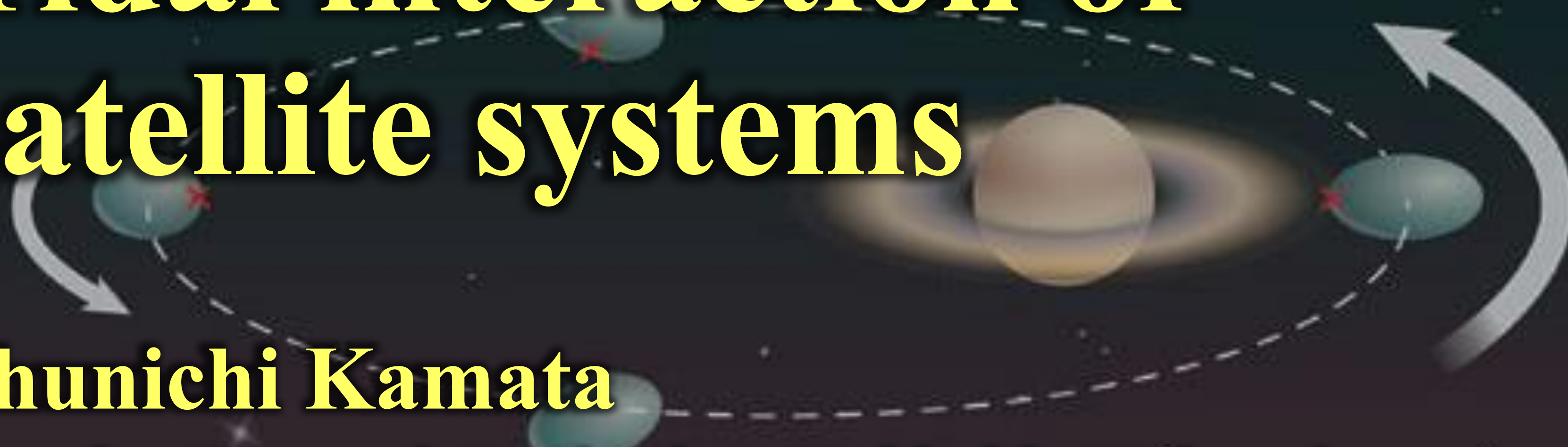
APCosPA-Planet2 RESCEU Summer School
Takayama, Gifu, Japan
August 25, 2016

Tidal interaction of satellite systems



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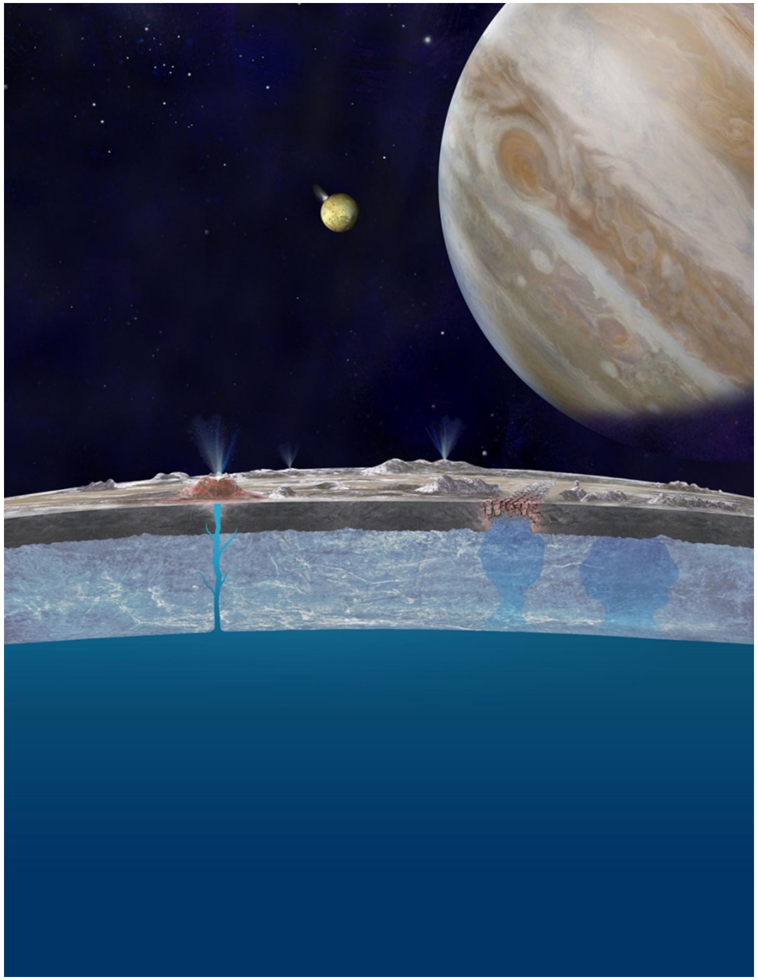
"Habitable worlds"?

