Icy moons in the Solar System

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Selected chapters on astrophysics (NAST021)
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Course overview

1. Motivation - why do we study icy moons.
   History of exploration - telescope observations, spacecraft missions.
   Surface characteristics - composition, age, and morphology.

2. Interior structure - layered models: from gravity, shape, composition.
   Hydrosphere structure - H_2O phase diagram, presence of oceans.
   Preferred models for selected satellites.

3. Dynamics of the different planetary layers.
   Thermal evolution - heat sources, heat transfer.
   Melting/crystallization, anti-freezers.
   Implications for the long-term stability of subsurface oceans.

4. Selected applications.
   Overview of future missions.

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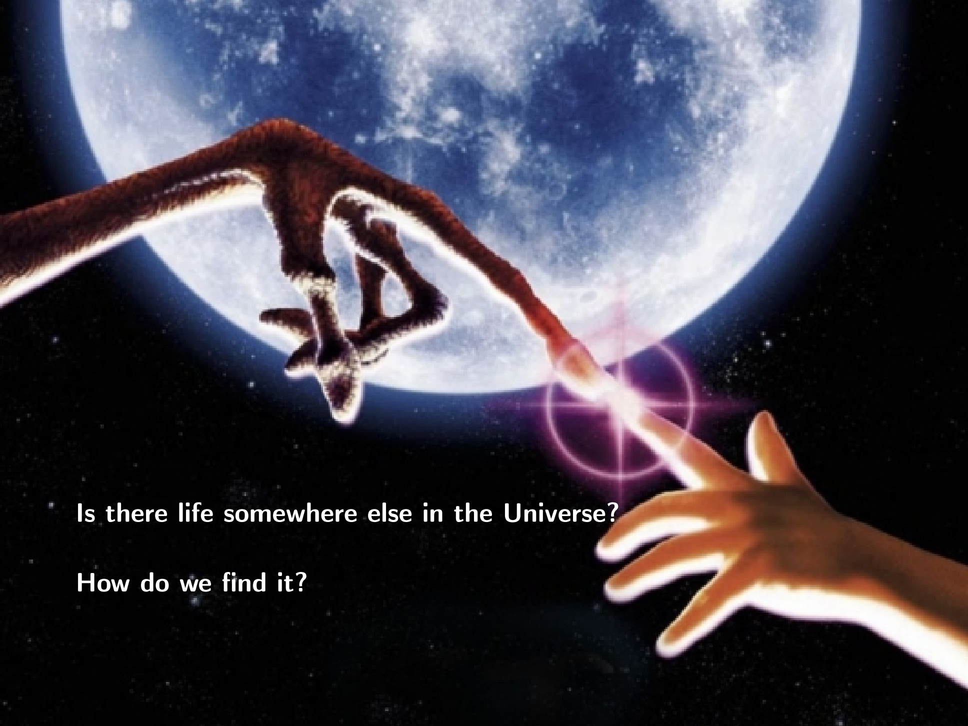

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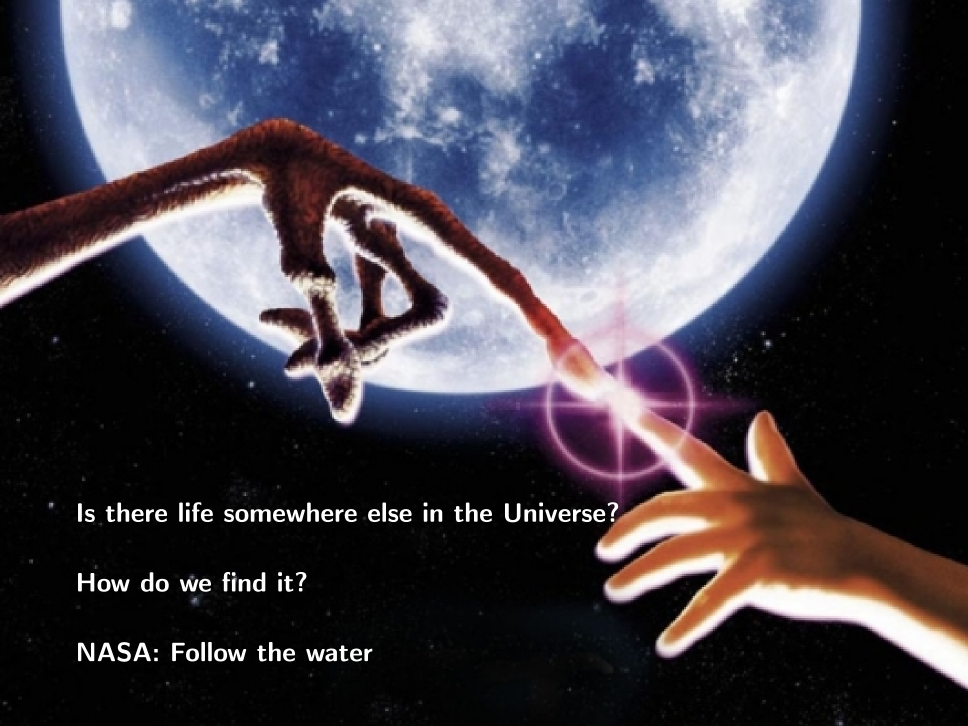
How do we find it?



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How do we find it?

NASA: Follow the water

Follow the water

- life might have started at the bottom of Earth's oceans

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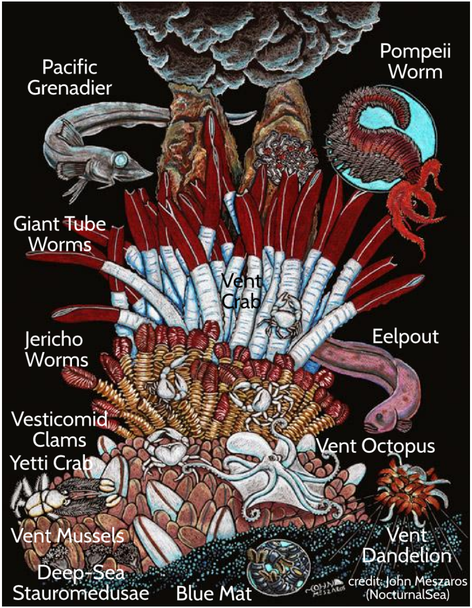
- water-rock interactions $\rightarrow$ rich communities of organisms



Ocean worlds

Ocean worlds - habitable?

Habitability

- ability to generate life endogenously
- potential to sustain life

Habitability requirements

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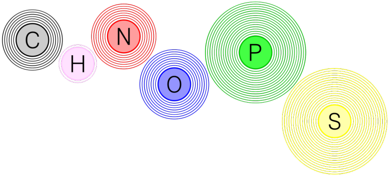
1. material: C, H, N, O, P, S (∼98% of bio molecules on Earth)



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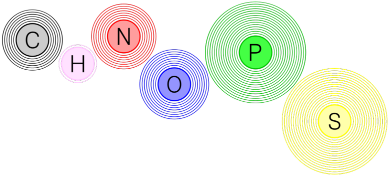

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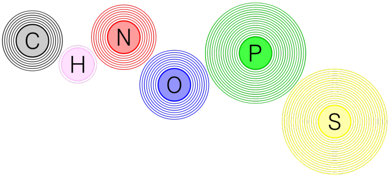

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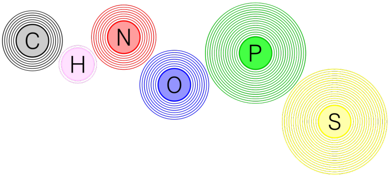
4. stable environment





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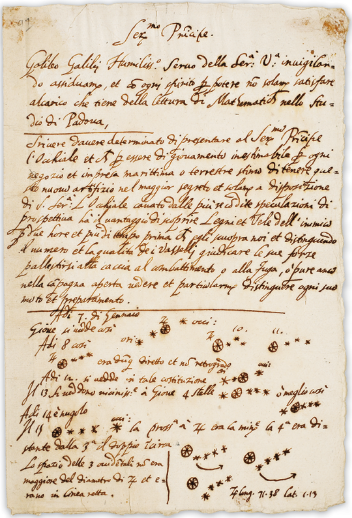
Discovery of Galilean satellites of Jupiter

- first observed on January 7–8, 1610, by Galileo Galilei (*Siderius Nuncius*) → *Medician satelites*



Ser.mo Principe.

