氷衛星の内部構造と熱進化

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要旨：
本発表では氷衛星の内部構造と熱進化に関するイントロ的レビューを行った。まず今回の研究会における本発表の位置づけを示した。具体的には、内部構造と熱進化の研究は「かぜ＆つち」に分類されるものの、「創造」など他のテーマと密接に関わることを明確にした。その後、内部構造や熱進化の研究法の一般論を展開した。具体的には、現在の内部構造を制約するためには地球物理学的な観測が重要であること、熱進化を制約するためには地質学的な観測や理論的研究が重要であることを示した。その後、木星や土星の衛星を対象とした個別の議論を展開した。その際、本セッションが JUICE チーム後援ということもあり、巨大氷惑星に分類されるガニメデとタイタンに絞って議論した。ガニメデは、地球物理学的観測により、分化が特に進行したエンドメンバーとされている。地質学的な観測からは衛星が全球膨張を経験したと考えられるが、その原因はよく分かっていない。これに関して、鎌田らの研究グループでは初期分化における衛星膨張を研究していることを紹介した。タイタンはガニメデに近い大きさをもつ天体であるが、内部構造の不確定性は非常に大きい。最近になって潮汐ラブ数が大きく修正され、内部構造の見直しが進んでいることを紹介した。これらのことを踏まえ、内部構造と熱進化をより制約するにあたり、将来の地震学的観測の重要性やデータ解析における理論屋の積極的関与の重要性を指摘した。

Interior structure and thermal evolution of icy satellites in our Solar System

Shunichi Kamata
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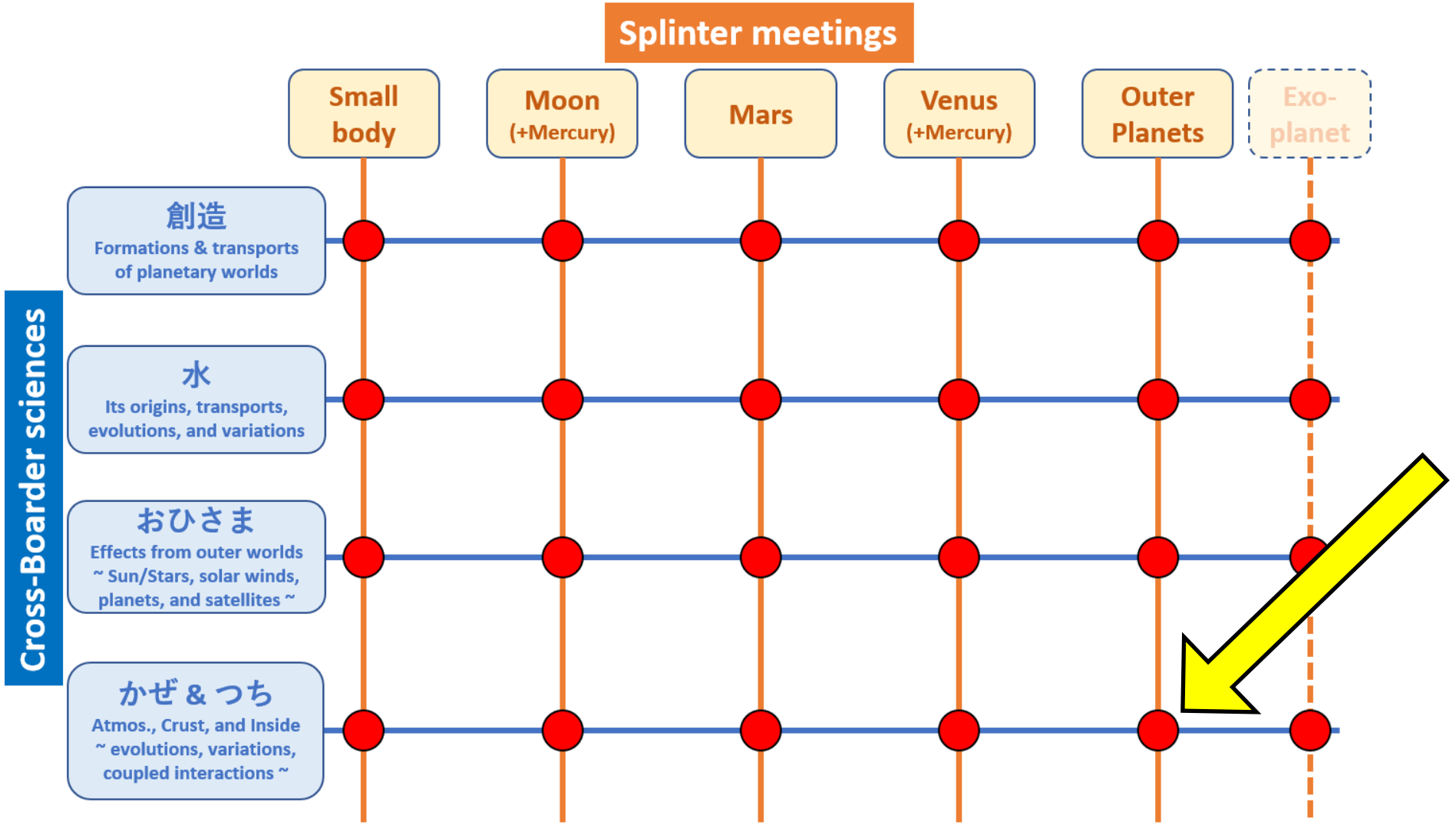
Focus points of the Symposium

