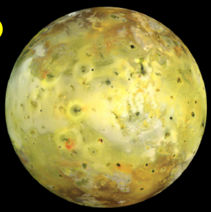
Large Moons

Björn Grieger

- Overview
- (No) atmospheres on large moons
- Surface structures of Galilean Satellites
- Tidal heating
- Subsurface oceans
- Titan

Part 1: Overview

Earth's Moon



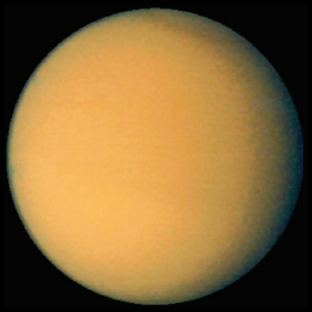
Io

Europa

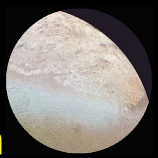
Ganymede

The four Galilean moons of Jupiter

Callisto

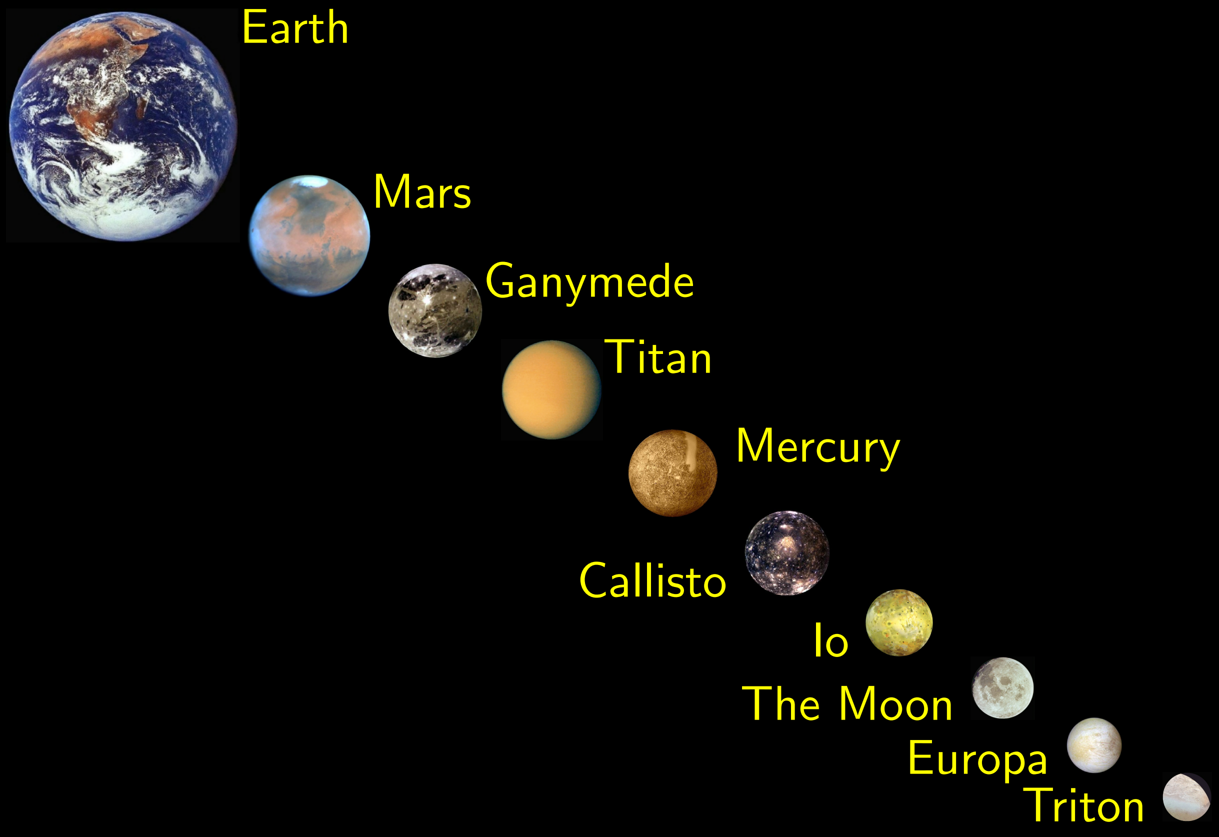


Saturn's moon Titan

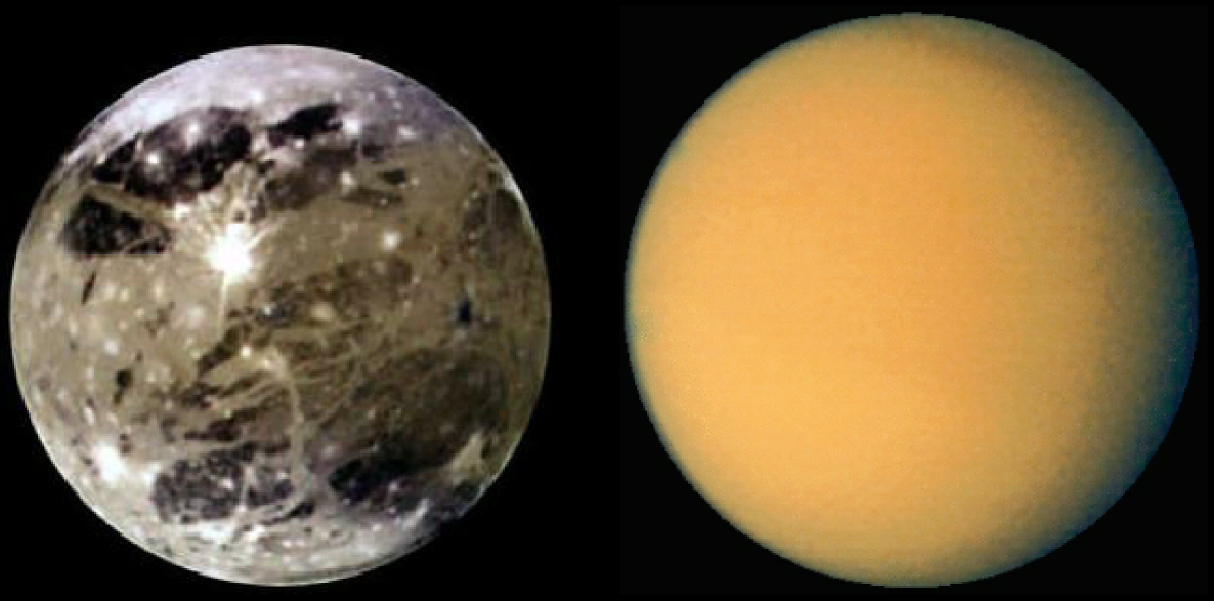


Neptune's moon Triton

Size comparison



Part 2: (No) atmospheres on large moons



Acknowledgement: This part is based on a presentation by Nick Hoekzema.

Erosion of atmospheres

1. Thermal escape (escape of exospheric molecules)
2. Hydrodynamic outflow ("planetary wind")
3. Chemical escape (ultra violet light)
4. Sputtering (solar wind, ions in magnetospheres)

$\Longrightarrow$ Mainly by processes 3. and 4., Ganymede and Callisto could have lost at most 1 bar of an atmosphere since the formation of the solar system.

