Interior evolution of Galilean satellites

Shunichi Kamata[1] & Jun Kimura[2]

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The Galilean satellites, four major Jovian satellites, have distinctively different surfaces, implying their diverse histories. The exploration of the Galilean satellites by the Galileo mission provided data required to infer their current interior structures, which are important clues to understand their evolution. Based on such data, our understanding of the interior evolution of the Galilean satellites has been progressed. In this presentation, we briefly summarize what kinds of data are particularly important to estimate the current interior structure of a satellite and what we know today about the interior evolution of icy Galilean satellites. We also discuss what kinds of future studies are needed to advance our understanding of the interior evolution of Galilean satellites.

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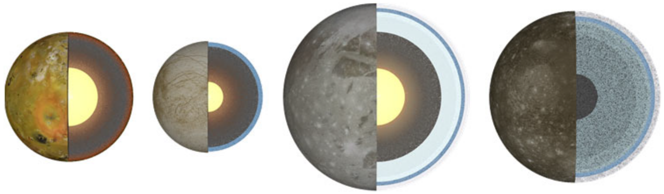
Interior Evolution of Galilean Satellites



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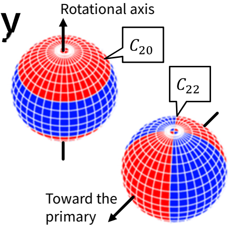
Evolution of the Interior Structure

- Questions
  1. How do we estimate the current interior structures and their evolutions?
     - Observation: Current state = the boundary condition
     - Theory: Physics that governs evolution
  2. What do we know now about the evolutions of the interior structures?
     - Geology, ocean, and magnetic field history of each satellite
     - Co-evolution of satellites
  3. What should we do next for a better understanding of this subject?

Galilean satellites (scaled)

Observation (1/2): Theory



1. Gravity field

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

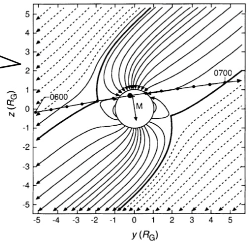
V: Potential
r: Radial dist.
ϕ: Latitude
λ: Longitude
R: Radius
G: Grav. Const.
M: Mass
n: Degree
m: Order
P_{nm}: Legendre Polynom.

- Degree 0: Mass (mean density)
- Degree 2
  - J_2 (= $-C_{20}$): Polar flattening
  - C_{22}: Equatorial flattening

} Moment of inertia

2. Magnetic field

- Dipolar field: Intrinsic (dynamo)
- Reduction of surrounding field: Induction
  - Satellites are embedded in a strong, time-varying magnetic field
  - (Electromagnetically) conductive layer, such a salty subsurface ocean, generates induced magnetic field



Magnetic field around Ganymede [Kivelson et al., 1996]

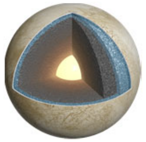
Observation (2/2): Results

		Io	Europa	Ganymede	Callisto
Imaging	Radius (km)	1821.6±0.5	1560.7±0.3	2631.2±1.7	2410.3±1.5
	Shape	Hydrostatic	Hydrostatic	Probably	Probably
Gravity field	Mean density (kg/m³)	3527.5±2.9	2989±4.6	1942±4.8	1834.4±3.4
	J2/C22 ratio	Measured	Assumed	Assumed	Assumed
	Moment of inertia	0.37824	0.346	0.3115	0.3549*
Magnetic field	Intrinsic	No	No	Yes	No
	Induced	Yes	Yes	Yes	Yes
	Plume	No	Yes	No	No
IR (mid-far)	Heat output (TW)	~100	?	?	?
Orbit	Period (days)	1.769	3.551	7.155	16.689
	Semimajor axis (km)	4.216 x 10^5	6.709 x 10^5	1.070 x 10^6	1.883 x 10^6
	Eccentricity	0.0041	0.0101	0.0006	0.007

* May be overestimated by ~10% [Gao & Stevenson, 2013]

[Anderson et al., 2001; Sohl et al., 2002; Tobie et al., 2003; Veeder et al., 2004; Schubert et al., 2004; Nimmo et al., 2007; Khurana et al., 2011; Roth et al., 2014; Jia et al., 2018; Arnold et al., 2019]

