 km). The observations of mutual events, known to be among the most accurate observations, have a 1σ accuracy of about 0.025 arcsec and provide the best constraint of the satellite orbits for the past decades. Moreover, instead of considering the position of each satellite as given on the celestial sphere (that is, in arcseconds), we have considered only the relative positions of the observed satellites in the fitting process. For example, for the declination coordinate δ_i we did not fit $\delta_i^{\text{observed}} - \delta_i^{\text{computed}}$ but instead the quantity $[(\delta_i/\delta')^{\text{observed}} - (\delta_i/\delta')^{\text{computed}}]\delta_i^{\text{computed}}$, where $\delta' = \sqrt{\sum_{j=1}^N \delta_j^2}$ and N is the number of Galilean moons present in an observation. This allowed us to remove systematic errors in the scale factor introduced by the observers during the astrometric calibration of their observations.

The global energy dissipation, \dot{E} , in Io can be determined from $k_2/Q = 0.015 \pm 0.003$ using¹¹

$$\dot{E} = -\frac{21}{2} \frac{k_2}{Q} \frac{n^5 R^5}{G} e^2$$

where R is the radius of Io, G the gravitational constant and e the orbital eccentricity. We obtain $\dot{E} = (9.33 \pm 1.87) \times 10^{13}$ W. If energy were transported out of Io at the same rate, the associated surface heat flux would be 2.24 ± 0.45 W m⁻², which is similar to the observed surface heat flux (Fig. 2). This suggests that Io's interior is close to thermal equilibrium and that Io's internal heat is not the remnant of a past highly dissipative orbital configuration^{12–15}.

Theoretical studies have not been able to reproduce in a consistent equilibrium model both the tidal energy dissipation and the transport of this internally generated energy to the surface by mantle convection at the observed high surface heat flux^{15,16}. It has been argued that mantle viscosities cannot be chosen to satisfy both

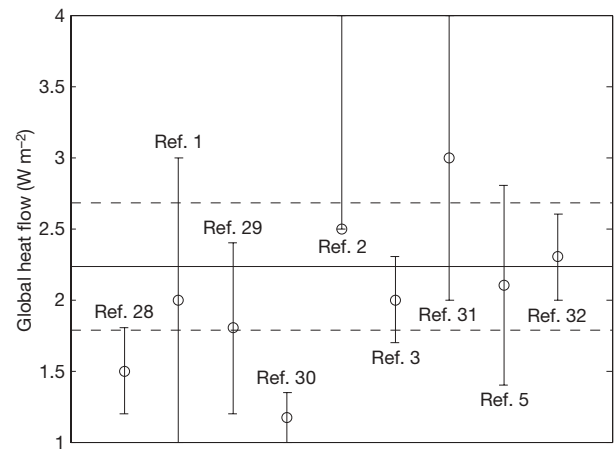


Figure 2 | Comparison of Io's thermal emission with the global dissipation determined in the present study. Io's intensive volcanic activity is associated with a large surface heat flow. The value determined by the present study (2.24 ± 0.45 W m⁻², shown by the horizontal lines) is in good agreement with the results of the remote observations^{1–3,5,28–32} of Io's thermal emission (the stated error bars mostly indicate ranges for the solutions rather than the standard deviations), suggesting that Io is close to thermal equilibrium. The average surface heat flow of Io is much larger than that of the Earth³³ (0.09 W m⁻²) and could be comparable to the high surface heat flow of the early Earth.

constraints: viscosities needed to generate the observed tidal dissipation (on the order of 10^{13} – 10^{16} Pa s; ref. 11) are too high to transport the produced heat to the surface by convection¹⁶. If Io is in thermal equilibrium as suggested here, a more efficient heat transport mechanism with a different viscosity dependence on temperature is required. The magma migration in Io's partially molten interior indicated by high eruption temperatures (larger than 1,300 K)¹⁷ is a possible mechanism¹⁸.