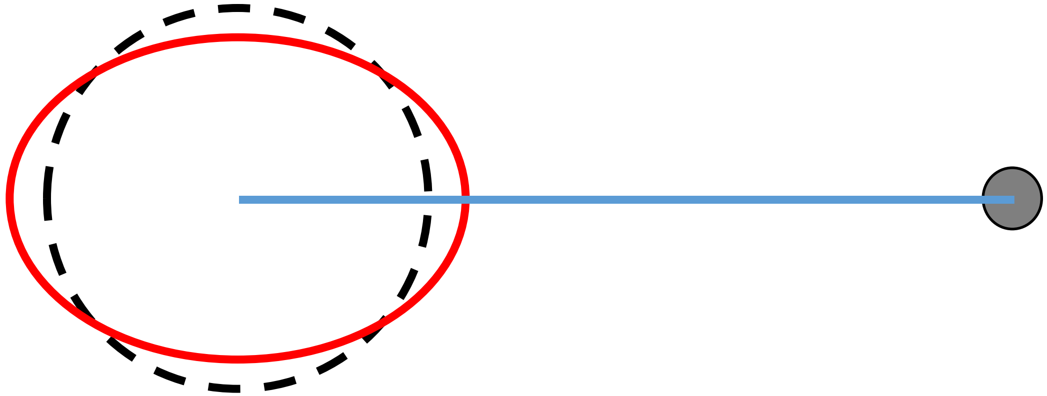
- Habitability is difficult to define
- But a key issue is the presence of a large amount of liquid water
- A uniqueness of the Earth: surface ocean
- Subsurface oceans may be common in Solar System
  - Europa, Enceladus, Pluto, Ganymede(?), Callisto(??), Mimas(???)



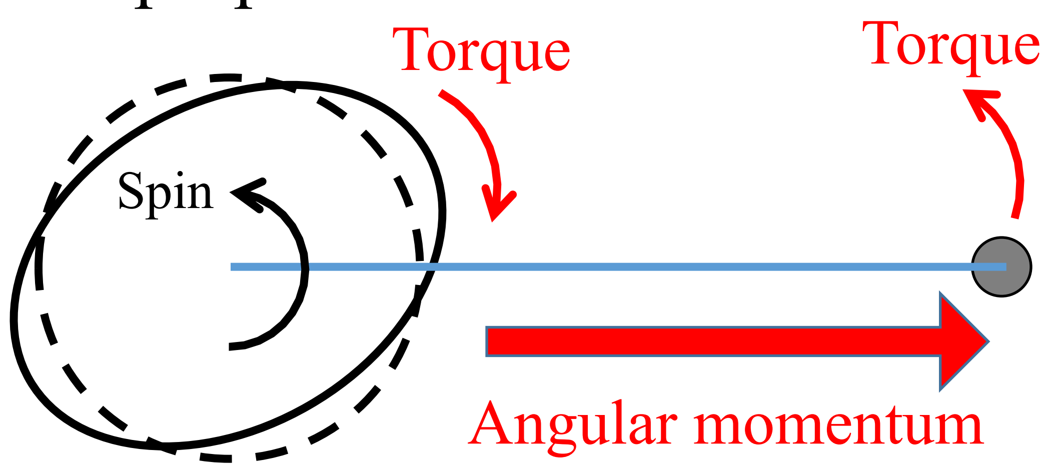
Credit: NASA/JPL-Caltech

Tidal interaction

1. Elongate the shape

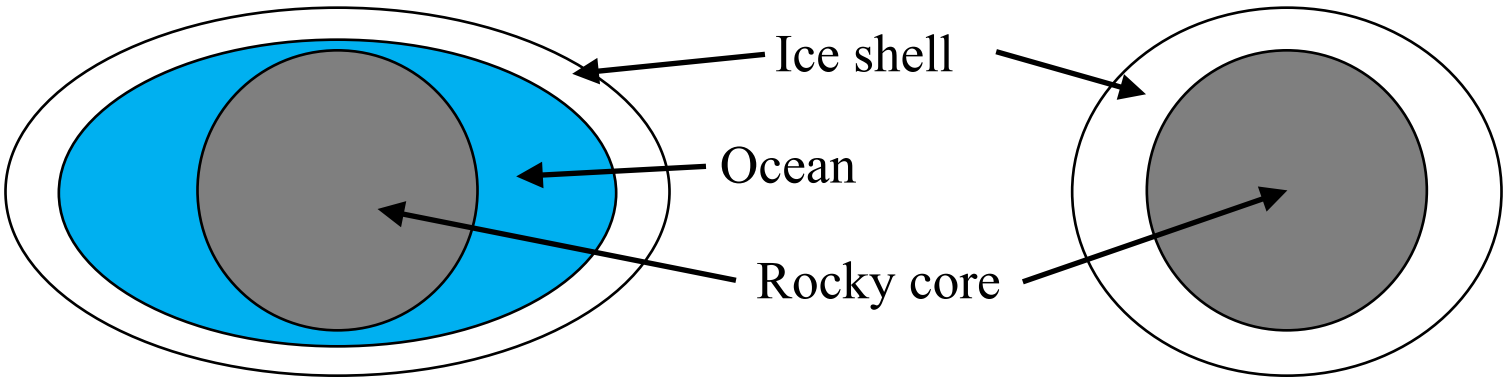


2. Modify orbital properties



1. Interior structure

- Deformation is large if the interior is soft
  - Large deformation is expected if a subsurface ocean exists