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Adi 7. di Gennaio Giove si vedde così

Adi 8 così

era dunq. diretto et non retrogrado

Adi 12. si vedde in tale costituzione

Il 13 si veddono vicinissime à Giove 4 stelle

Adi 14 è nugolo

Il 15 la pross.a à Giove era la minore la 4.a era distante dalla 3.a il doppio tiàrca

Lo spatio delle 3 occidentali non era maggiore del diametro di Giove et erano in linea retta.

Giove long. 71.38 lat. 1.13

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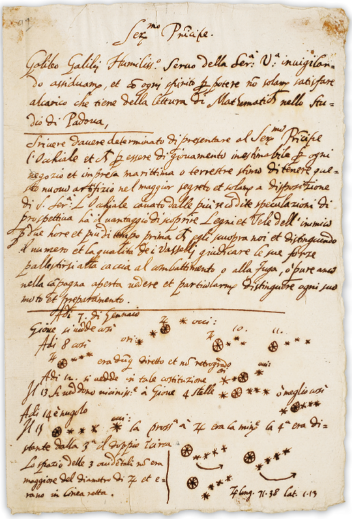
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- Marius (1614) suggested names Io, Europa, Ganymede, Callisto (lovers of Zeus/Jupiter)


Io (Paris Bordone)


Ganymede (Eustache Le Sueur)


Europa (Assteas)


Callisto (Francois Boucher)

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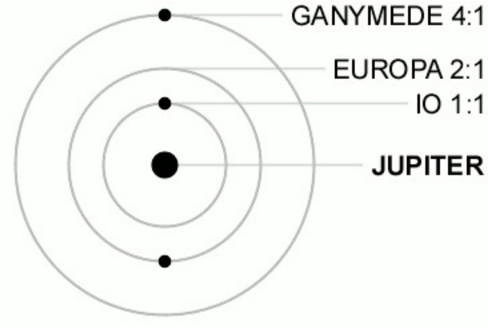
- named by John Herschel (1847) after the *Titans* of Greek mythology, siblings of Cronus/Saturn

Galilean satellites - further observations & theories

(*Alexander* +, 2009)

- 1805: *Laplace resonance* → orbits cannot be circularized



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- 1805: *Laplace resonance* → orbits cannot be circularized
- 1800s-1970s: observations → mass, diameter, shape, albedo
- *Pickering* (1908): density + albedo → composition
- *Jeffreys* (1923): first published suggestion of an icy composition
- *Urey* (1952): outer solar system is filled with water ice
- 1958: creation of NASA → first proposals for spacecraft missions
- *Moroz* (1965): surfaces of Europa & Ganymede covered by H_2O ice
- *Lewis* (1971): first notion of liquid ocean from simple heat balance
- *Consolmagno* (1975): thermal evolution model
  → Europa: ice crust covers an ocean above the silicate core
  → first notion of organic chemistry at ocean/silicate interface

Saturnian satellites - further observations & theories

(*Ip* +, 2014; *Dougherty* +, 2018)

Titan

- *Solá* (1908): limb darkening → suggestion of atmosphere
- *Jeans* (1916): atmosphere possible despite Titan's small mass
- *Kuiper* (1943): CH_4 absorption bands → evidence for atmosphere

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- *Veverka* (1973): thick cloud/haze layer
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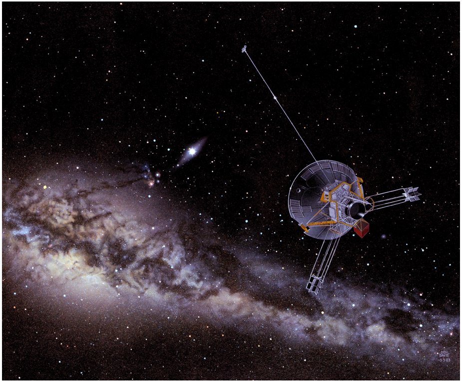
Enceladus

- *Lowell & Slipher* (1912-13)
Franz & Millis (1972-73) } increase in brightness @ trailing side → early hints on activity
- 1907-52: intermittent observation of a 'dusky' outer ring
- 1966-67: definitive evidence for what we now know as the E ring

Spacecraft observations

Pioneer 10 & 11

- Pioneer 10 (1972-2003): Jupiter flyby 1973
- Pioneer 11 (1973-1995): Jupiter flyby 1974, Saturn flyby 1979



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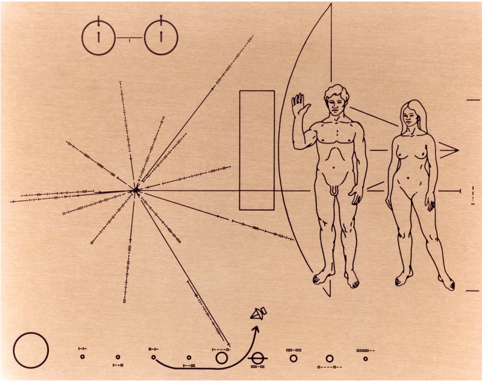

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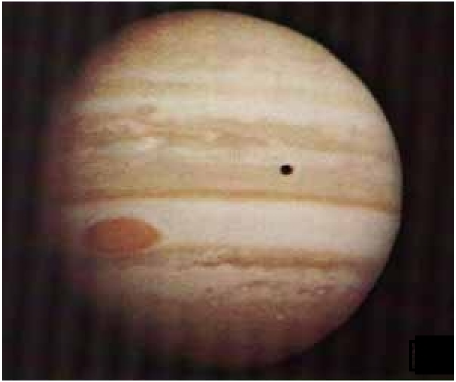

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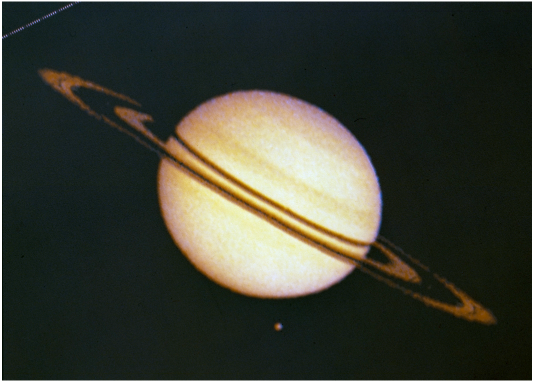
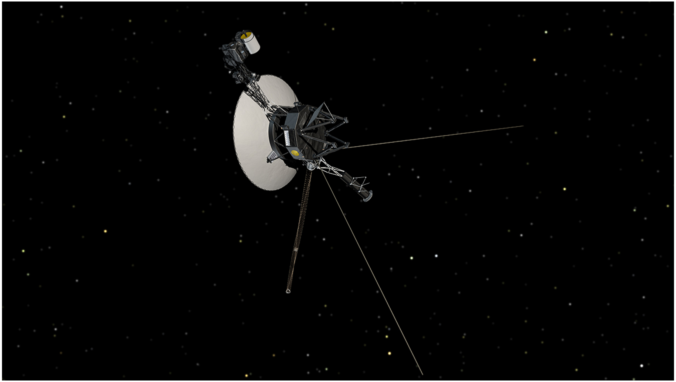
- Pioneer 10 (1972-2003): Jupiter flyby 1973
- Pioneer 11 (1973-1995): Jupiter flyby 1974, Saturn flyby 1979
- the Pioneer plaque
- close-up images of Jupiter, the Great Red Spot, polar regions
- close-up images of Saturn and its rings
- discovery of two small moons of Saturn and an additional ring
- direct measurements of Jupiter's & Saturn's magnetic field



Voyager 1 & 2

- Voyager 1: launched 1977, Jupiter flyby 1979, Saturn flyby 1980, left Solar System 2012
- Voyager 2: launched 1977, Jupiter flyby 1979, Saturn flyby 1981, Uranus flyby 1986, Neptune flyby 1989, left Solar System 2018



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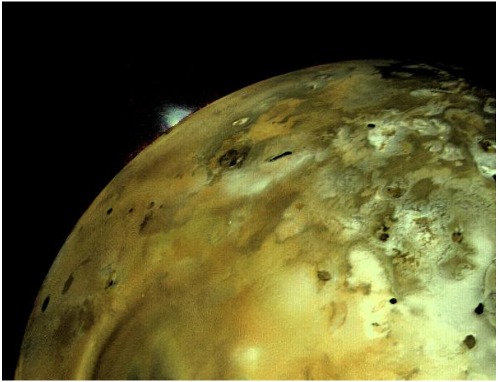
- Sounds of the Earth