Plausible ranges for the quality factor of Io can be studied from the measured ratios k_2/Q by using limit values of the Love number. An upper limit of $Q = 82$ is found by considering Io as a body without strength, that is, by replacing the tidal Love number (k_2) by the fluid Love number, $k_2^f = 1.23$ (ref. 19). A much smaller quality factor is obtained for more realistic models in which Io is composed of a metallic core, a viscoelastic silicate mantle and an elastic lithosphere, depending on the viscosity and shear modulus of the mantle¹¹. A typical model with a core radius of 700 km, a core density of $6,944$ kg m⁻³, a mantle density of $3,375$ kg m⁻³ and a 40-km-thick lithosphere with a density of $2,600$ kg m⁻³, in agreement with the observations made by NASA's Galileo spacecraft¹⁹, yields $k_2 \approx 0.04$ and $Q \approx 3$ for a mantle rigidity of 50 GPa and viscosity of 4.1×10^{15} Pa s. However, if a low-viscosity asthenosphere exists in Io, the tidal Love number would increase to 0.7–0.8, resulting in a larger quality factor, of ~ 50 .

The dissipation in Jupiter (at the induced frequency of Io's tidal excitation) is determined to be $Q = (3.56 \pm 0.66) \times 10^4$ for the conventional value $k_2 = 0.379$ (ref. 20). This dissipation value is close to the lower limit over the age of the Solar System, $Q \geq 6 \times 10^4$, determined from the expansion of the orbits⁷, implying important dissipation in Jupiter. Estimates from numerical dissipation models of Jupiter suggest that Q undergoes large fluctuations as a function of tidal frequency^{21,22} and that the observed dissipation may be different from its long-term average (Supplementary Information).

Our results show that the mean motion of Io increases whereas those of Europa and Ganymede decrease. Therefore, Io moves inwards, towards Jupiter, and loses more orbital energy by dissipation of solid-body tides raised by Jupiter and by the Laplace resonance interaction than it gains from the exchange of angular momentum with Jupiter's rotational energy through tidal dissipation in Jupiter. The evolution of the Laplace resonance can be expressed in terms of the rate of change of the satellite mean motions, \dot{n}_1 , \dot{n}_2 and

\dot{n}_3 , where the subscripts correspond to Io, Europa and Ganymede, respectively^{7,13,23}. We have

$$\dot{v} = \dot{n}_1 - 2\dot{n}_2 = \dot{n}_2 - 2\dot{n}_3$$

The system is in stable equilibrium for $\dot{v} = 0$, which requires a balance between the dissipation rates in Jupiter and Io. With our rates of change of the mean motions, we have $\dot{v} = (0.74 \pm 0.24) \times 10^{-7} \text{ rad yr}^{-2}$, suggesting that the satellites are evolving away from exact resonance.

