Current understandings and future perspectives for research of icy moons

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Is there a life elsewhere in the universe? Pursuing this question is a fundamental part for human beings, and a clue to the answer of this question may be found on the icy moons around giant planets. After magnificent achievements of the Cassini, Galileo and Voyager spacecraft missions, the existence of a thick liquid water layer underneath solid ice crusts with various icy tectonic features has been inferred for several icy moons. Such liquid layers are now understood as subsurface oceans. To date, the evidence for oceans is not fully conclusive and mainly based on electro-magnetic induction signals, surface morphology and thermal modeling. In addition, hydrated salts on surface and water pluming including non-water volatiles and organics support to exist the subsurface ocean and the environment to emerge and sustain life there.

In the following, I review our current knowledge for the icy moons in terms of interior, surface tectonics, chemical composition and habitability, and also present possible science research targets and exploration missions in future. On each giant planet system, only one or two explorations have been performed to date. No spacecraft explorations orbiting icy moons have not yet been achieved and there are still many big issues to be solved for direct investigation of extra-terrestrial life.

衛星研究の現状と将来展望

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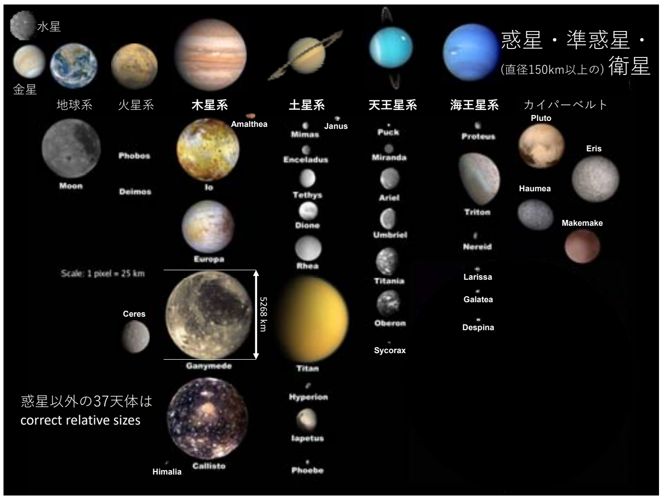
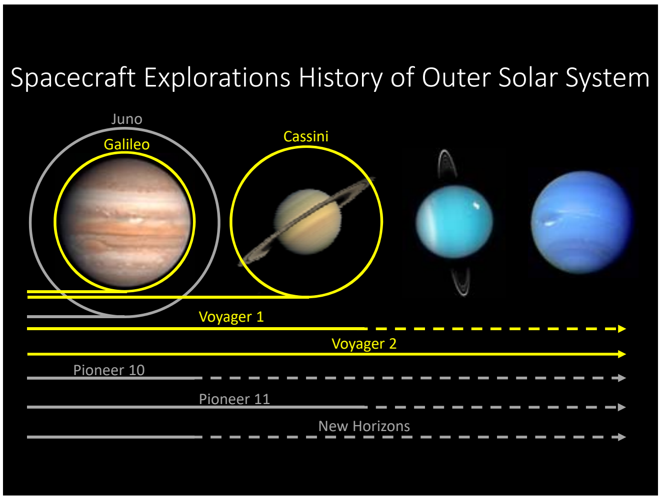
惑星圏研究会＠東北大学 28th Feb., 2018





Science of icy moons

Interior
- Ocean: depth, thick, composition
- Degree and timing of layering
- Type of “Rock”

Atmo/Magnetosphere
- (Tomoki-san’s & Shimizu-san’s talk)
- When magnetosphere formed?
- Chemical reactions (Titan)

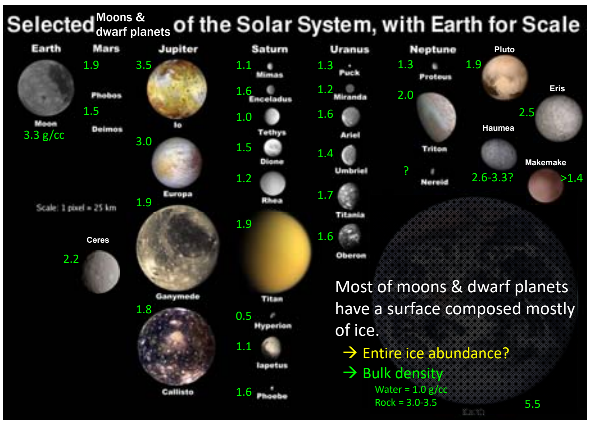
Habitability

Tectonics
- Origin of crustal stress
- Ice rheology
- Subduction/material transfer
- Geologic age

