Geophysics and Interior Processes of Rocky and Icy Bodies

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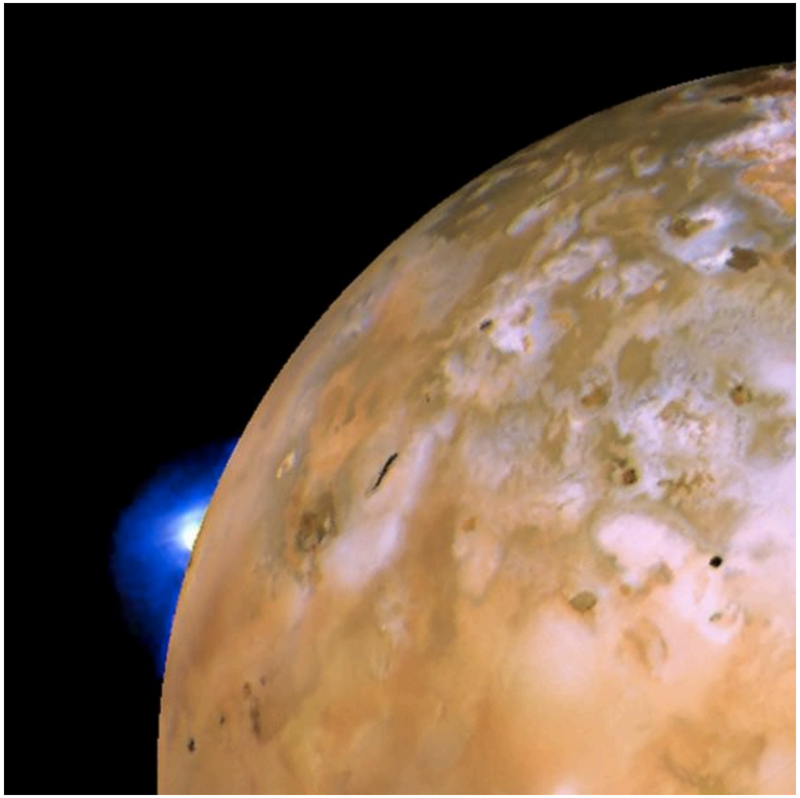
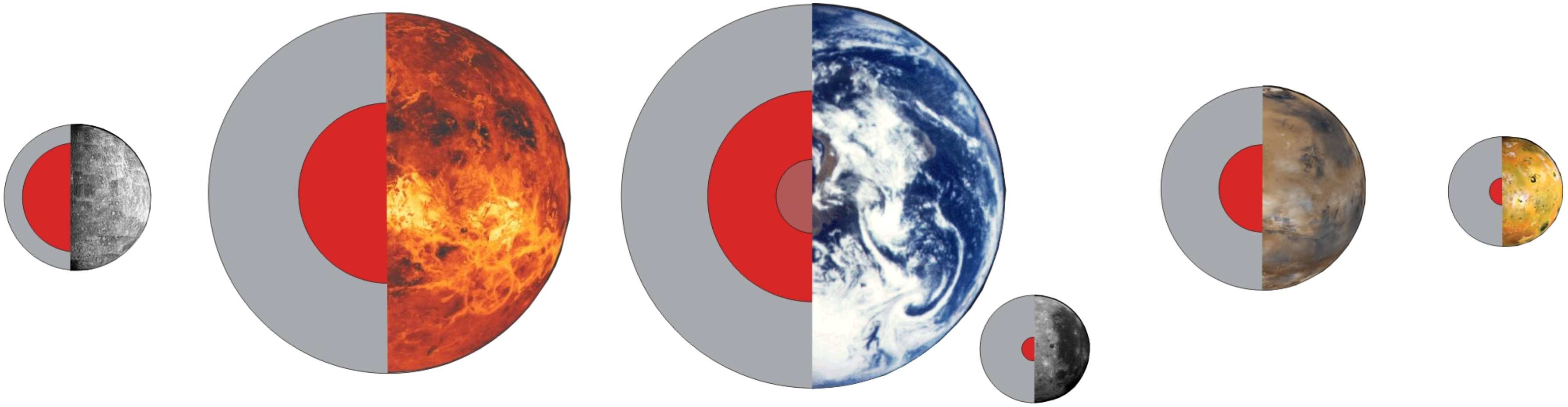


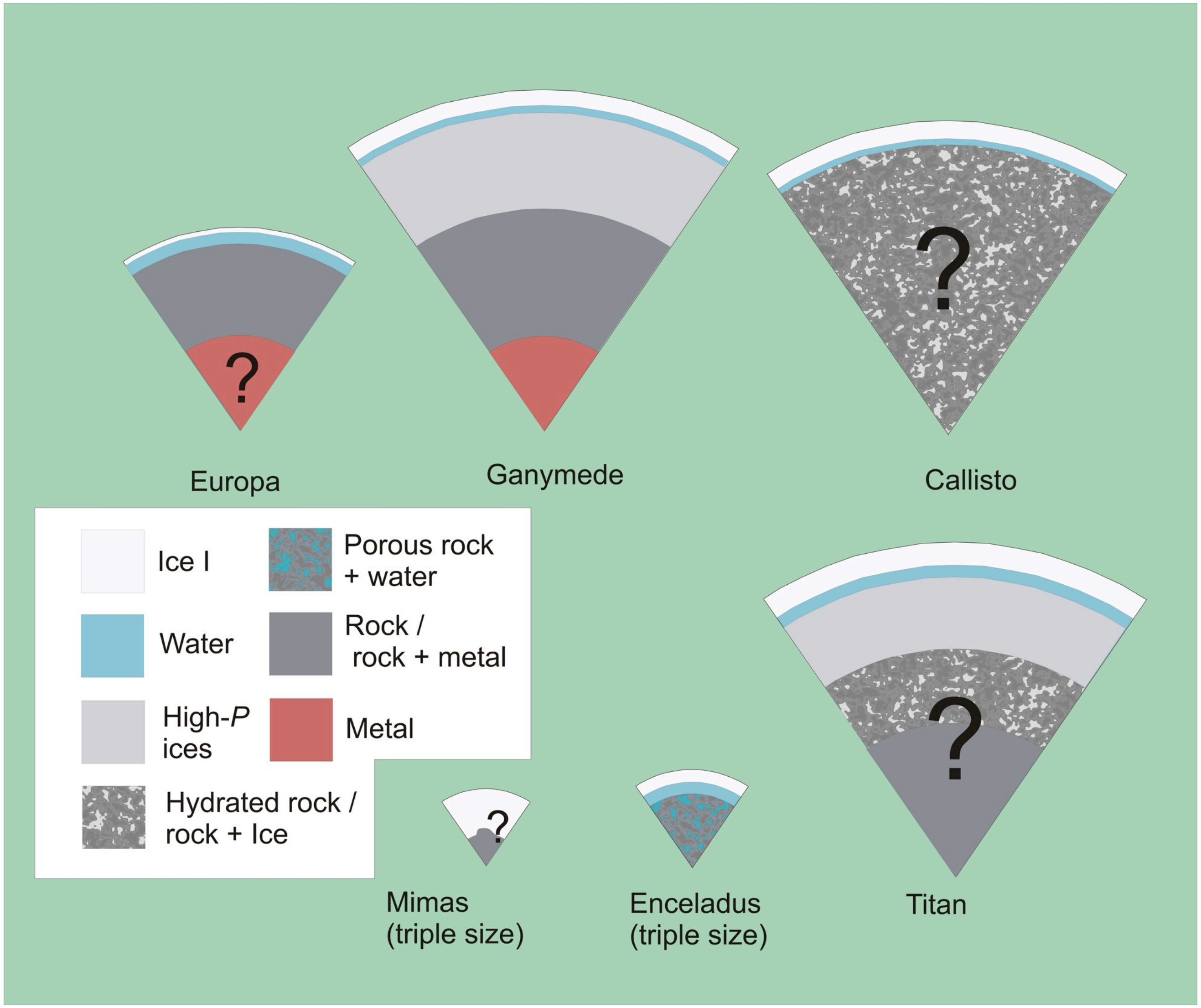
Outline

- 1. Internal structure & rheology (McCarthy)
- 2**. Tides and tidal response** (Stevenson)
- 3. **Tidal heating** (Stevenson, Matsuyama)
- 4. Thermal-orbital evolution (Fuller)
- 5. Heat flow (Davies)