Inferred Current Interior Structure

	Io	Europa	Ganymede	Callisto
				
Ice shell	No	Yes	Yes	Yes
Subsurface ocean	No	Most likely	Probably	Probably
High-pressure ice	No	No	Most likely	Most likely
Silicate mantle/core	Yes	Yes	Most likely	Probably
Metallic iron core	Yes	Probably	Yes	Unlikely?
Other feature	Global magma ocean	Plume activity	Active dynamo	Ice-rock mixture?
Radiogenic heat (TW)	0.447	0.230	0.502	0.342

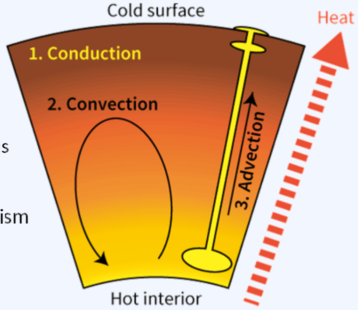
[Sohl et al., 2002; Tobie et al., 2003; Schubert et al., 2004; Kuskov & Kronrod, 2005; Khurana et al., 2011; Hussmann et al., 2015]

Physics of Evolution (1/3): Cooling vs. Heating

- Heat balance equation [e.g., Hussmann & Spohn, 2004; Melosh, 2011; Kamata, 2018]
  - $\rho C \frac{dT(r)}{dt} = -\left(\frac{1}{r^2}\frac{d}{dr}(q_{\mathrm{cond}} + q_{\mathrm{conv}}) + Q_{\mathrm{vol}} + \cdots\right) + (H_{\mathrm{rad}} + H_{\mathrm{tide}} + \cdots)$

ρ: Density
C: Specific heat
T: Temperature
t: time
r: Radial dist.
k: Conductivity
η: Viscosity
D: Layer thickness
g: Grav. acceleration
ΔT: Temperature drop
L: Latent heat
Q_e: Eruption rate

- Cooling (heat transportation)
  1. $q_{\mathrm{cond}}\ (= -k \cdot dT/dr)$: Conductive heat flux
     - Least effective, but is dominant near the surface
  2. $q_{\mathrm{conv}}(\eta(T), D, g, \cdots)$: Convective heat flux
     - More effective, but the layer needs to be less viscous
     - Thick shell is more convective
  3. $Q_{\mathrm{vol}}(\Delta T, L, Q_e, \cdots)$: Heat removed due to volcanism
     - Important only on Io



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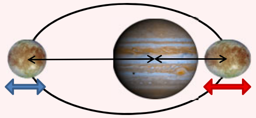
ρ: Density
C: Specific heat
T: Temperature
t: time
r: Radial dist.
C_i: Init. concentration
Q_i: Heat prod. rate
τ_i: Decay const.
η: Viscosity
e: Eccentricity
ω: Orbital freq.
$Q_{\mathrm{Primary/Satellite}}$: Tidal quality factor

- Heating (long-term heat produciton)
  1. $H_{\mathrm{rad}}\ (= \sum_{i=\mathrm{U,Th,K}} C_i Q_i \exp(-t/\tau_i))$: Radiogenic heating
     - Depends on the mass of rocky mantle/core
  2. $H_{\mathrm{tide}}(\eta(T), e(t), \omega(t), \cdots)$: Tidal heating
     - Depends on the interior structure ($\eta(T(r,t))$)
     - Depends on orbital properties (e, ω)
       - $\frac{de}{dt} = C_1(Q_{\mathrm{Primary}}, \omega) \cdot e^2 (1 - C_2(Q_{\mathrm{Primary}}, Q_{\mathrm{Satellite}}) \cdot e^2)$
         - Depends on the interior structure

         → **Thermal-orbital coupled evolution**

Radioactive decay of UO_2

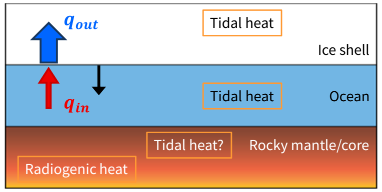
https://www.youtube.com/watch?v=ZiscokCGOhs