Composition
- Identification of organics
- Primordial? Delivered?
- Oxidants/Reductants flux
- Role of clathrates

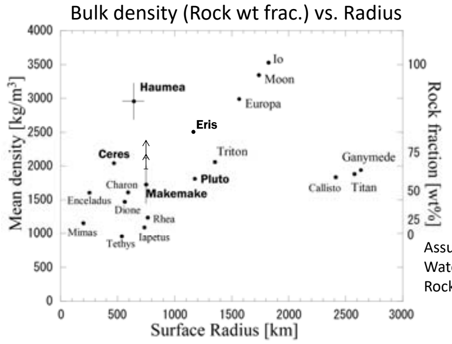
Interior

- Bulk density! (Radius & mass)
- Geodetic measurements
  - Global shape, Gravity field
    - Tidal responses (deformation, libration, obliquity)
    - Moment of Inertia
- Electro-Magnetic responses
  - Inductive M-field, Aurora
- Radar/Radio wave
- Plume dynamics
- Seismological measurements



How can we know about ice abundance (ice/rock ratio)?

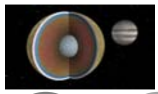
Bulk density (Rock wt frac.) vs. Radius

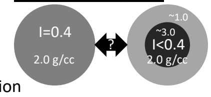


Assuming:
Water = 1.0 g/cc
Rock = 3.5

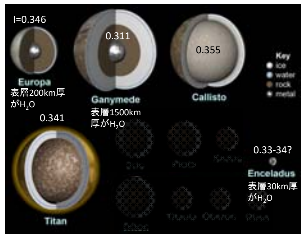
Interior

- Bulk density! (Radius and mass)
- Geodetic measurements
  - Global shape, Gravity field
    - Tidal responses (deformation, libration, obliquity)
      → large response = soft interior (e.g., ocean)
    - Moment of Inertia
      → Small MoI = high deg of mass concentration



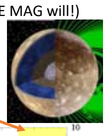


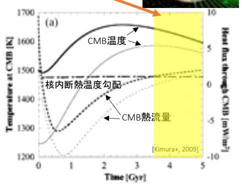
- Electro-Magnetic responses
  - Inductive magnetic field, Aurora
  → int. conductivity (e.g., salty ocean)
- Radar/Radio wave
- Plume dynamics
- Seismological measurements



Magnetic field

- Inductive field (Eu, Ga, Ca), depends on…
  - Primary field changing and subsurface ocean properties; depth, thickness and conductivity (Galileo MAG couldn't discern, but JUICE MAG will!)
- Metallic core driven field (Ga)
  - Convection in the molten core : recently induced?
  - When the core has been formed?
    - Accretional heat is insufficient (cold start).
    - If the core has a low eutectic point (e.g., FeS-Fe_3O_4, 1250 K), only radiogenic heat could form the core later (Kimura in prep.).
- How to know the timing of core formation and of starting dynamo?
  - e.g., Irradiated alteration signature on surface? (Tomoki-san's talk)

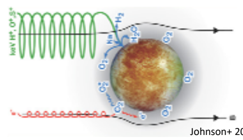




Eu=Europa, Ga=Ganymede, Ca=Callisto

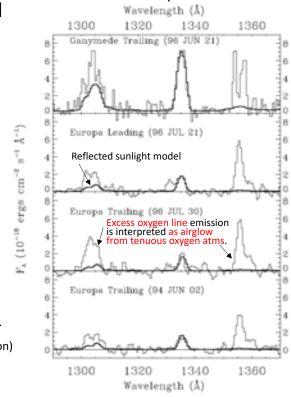
Atmosphere/ionosphere

- Thin, radiolytically/thermally-formed
  - Eu (O_2, 0.1uPa), Ga (O_2, 1uPa), Ca (CO_2, 0.8uPa), Rh (O_2, CO_2), Di (CO_2), Tt (CO_2)



- Thin, volcanically-formed
  - Io (SO_2, 0.1u-0.1mPa), En (H_2O), Tr (N_2, 1Pa)
- Thick, Earth-like (Titan)
  - 1.45 atm@surface, N_2 (97%), CH_4 (2.7%), H_2 (0.1%), hydrocarbons, tholins, lack of noble gases.
  - Climate (CH_4-C_2H_6-circulation: cloud, rain and lake, season)