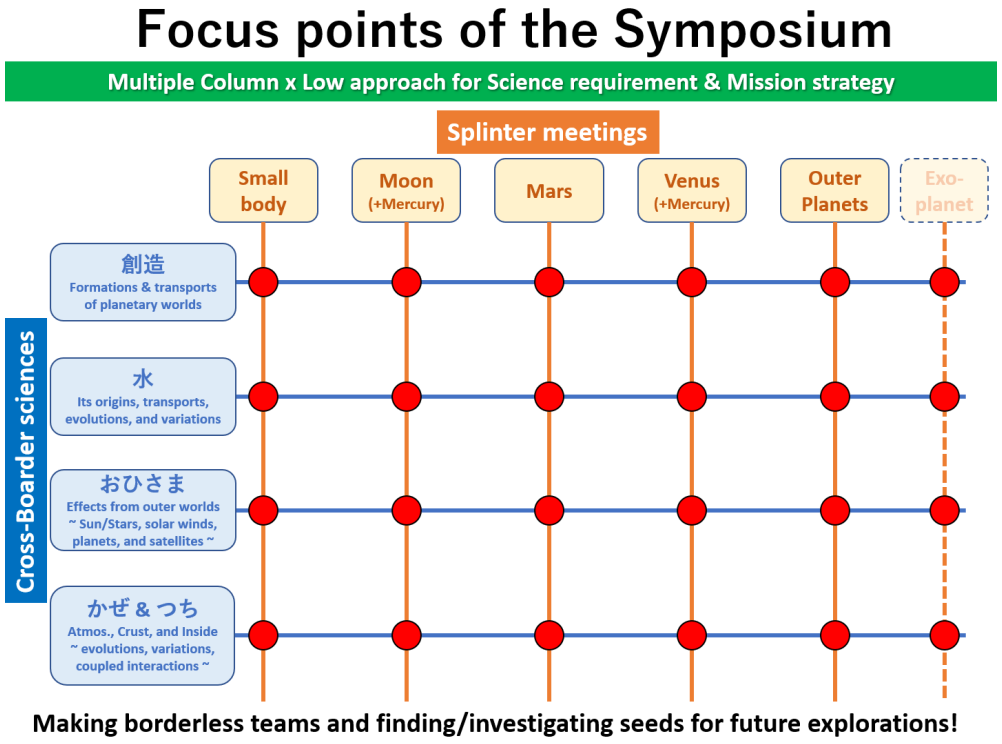
Multiple Column x Low approach for Science requirement & Mission strategy



Making borderless teams and finding/investigating seeds for future explorations!

Motivations, research impacts

- Formation ← **Bulk composition**
  - Ice/rock ratio, ice/ocean/rock compositions, …
- Water ← **Subsurface ocean**
  - Presence/absence, location, composition, evolution, …
- Outer worlds ← **Tidal & magnetic interactions**
  - Heating rate & orbital evolution rate
  - Induction (ocean) and/or intrinsic (core dynamo)