$\Longrightarrow$ If they once had at least an atmosphere like Titan Today (1.5 bar), it should still persist substantially.

Sputtering by BIG particles: comets and asteroids

. . . usually called *impact erosion.*

- Important during the late heavy bombardment.
- Slow impacts deliver, fast impacts erode atmospheres; the critical velocity depends on the escape velocity and is about 12 km/s for a large moon.

Average impact velocity of short period comets:

Titan	Callisto	Ganymede
11 km/s	16 km/s	20 km/s

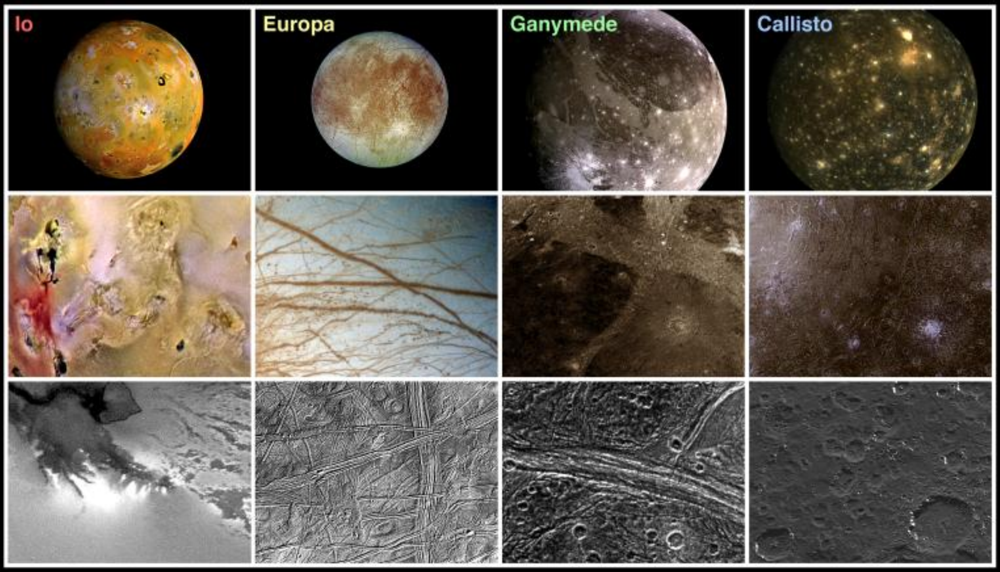
Impact erosion or delivery?

Predictions from comparison of critical velocities with average impact velocities of short period comets:

- Impact erosion on Mercury, the Moon, and the Galilean satellites.
- Impact delivery on Venus, Earth, Titan, and Pluto.
- Mars is on the edge.

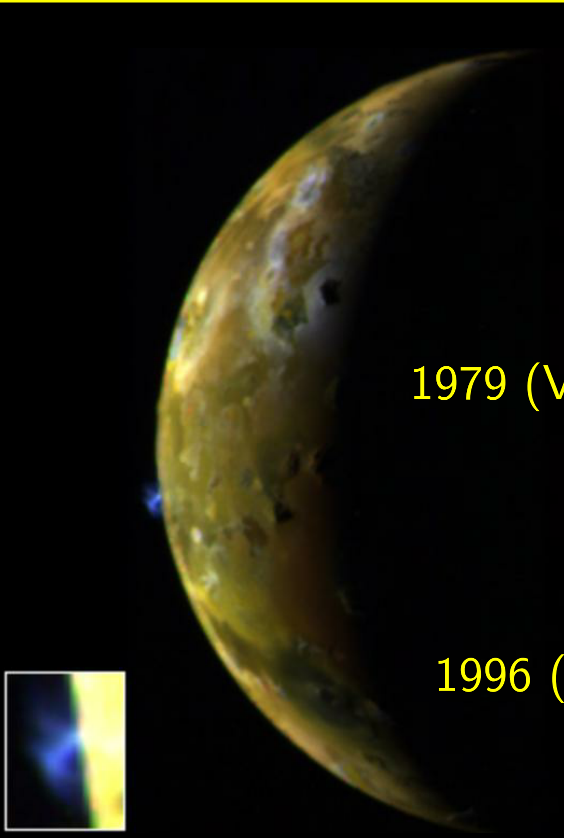
Looks very appealing, but open questions remain.