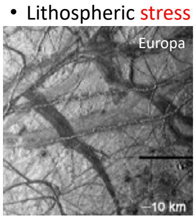
HST G140L spectra Hall+ 1998



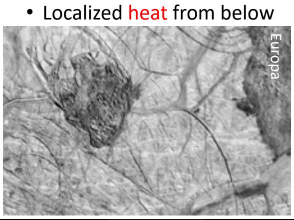
En=Enceladus, Rh=Rhea, Di=Dione, Tt=Titania, Tr=Triton

Surface Morphology/Tectonics

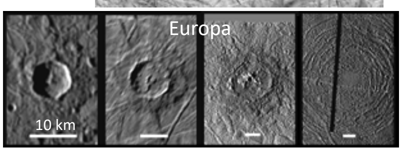
- Linear deformation:
  crack, ridge, fault, band, groove…
  - Lithospheric stress



- Spotted deformation:
  chaos, macula, lenticula…
  - Localized heat from below



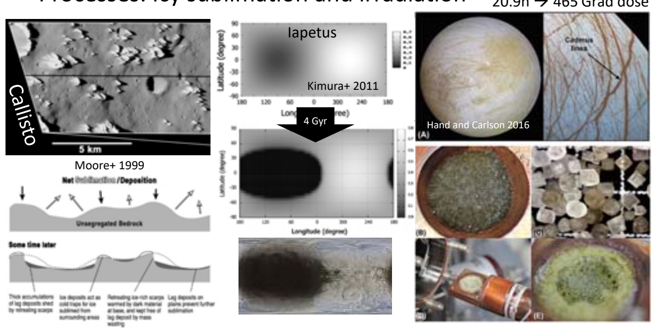
- Impact crater:
  central peak/pit, rampart, multi-ring, palimpsest…



Coloring agent and process

- Agents: non-H_2O compounds
  Rocks, organics, salts(?), acids(?)…
- Processes: Icy sublimation and irradiation

NaCl: 10 keV electrons,
20.9h → 465 Grad dose

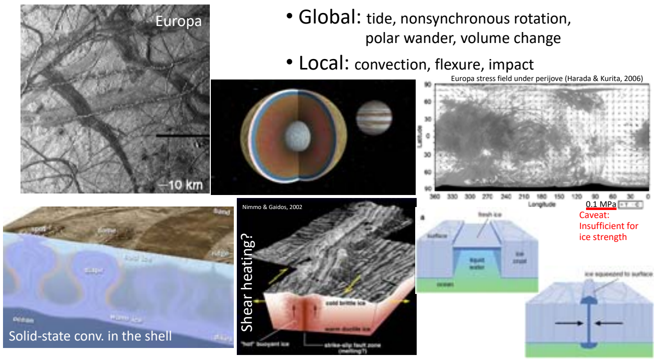


Surface Morphology/Tectonics

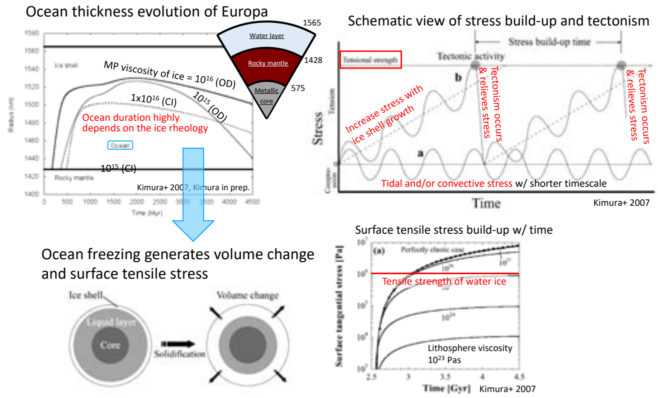
- Linear deformation: crack, ridge, fault, band, groove…
  - Lithospheric stress → stress source & ice shell thickness/rheology

unknown

- Global: tide, nonsynchronous rotation, polar wander, volume change
- Local: convection, flexure, impact

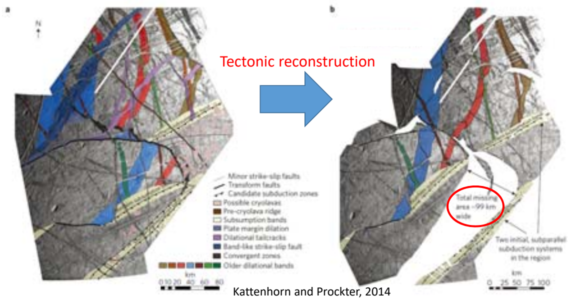


How drive surface tectonics



Icy Plate Tectonics?