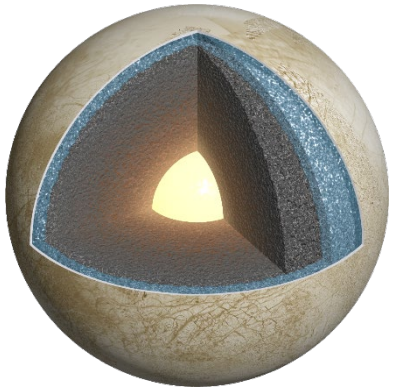


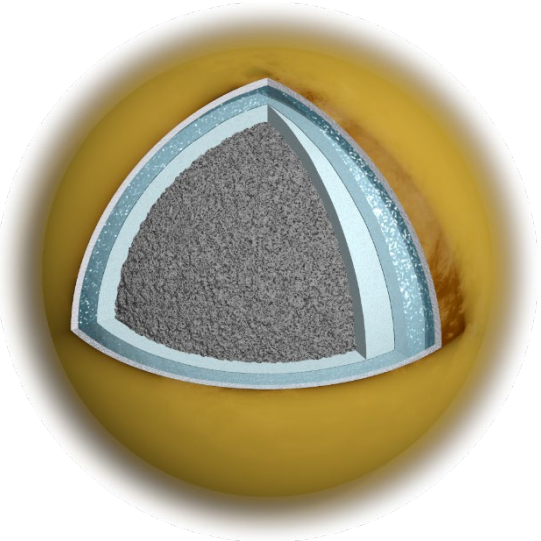
This talk

1. How do we estimate the current interior structure and its evolution?
   - Observations & analyses
   - Theory of evolution

2. What do we know (think) about the past and the present of icy satellites
   - Jovian system
   - Saturnian system

3. What should we do next for a better understanding of this (and related) subject?





Geophysical observations & analyses

V: Gravitational potential
Ψ: Magnetic potential
t: Time
r: Radial distance
ϕ: Latitude
λ: Longitude
G: Gravitational constant
M: Mass of the body
R: Radius of the body
n: Degree
m: Order
P_{nm}: Legendre Polynomials
$C_{nm}, S_{nm}\ g_{nm}\ h_{nm}$: Coefficients

- Field analyses using spherical harmonics
  1. Gravity field: $\boldsymbol{F}_{\mathrm{grav}} = -\boldsymbol{\nabla} V$

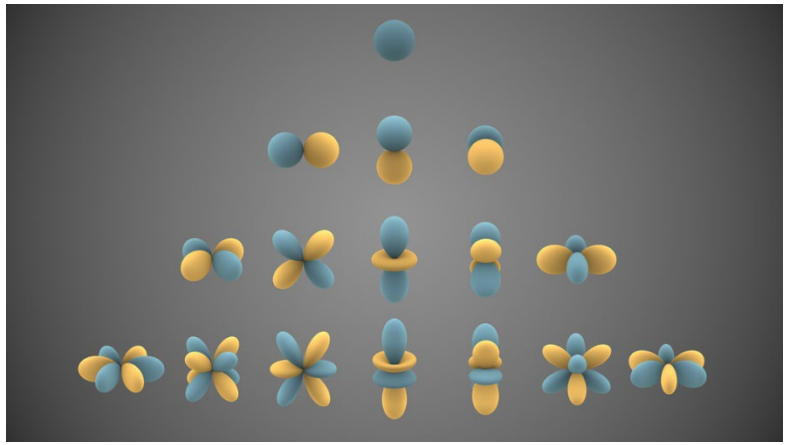
$$V(t,r,\theta,\varphi) = \frac{GM}{R}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1}(C_{nm}\cos m\varphi + S_{nm}\sin m\varphi)P_{nm}(\sin\theta)$$

     - Degree (n) 0, time-independent component → Mean density
     - $n = 2$, time-indep. comp. → Moment of inertia
     - $n = 2$, time-dep. comp. → Love number k_2

  2. Magnetic field: $\boldsymbol{B} = -\boldsymbol{\nabla}\Psi$

$$\Psi(t,r,\theta,\varphi) = R\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{n+1}(g_{nm}\cos m\varphi + h_{nm}\sin m\varphi)P_{nm}(\sin\theta)$$

     - $n = 1$ comp. (i.e., dipole) → Intrinsic field (dynamo)
     - Time-dep. component → Induction field (ocean)