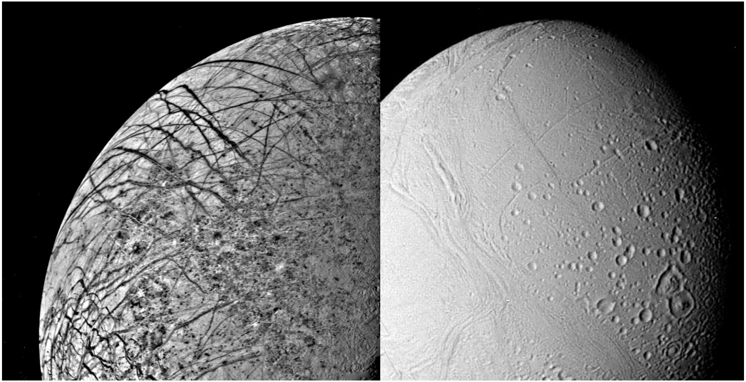
Voyager 1 & 2 - main discoveries

- active volcanism on Io
- Io torus - ring of ionized sulfur & oxygen in Jupiter's magnetosphere



Voyager 1 & 2 - main discoveries

- indication of an ocean beneath the cracked icy crust of Europa
- complex and diverse surfaces of frozen moons shaped by icy volcanism and faults



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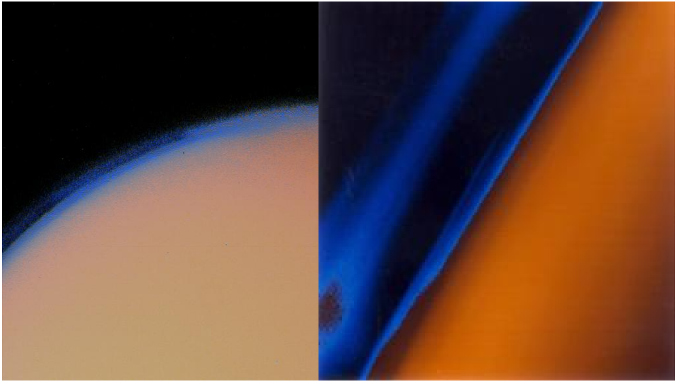
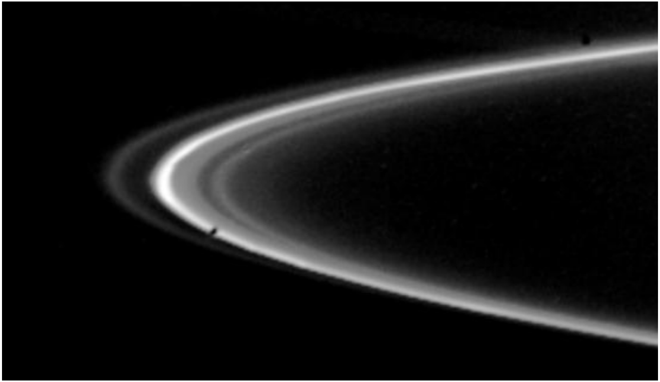
- deep, hazy nitrogen atmosphere on Titan
- possibility of clouds and rain of methane



Voyager 1 & 2 - main discoveries

- waves and fine structure in Saturn's icy rings
- small moons shepherding the narrow F-ring



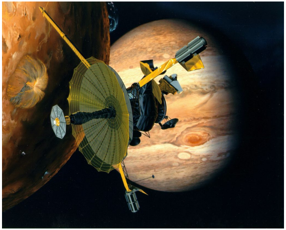
Voyager 1 & 2 - main discoveries

- Jupiter's turbulent atmosphere with dozens of interacting hurricane-like storm systems

Galileo mission 1989–2003

timeline

- 1989: launch aboard space shuttle Atlantis
- 1995: Jupiter orbit insertion, atmospheric probe entry and relay
- 1989-97: primary mission
- 1997-03: three extended missions
- 2003: mission end in Jupiter's atmosphere



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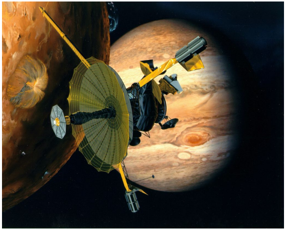
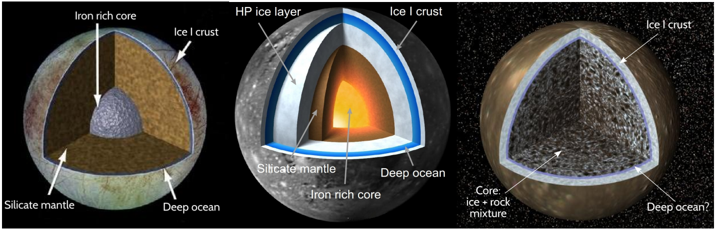
numbers

- 34 Jupiter orbits
- moon flybys: Io 7, Callisto 8, Ganymede 8, Europa 11, Amalthea 1
- distance traveled: $\sim 4.6 \times 10^9$ km
- 800 people worked on some part of the mission
- cost: 1.39×10^9 USD + 0.11×10^9 USD (int.)



Galileo mission - Some of the major discoveries

- global liquid water ocean exists under the icy surface Europa
- Ganymede and Callisto also likely have a liquid saltwater layer



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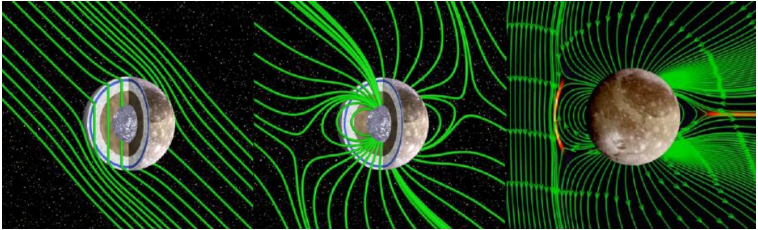

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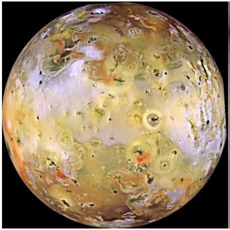

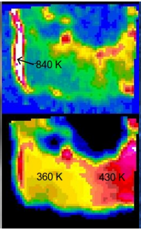

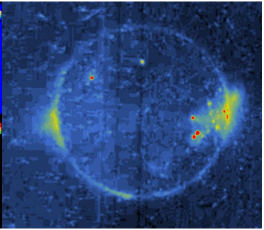

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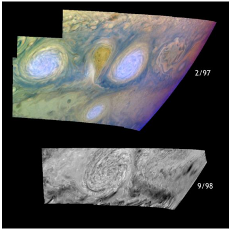

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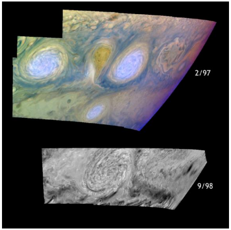

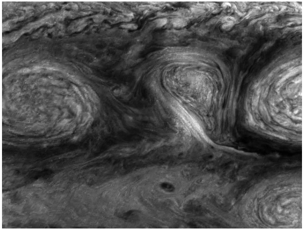

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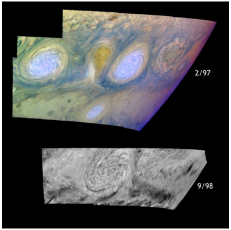

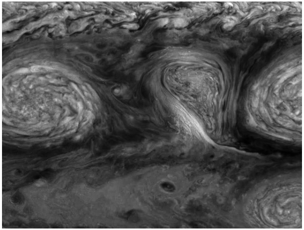

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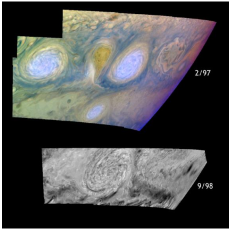
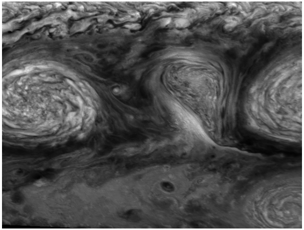
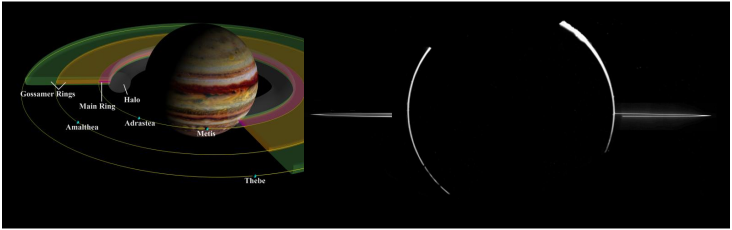