1. Internal Structures

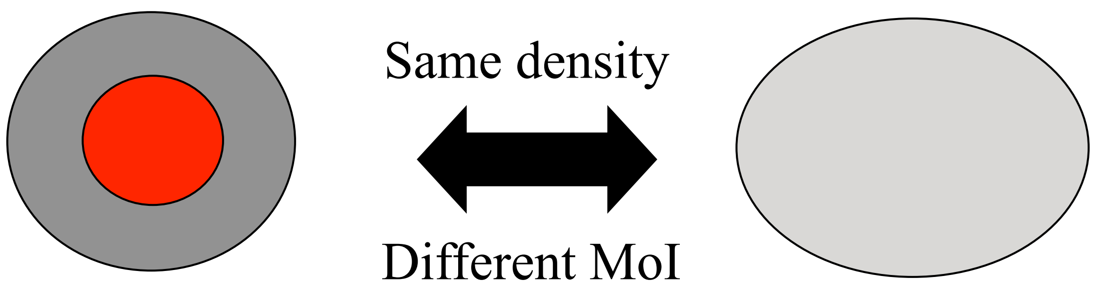


Outer solar system moons



Planet/Satellite Shape

- Long-term shape is controlled by secular ("fluid") Love number (h_{2s})
- h_{2s} depends on density distribution (MoI)
- Can use shape to determine MoI ("Darwin-Radau approximation") – *as long as the body behaves like a fluid*
- This may not be true for small/cold bodies



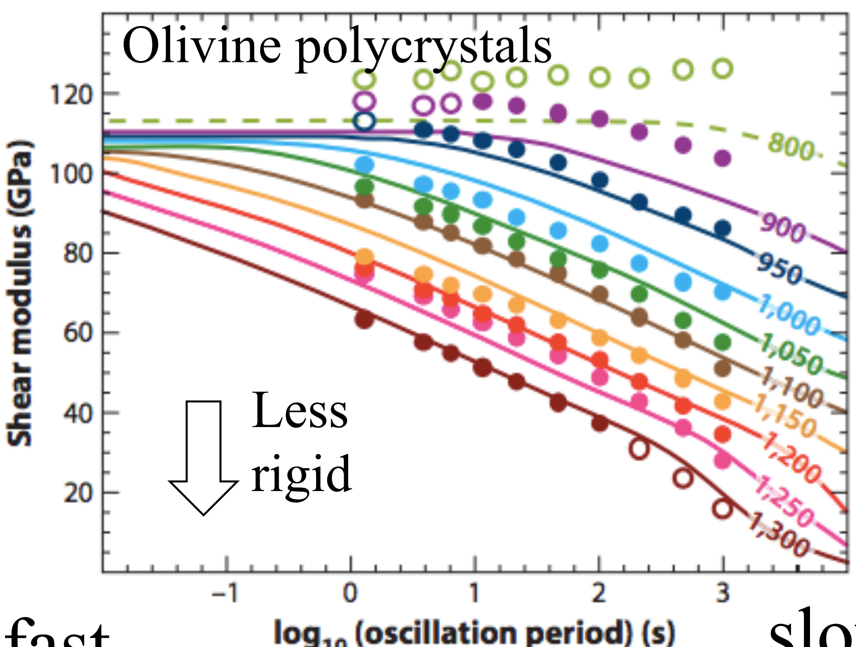
Less distorted (smaller h_{2s})

More distorted (larger h_{2s})

Rheology

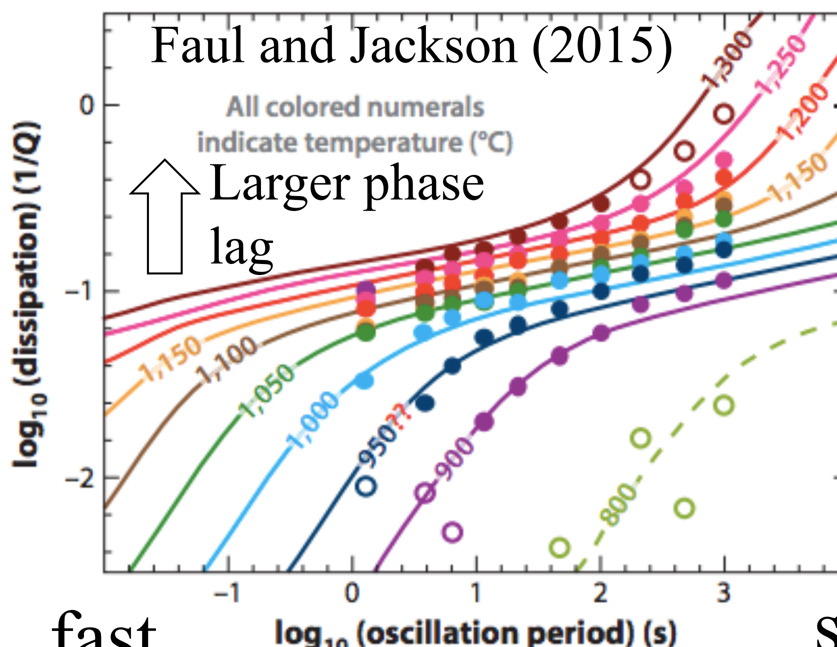
- Material properties are frequency-dependent!
- So tidal response depends on tidal frequency