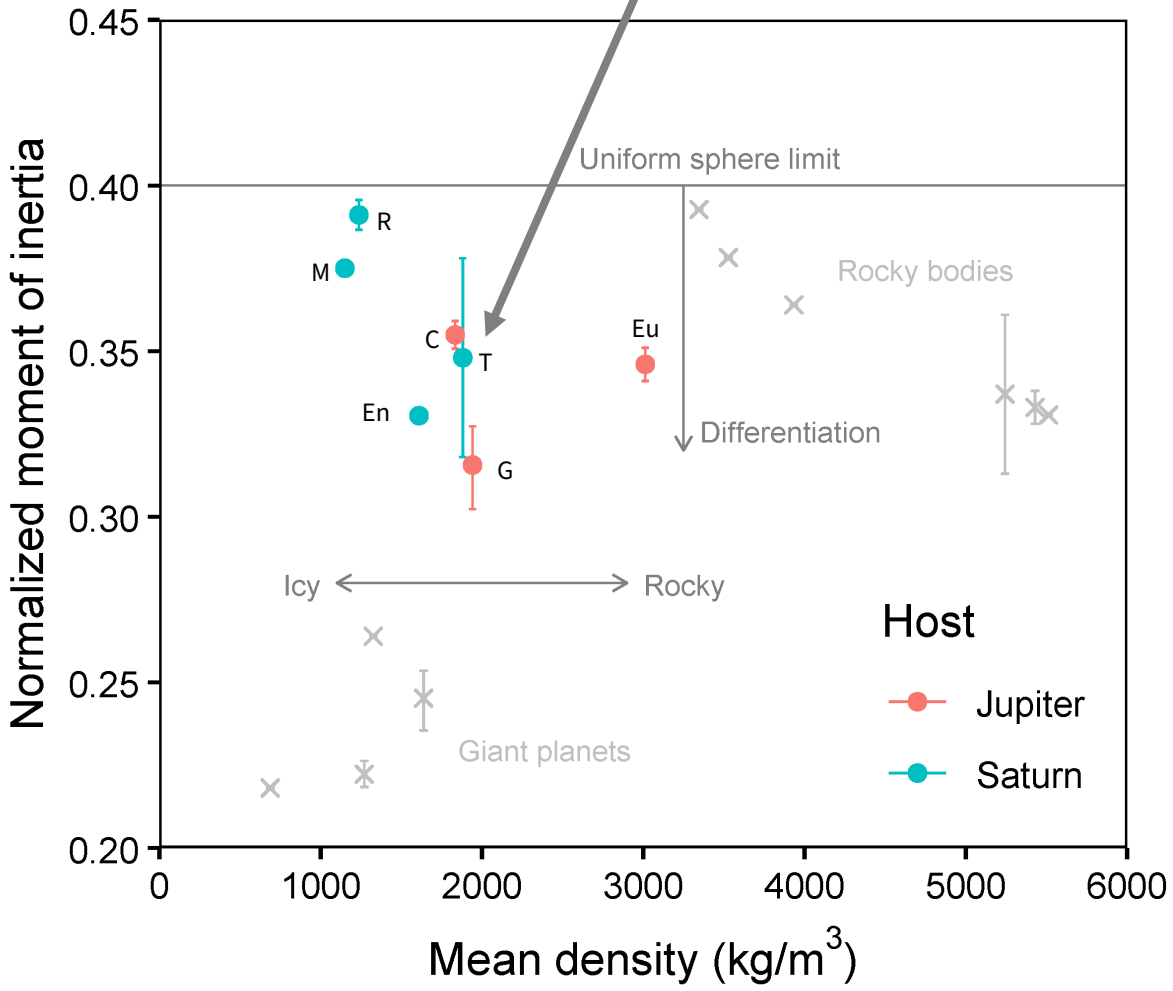
Note: High-degree terms contain information of shallow structures (i.e., crustal thickness, remnant magnetic field, …)

Selected results

Titan's gravity field [e.g., Goossens+ 24]