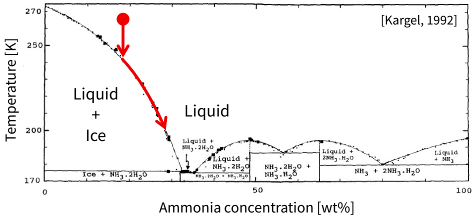
Physics of Evolution (3/3): Phase Change

1. Heat flux balance at the base of the ice [e.g., Hussmann & Spohn, 2004]
   - $\rho_{\mathrm{ice}} L \frac{dD}{dt} = q_{\mathrm{out}} - q_{\mathrm{in}}$
     - q_{out}: Outgoing heat flux to above
       - Heat transfer in the ice shell
     - q_{in}: Incoming heat flux from below
       - Heat from the core and ocean

ρ: Density
L: Latent heat
D: Layer thickness
t: time

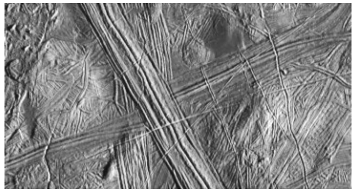


2. Chemical composition of the ocean
   - Ammonia and/or salts
   - Depresses melting point (“antifreeze”)
   - Concentrations increases with freezing

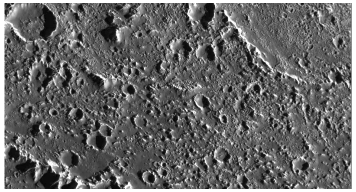


Current Knowledge (1/4): Geologic Evolution

- **Europa: Currently active**
  - Small number of impact craters
  - Plate tectonics: Spreading and subducting
  - Tide-related fractures: Thin ice shell over an ocean
- **Ganymede: Previously active**
  - Diversity in crater density: Dark vs. bright terrains
  - Faults and bands: Global expansion
  - Tidal heating in the past
- **Callisto: Inactive**
  - Crater-dominated surface
  - Sublimation and deposition (insolation)



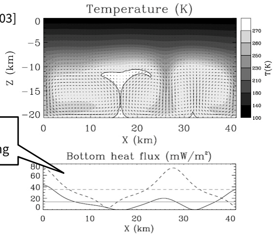
(Top) Europa, ~12N 268W, ~80 km width (NASA/JPL/ASU).
(Bottom) Callisto, ~27N 142W, ~80 km width (NASA/JPL).



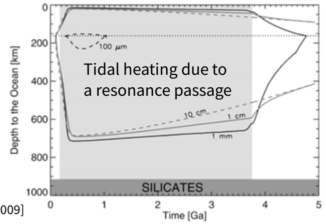
Current Knowledge (2/4): Ocean Maintenance

- **Europa: Plausible** (>~100 km thick)
  - Tidal heating is sufficient [e.g., Hussmann et al., 2002]
    - Ice shell heating reduces heat flux from the ocean
- **Ganymede & Callisto: Difficult**
  - Tidal heating is currently negligible [e.g., Showman & Malhotra, 1997]
  - Ice shell is thick and thus convective [e.g., Barr et al., 2004]
  - Solutions
    1. Strong heating in the past [e.g., Showman & Malhotra, 1997]
    2. Antifreeze materials [e.g., Kargel, 1998]
    3. Highly viscous ice (large grain size?) [e.g., Bland et al., 2009]

[Tobie et al., 2003]



Solid: With tidal heating
Dashed: Without tidal heating

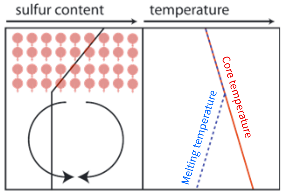


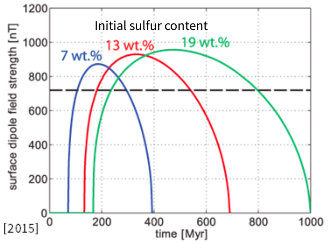
Tidal heating due to a resonance passage

[Bland et al., 2009]

Current Knowledge (3/4): Dynamo on Ganymede

- Dynamo requires convection in a metallic core
  - Compositional convection is important [Hauck et al., 2006]
- Snow of Fe falls and melts at depth, rather than the inner core growth from the bottom
  - No inner core at present? [Rückriemen et al., 2015]
- **Recent and short dynamo activity**
  - Radiogenically heated early rocky mantle is too hot to extract heat from the core [e.g., Kimura et al., 2009]
  - Chemical gradient remains small only for < 0.8 Gyr [Rückriemen et al., 2015]
  - Late core formation is preferred [Bland et al., 2008]