- Measurements using spacecraft
  - Shape: Laser altimetry (+ precise orbit determination)
  - Gravity: Radio tracking of the spacecraft or astrometry

Measurements of tidal response

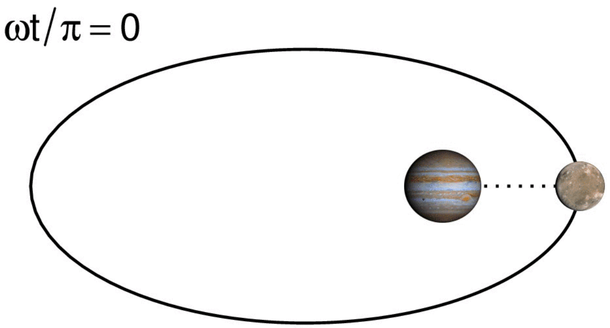
- Love number: shape/gravitational response normalized by the tidal potential

Planet/satellite	***h*2 (shape)**	***k*2 (gravity)**	**Missions**
Mercury		0.45	MESSENGER
Venus		0.295	PVO, Magellan
Earth	~0.6 (~1d)	~0.3 (~1d)	Satellites/VLBI
Moon	0.0371 (1m)	0.024 (1m)	LRO, GRAIL
Mars		0.170	MGS, M Ody, MRO
Jupiter		(Est: ~0.59)	Juno
Ganymede	(Est: <1.7)	(Est: <0.6)	JUICE
Saturn		0.39	Cassini
Titan		0.59-0.63 (Subsurface Ocean!)	Cassini

[References] Mercury: Mazarico+, *JGR*, 2014; Venus: Konopliv & Yoder, *GRL*, 1996; Earth: Wahr, *Global Earth Physics: A Handbook of Physical Constants*, 1995; Lunar *h*2: Mazarico+, *GRL*, 2014; Lunar *k*2: Williams+, *JGR*, 2014; Mars: Genova+, *Icarus*, 2016; Jupiter: Wahl+, *arXiv*, 2016; Ganymede: Kamata+, *JGR*, 2016; Saturn: Lainey+, *arXiv*, 2015; Titan: Iess+, *Science*, 2012

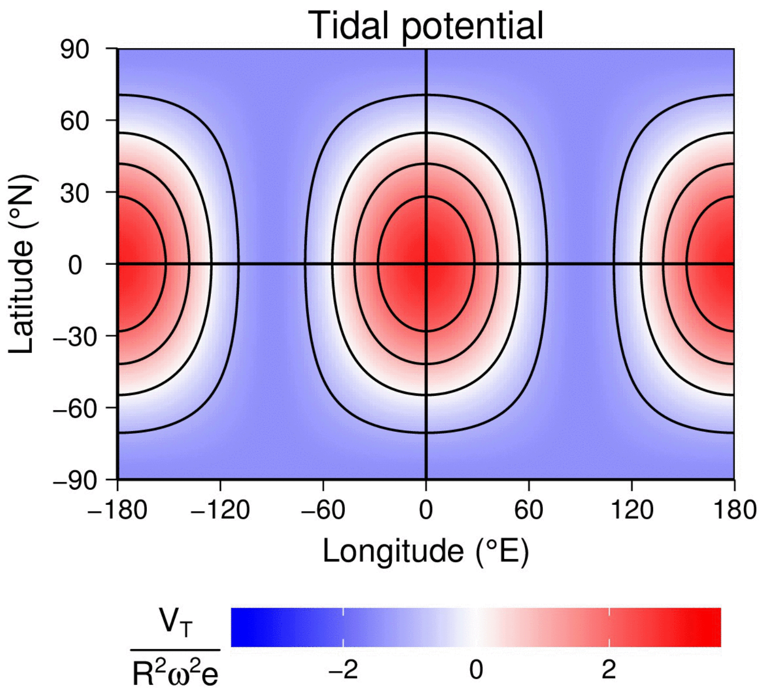
2. Energy input for satellites

- Satellites generally have non-zero eccentricity
  - Periodical change in the shape
  - Frictional heating



- The heating rate of a solid body for eccentricity tides: H
  - $H = \frac{21}{2}\frac{\color{red}{k_2}}{Q}\frac{(nR_s)^5}{G}e^2$

k_2: Love number
Q: Dissipation factor
n: mean motion
R_s: Radius
G: Grav. const.
e: eccentricity



Jovian satellite Io: No longer icy!