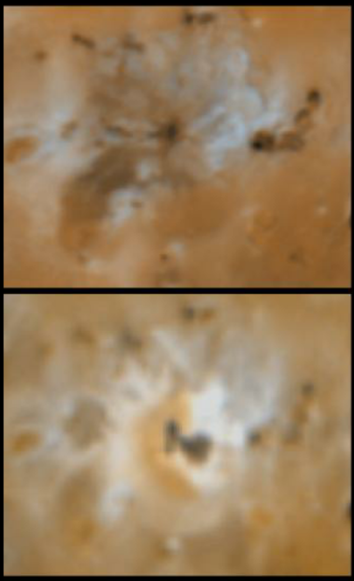
Part 3: Surface structures of Galilean Satellites



Acknowledgement: This part benefited from a review manuscript by Lars Reuen.

Io, the vulcanic world





Ra Patera

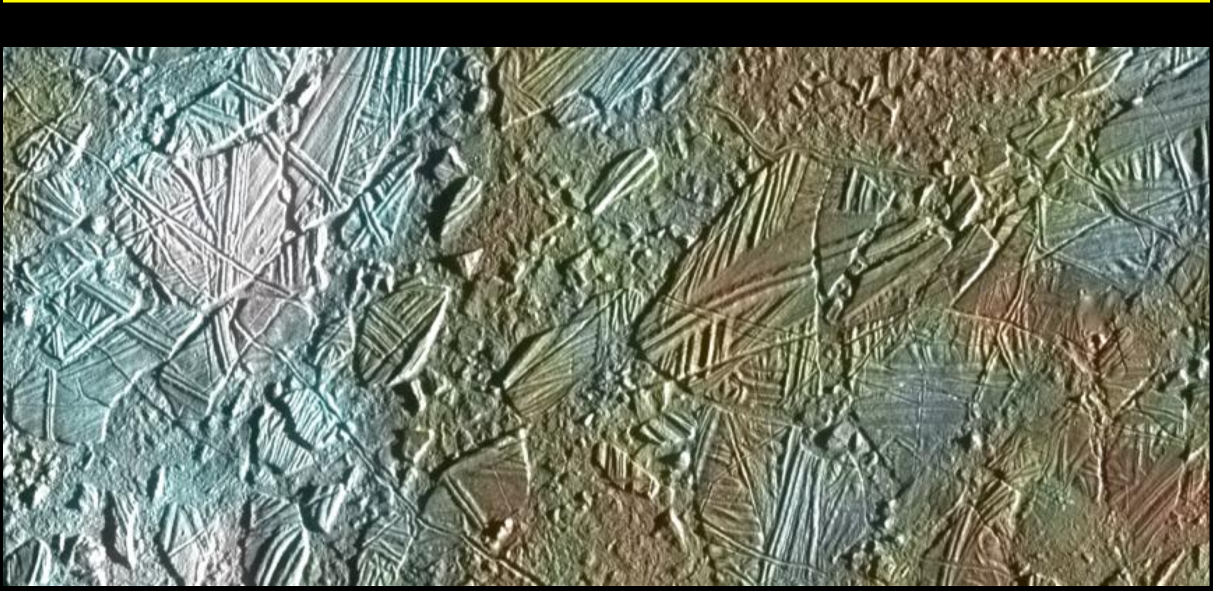
1979 (Voyager)

1996 (Galileo)

Io

- Lack of impact features.
- Youngest solid state surface in the solar system.
- Primary color is yellow, due to sulfur and sulfur compounds.
- Abundant vulcanic landforms:
  - About 200 calderas larger than 20 km.
  - Long lava flows.
  - Plumes of ejecta, indicating a geyser like origin.

Europa, covered with rafting ice

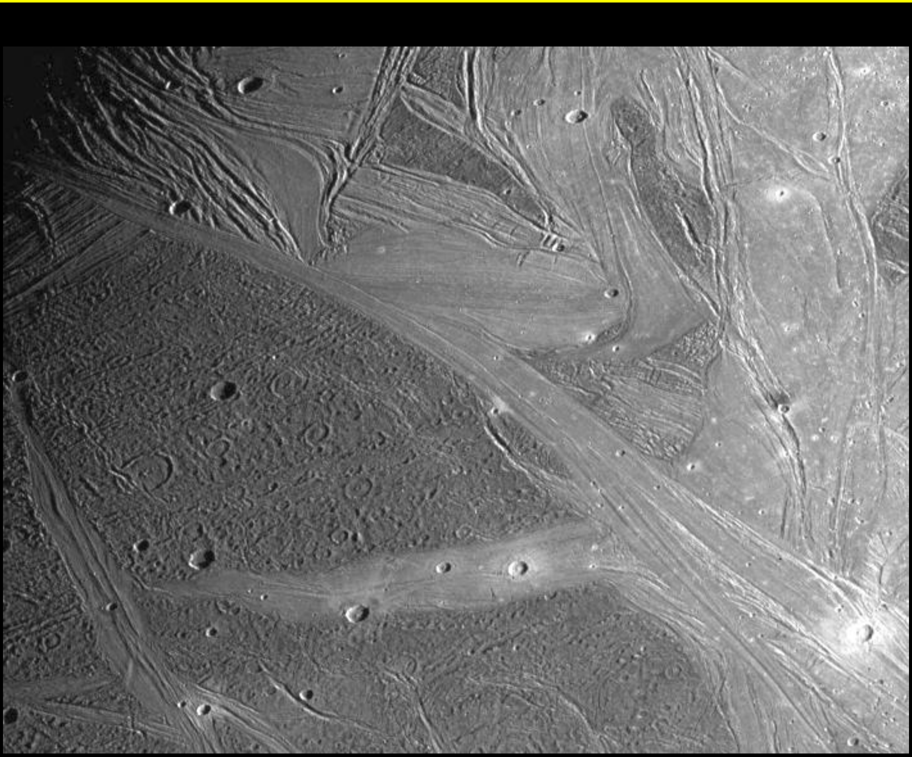


70 × 30 km

Europa

- High albedo.
- Smooth surface, showing similarities to pack ice on Earth's poles.
- Only few craters, indicating a young surface, perhaps only 100 million years old.
- Liquid water layer under the ice crust?