Rigidity



fast slow

Phase lag

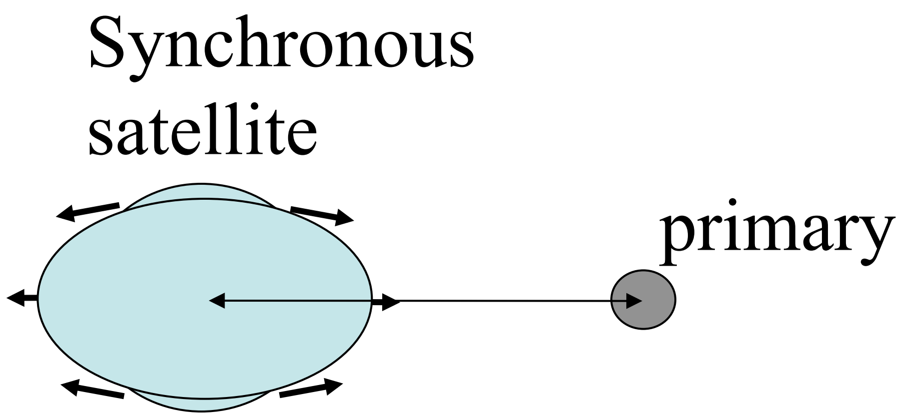


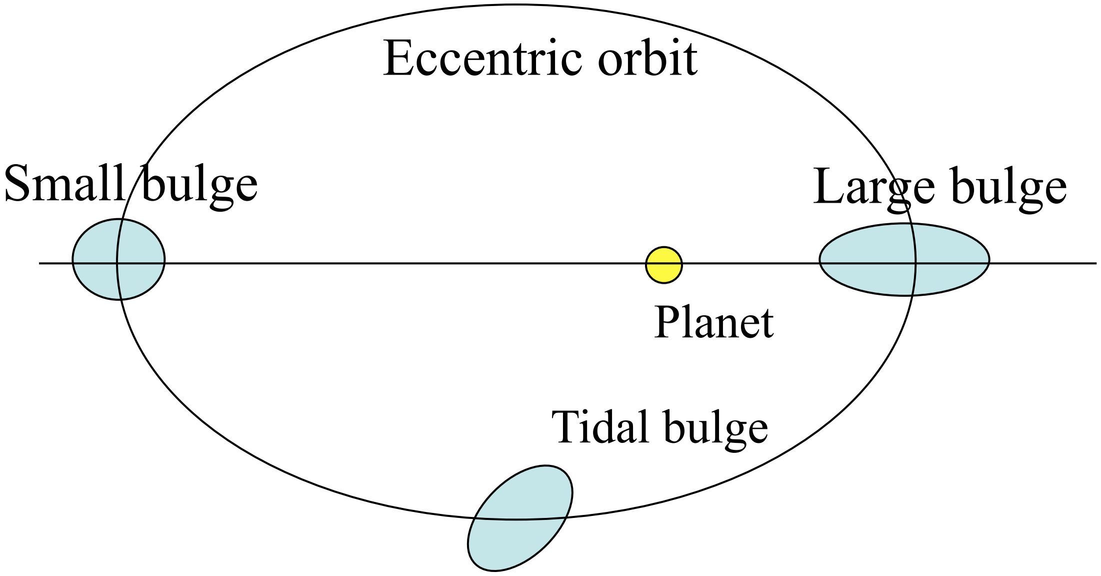
fast slow

- *Melt* and *water* also matter (poorly understood)

2. Tides

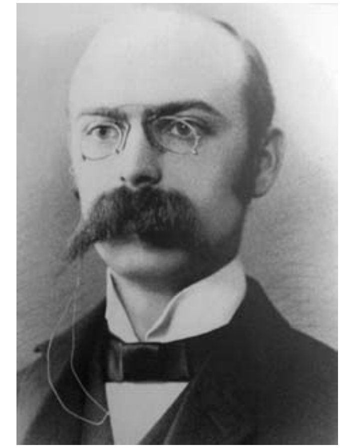
Basics





- Satellites are distorted by tides
- Time-varying stresses and heating result
- Tidal heating can be an important energy source (see below)

Amplitude of tidal response h_2, k_2

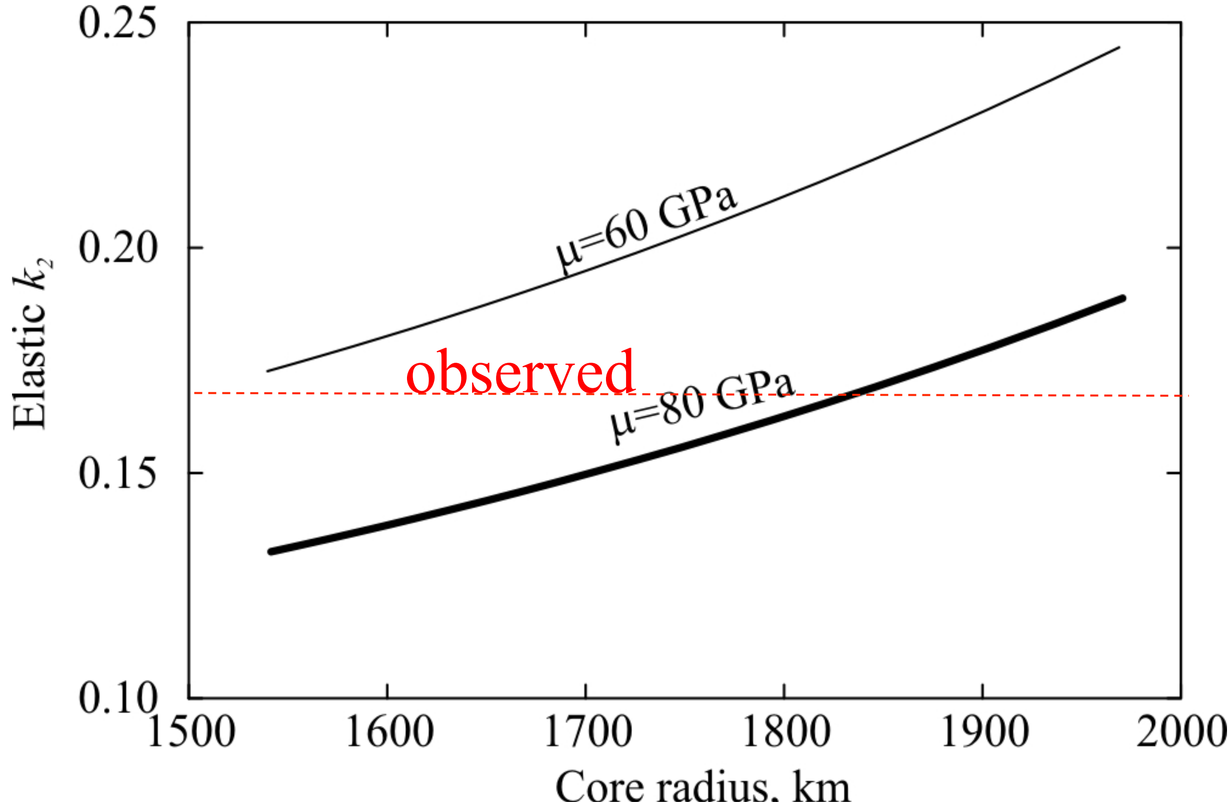


A.E.H. Love

- Love numbers: dimensionless degree-2 response of **shape** (h_2) and **gravity** (k_2) to applied tidal potential
- Large k_2, h_2 means large response
- k_2 is easier to measure . .
- But measuring *both* is advantageous
- For a uniform, strengthless body h_2=2.5 and k_2=1.5
- Rigidity and/or density concentration will reduce Love numbers
- Effective rigidity is dependent on *forcing frequency* – at long periods, body will have larger Love numbers
- So **tidal** h_2, k_2 < long-term ("fluid") h_2,k_2 in general

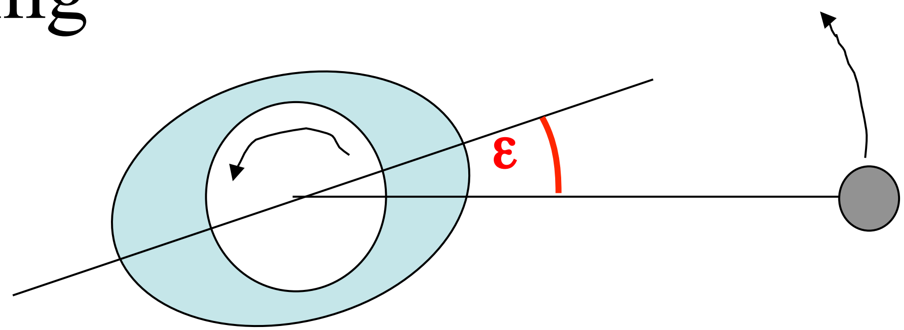
Liquid layers affect tidal response

- Io (Bierson & Nimmo 2016)
  - Partially molten mantle k_2=0.1
  - Fully molten magma ocean k_2=0.5
- Mars



Phase of tidal response

- Tidal response lags forcing
- This lag causes
  - spin-down
  - orbital expansion
  - tidal heating