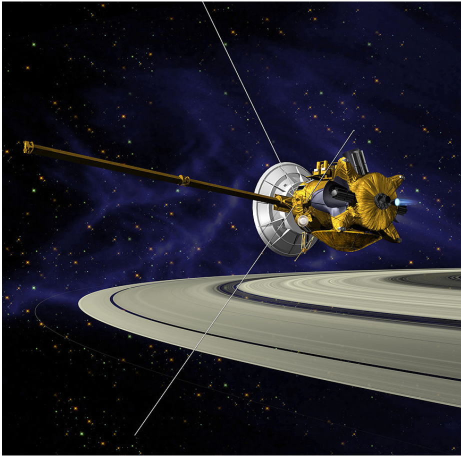
Galileo mission - Some of the major discoveries

- global liquid water ocean exists under the icy surface Europa
- Ganymede and Callisto also likely have a liquid saltwater layer
- Ganymede is the first moon known to possess a magnetic field
- Io's volcanic activity may be 100$\times$ Earth's
- plasma interactions in Io's atmosphere, coupling with J atmosphere
- Jupiter has thunderstorms many times larger than Earth's
- Jupiter's rings formed by dust from the four small inner moons



Cassini-Huygens mission 1997–2017 - mission of firsts

- spacecraft in orbit of Saturn
- landing in outer solar system
- sample of extraterrestrial ocean



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timeline

- 1997: launch
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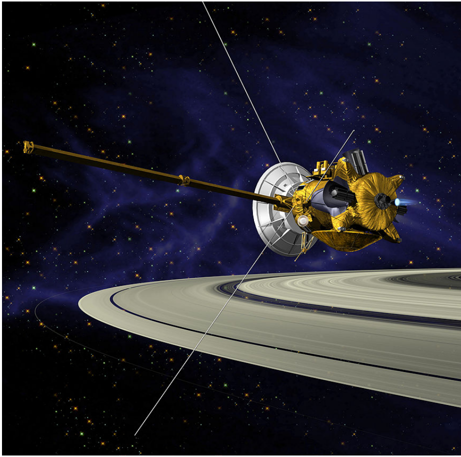

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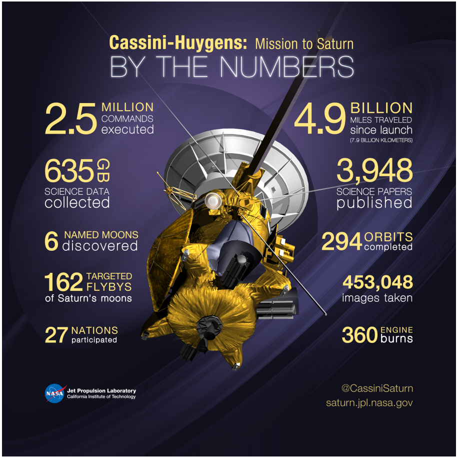
numbers

- 2 oceans, 3 seas, 100s lakes
- $>$5000 people
- cost: 3.9×10^9 USD



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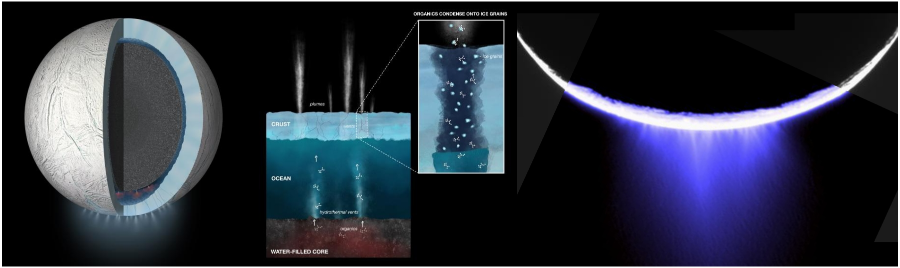

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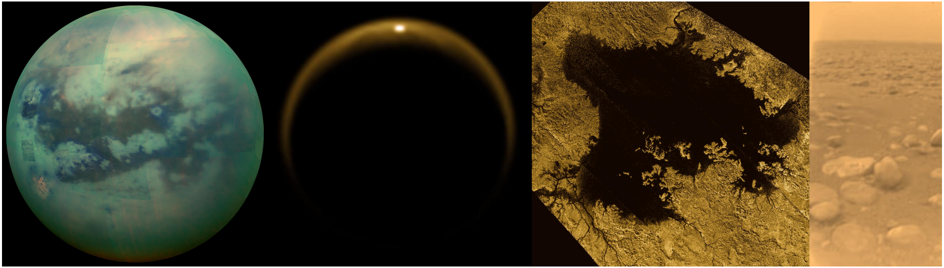

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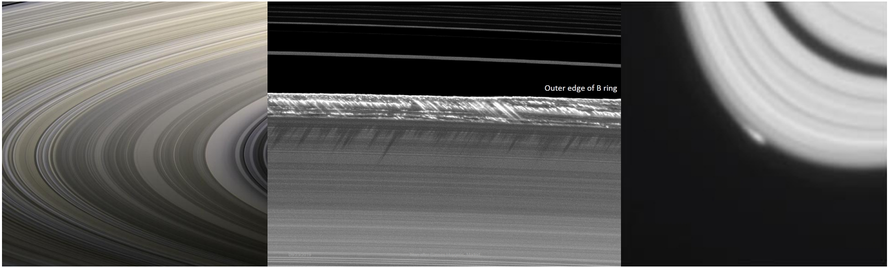

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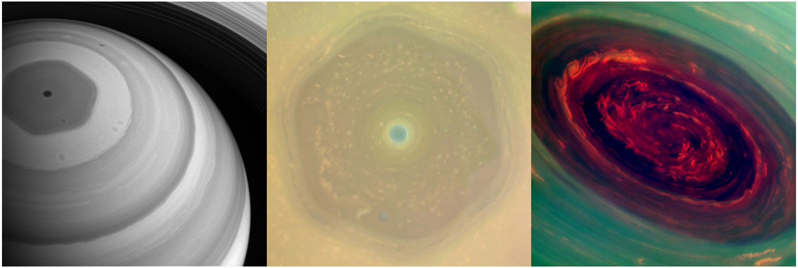

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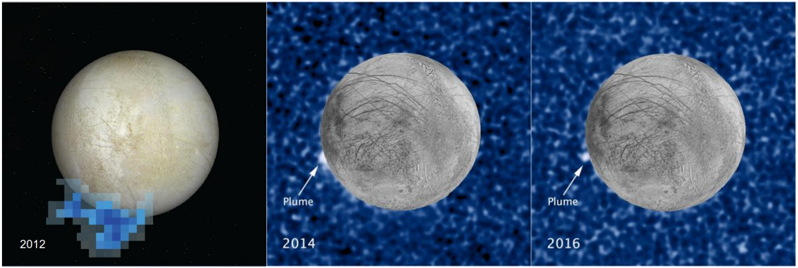

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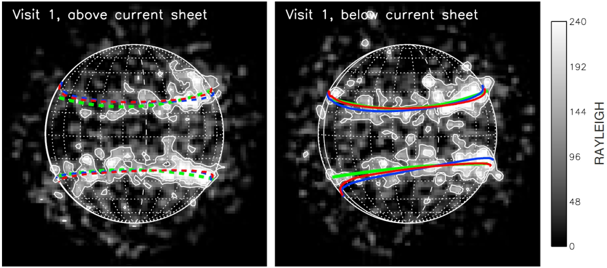

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- detection of monodeuterated methane (CH_3D) in Titan's atmosphere by ALMA (Atacama Large Millimeter/submillimeter Array) (*Thelen* +, 2019)
- revealing the effects of seasonally variable chemistry and dynamics in Titan's atmospher by ALMA (*Cordiner* +, 2019)
- detection of propadiene (C_3H_4) on Titan by TEXES (Texas Echelle Cross Echelle Spectrograph), IRTF @ Mauna Kea (*Lombardo* +, 2019)

Course overview

1. Motivation - why do we study icy moons.
   History of exploration - telescope observations, spacecraft missions.
   Surface characteristics - composition, age, and morphology.

2. Interior structure - layered models: from gravity, shape, composition.
   Hydrosphere structure - H_2O phase diagram, presence of oceans.
   Preferred models for selected satellites.

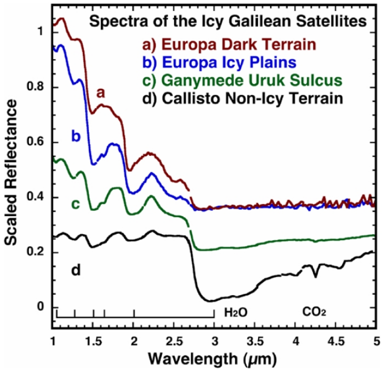
3. Dynamics of the different planetary layers.
   Thermal evolution - heat sources, heat transfer.
   Melting/crystallization, anti-freezers.
   Implications for the long-term stability of subsurface oceans.