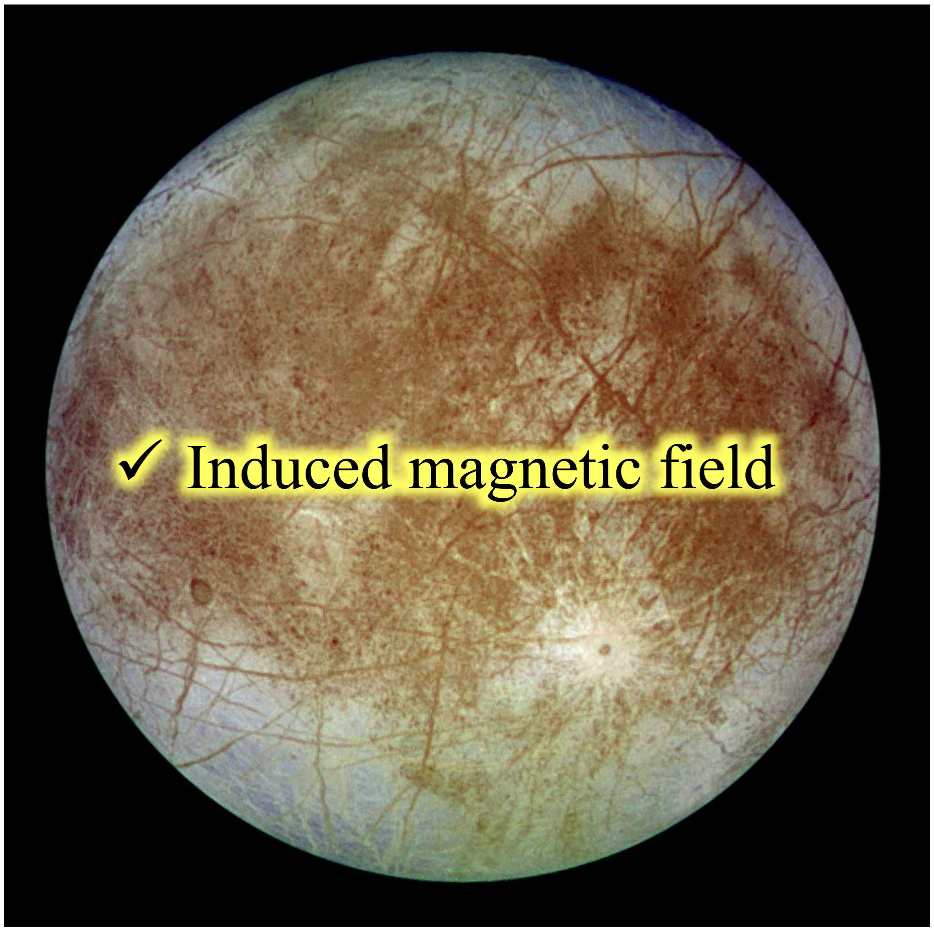
- Close to Jupiter, large eccentricity (0.0041)

Credit: Galileo mission/NASA/JPL

Credit: NASA/JHUAPL/SwRI

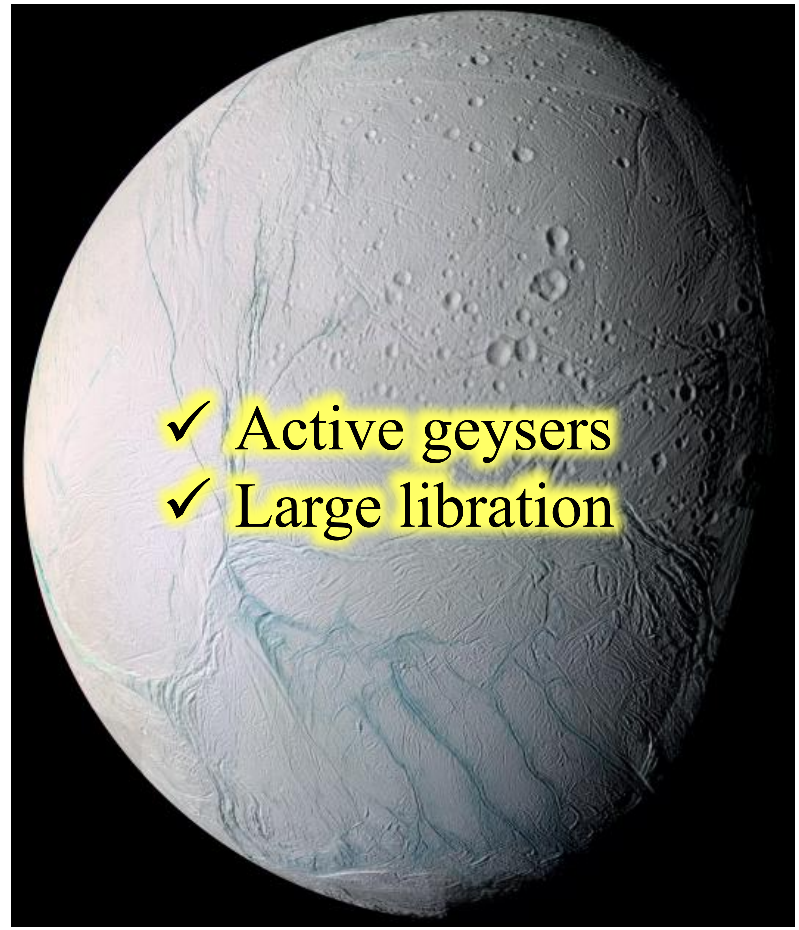
"Ocean satellites"