Ganymede, bright and dark



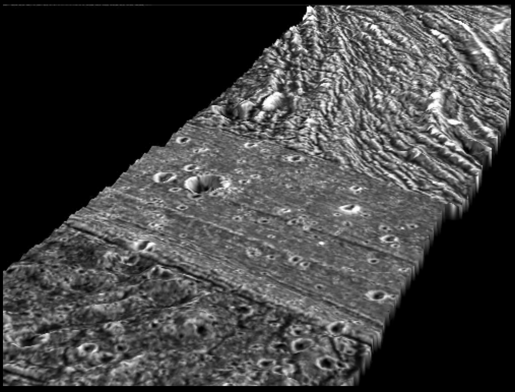
664 × 518 km

Ganymede

- Thin polar caps of H_2O-ice.
- Two types of terrain, dark and bright.
- Dark terrain is heavily cratered, probably created during the late heavy bombardment.

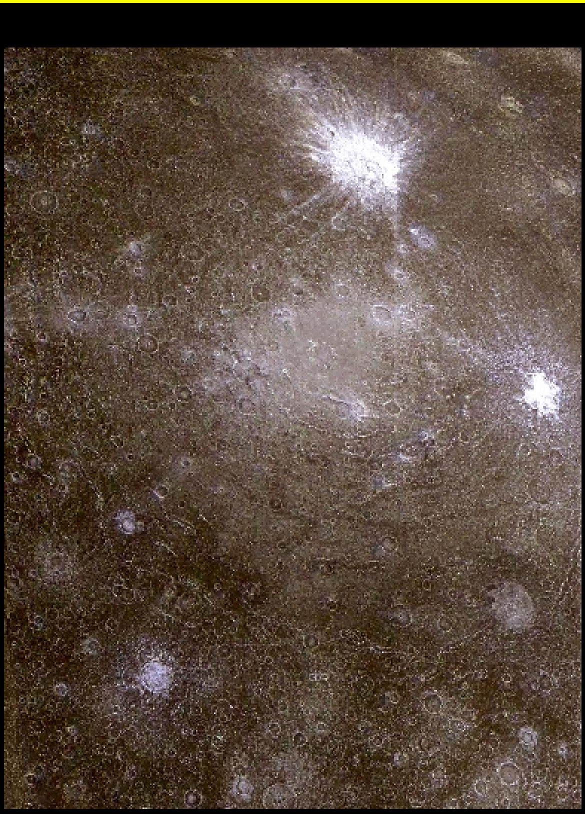
Ganymede's bright terrain

Bright terrain comes as "grooved regions" and "smooth regions".



- Grooved regions indicate a global expansion, possibly due to differentiation.
- Smooth regions were created by tectonic activities next to the expansion.

Callisto, dark and old



Impact structure Asgard,
≈ 1 400 km across

Callisto

- Heavily cratered, most uniformly in the solar system.
- Maximum crater size about 100 km, no lunar like plains.
- Craters are much flatter than those on rocky surfaces due to vicious relaxation.
- Large multi-ring structures created by major impacts.
- Old surface, created during or shortly after the late heavy boambardment.
- No tectonic activity.

Summary: Surface structures of Galilean Satellites

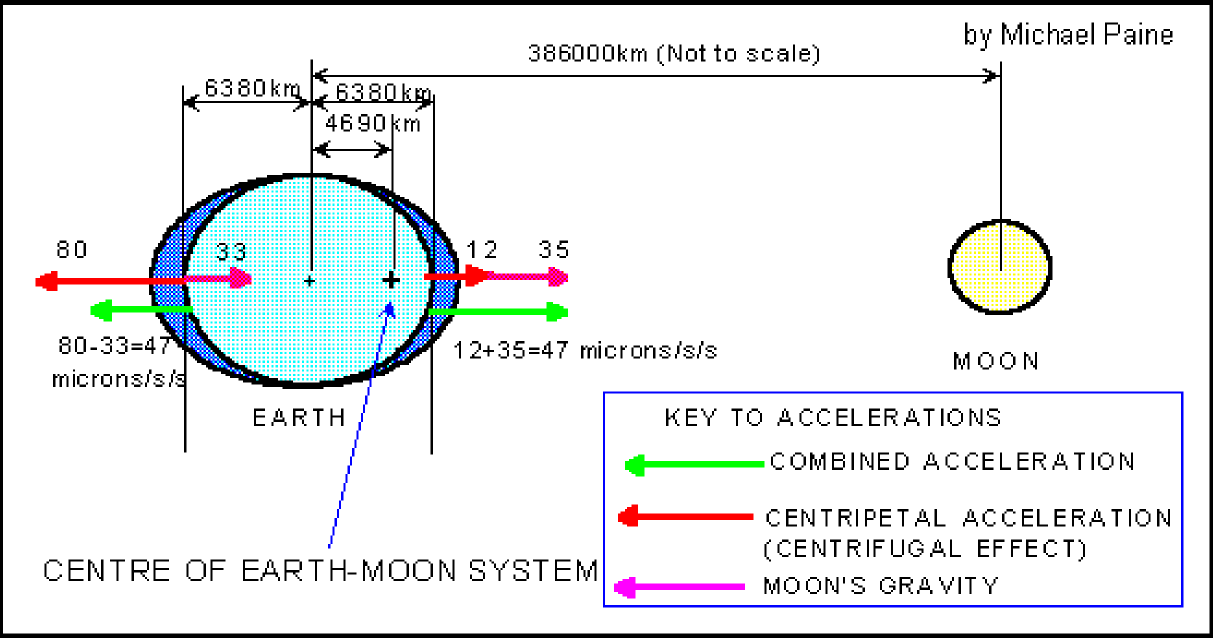
Io: Young surface, formed by ongoing vulcanic activety.