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- Matson, D. L., Ransford, G. A. & Johnson, T. V. Heat flow from Io. *J. Geophys. Res.* **86**, 1664–1672 (1981).
- Veeder, G., Matson, D., Johnson, T., Blaney, D. & Goguen, J. Io's heat flow from infrared radiometry: 1983–1993. *J. Geophys. Res.* **99**, 17095–17162 (1994).
- Spencer, J. R. et al. Io's thermal emission from the Galileo photopolarimeter-radiometer. *Science* **288**, 1198–1201 (2000).
- Peale, S. J., Cassen, P. & Reynolds, R. T. Melting of Io by tidal dissipation. *Science* **203**, 892–894 (1979).
- McEwen, A. S., Keszthelyi, P., Lopes, R., Schenk, P. M. & Spencer, J. R. in *Jupiter: The Planet, Satellites and Magnetosphere* (eds Bagenal, F., Dowling, T. E. & McKinnon, W. B.) 307–328 (Cambridge Univ. Press, 2004).
- Moore, B., Schubert, G., Anderson, J. D. & Spencer, J. R. in *Io After Galileo: A New View of Jupiter's Volcanic Moon* (eds Lopes, R. M. C. & Spencer, J. R.) 89–105 (Springer, 2007).
- Yoder, C. F. & Peale, S. The tides of Io. *Icarus* **47**, 1–35 (1981).
- Levrard, B. et al. Tidal dissipation within hot Jupiters: a new appraisal. *Astron. Astrophys.* **462**, L5–L8 (2007).
- De Sitter, W. Orbital elements determining the longitudes of Jupiter's satellites, derived from observations. *Leiden Ann.* **16**(2), 1–92 (1928).
- Lieske, J. H. Galilean satellite evolution - observational evidence for secular changes in mean motions. *Astron. Astrophys.* **176**, 146–158 (1987).
- Segatz, M., Spohn, T., Ross, M. N. & Schubert, G. Tidal dissipation, surface heat flow, and figure of viscoelastic models of Io. *Icarus* **75**, 187–206 (1988).
- Ojakangas, G. & Stevenson, D. Episodic volcanism of tidally heated satellites with application to Io. *Icarus* **66**, 341–358 (1986).
- Greenberg, R. Galilean satellites - evolutionary paths in deep resonance. *Icarus* **70**, 334–347 (1987).
- Fischer, H. J. & Spohn, T. Thermal-orbital histories of viscoelastic models of Io (J1). *Icarus* **83**, 39–65 (1990).
- Hussmann, H. & Spohn, T. Thermal-orbital evolution of Io and Europa. *Icarus* **171**, 391–410 (2004).
- Moore, W. Tidal heating and convection in Io. *J. Geophys. Res.* **108**, doi:10.1029/2002JE001943 (2003).
- Keszthelyi, L. et al. New estimates for Io eruption temperatures: implications for the interior. *Icarus* **192**, 491–502 (2007).
- Moore, W. The thermal state of Io. *Icarus* **154**, 548–550 (2001).
- Anderson, J. D., Jacobson, R. A. & Lau, E. L. Io's gravity field and interior structure. *J. Geophys. Res.* **106**, 32963–32969 (2001).
- Gavrilov, S. V. & Zharkov, V. N. Love numbers of the giant planets. *Icarus* **32**, 443–449 (1977).
- Ogilvie, G. I. & Lin, D. N. C. Tidal dissipation in rotating giant planets. *Astrophys. J.* **610**, 477–509 (2004).
- Wu, Y. Origin of tidal dissipation in Jupiter. II. The value of Q. *Astrophys. J.* **635**, 688–710 (2005).
- Yoder, C. F. How tidal heating in Io drives the Galilean orbital resonance locks. *Nature* **279**, 747–770 (1979).
- Goldstein, S. J. Jr & Jacobs, K. C. A recalculation of the secular acceleration of Io. *Astron. J.* **110**, 3054–3057 (1995).
- Vasundhara, R., Arlot, J.-E. & Descamps, P. in *Dynamics, Ephemerides and Astrometry of the Solar System* (eds Ferraz-Mello, S., Morando, B. & Arlot, J.-E.) 145–149 (Proc. 172nd Symp. Int. Astron. Union, IAU, 1996).
- Aksnes, K. & Franklin, F. A. Secular acceleration of Io derived from mutual satellite events. *Astron. J.* **122**, 2734–2739 (2001).
- Stone, R. C. Positions for the outer planets and many of their satellites. V. FASTT observations taken in 2000–2001. *Astron. J.* **122**, 2723–2733 (2001).
- Morrison, D. & Telesco, C. M. Io - observational constraints on internal energy and thermophysics of the surface. *Icarus* **44**, 226–233 (1980).
- Sinton, W. M. The thermal emission spectrum of Io and a determination of the heat flux from its hot spots. *J. Geophys. Res.* **86**, 3122–3128 (1981).
- Johnson, T. V. et al. Volcanic hotspots on Io - stability and longitudinal distribution. *Science* **226**, 134–137 (1984).
- Veeder, G. J., Matson, D. L., Johnson, T. V., Davies, A. G. & Blaney, D. L. The polar contribution to the heat flow of Io. *Icarus* **169**, 264–270 (2004).
- Rathbun, J. A. et al. Mapping of Io's thermal radiation by the Galileo photopolarimeter-radiometer (PPR) instrument. *Icarus* **169**, 127–139 (2004).
- Lay, T., Hernlund, J. & Bussett, B. A. Core-mantle boundary heat flow. *Nature Geosci.* **1**, 25–32 (2008).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions All authors contributed to the writing of the manuscript. V.L. developed and fitted to the observations the full numerical model presented in this work. J.-E.A. fitted to the observations the secular accelerations using L1 astrometric residuals (Supplementary Information). Theoretical calculations of the energy dissipation and Fig. 2 were made by Ö.K. T.V.H. and Ö.K. contributed to the geophysical interpretations of the secular accelerations.

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