$C_{20} = -3.3089 \times 10^{-5}, C_{22} = 1.0385 \times 10^{-5}$

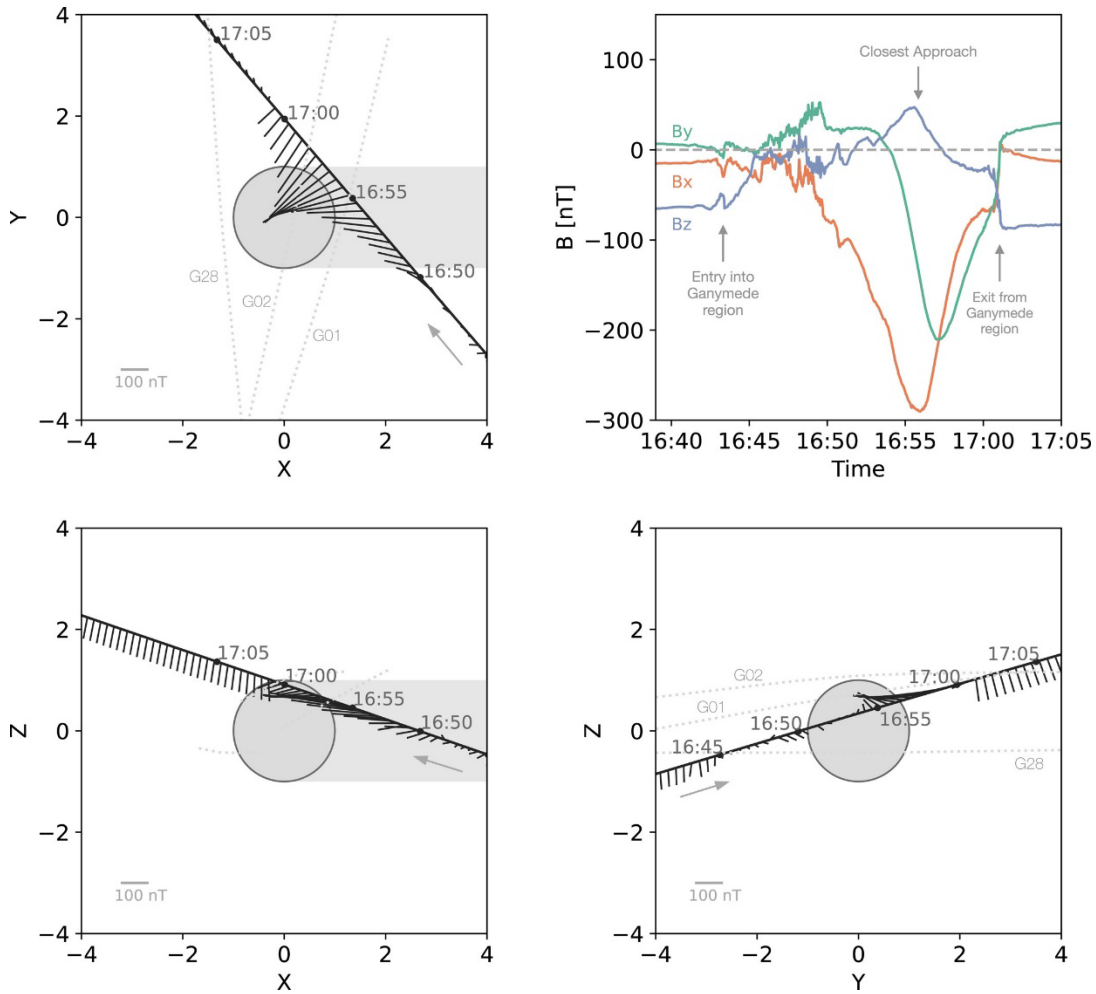
$k_2 = 0.375$



Ganymede's dipolar field [Weber+ 22]

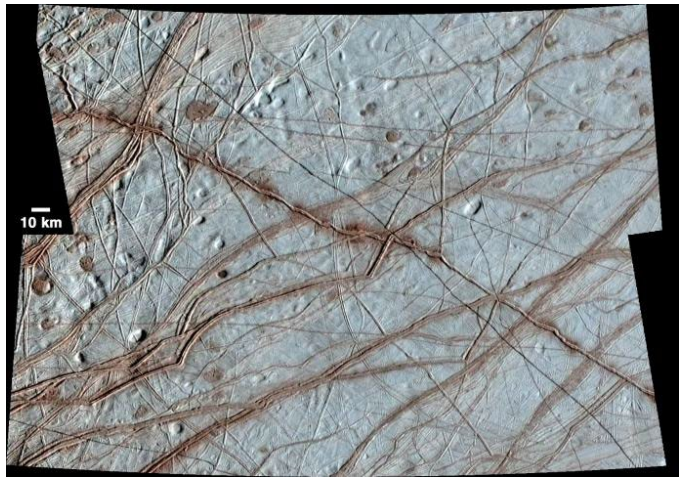
$g_{10} = -716.4,\ g_{11} = 56.0,\ h_{11} = 27.0$ [nT]