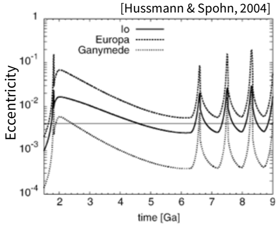


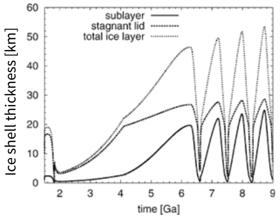
Adapted from Rückriemen et al. [2015]

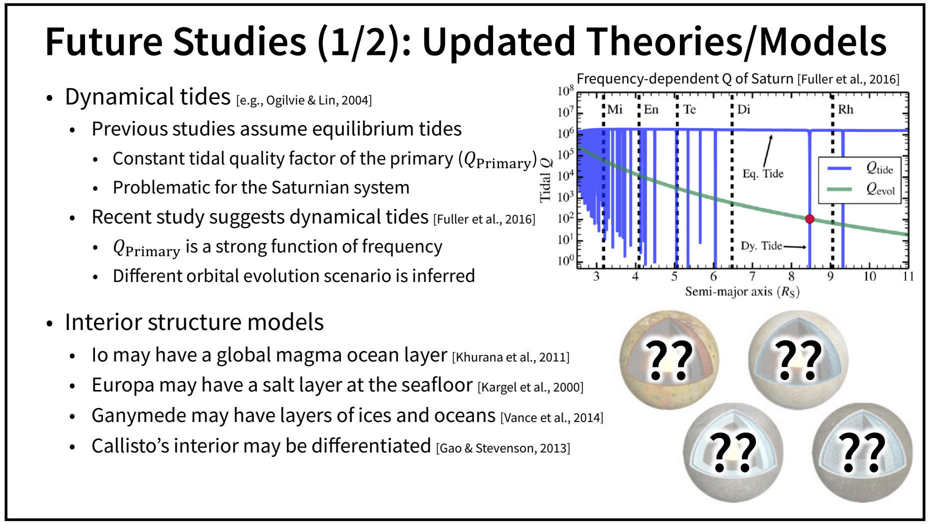
Current Knowledge (4/4): Co-Evolution

- Laplace resonance
  - Orbital period of Io : Europa : Ganymede = 1 : 2 : 4
  - Eccentricity can be increased due to resonance
- **Oscillatory behavior may appear**
  - Typical example of strong thermal-orbital coupled evolution [e.g., Ojakangas & Stevenson, 1986]
    - (High-*T*, high-*e*) *e* and $H_{\rm tide}$ decrease → Heat loss overcomes heat production, decreasing *T* → (Low-*T*, low-*e*) *e* and $H_{\rm tide}$ increase → Heat production overcomes heat loss → …
- For Ganymede, a different resonance in the past may be important [e.g., Showman et al., 1997]

[Hussmann & Spohn, 2004]