- The phase lag ε is described by the **dissipation factor** Q: $Q \sim 1/\varepsilon$
- High Q means low dissipation
- Q controls the **rate** at which processes happen

Measured tidal k_2 and Q values

	Tidal k_2	**Tidal Q**	**Reference**
Mercury	0.45	n/a	Verma & Margot 2016
Earth	0.3	~300	Jagoda et al. 2018; Ray et al. 2001
Moon (monthly)	0.024	38	Williams & Boggs 2015
Mars	0.166	~90	Konopliv et al. 2016; Lainey et al. 2007
Io	[0.1]*	[6]*	Lainey et al. 2009
Titan	0.6	n/a	Iess et al. 2012

*k_2/Q=0.015 from astrometry. Here I assume k_2=0.1

Summary

- Tidal response **amplitude** (k_2, h_2) and **phase** (Q)
- k_2, h_2, Q depend on rigidity, density and frequency
- Liquid layers increase amplitude
- Measured tidal response can be used to infer internal structure

- It helps conceptually to put yourself on the satellite surface

3. Tidal heating

Tidal heating

For a synchronous satellite:

$$H = \frac{3}{2}\frac{k_2}{Q}\frac{n^5 R^5}{G}\left(7e^2 + \sin^2\theta\right)$$

depends on internal structure

eccentricity

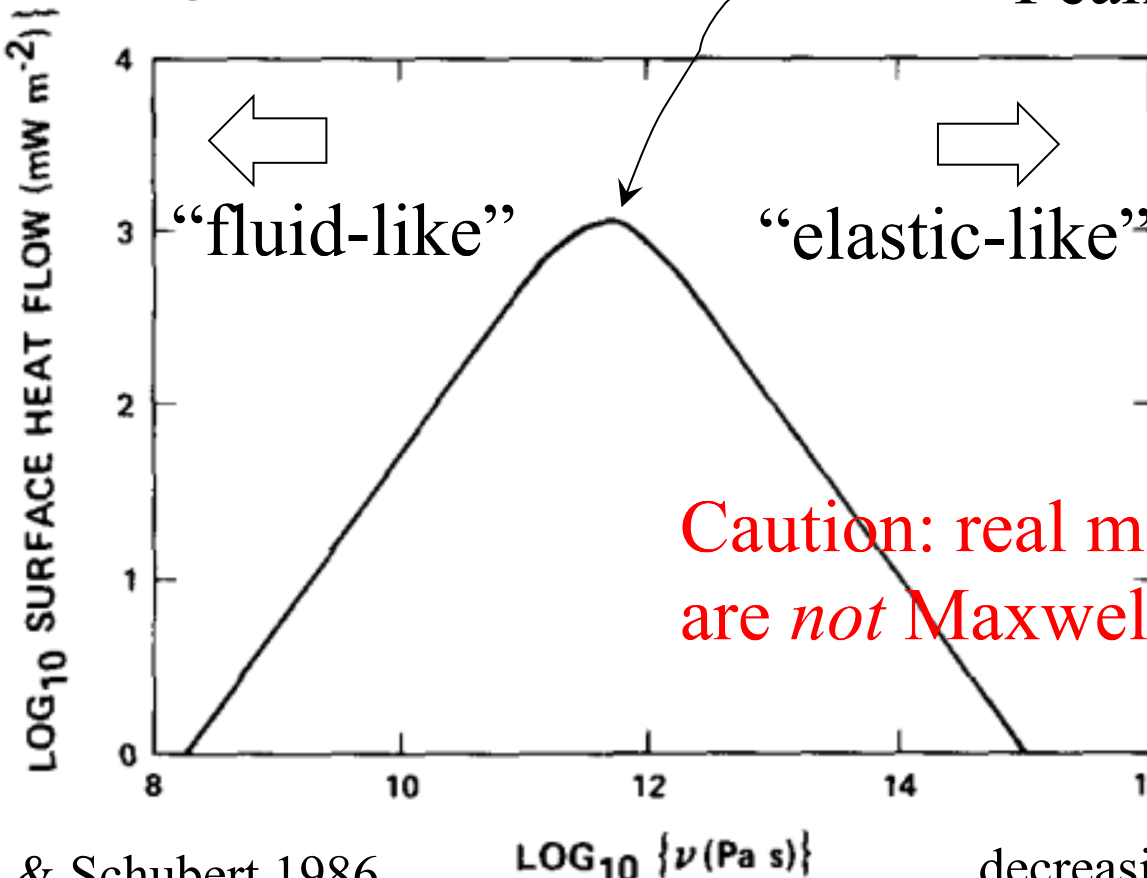
obliquity (“tilt”)

- Heating depends on amplitude (k_2) and phase (Q)
- A purely elastic (Q->∞) body generates no heat

Viscoelasticity & tidal heating

- "Maxwell time" $\tau = \eta / \mu$
- Peak heating when $\omega\tau \sim 1$

Peak heating



Caution: real materials are *not* Maxwellian!