Europa: Completely covered by rafting(?) ice.

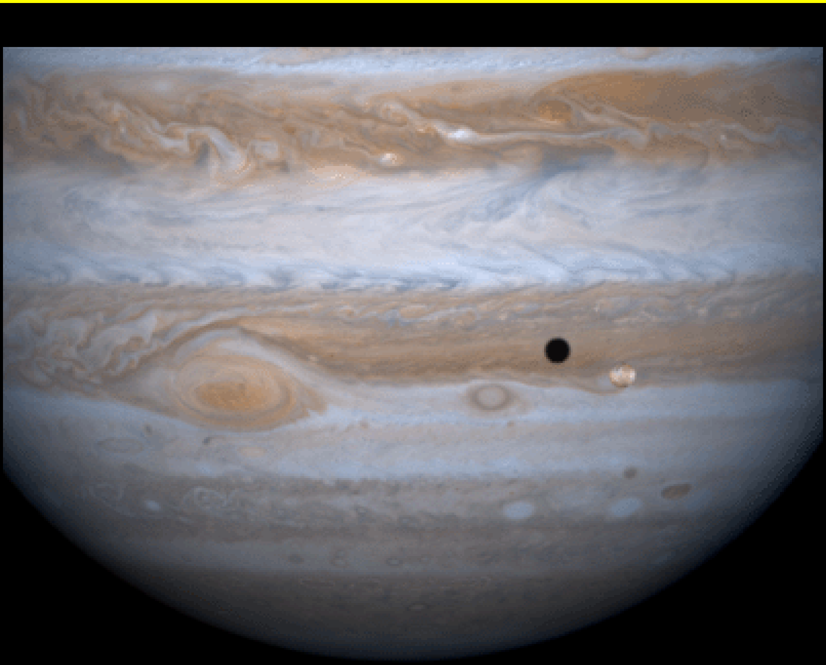
Ganymede: Dark (older) and bright (younger) areas, expansion indicated by the latter.

Callisto: Heavily cratered, old surface.