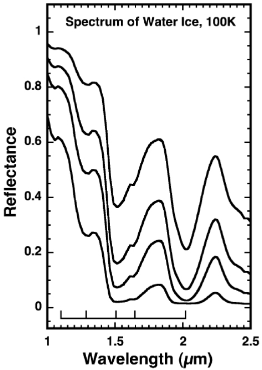
4. Selected applications.
   Overview of future missions.

Surface composition: Europa & Ganymede (Galileo NIMS)

(*Dalton* + 2010)

- H_2O ice is a major constituent





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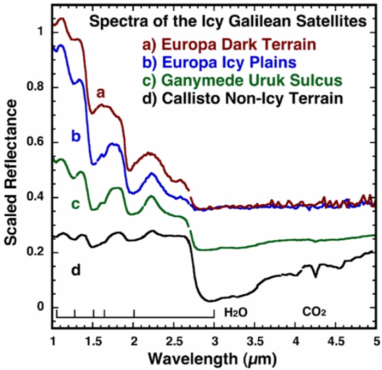

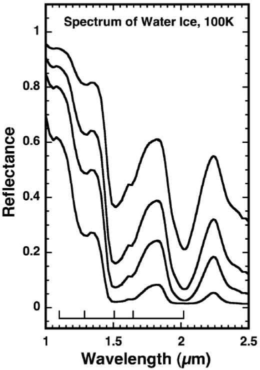

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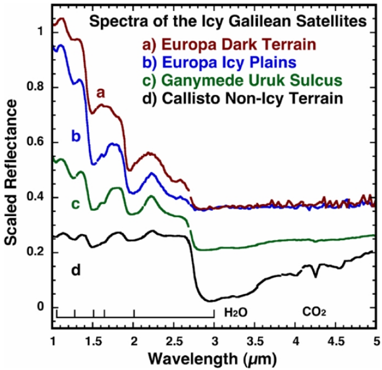

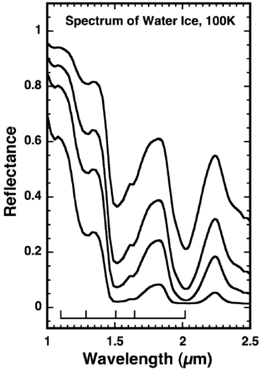

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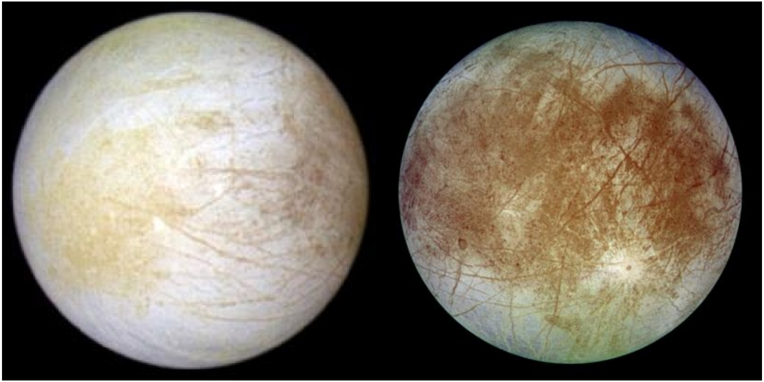
- Europa:
  - leading-trailing hemisphere dichotomy
  - hydrates correlated with disrupted reddish terrains - S_4, S_8?



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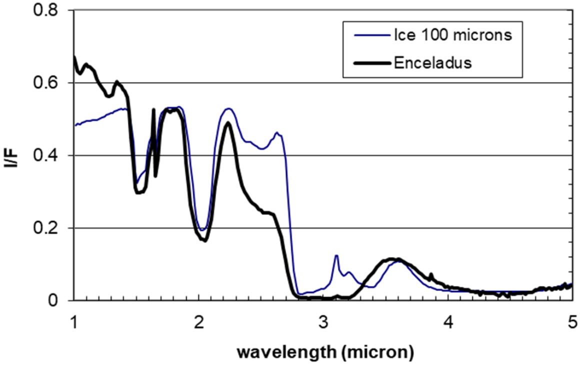

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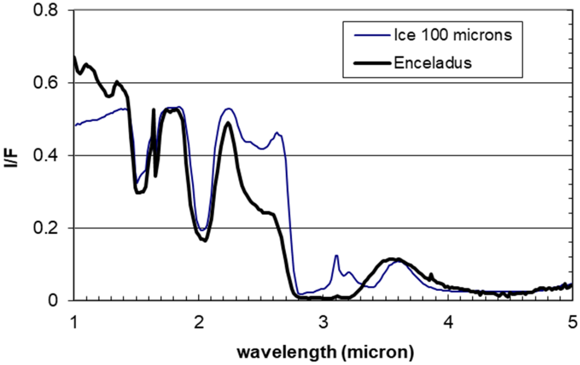
- other species: CO_2, organics, NH_3/NH_4OH, Na salts
- particles from Enceladus' plume can supply the entire E-ring



Titan's atmosphere

(*Hörst* +, 2017)

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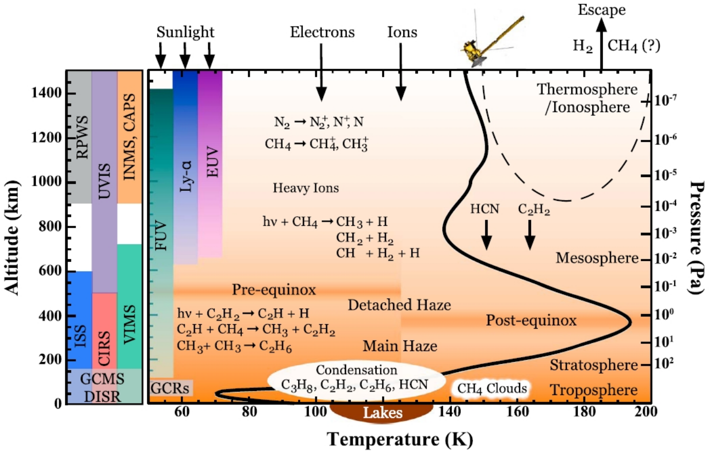
- N_2 (>90%) & CH_4 (5.65% surface – ~1% upper atmosphere)



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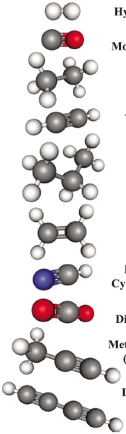
	Stratosphere			Mesosphere	Thermosphere
Formula	Ground Based[b]	ISO[g]/Herschel	CIRS[m]	UVIS[s]	INMS (CSN)[t]
H_2			$9.6 \pm 2.4 \times 10^{-4}$[n]		$3.9 \pm 0.01 \times 10^{-3}$
^{40}Ar					$1.1 \pm 0.03 \times 10^{-5}$
C_2H_2		$5.5 \pm 0.5 \times 10^{-6}$	2.97×10^{-6}	$5.9 \pm 0.6 \times 10^{-5}$	$3.1 \pm 1.1 \times 10^{-4}$
C_2H_4		$1.2 \pm 0.3 \times 10^{-7}$	1.2×10^{-7}	$1.6 \pm 0.7 \times 10^{-6}$	$3.1 \pm 1.1 \times 10^{-4}$
C_2H_6		$2.0 \pm 0.8 \times 10^{-5}$	7.3×10^{-6}		$7.3 \pm 2.6 \times 10^{-5}$
CH_3C_2H		$1.2 \pm 0.4 \times 10^{-8}$	4.8×10^{-9}		$1.4 \pm 0.9 \times 10^{-4}$
C_3H_6			$2.6 \pm 1.6 \times 10^{-9}$[o]		$2.3 \pm 0.2 \times 10^{-6}$[u]
C_3H_8	$6.2 \pm 1.2 \times 10^{-7}$[c]	$2.0 \pm 1.0 \times 10^{-7}$	4.5×10^{-7}		$<4.8 \times 10^{-5}$
C_4H_2		$2.0 \pm 0.5 \times 10^{-9}$	1.12×10^{-9}	$7.6 \pm 0.9 \times 10^{-7}$	$6.4 \pm 2.7 \times 10^{-5}$
C_6H_6		$4.0 \pm 3.0 \times 10^{-10}$	2.2×10^{-10}	$2.3 \pm 0.3 \times 10^{-7}$	$8.95 \pm 0.44 \times 10^{-7}$
HCN	5×10^{-7}	$3.0 \pm 0.5 \times 10^{-7}$	6.7×10^{-8}	$1.6 \pm 0.7 \times 10^{-5}$	
HNC	$4.9 \pm 0.3 \times 10^{-9}$[d]	$4.5 \pm 1.2 \times 10^{-9}$[h]			
HC_3N	3×10^{-11}	$5.0 \pm 3.5 \times 10^{-10}$	2.8×10^{-10}	$2.4 \pm 0.3 \times 10^{-6}$	$3.2 \pm 0.7 \times 10^{-5}$
CH_3CN	8×10^{-9}		$< 1.1 \times 10^{-7}$[p]		$3.1 \pm 0.7 \times 10^{-5}$
C_2H_5CN	2.8×10^{-10}[e]				
C_2N_2			9×10^{-10}[q]		$4.8 \pm 0.8 \times 10^{-5}$
NH_3		$< 1.9 \times 10^{-10}$[i]	$< 1.3 \times 10^{-9}$[p]		$2.99 \pm 0.22 \times 10^{-5}$
CO	$5.1 \pm 0.4 \times 10^{-5}$[f]	$4.0 \pm 5 \times 10^{-5}$[j]	$4.7 \pm 0.8 \times 10^{-5}$[r]		
H_2O		8×10^{-9}[k]$/7 \times 10^{-10}$[l]	$4.5 \pm 1.5 \times 10^{-10}$[r]		$< 3.42 \times 10^{-6}$
CO_2		$2.0 \pm 0.2 \times 10^{-8}$	1.1×10^{-8}		$< 8.49 \times 10^{-7}$