Ross & Schubert 1986

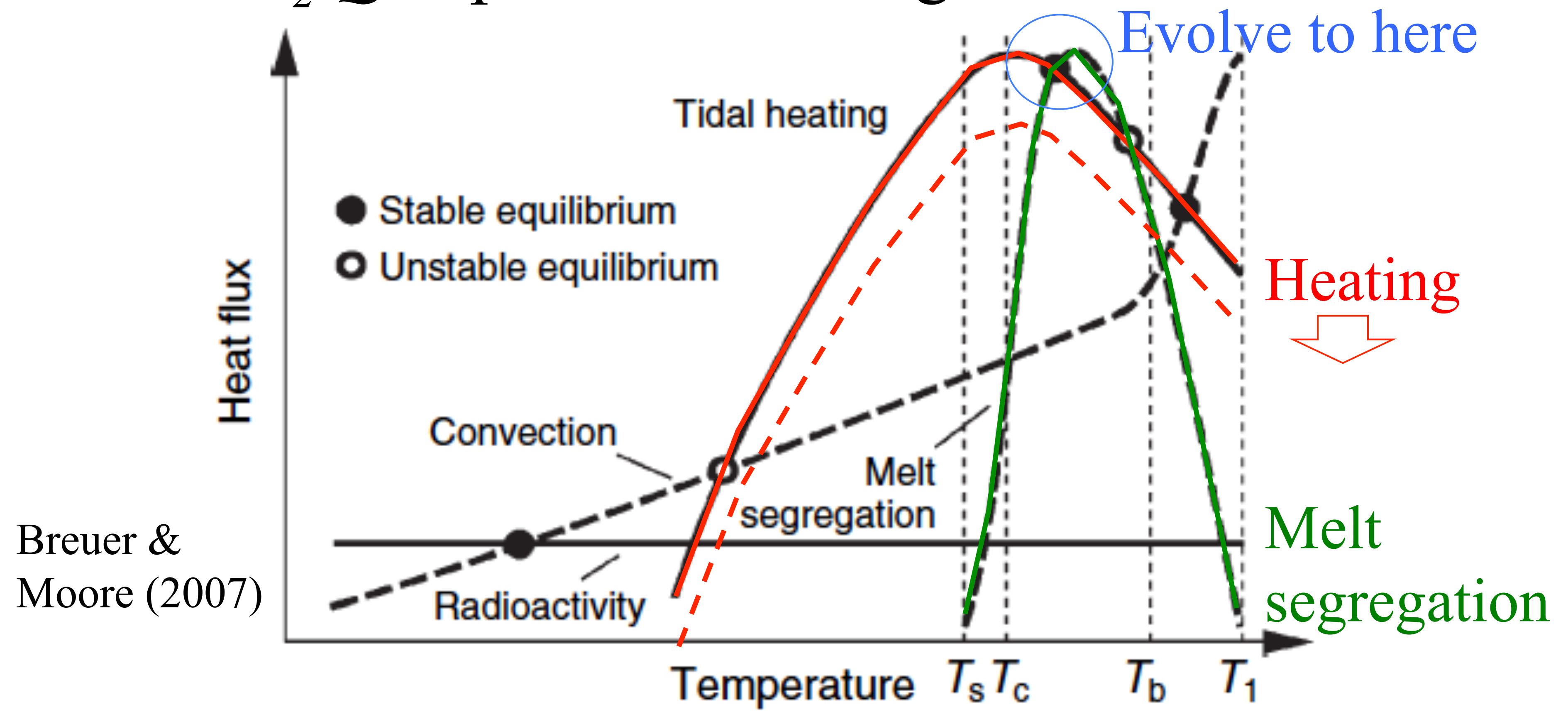
viscosity

decreasing T

increasing ω

Runaways

- Tidal heating rate depends on k_2/Q
- But k_2/Q depends on heating rate – feedbacks!



- Eccentricity will also evolve . . .

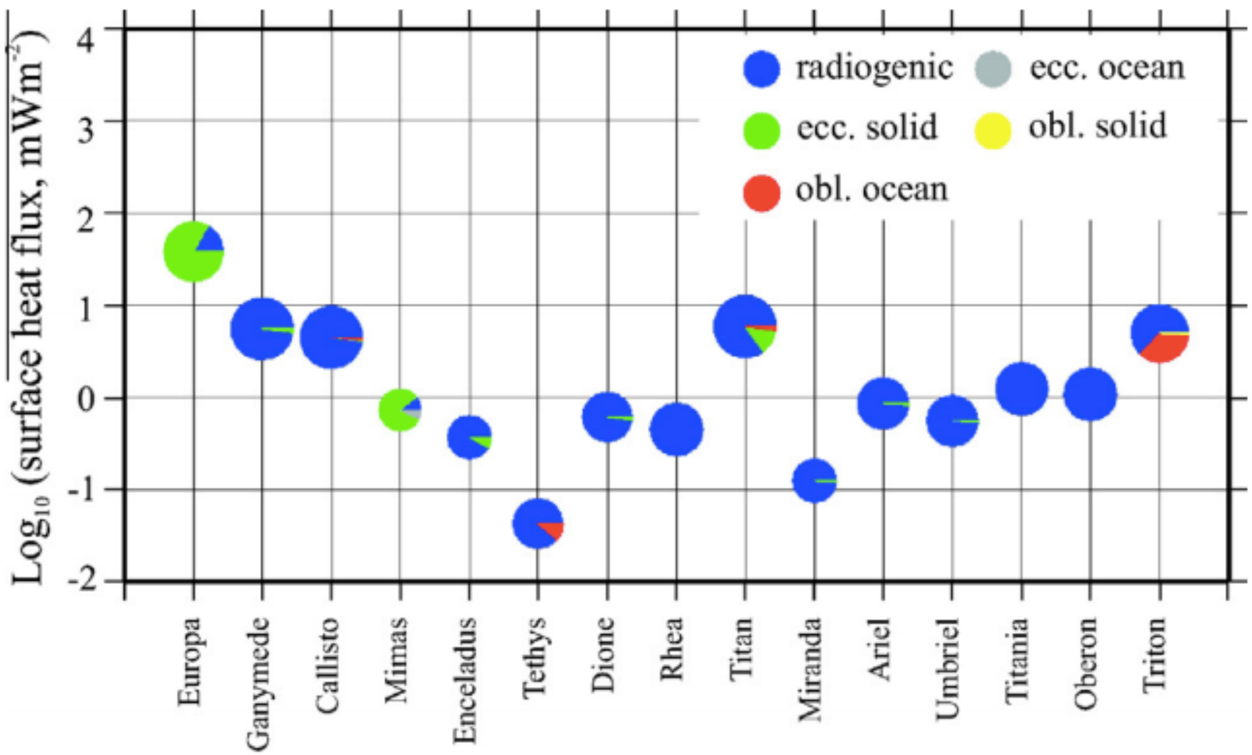
Ocean tidal heating

- A liquid ocean can experience tidal heating from obliquity tides (Tyler 2008)
- However, except for Triton, this heating is small compared to other sources

k_2=3/2

elastic k_2

Chen et al. (2014)

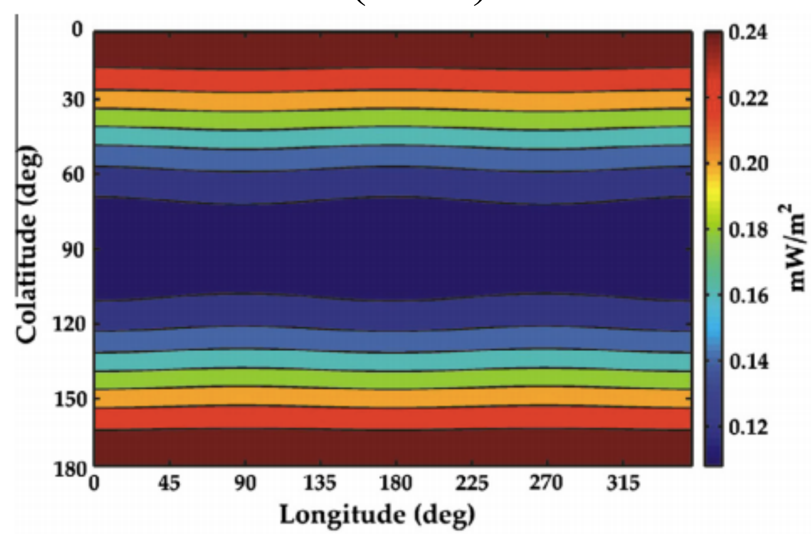


Spatial patterns of heat flow

- Radial structure controls pattern of heat flow

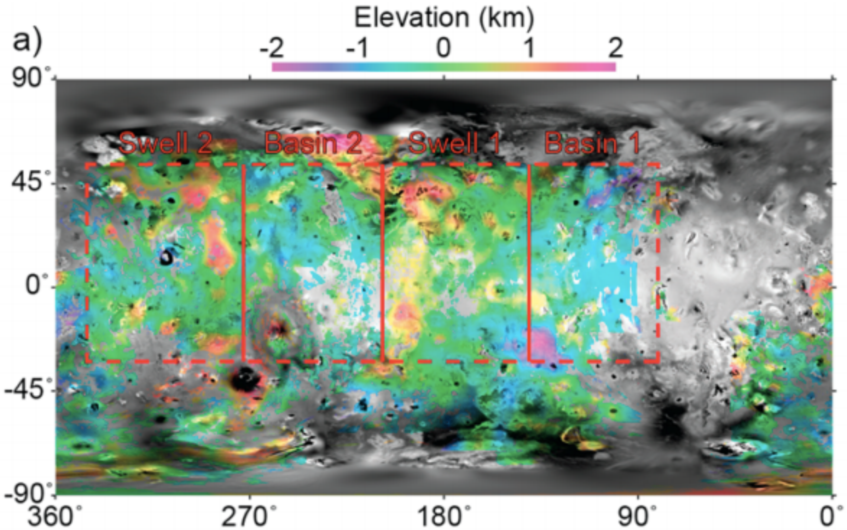
Partially-molten Io
Bierson & Nimmo (2016)