Europa



Credit: NASA/JPL/DLR

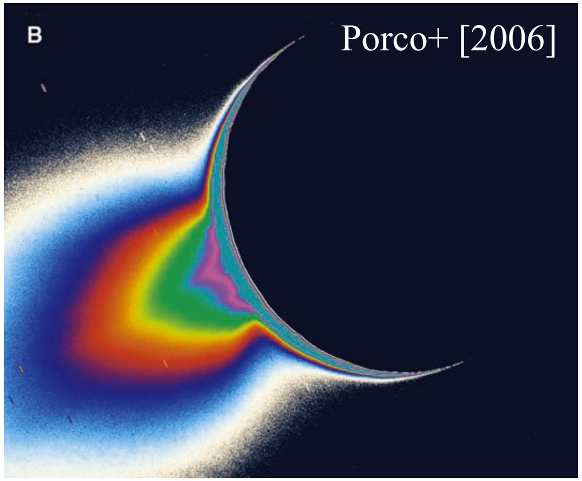
Enceladus



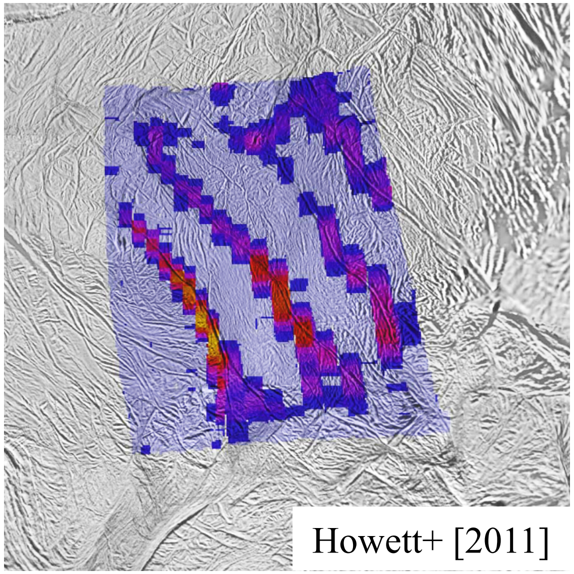
Credit: NASA/JPL/SSI

Active South Pole of Enceladus

- Observation
  - Large amount of thermal emission
    - ~10 GW [e.g., Howett+ 2011]
- Heat source
  - Primodial heat/chemical reaction
    - Negligible [e.g., Malamud & Prialnik 2013]
  - Radiogenic heating
    - ~0.3 GW [Roberts & Nimmo 2008]
  - Episodic heat loss
    - Could work in principle [O'Neill & Nimmo 2013]
  - Tidal heating??

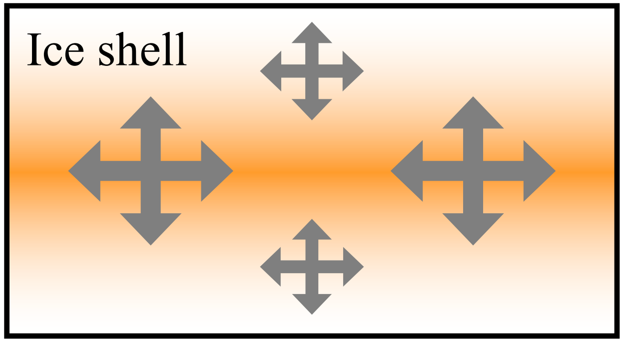


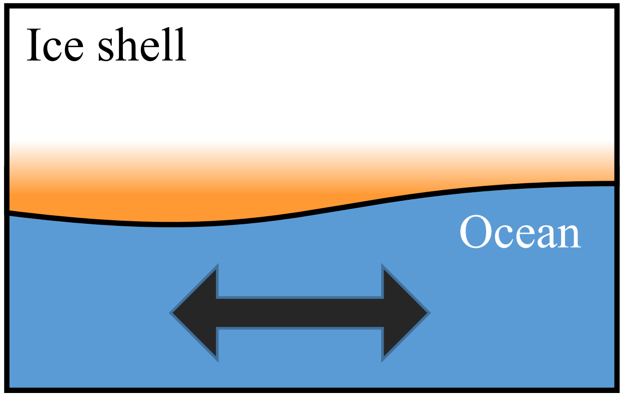
Porco+ [2006]


Howett+ [2011]