Titan's atmosphere

(*Hörst* +, 2017)

- complex chemistry (energetic particles + solar UV photons)
  - dissociation of N_2 and $CH_4 \to H_2$ + oganic molecules
  - aggregation $\to$ aerosols (orange color + haze)



	Production	Loss
Hydrogen (H_2)	CH_4 photolysis	Escape
Carbon Monoxide (CO)	$O(^3P) + CH_3 \to H_2CO + H$ $H_2CO + h\nu \to CO + H_2/2H$	$CO + OH \to CO_2 + H$
Ethane (C_2H_6)	$CH_3 + CH_3 + M \to C_2H_6 + M$	Condensation
Acetylene (C_2H_2)	$C_2H + CH_4 \to C_2H_2 + H_2$	$C_2H_2 + h\nu \to C_2H + H$ Condensation
Propane (C_3H_8)	$CH_3 + C_2H_5 + M \to C_3H_8 + M$	Condensation
Ethylene (C_2H_4)	$CH + CH_4 \to C_2H_4 + H$ $^3CH_2 + CH_3 \to C_2H_4 + H$	$C_2H_4 + h\nu \to C_2H_2 + H_2/2H$
Hydrogen Cyanide (HCN)	$N(^4S) + CH_3 \to H_2CN + H$ $H_2CN + H \to HCN + H_2$	Condensation
Carbon Dioxide (CO_2)	$CO + OH \to CO_2 + H$	Condensation
Methylacetylene (CH_3CCH)	$CH + C_2H_4 \to C_3H_4 + H$	$C_3H_4 + h\nu \to C_3H_3 + H$ $H + CH_3CCH \to C_3H_5$
Diacetylene (C_4H_2)	$C_2H + C_2H_2 \to C_4H_2 + H$	$C_4H_2 + h\nu \to C_4H + H$

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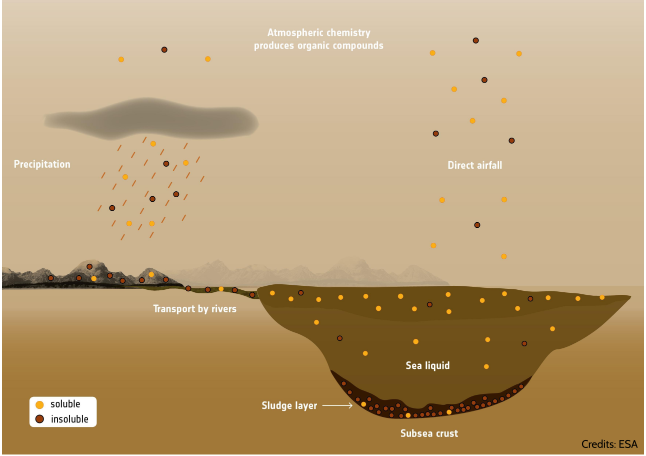
  - organics deposition on the surface

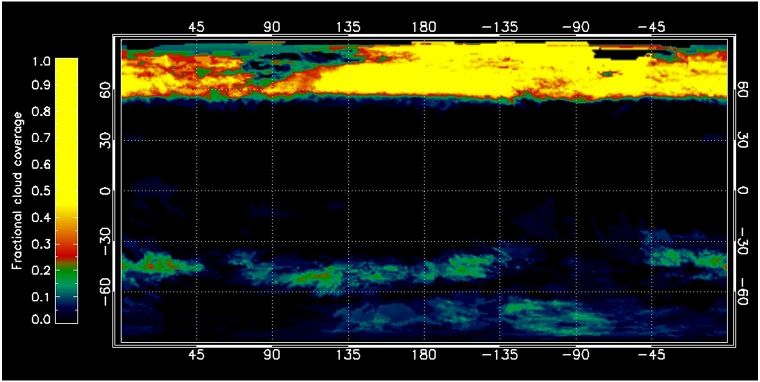


Titan's atmosphere, weather

(*Hörst* +, 2017)

- important seasonal effects (Titan year $\sim$ 29.5 Earth years)
- formation of clouds, precipitaion
- greenhouse effect (T_{ef}~82 K vs. T_{s}~94 K)
- T_{s}~94 K & P_{s}~1.5 bar: $\sim$ tripple point of CH_4 ($\sim$ H_2O on Earth) $\rightarrow$ liquid on surface, gas in atmosphere $\rightarrow$ methane cycle

- CH_4 constantly destroyed - need a source (interior?)
- most CH_4 in the atmosphere



Titan's atmosphere, weather, and surface composition

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- small wavelength windows where it is possible to observe the surface
- H_2O ice: $>30\%$ of Titan's mass; observed (ground, VIMS, DISR)
- hydrocarbons (C_6H_6, C_2H_6), nitriles (HC_3N), CO_2, ...

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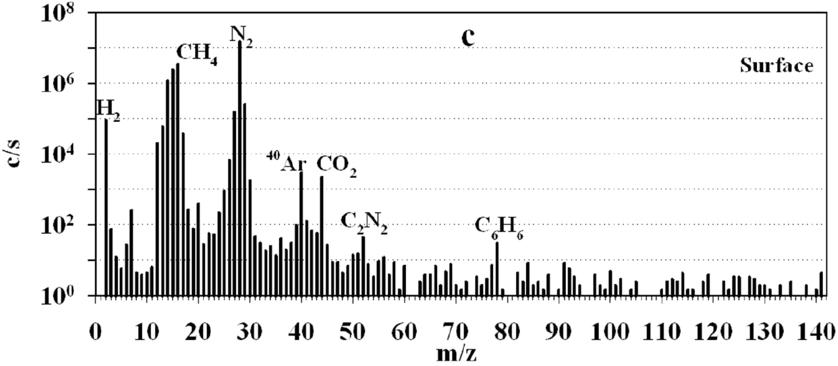
- Huygens landing site: fine grained, soft, few mm thick 'fluffy' cover + volatiles



Surface morphology - craters

(*Prockter* +, 2010; *Soderlund* +, in rev.)