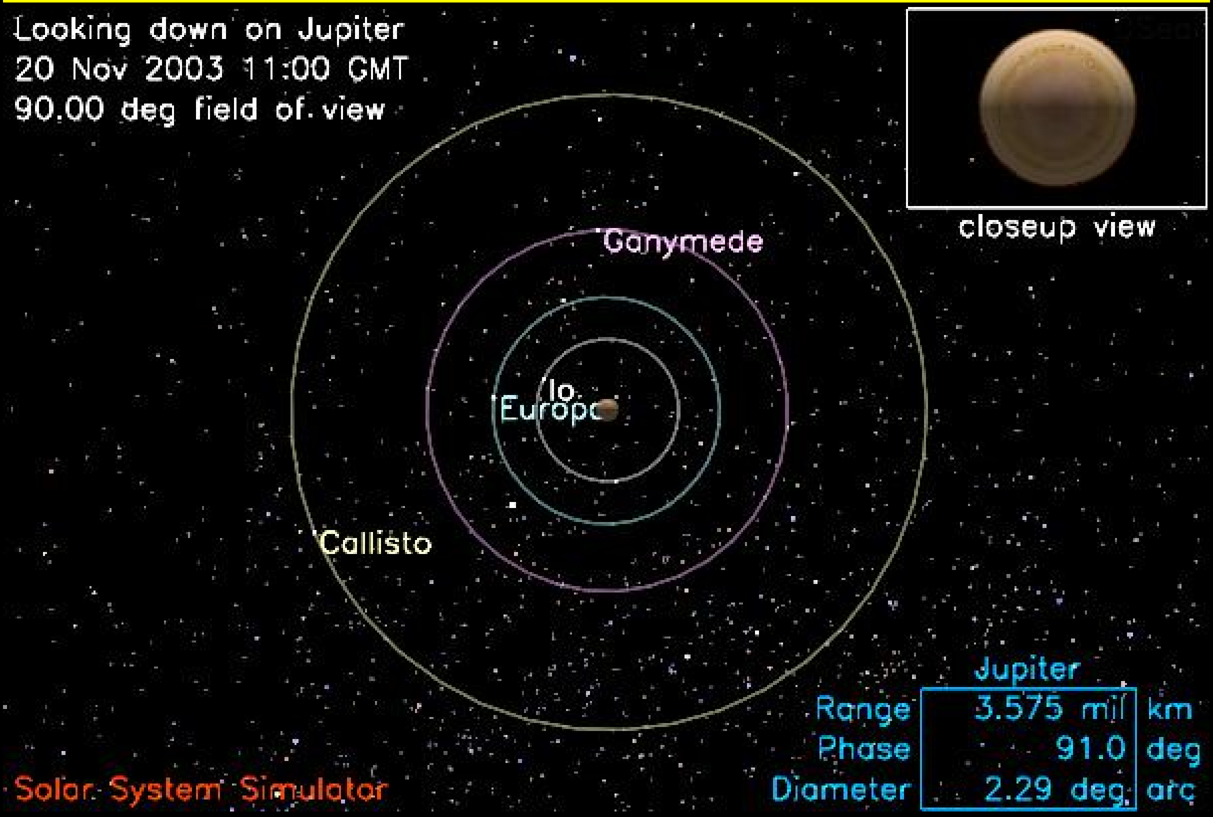
Part 4: Tidal heating



Tidal forces of giant Jupiter



Orbits of the Galilean Satellites



Looking down on Jupiter
20 Nov 2003 11:00 GMT
90.00 deg field of view

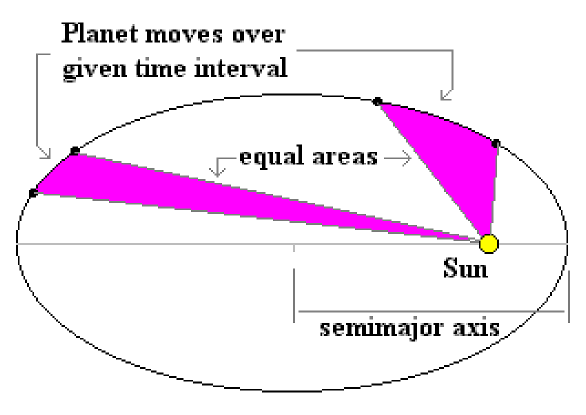
Jupiter
Range 3.575 mil km
Phase 91.0 deg
Diameter 2.29 deg arc

Tidal despinning

Like Earth's Moon, the rotational period of the Galilean satellites had been decellerated until it was locked with the orbital period (Laplace Resonance).

$\Longrightarrow$ Today, there are no tides like on Earth (but tidal heating due to despinning was very important earlier on).

Tides by orbital eccentricity



1. Jupitercentric longitude varies non-uniformly.
2. Rotation is uniform.

⟹ Tidal flexing.

Consequences of tidal heating

Io: Differentiated, molten interiour. Because of continuous recycling of the surface, all water, CO_2, and other volatiles escaped long ago.

Europa: Differentiated, metal-silicate core with 100–200 km thick ice layer; possibly liquid water below an ice crust.

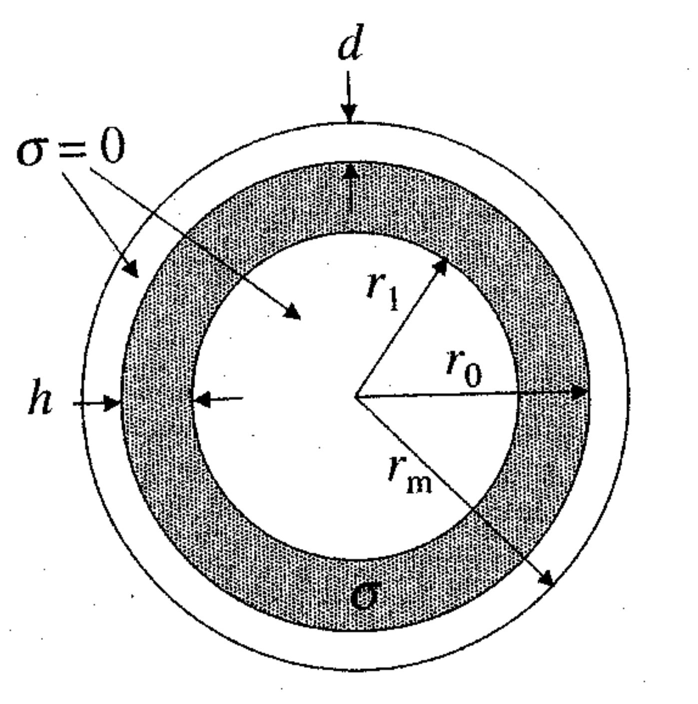
Ganymede: Partly differentiated, the corresponding expansion caused grooved regions.

Callisto: Minor differentiation.

Summary: Tidal heating

Tidal heating by Jupiter can account for the different evolution and surface structures of the Galilean satellites.

Part 5: Subsurface oceans



This part is based on Zimmer et al. (2000), Icarus *147*, 329–347.

Induced magnetic field

- Jupiter's magnetic dipole axis is tilted with respect to the rotation axis.
- Moons orbiting in the equatorial plane experience a varying magnetic field.
- This can induce electric currents in the moons, provided regions of sufficient electric conductivity.
- The produced secondary (or induced) magnetic field adds to the background field of Jupiter.
- The total field was observed by the magnetometer of the Galileo spacecraft.