- Missing surface area to balance the observed extension
- Transporting surface materials (e.g., irradiated-formed oxidants) in deep?



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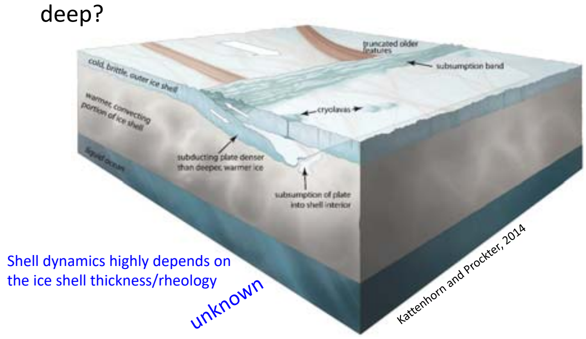


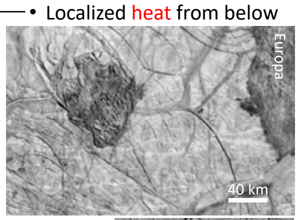
Surface Morphology/Tectonics

- Spotted deformation: chaos, macula, lenticula…
  - Localized heat from below

Structure and dynamics of the ice shell

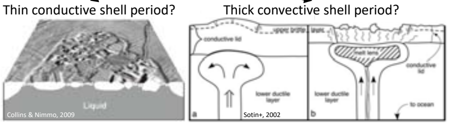
- Solid-state ice convection
- Shallow ocean
- Melt pocket in the shell

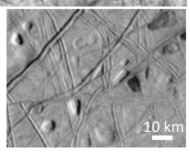
Depends on interior evolution & Ice shell thickness changing



Thin conductive shell period?

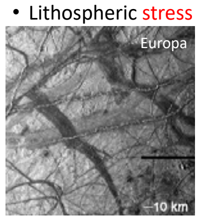
Thick convective shell period?





Surface Morphology/Tectonics

- Linear deformation: crack, ridge, fault, band, groove…
  - Lithospheric stress



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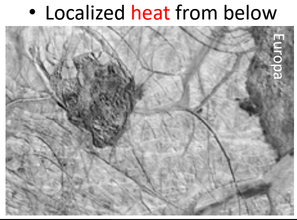
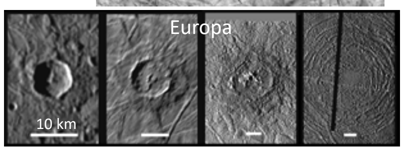
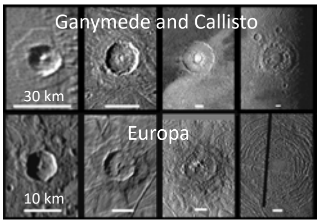


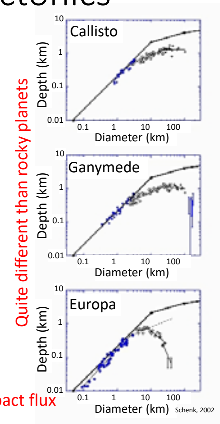
- Impact crater: central peak/pit, rampart, multi-ring, palimpsest…



Surface Morphology/Tectonics

- Impact Crater: central peak/pit, rampart, multi-ring, palimpsest…
  - Size-depth rel.: larger craters penetrate deeper
    → Reflects heat flux, ice shell thickness and rheology mainly when the crater was formed.