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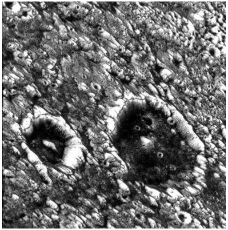

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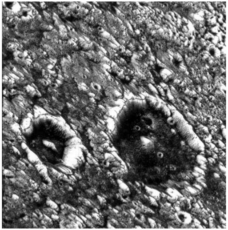

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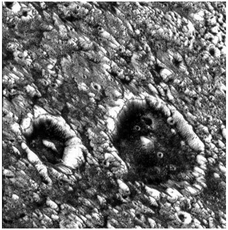

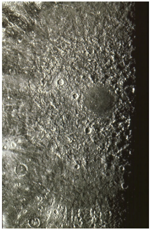

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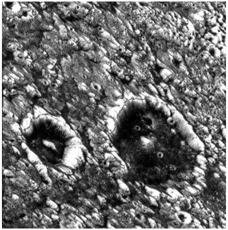
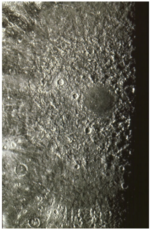
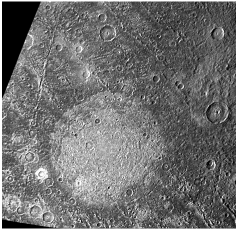
- palimpsets: remnants of impact craters



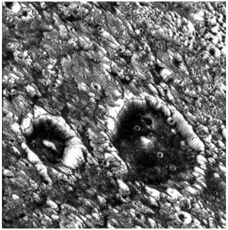


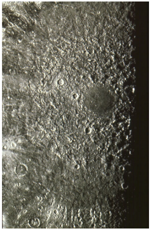


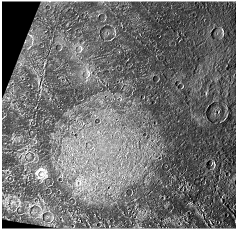
Surface morphology - craters

(*Prockter* +, 2010; *Soderlund* +, in rev.)

- Ganymede: widest range in crater morphology
- small: raised rims, bowl-shaped interior
- complex: grooved rims, flat floors, interior structures
- multi-ringed basins: > 100s km (Gilgamesh)
- palimpsets: remnants of impact craters
- bright rays (100s – 1000s km from crater)







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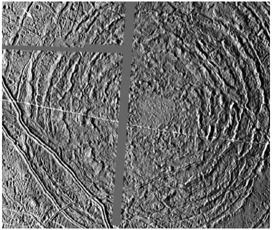

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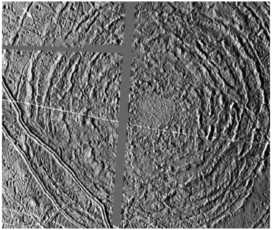

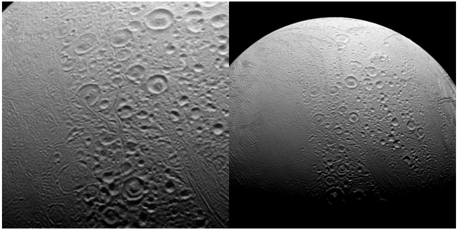

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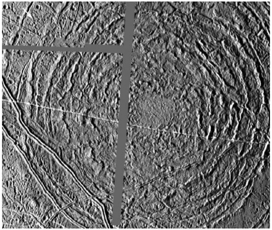
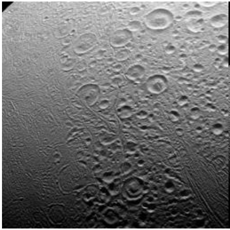
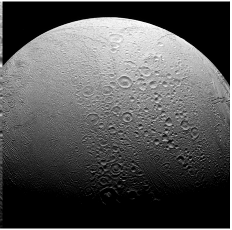
- Titan: very few identified, lack of impact craters poleward of approximately $\pm 60^\circ$ lat.







Surface age

(*Bierhaus* +, 2009; *Hörst*, 2017; *Patterson* +, 2018; *Soderlund* +, in rev.)

method

- cataloguing crater size-frequency distributions, areal densities, and spatial variations in context of impactor rates
- number of craters $\mathrm{d}N$ within the diameter range D to $D + \mathrm{d}D$:

$$\mathrm{d}N = k\, D^b \mathrm{d}D$$

- k: crater surface density ($\rightarrow$ age), b the 'slope'
- Moon: reference for correlating crater density to surface age
- different impactor populations: asteroids (inner) vs. comets (outer)

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Ganymede	dark terrain ($>$ 4 Gyr) vs. light terrain ($\sim$2 Gyr)
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Titan	geologically active surface, resurfacing (atmospheric processes), $\sim$200 Myr–1 Gyr

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Earth	seafloor: $\lesssim$200 Myr, continents: $\sim$2.4 Gyr

Surface morphology - tectonics

(*Prockter* +, 2010; *Patterson* +, 2018; *Soderlund* +, in rev.)

ridges

Surface morphology - tectonics

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ridges

- Europa: mostly double ridges
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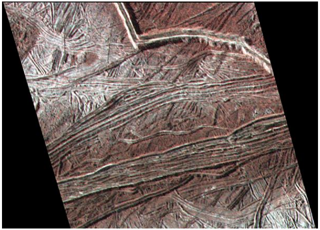

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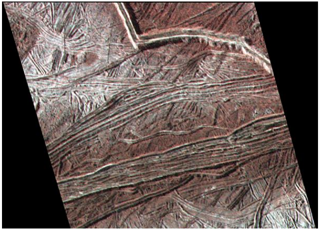

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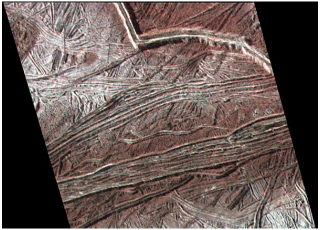

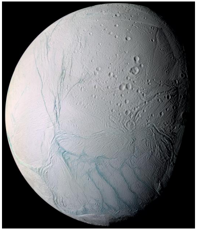

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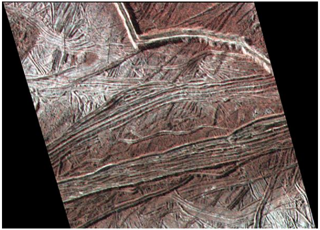

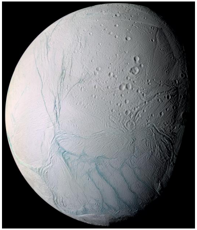

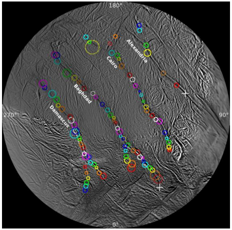

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ridges

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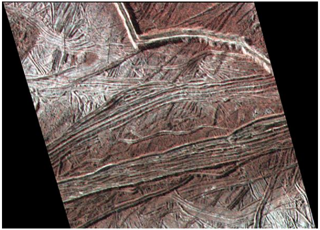
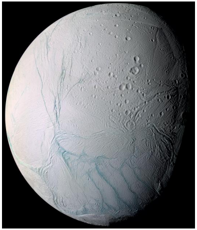
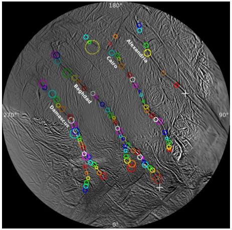
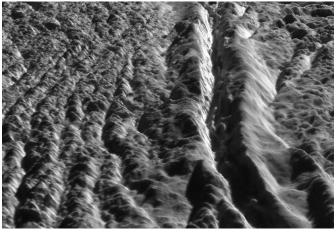
- Ganymede: grooves
- Enceladus: tiger stripes
  - geologically active, associated with anomalously high heat flows
  - flanked by a double ridge









Surface morphology - tectonics
(*Kattenhorn & Hurford*, 2009)

bands

- Europa: dilational bands (subsurface material emplaced at surface)
  - similar formation as terrestrial mid-ocean ridges?

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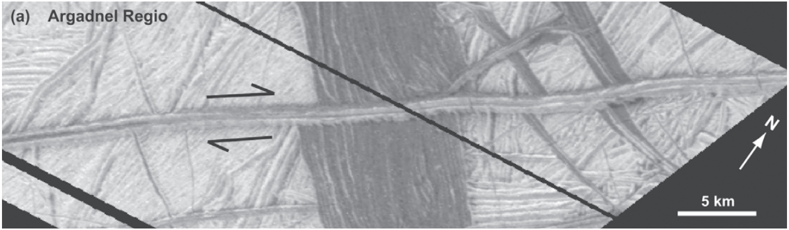
- offsets of few 10s of km
- formation: tidal walking



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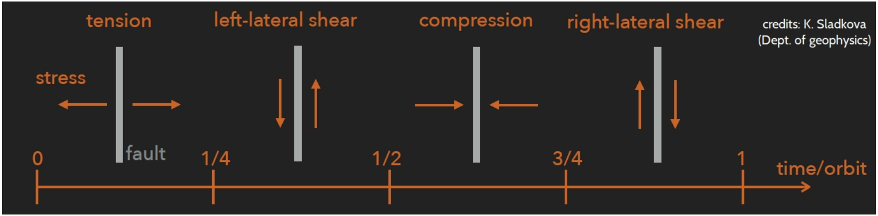
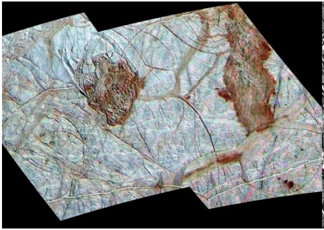
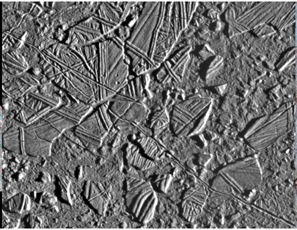