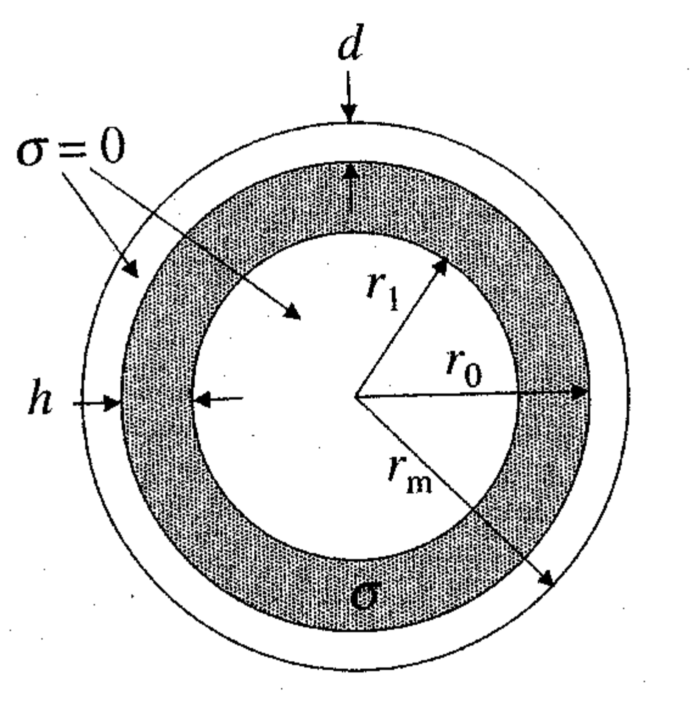
Primary magnetic field

1. Background field:
    (a) Internal field of Jupiter,
    (b) contribution from large-scale magnetospheric current system.
2. Contribution from local plasma currents caused by nonelectromagnetic interaction with the moon.

ad 1: Can be considered uniform on the spatial scale of the moons.

ad 2: Can be neglected for Callisto.

Assumed electrical structure of the moon



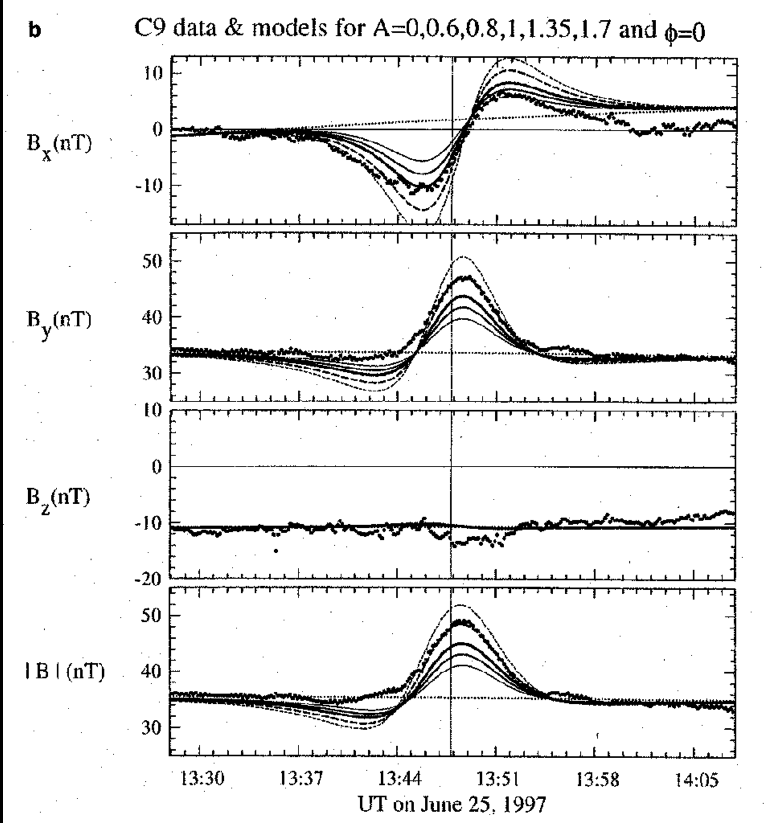
A uniformly conducting shell of conductivity σ. Its response to a time-varying magnetic field is a classical problem of electromagnetic theory.

Secondary magnetic field

$$\mathbf{B}(t) = A\,\mathbf{B}_{\sigma=\infty}(t)\,\left(t - \frac{\phi}{\omega}\right)$$

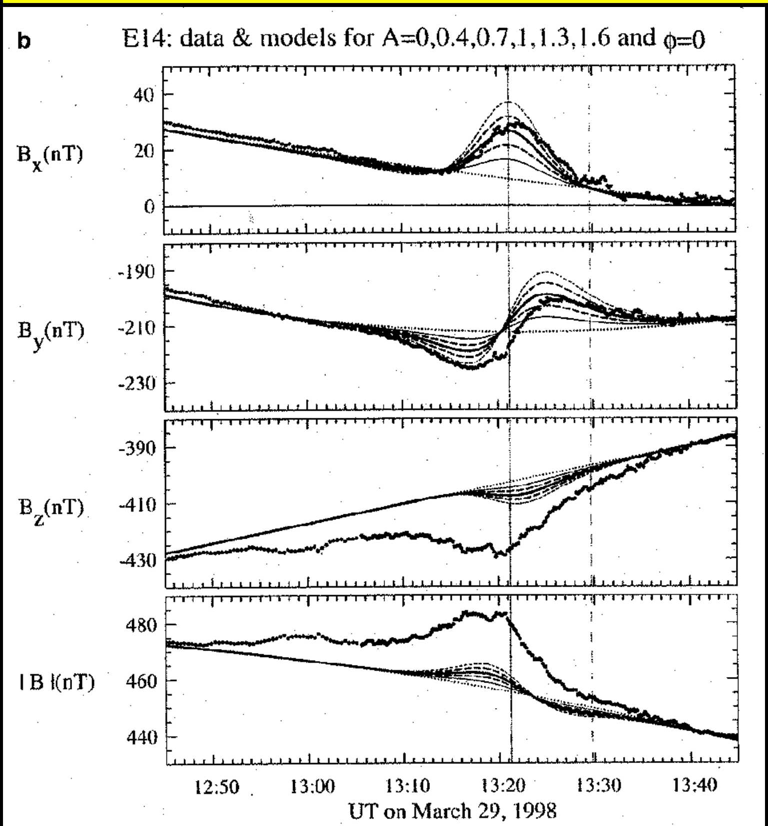
Amplitude: $0 \leq A < 1$
Phase lag: $0^\circ < \phi \leq 90^\circ$