Tidal heating

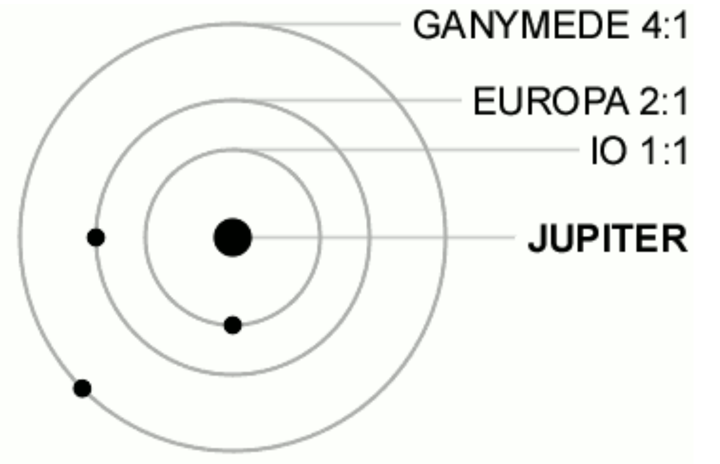
- Friction inside solid layers
  - "Solid tides"
  - Large H for a soft ice shell
- Friction at solid-liquid boundaries
  - "Ocean tides" [e.g., Tyler 2008]
  - Large H for a thin ocean
- Tidal heating could be ~10 GW in principle but requires extreme conditions and is unlikely to maintain for a long time





Equilibrium tidal heating rate

- Enceladus is in a 2:1 mean-motion resonance with Dione

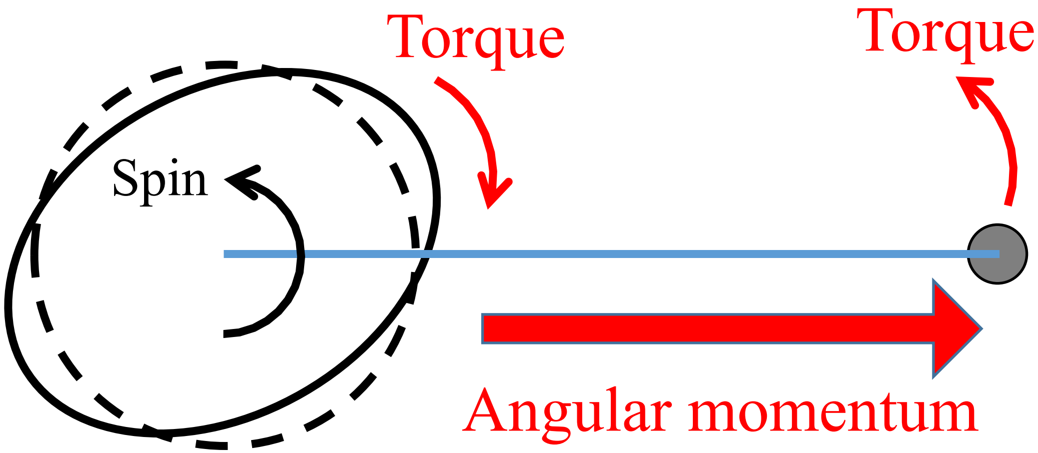


- Equilibrium tidal heating rate is determined by the dissipation factor Q of the planet
  - Increase in e due to dissipation in planet is balanced by decrease in e due to dissipation in satellites

- Equilibrium tidal heating rate is 1.1 GW for Enceladus under $Q_{\mathrm{Saturn}} = 18{,}000$ [Meyer & Wisdom 2007]

Q_{Saturn}

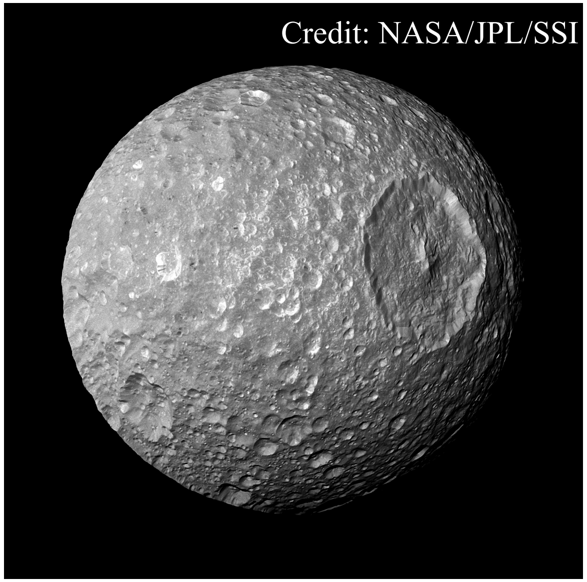
- Controls orbital evolution and tidal heating
- Nearly constant for equilibrium tides