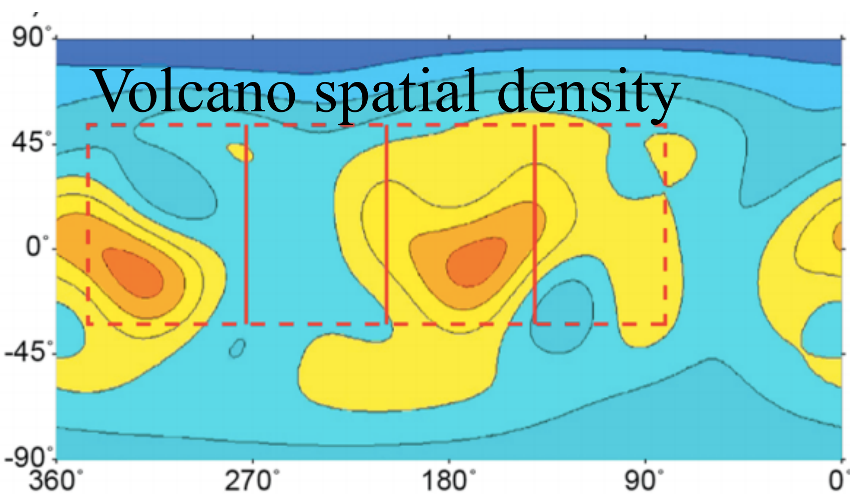
Ocean Heating
Chen et al. (2014)



(a) Obliquity heating

Topography etc.





White et al. (2014)

- Heat flux variations will create topography
  - Shell thickness variations
  - Dynamic support etc.

Where does the energy come from?

- In the first instance, from the satellite's orbit
- e-tides: orbit will *circularize*, heating -> 0
- θ-tides: inclination will damp, heating -> 0

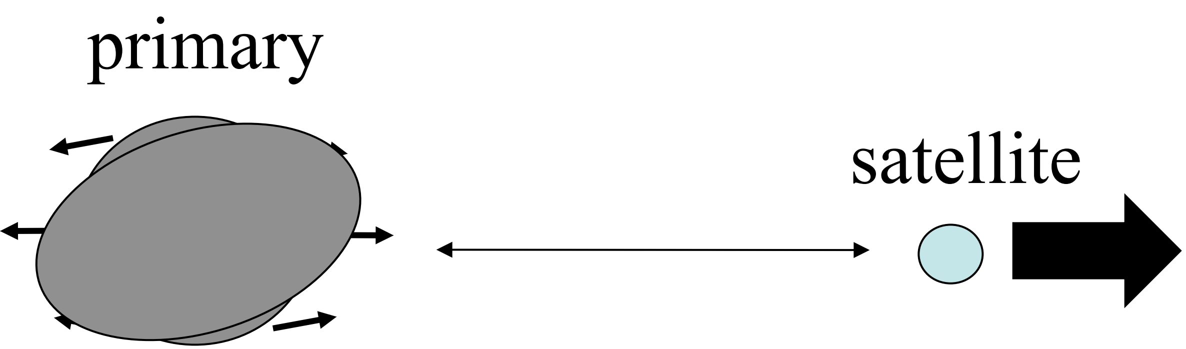
- Unless a *resonance* with a neighbouring satellites excites the eccentricity/inclination
- Resonance allows the spin energy of the primary to be tapped (large reservoir)
- Can get equilibrium state in which heat dissipated depends only on Q of the *primary*

Summary

- Tidal heating goes as $e^2\, k_2/Q$
- Feedbacks between internal structure and heating rate
- Ocean tidal heating usually negligible
- Eccentricity of an isolated satellite will damp
- Satellites in resonance may exhibit much more complex behaviour (see below)

4. Thermal-orbital

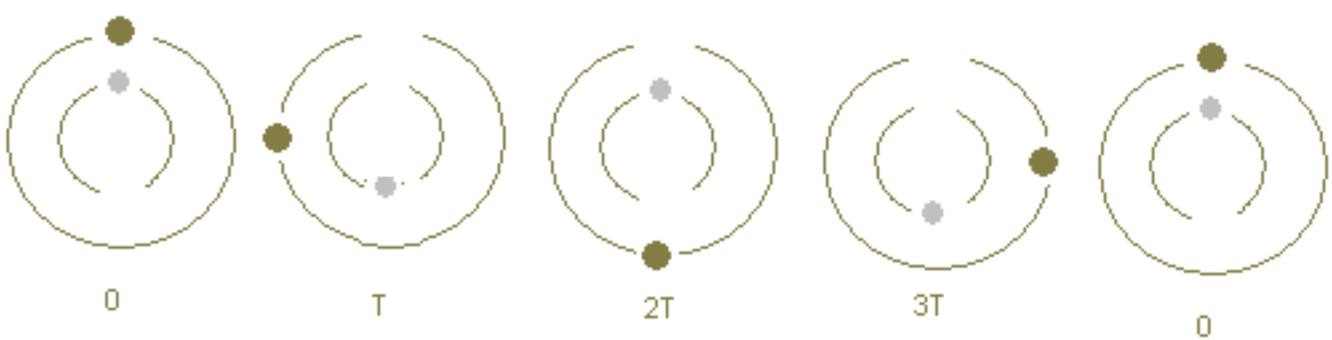
Outwards evolution



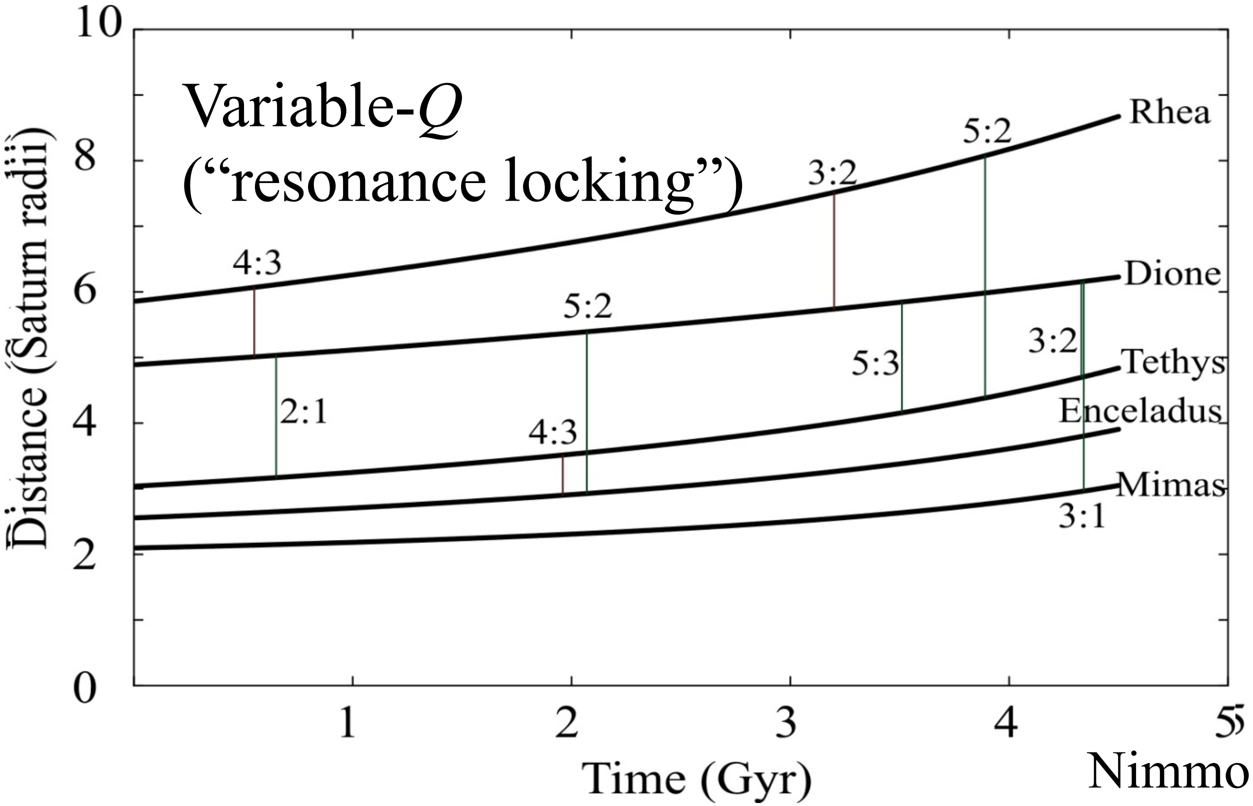
- Tides in the *primary* dissipate energy
- Tidal torques push the satellite *outwards*

- The rate of recession depends on $k_2/Q_{primary}$

- Outwards satellite motion may result in *resonances*
- Resonances excite the eccentricities & cause heating



Is Q_{Saturn} constant?