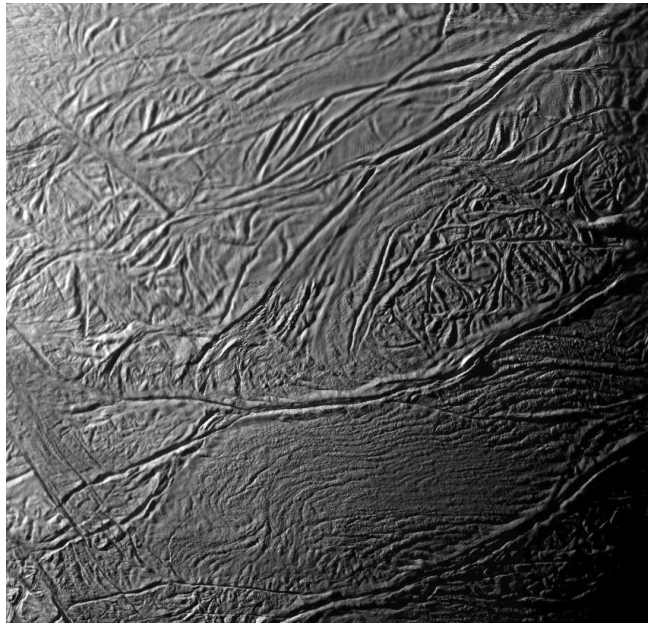
(Time-dep. comp. are not considered here)

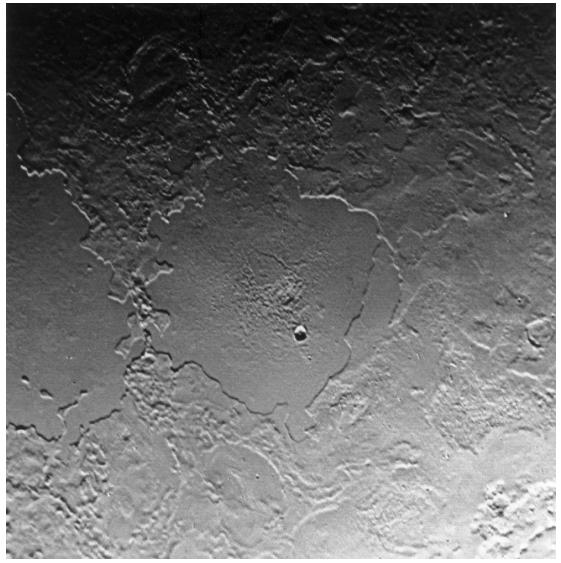


Geological observations & analyses

- Traces of evolution left on the surface
  1. Impact craters
     - Number density
     - Depth/diameter ratio
  2. Tectonic features (faults)
     - Types (normal, thrust, strike-slip)
     - Direction, length and height
     - Cross-cutting relation
  3. (Cryo-)Volcanic features
     - Smooth plains
     - Domes

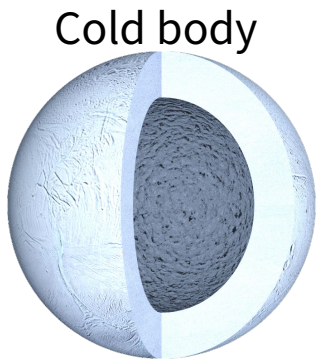


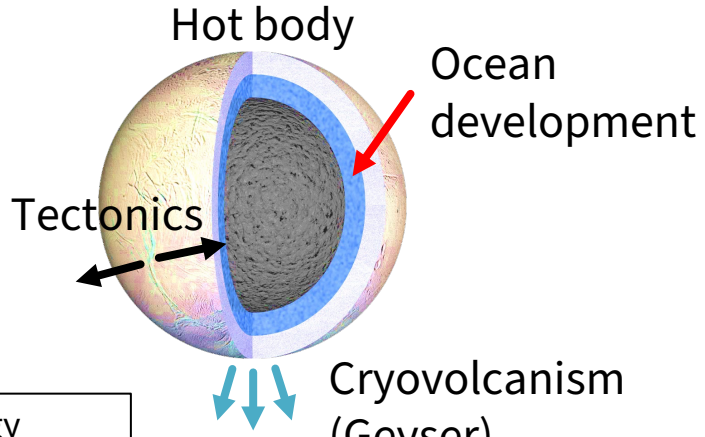




Theory of planetary evolution

- Heat drives planetary evolution
  - Nothing happens if it is(was) cold
  - Evolution occurs if it is(was) hot