  - Size-freq. distribution: surface age estimation
    → Large ambiguity (~Gyr) : low res. image & unk. impact flux

Cratering rates and estimated age are highly ambiguous

Projectiles population based on Eu & Ga's CSFD | [km^{-2} yr^{-1}] | Projectiles population based on Triton's CSFD | Smith+ 1981 | Halley-type + Long-period comet

Saturnian moons	Cratering rates $\dot{C}_A(>10)$	$\dot{C}_B(>10)$	$\dot{C}_S(>10)$	$\dot{C}_{NIC}(>10)$	Cratering times τ_A	τ_B
Mimas	$5.6 \cdot 10^{-14}$	$5.0 \cdot 10^{-13}$	$1.6 \cdot 10^{-14}$	$5.6 \cdot 10^{-16}$	80	17
Enceladus	$3.7 \cdot 10^{-14}$	$2.8 \cdot 10^{-13}$	$1.0 \cdot 10^{-14}$	$4.2 \cdot 10^{-16}$	80	19
Tethys	$2.6 \cdot 10^{-14}$	$1.8 \cdot 10^{-13}$	$4.3 \cdot 10^{-15}$	$2.8 \cdot 10^{-16}$	25	6.5
Dione	$1.7 \cdot 10^{-14}$	$1.0 \cdot 10^{-13}$	$2.7 \cdot 10^{-15}$	$2.2 \cdot 10^{-16}$	34	10
Rhea	$1.1 \cdot 10^{-14}$	$6.2 \cdot 10^{-13}$	$1.5 \cdot 10^{-15}$	$1.6 \cdot 10^{-16}$	29	9
Titan	$3.4 \cdot 10^{-15}$	$1.4 \cdot 10^{-14}$	$1.3 \cdot 10^{-15}$	$9.0 \cdot 10^{-17}$	9	4
Hyperion	$7.0 \cdot 10^{-14}$	$6.2 \cdot 10^{-14}$	$1.8 \cdot 10^{-15}$	$2.3 \cdot 10^{-16}$	1,400	300
Iapetus	$1.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-15}$	$7.9 \cdot 10^{-16}$	$1.1 \cdot 10^{-16}$	380	180
Phoebe	$3.4 \cdot 10^{-16}$	$1.4 \cdot 10^{-15}$	$1.3 \cdot 10^{-15}$	$1.2 \cdot 10^{-16}$	54,000	2,400

Dones+ 2009

Cratering rates could be changed >10 times because of unknown population of projectiles to form crater with D>10km

Table 19.3 Terrain ages in Gyr Dones+ 2009

Satellite	D ≥ 5 km A	D ≥ 5 km B	D ≥ 10 km A	D ≥ 10 km B
Mimas	4.39	0.75	4.35	1.33
Tethys	4.56	1.66	4.44	2.10
Odysseus basin	–	–	3.76	1.06
Dione – cp	4.56	2.60	4.56	3.22
Dione – sp	4.55	1.97	4.43	1.96
Evander basin	3.62	0.60	3.61	1.00
Rhea – cp	4.56	3.05	4.56	3.67
Rhea – sp	–	–	4.48	2.47

Estimated ages have a great uncertainty (e.g., Mimas' age ~4.4 Gyr? or 0.75 Gyr?).

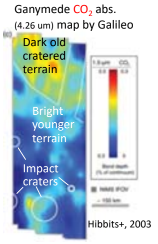
Need to know a population of ecliptic comets (e.g., by impact flash of Giant Planets?).

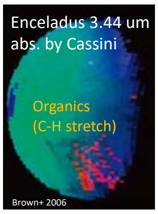
CSFD=Cater Size-Frequency Distribution

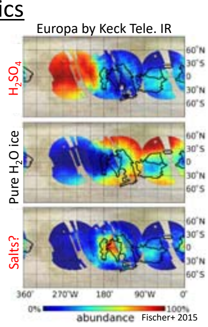
Chemical composition

- Constraints: Bulk density, IR/UV reflectance, plume analysis
  - Major: H_2O and Rock (CI-chondritic? → should be confirmed by future Trojan expl.)
  - Minor: no-H_2O ices, Salts, Acids, Organics

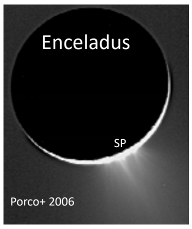
CO_2, SO_2, CH_4, NH_3, N_2, CO | $MgSO_4$, Na_2SO_4 | H_2SO_4 | C_xH_y, H_2CO, CH_3CHO, CH_3OH, HCN







Water +α plume(s)

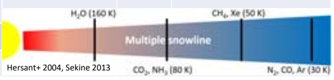


- ~100 indv. jets in some cases turn on/off
  - no systematic relation to orbital phase
- ~1 km/s (vapor), ~10s m/s (grain), ~ 100 kg/s
- Comet-like compositions
  - Gas: H_2O, CO_2, CH_4, NH_3, organics
  - Solid: H_2O, NaCl, carbonates, silica

- 3~4 jets in some cases turn on/off
- ~ 1 km/s, ~ 500 kg/s/plume
  - Not all observations could detect.
  - Likely to appear at apocenter? Tidally controlled?
- Detected only H_2O (only by UV obs)

Volatile composition reflects a nebula temperature?