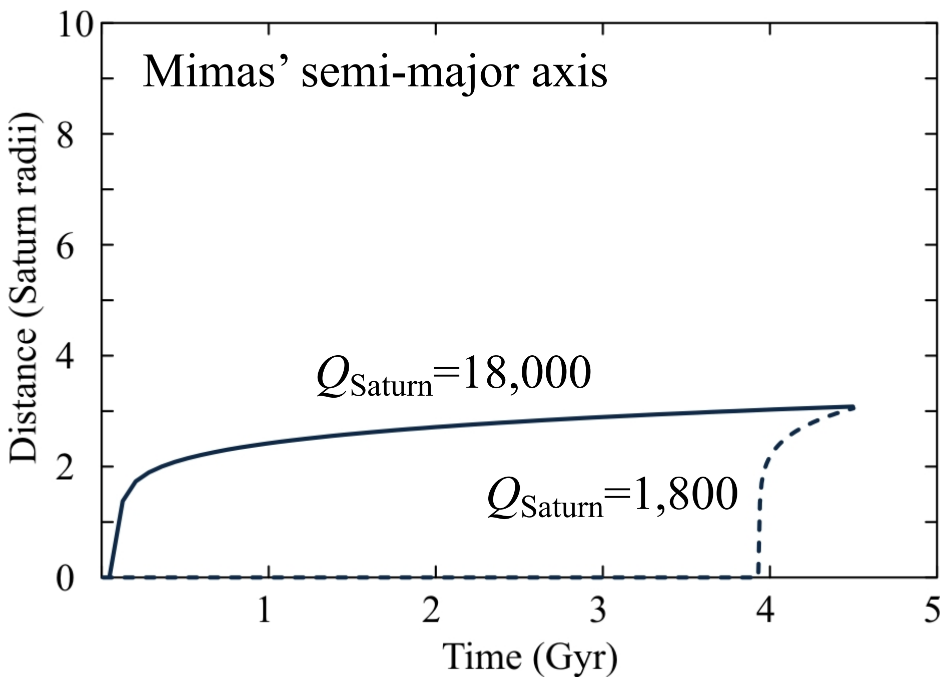


- A lower Q means more torque, more tidal heating, and faster outwards evolution
  - The lower bound of Q_{Saturn} can be obtained from orbits of satellites

"Mimas test"

- Innermost, regular, mid-sized satellite
  - Heavily cratered = old surface
- Lower Q requires younger satellite
  - If Mimas is 4.5 Gyr old, $Q_{Saturn} > 18,000$

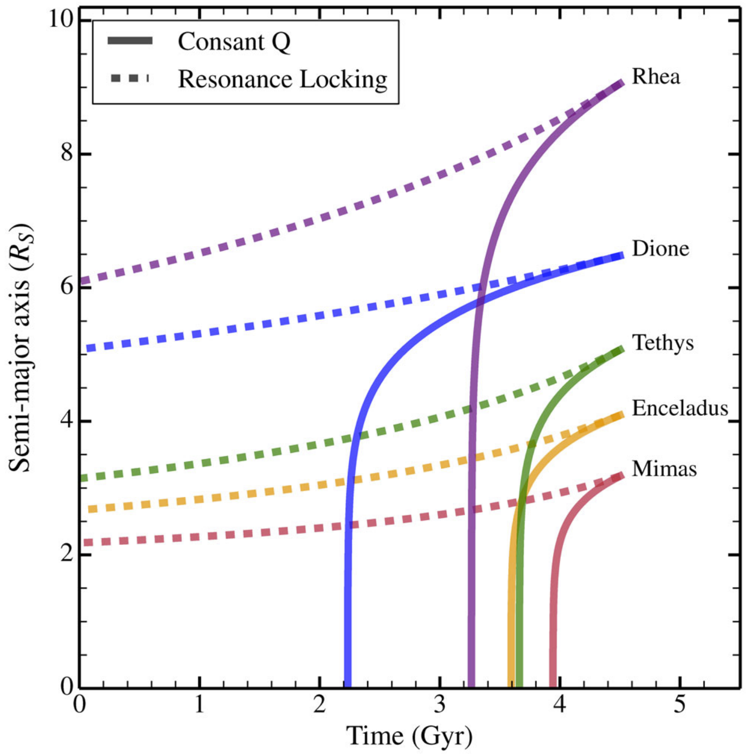




Astrometry and astrophysics

- Recently a $Q_{\text{Saturn}} \sim 1{,}800$ is inferred from astrometry of satellites [Lainey+ 2012]
  - Pros: ~10 GW of tidal heat
  - Cons: Unrealistically young satellites

- "Resonance locking" due to dynamical tides [Fuller+ 2016]
  - *Q* depends on frequency
  - Migration rate is controlled by the rate of internal evolution of Saturn
  - Strong tidal heating + old satellites are accepted!



Summary

- The presence of a subsurface ocean is a key to understand habitability of a planetary body

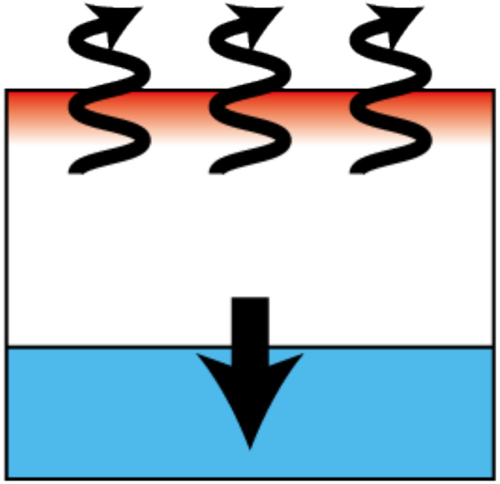
- Tidal interaction is important because it
    1. Provides information on the interior structure
    2. Provides heat to prevent complete freezing

- Tiny Enceladus has a global subsurface ocean indicates tidal heating much larger than previously expected
    - Dissipative property of the ***primary*** is the key