Nimmo et al.,
U.Az *Enceladus* book

- Saturn's Q is *low* (~2000) = high dissipation
- But it may not be constant with time

Feedbacks

- Satellite orbital and thermal evolution are *coupled*:

Internal structure

$$\frac{k_2}{Q}$$

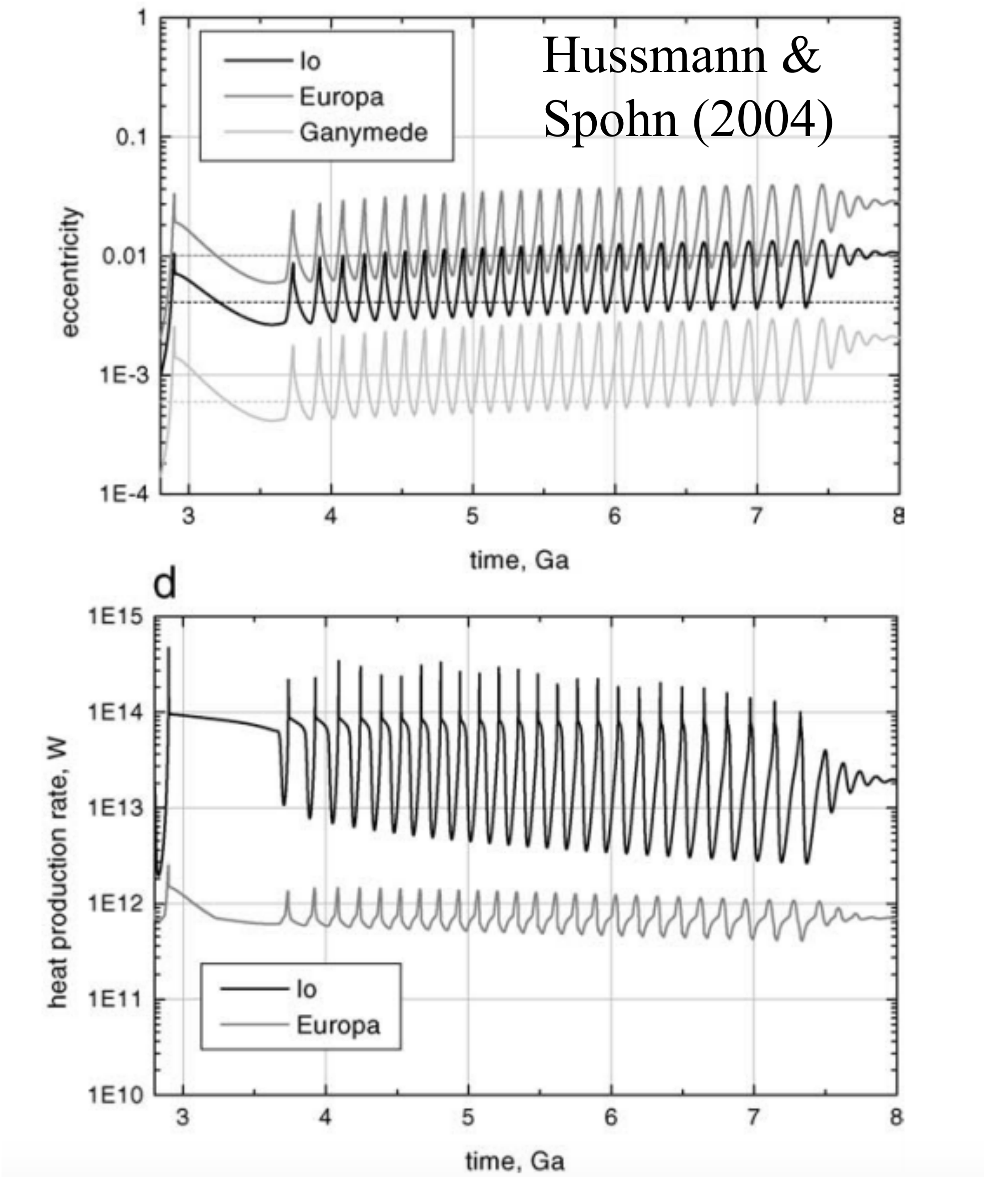
Orbital evolution (e)

Tidal heating ($\frac{k_2}{Q}$, e)

k_2/Q is a measure of how much dissipation occurs in the satellite

- The feedback makes for complicated thermal-orbital histories – *especially* when resonances are involved

Periodic Behaviour



- Thermal adjustment timescale comparable to eccentricity evolution timescale
- Can get "hot Europa, cold Io" states
- Oscillation period comparable to Europa's surface age (~50 Myr)

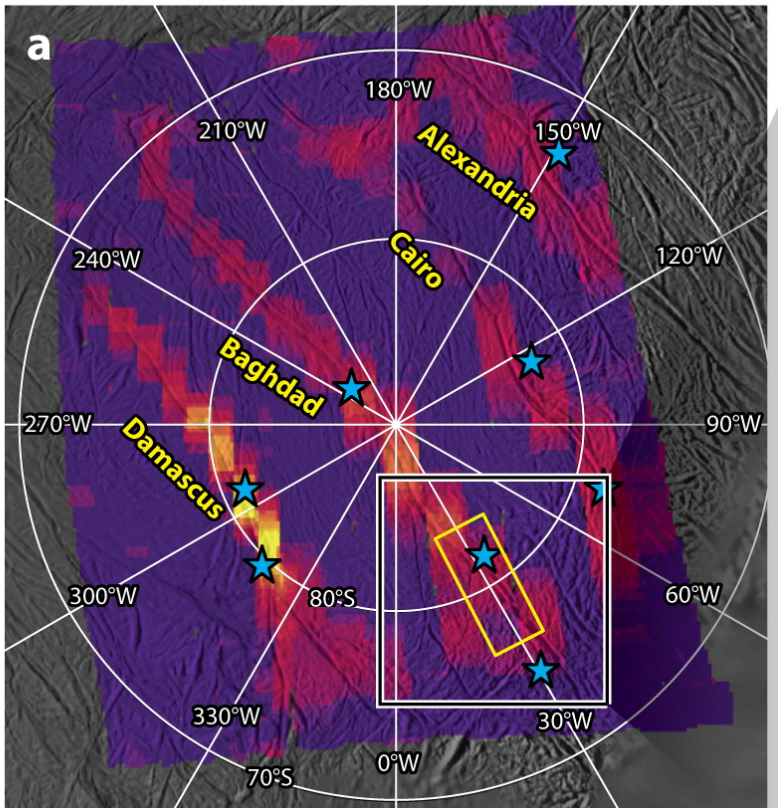
5. Heat flow estimates

Why?

