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

- Europa
- Ganymede
- Callisto
- Mimas (triple size)
- Enceladus (triple size)
- Titan

Legend:
- Ice I
- Porous rock + water
- Water
- Rock / rock + metal
- High-P ices
- Metal
- Hydrated rock / rock + ice

Diagram shows the internal structure of each moon with different layers and materials.
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

![Diagram showing different shapes with same density but different MoI](image)

Less distorted (smaller $h_{2s}$)  More distorted (larger $h_{2s}$)
Rheology

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

Rigidity

- Less rigid
- Fast

Phase lag

- Faul and Jackson (2015)
- Larger phase lag
- Fast

- 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 $h_2, k_2$

- 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 $\varepsilon$ 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

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

$k_2/Q=0.015$ 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:

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

- Heating depends on amplitude \((k_2)\) and phase \((Q)\)
- A purely elastic \((Q \rightarrow \infty)\) body generates no heat

depends on internal structure

eccentricity

obliquity ("tilt")
Viscoelasticity & tidal heating

- “Maxwell time” \( \tau = \frac{\eta}{\mu} \)
- Peak heating when \( \omega \tau \sim 1 \)

Caution: real materials are not Maxwellian!
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

$k_2 = \frac{3}{2}$

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)
Topography etc.

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

White et al. (2014)
Where does the energy come from?

- In the first instance, from the satellite’s orbit
  - $e$-tides: orbit will \textit{circularize}, heating $\rightarrow 0$
  - $\theta$-tides: inclination will damp, heating $\rightarrow 0$

- Unless a \textit{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 \textit{primary}
Summary

• Tidal heating goes as $e^2 \frac{k_2}{Q}$
• 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 $k_2/Q_{\text{primary}}$
- Outwards satellite motion may result in resonances
- Resonances excite the eccentricities & cause heating
Is $Q_{Saturn}$ constant?

- Saturn’s $Q$ is low ($\sim 2000$) = high dissipation
- But it may not be constant with time
Feedbacks

- Satellite orbital and thermal evolution are *coupled*:

  
  \[ \frac{k_2}{Q} \]

  \[ k_2/Q \text{ is a measure of how much dissipation occurs in the satellite} \]

  
  \[ (\frac{k_2}{Q}, e) \]

  \[ \text{Tidal heating} \]

  \[ \text{Orbital evolution (e)} \]

  \[ \text{Internal structure} \]

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

Hussmann & Spohn (2004)

- 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?

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

- 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

Indirect estimates

- Elastic/viscous response depends on temperature gradient $\rightarrow$ heat flux
- Provides information on ancient heat fluxes

Enceladus

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

Tethys

- (Giese et al. 2007)
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