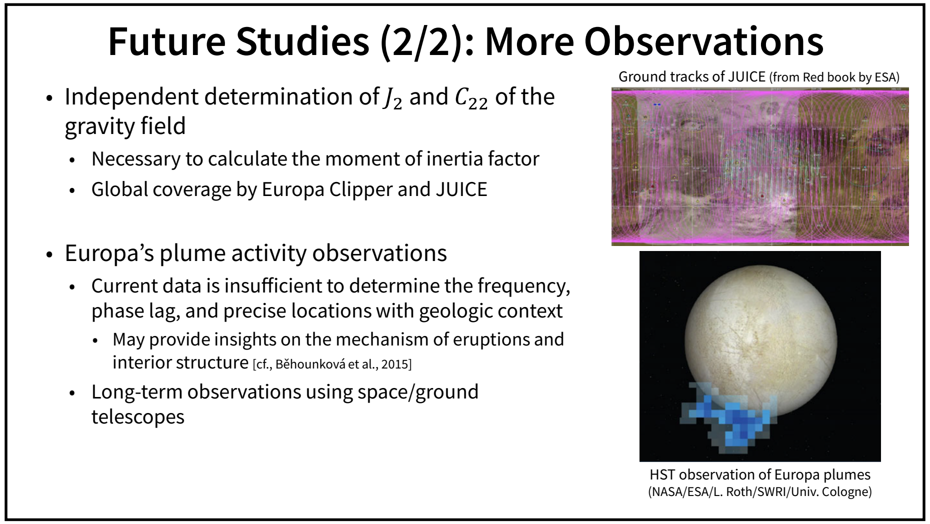


Future Studies (1/2): Updated Theories/Models

- Dynamical tides [e.g., Ogilvie & Lin, 2004]
  - Previous studies assume equilibrium tides
    - Constant tidal quality factor of the primary (Q_{Primary})
    - Problematic for the Saturnian system
  - Recent study suggests dynamical tides [Fuller et al., 2016]
    - Q_{Primary} is a strong function of frequency
    - Different orbital evolution scenario is inferred

Frequency-dependent Q of Saturn [Fuller et al., 2016]

- Interior structure models
  - Io may have a global magma ocean layer [Khurana et al., 2011]
  - Europa may have a salt layer at the seafloor [Kargel et al., 2000]
  - Ganymede may have layers of ices and oceans [Vance et al., 2014]
  - Callisto's interior may be differentiated [Gao & Stevenson, 2013]



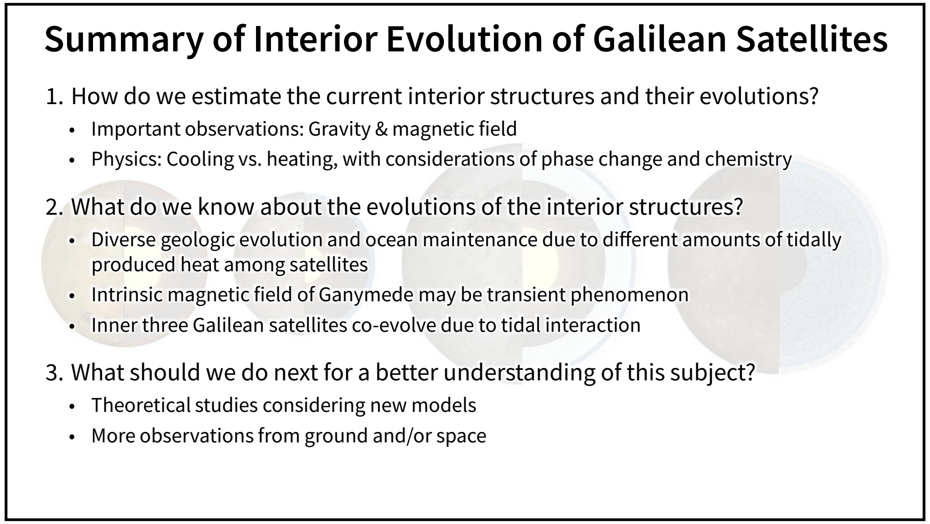
Future Studies (2/2): More Observations

- Independent determination of J_2 and C_{22} of the gravity field
  - Necessary to calculate the moment of inertia factor
  - Global coverage by Europa Clipper and JUICE

Ground tracks of JUICE (from Red book by ESA)

- Europa's plume activity observations
  - Current data is insufficient to determine the frequency, phase lag, and precise locations with geologic context
    - May provide insights on the mechanism of eruptions and interior structure [cf., Běhounková et al., 2015]
  - Long-term observations using space/ground telescopes

HST observation of Europa plumes
(NASA/ESA/L. Roth/SWRI/Univ. Cologne)



Summary of Interior Evolution of Galilean Satellites

1. How do we estimate the current interior structures and their evolutions?
   - Important observations: Gravity & magnetic field
   - Physics: Cooling vs. heating, with considerations of phase change and chemistry
2. What do we know about the evolutions of the interior structures?
   - Diverse geologic evolution and ocean maintenance due to different amounts of tidally produced heat among satellites
   - Intrinsic magnetic field of Ganymede may be transient phenomenon
   - Inner three Galilean satellites co-evolve due to tidal interaction
3. What should we do next for a better understanding of this subject?
   - Theoretical studies considering new models
   - More observations from ground and/or space