- Critical issue is the energy balance

$$\frac{dE}{dt} = -\nabla \cdot \boldsymbol{q} + H$$

E: Energy
t: Time
$\boldsymbol{q}$: Heat flux
H: Heating rate

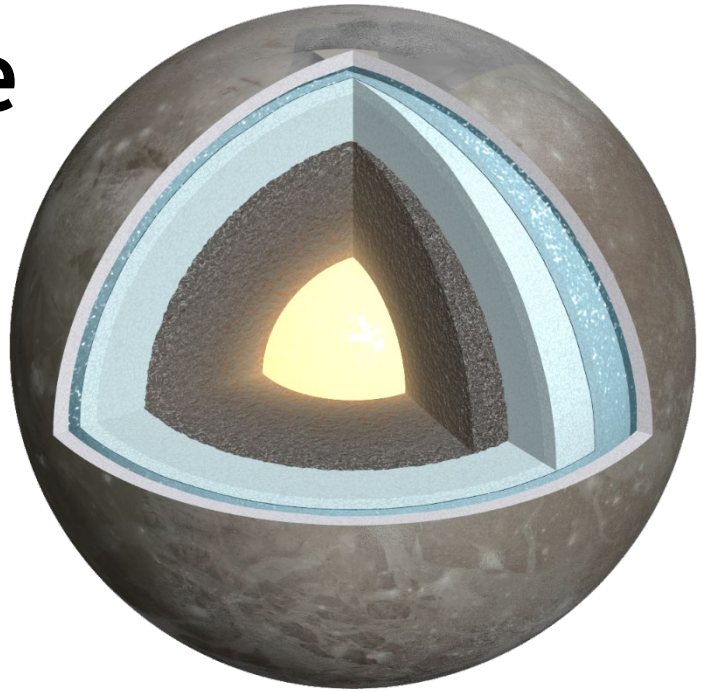
Energy change
- Temperature change
- Phase change
- Mechanical change, …

Transport (cooling)
- Conduction
- Convection
- Volcanism,…

Heating
- Radiogenic
- Tides
- Chemical reaction, …

- Equation itself is very simple, but each term is very complex and uncertain

Case 2: Ganymede



- Present
  - Dichotomy in geology
    - Heavily-faulted Bright Terrain
    - Heavily-cratered Dark Terrain
  - Most differentiated
  - Dynamo

- Evolution
  - Global Expansion at some point
    - Ocean freezing leads to a shrink because of HP ices
  - Cold formation + slow evolution? [Takahashi+ in prep.]
    - Expansion due to late differentiation
    - Recently activated dynamo?

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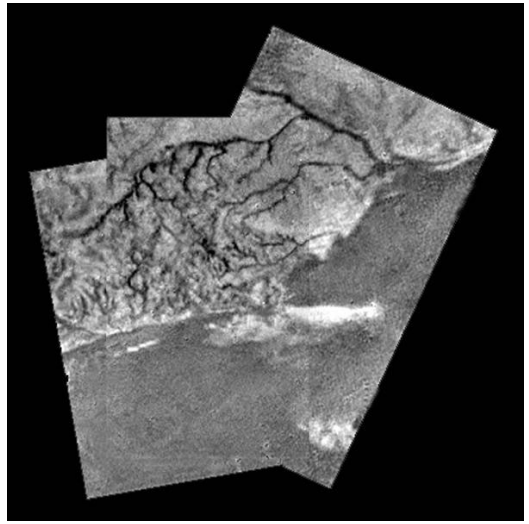
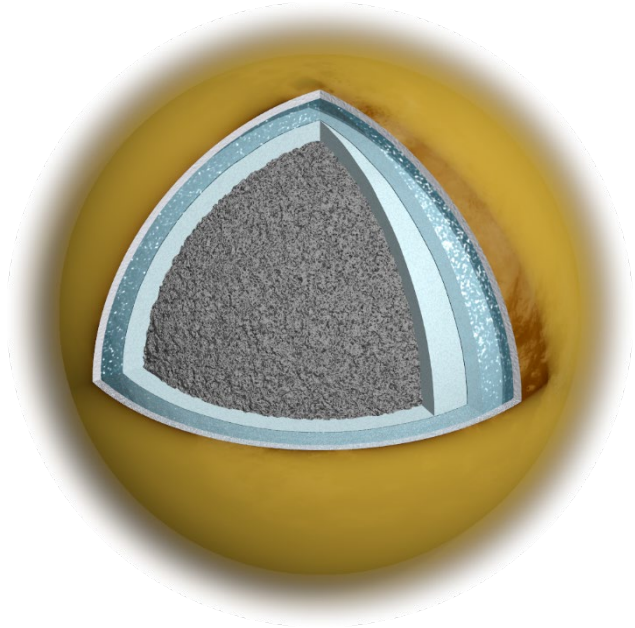
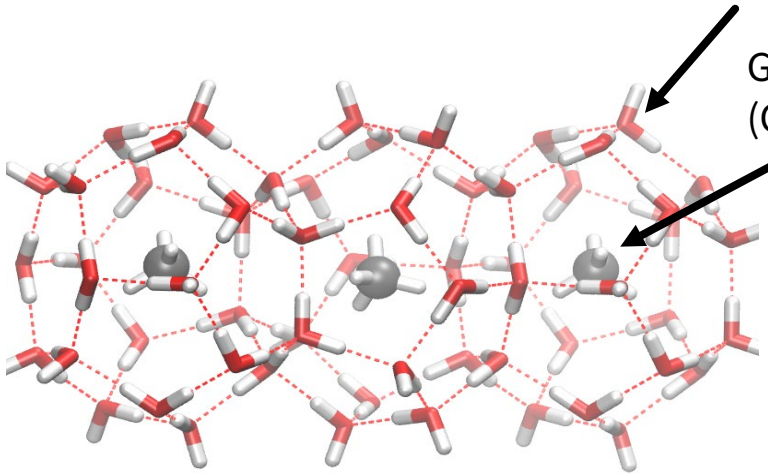
Case 5: Titan