Planets	Moons	non-H_2O volatiles	Salts	Acids	Organics
Jupiter	Europa	SO_2	$MgSO_4$, Na_2SO_4	H_2SO_4	
	Ganymede	CO_2, SO_2	$MgSO_4$, Na_2SO_4		
	Callisto	CO_2, SO_2	$MgSO_4$?		
Saturn	Enceladus	CO_2, CH_4, NH_3			C_xH_y, H_2CO, HCN, CH_3CHO, CH_3OH
	Titan	CH_4, NH_3, CO_2, N_2, CO			C_xH_y, C_3HN, C_2N_2, PAH
	Others	CO_2			
Uranus	M, A, U, T, O	CO_2			
Neptune	Triton	CO_2, CH_4, NH_3, N_2, CO			

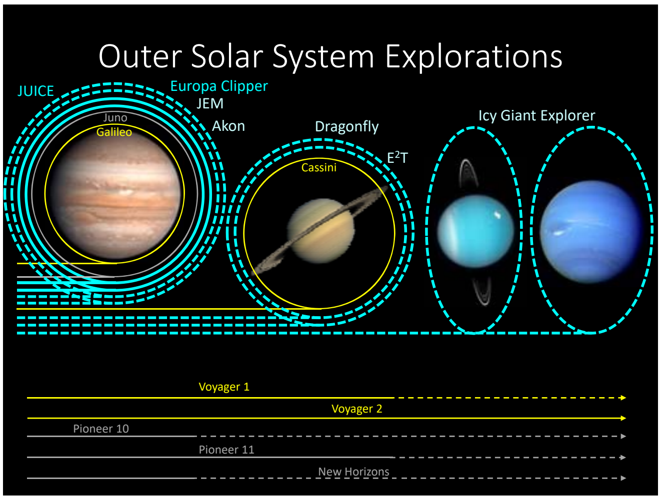


Toward understanding the Solar nebula,
- Radial variation/gradient of volatiles in the Solar System
  - Comparing plume compositions, e.g., Europa's and Enceladus'
  - Comparing the volatiles on C-type asteroid (Hayabusa-2), Phobos/Deimos (MMX) and Trojans (Solar-Sail)

Habitability

Planets	Moons	Energy	Composition	Solvent
Jupiter	Europa	Tidal, Radiogenic	Sulfate/Acid No organics detected	Water ocean (E-M rsp)
	Ganymede	Tidal (?), Radiogenic	Sulfate No organics detected	Water ocean (E-M rsp)
	Callisto	Radiogenic	Sulfate No organics detected	Water ocean (E-M rsp)
Saturn	Enceladus	Tidal (?)	CHON (SP?)	Water ocean (libration)
	Titan	Radiogenic, UV (atmsp)	CHON (SP?)	Lq-methane, ethane
Uranus	M, A, U, T, O	?	? No organics detected	?
Neptune	Triton	Tidal, Radiogenic	? No organics detected	?

Key questions for the next step,
- Energy: Thermal evolution coupled w/ orbial evolution.
- Composition: Identification of organics (SPONCH), which are primordial? or delivered? Oxidants/Reductants flux, Type of rocks, Role of clathrates
- Solvent: Characterizing ocean and its evolution, Titan's CH_4 lake is really suitable for life?



Future questions

- Formation and evolution
  - Circumplanetary disk P-T condition and material supply
  - Composition of seed materials for the moons ← Trojans exp.
  - Interior compositional/thermal structure and their history
  - Impact flux for crater chronology ← Impact flash on Planets
- Extra-terrestrial oceanology/habitability
  - Chemical composition of the oceans ← Plume, E-M response
  - Chemical reaction of the ice, esp. by irradiation ← Lab. exp.
  - Plate tectonics, material transport ← Global imaging w/ high res.
  - Ice rheology and mixed materials (clathrates) ← Lab. exp.
  - Seafloor (rocky materials) composition (incl. radioactive elem.) ← Trojans exp.