Surface morphology - chaos terrain

(*Prockter* +, 2010)

- unique to Europa, 20-30% of Europa's surface
  - large disrupted regions ('chaos')
  - smaller (10-15 km) features ('lenticulae')
- terrain disrupted into isolated plates of preexisting material with lumpy matrix material between the plates
- disrupt older features (ridges, bands, ...)
- some of the broken plates have been rotated and/or moved by as much as several kilometers

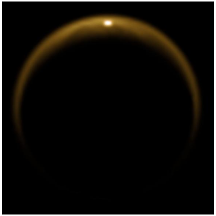




Titan surface morphology

(*Hörst*, 2017)

Lakes, seas, and fluvial features

- methane & ethane liquid **@** Titan's surface

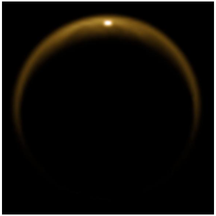


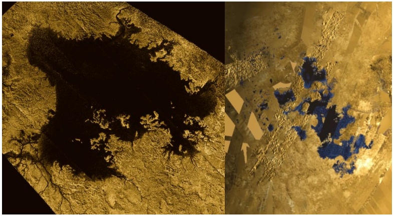
Titan surface morphology

(*Hörst*, 2017)

Lakes, seas, and fluvial features

- methane & ethane liquid **@** Titan's surface
- 3 seas (Kraken, Punga, Ligeia Mare), >30 lakes
- depths: 10s of m up to 160 m (Kraken)
- ~1% of Titan's surface
- N-S asymmetry in lakes distribution
- S: almost no filled lakes, evidence of paleoseas





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- methane & ethane liquid @ Titan's surface
- 3 seas (Kraken, Punga, Ligeia Mare), >30 lakes
- depths: 10s of m up to 160 m (Kraken)
- $\sim$1% of Titan's surface
- N-S asymmetry in lakes distribution
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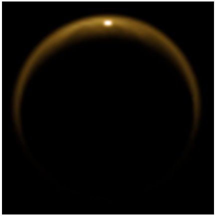
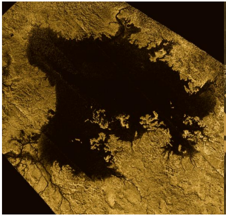
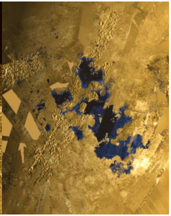
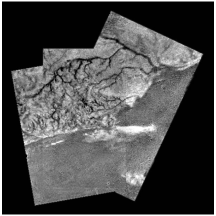
- fluvial erosion: channels + rounded pebbles









Titan surface morphology

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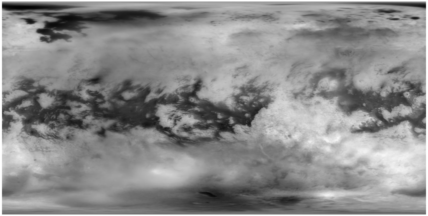
Dunes and aeollian features

- equatorial ($\pm 30^\circ$) regions, $\sim$10–20% of surface
- wind pattern: orientation (eastward), morphology



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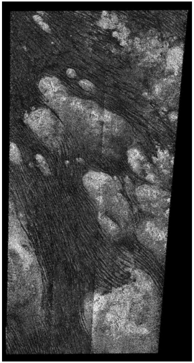

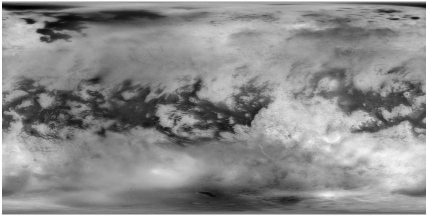

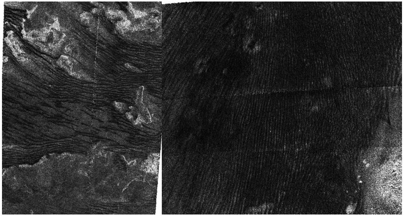

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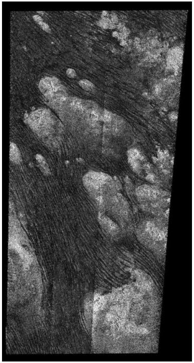
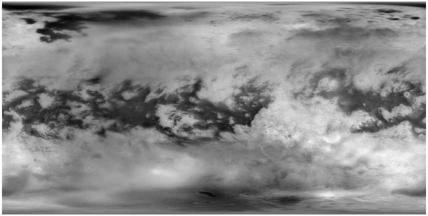
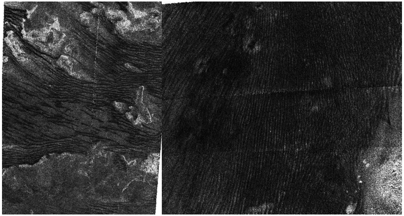
- 100–300 μm particles, organic/organic coated
- aeolian processes:
- 'bland-lands' ($\sim$17% of surface)?

$\rightarrow$ play a dominant role in shaping Titan's landscape







Cryovolcanism

(*Fagents* +, 2003; *Procktor* +, 2010; *Soderlund*, in rev.)

- proposed as feasible explanation for some terrain types due to morphological similarity with Earth lava flows

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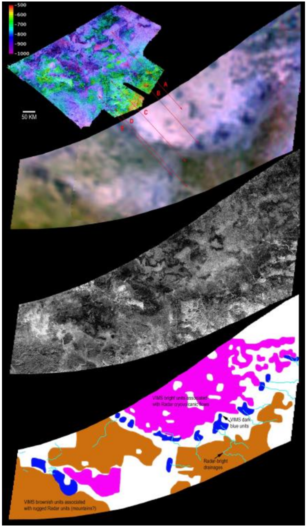
Titan

- several potential cryovolcanic features (series of flow fields, caldera-like depressions, candidate volcanic edifice)
- relatively young, not widely distributed across the surface



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buoyancy issue

- silicate volcanism: melts less dense than their solids
- cryovolcanism: liquid water denser than solid ice I

$\rightarrow$ obstacle to substantial cryovolcanism

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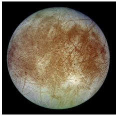
possibilities to overcome the negative buoyancy of water

(i) volatiles (CO_2, CO, SO_2, NH_3, CH_4, N_2) decrease fluid density

(ii) non-ice substances (silicate particles, clathrates) increase ice density

(iii) freezing of liquid reservoir → overpressurization → water ascent

Surface - summary

<table>
<tr><th></th><th>
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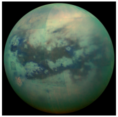
Enceladus</th><th>
Titan</th></tr>
<tr><td>Bond albedo</td><td>0.68</td><td>0.35</td><td>0.85</td><td>0.265</td></tr>
<tr><td>temperature [K]</td><td>102</td><td>110</td><td>75</td><td>94</td></tr>
<tr><td rowspan="7">composition</td><td>H_2O ice</td><td>H_2O ice</td><td>H_2O ice</td><td>H_2O ice</td></tr>
<tr><td colspan="2">hydrates</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">O_n, H_2O_2, XO_2</td><td>CO_2</td><td>CO_2</td></tr>
<tr><td>-</td><td>-</td><td>NH_3/NH_4OH</td><td>nitriles</td></tr>
<tr><td colspan="2">Na, K, Cl</td><td>Na salts</td><td>-</td></tr>
<tr><td colspan="2">organics?</td><td>organics</td><td>organics!</td></tr>
<tr><td>S_4, S_8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>crater density</td><td>low</td><td>high</td><td>low(S)/high(N)</td><td>low</td></tr>
<tr><td>age [Gyr]</td><td>0.03–0.09</td><td>2–4</td><td>0–2</td><td>0.2–1</td></tr>
<tr><td>tectonics</td><td>ridges, bands
strike-slip faults</td><td>grooves</td><td>tiger stripes</td><td>little</td></tr>
<tr><td>particular</td><td>chaos terrain</td><td>-</td><td>plume</td><td>atmosphere</td></tr>
</table>

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