- Present
  - Surface fluids erase traces of past internal activities
  - Maybe largely undifferentiated
- Evolution
  - Clathrates (gas-trapping ice) would play an important role (composition, thermal & mechanical states) [e.g., Schurmeier+ 24]
- Recent topic
  - Tidal Love number k_2 is reduced by 40%
    - 0.616 → 0.375 [Goossens+ 24]
      - Previous reports use wrong equations
    - Hyper-dense ocean is no longer supported



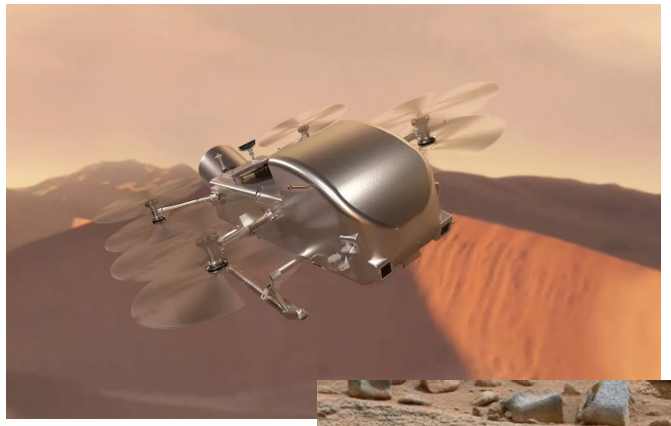




[NIST Clathrate Hydrate Physical Property Database]

Future

- Critical measurements
  - Seismology (particularly low freq.)
  - Heat flow
  - Ground truth on geol. evolution

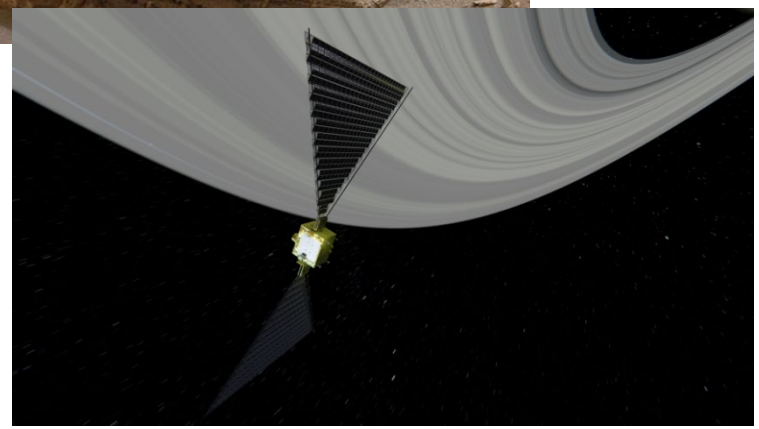


First seismic investigation of Titan by Dragonfly [NASA/JHUAPL/S. Gribben]

Sedimentary rock on Mars [NASA/JPL-Caltech/MSSS]

- Data analyses with reliable theory
  - Working with theoretical scientists is important
  - Development in theory is necessary

- Integration of knowledge
  - Physics, geology, chemistry, measurements, theory, …
  - Is team(s) sufficient? Or generalists?



Future outer Solar System exploration by JAXA [JAXA]

Summary

- Interior structure and thermal evolution are fundamental subjects related to various subjects

- Various observations provide constraints on them
  - Often not sufficient
  - Sometimes leading to wrong hypotheses

- Each satellite has its own unique features
  - Surface ages, degree of interior differentiation, heating mechanism, important materials, ..

- Observation, data analyses, theoretical developments are all necessary