Backup slides

Location of the heat deposition

- Heat deposited in a near-surface layer dissipates immediately to the outer space
  - Deposition of heat in a deep interior is necessary to maintain a subsurface ocean



- Heating rate ~ (stress) x (strain rate)

Need more heat output

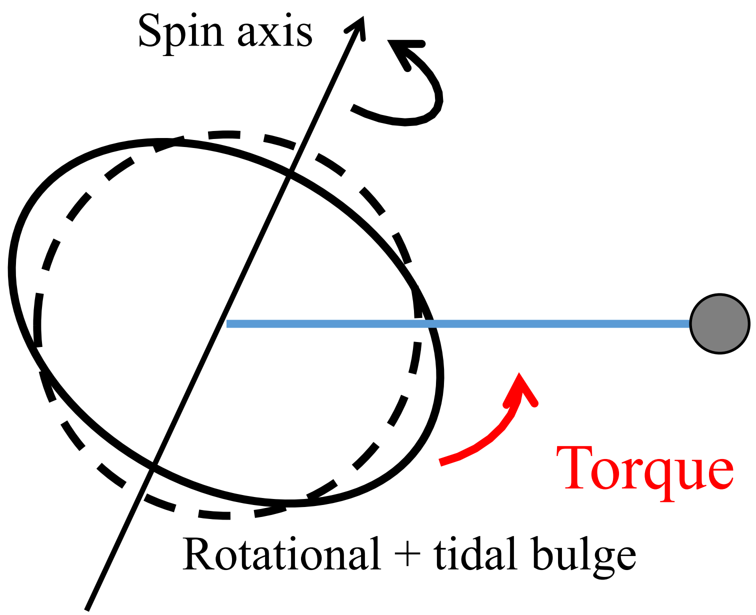
1. Episodic heat *production*
    - The thermal-orbital evolution of the Saturnian system
        - Additional heat is only <1 GW [Shoji+ 2014]
    - Tidal resonance [e.g., Matsuyama 2014, Kamata+ 2016]
        - Requires an ocean much thinner than that estimated from libration measurements [Thomas+ 2016]

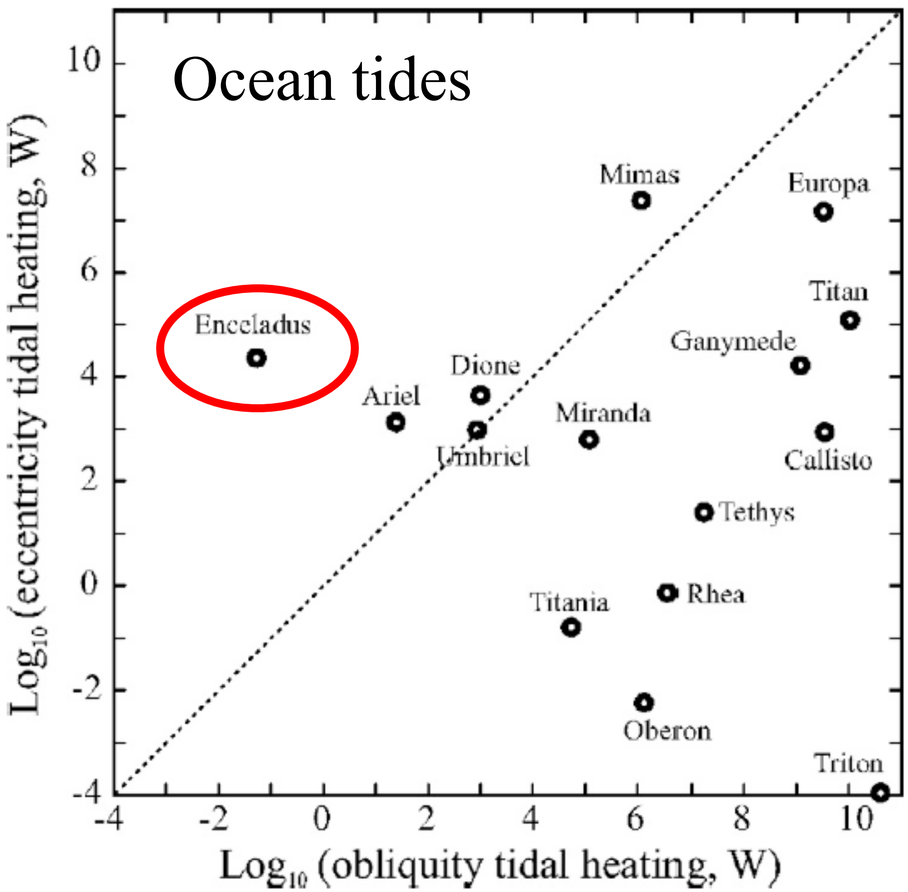
2. Episodic heat *loss*
    - Overturn of a convective ice shell [O'Neill & Nimmo 2008]
        - Requires us to be seeing Enceladus at a special time

3. Previous tidal heating models are wrong

Obliquity tides

- Non-zero obliquity also leads to tidal heating
- Mostly "ocean tides"





[Chen+ 2014]