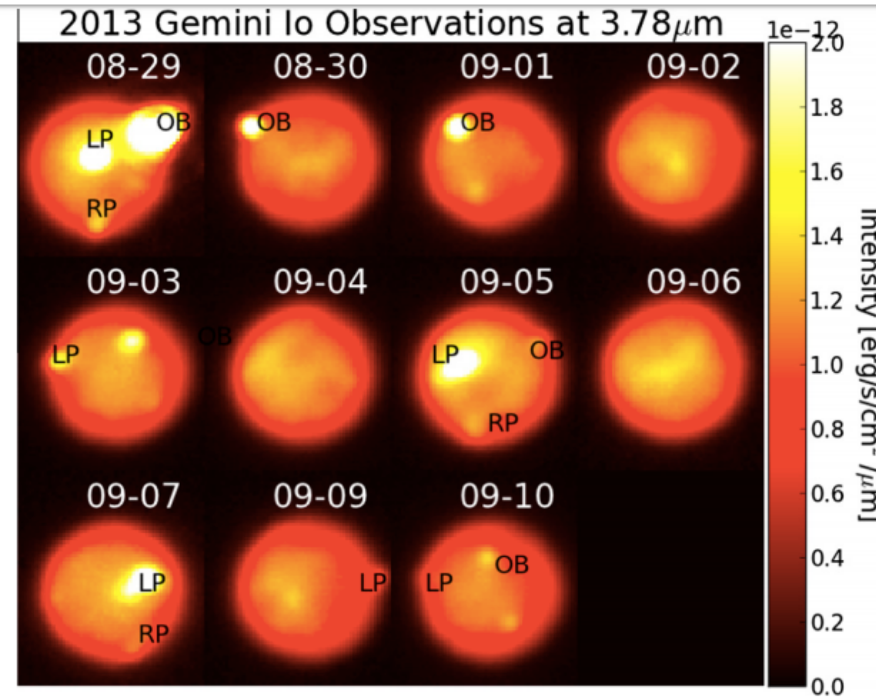
$$H = \frac{3}{2}\frac{k_2}{Q}\frac{n^5R^5}{G}\left(7e^2 + \sin^2\theta\right)$$

- Measuring the total power output gives k_2/Q (assuming heat produced = heat lost)
- Measuring the spatial distribution provides information on *where* heat is produced

Direct measurements



Enceladus

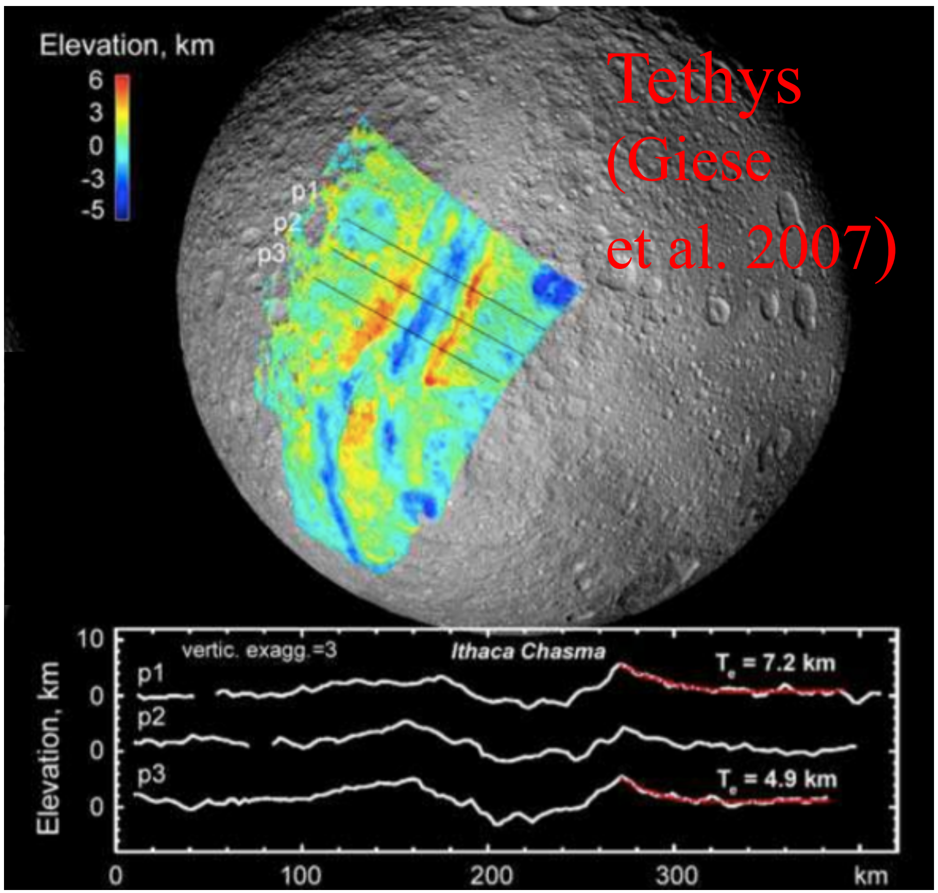


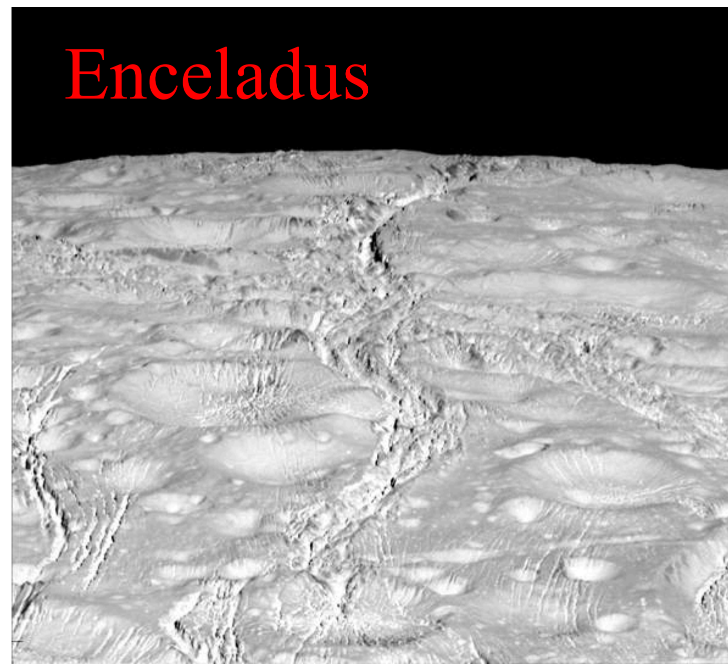
De Kleer et al. 2014

Spencer JR, Nimmo F. 2013.
Annu. Rev. Earth Planet. Sci. 41:693–717

Indirect estimates

- Elastic/viscous response depends on temperature gradient -> heat flux
- Provides information on ancient heat fluxes





Relaxed (shallow) ancient craters
Ancient heat flux > 150 mWm^{-2}
(Bland et al. 2012)

Takeaways

- Material properties are frequency-dependent
- k_2 gives amplitude, Q gives phase
- k_2 depends on rigidity & density structure
- Satellite tidal heating goes as $e^2\, k_2/Q_{satellite}$
- Heating rate depends on structure - feedbacks
- Heating pattern depends on internal structure
- Heating damps eccentricity (absent resonances)
- Orbital recession rate depends on $k_2/Q_{primary}$
- Thermal-orbital feedbacks & resonances
- Can use geophysics to infer heat fluxes