Observations at Callisto



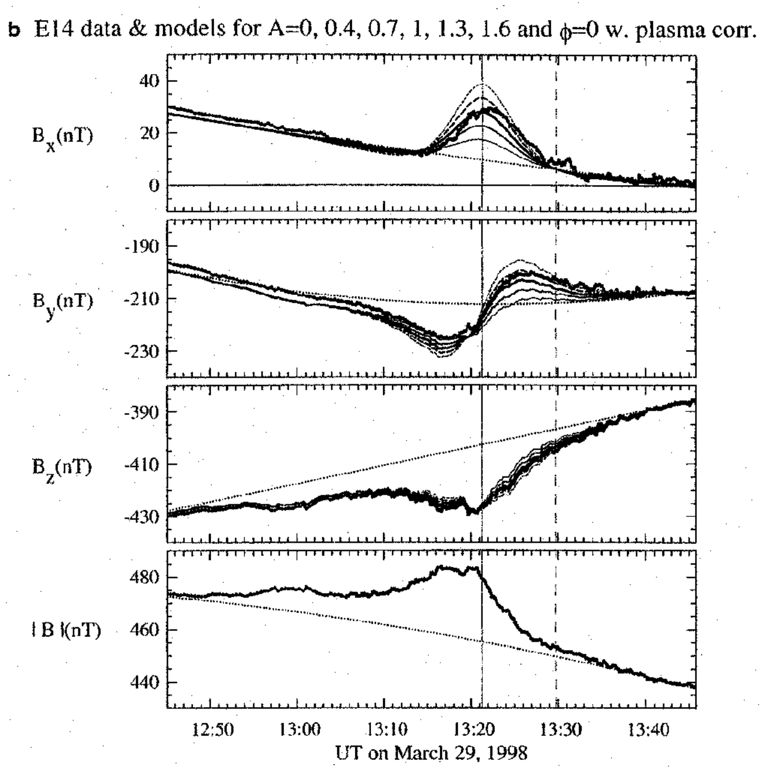
Acceptable values fall in the range $A = 0.7 \ldots 1$.

Observations at Europa



Observations indicate currents flowing in the ambient plasma.

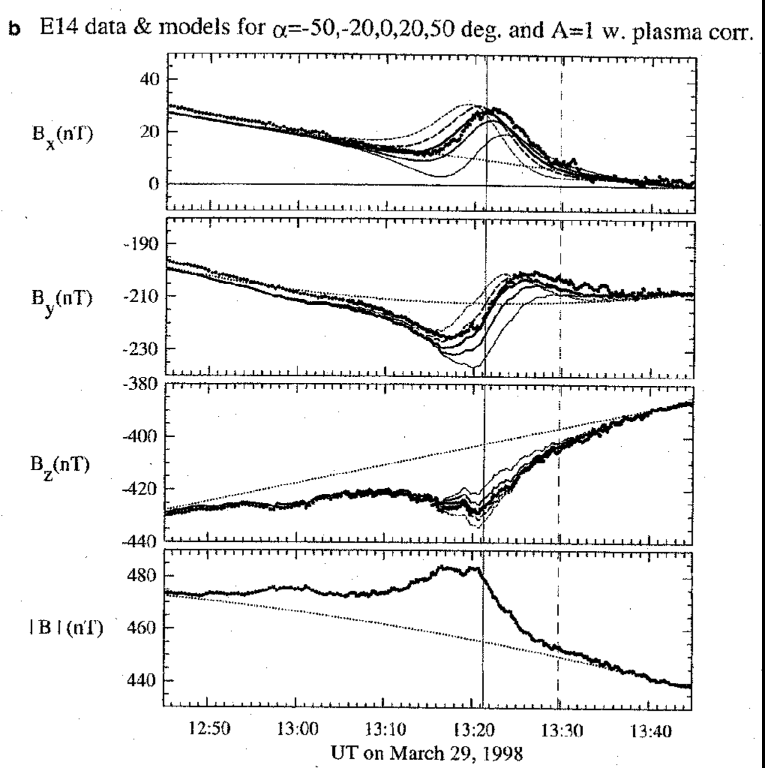
Model fields corrected for plasma effects



b E14 data & models for A=0, 0.4, 0.7, 1, 1.3, 1.6 and ϕ=0 w. plasma corr.

Acceptable values fall in the range $A = 0.7 \dots 1$.

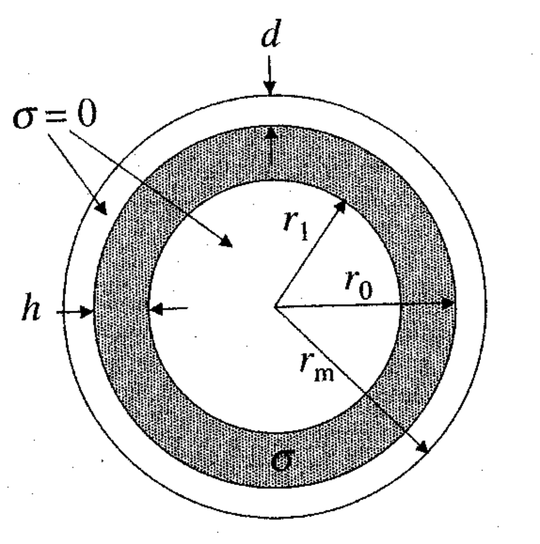
Model fields for different phase lags



b E14 data & models for α=-50,-20,0,20,50 deg. and A=1 w. plasma corr.

Data are reasonably well reproduced with $(A, \phi) = (1, 0^\circ)$.

Conclusions for Callisto



$A > 0.7$ requires:

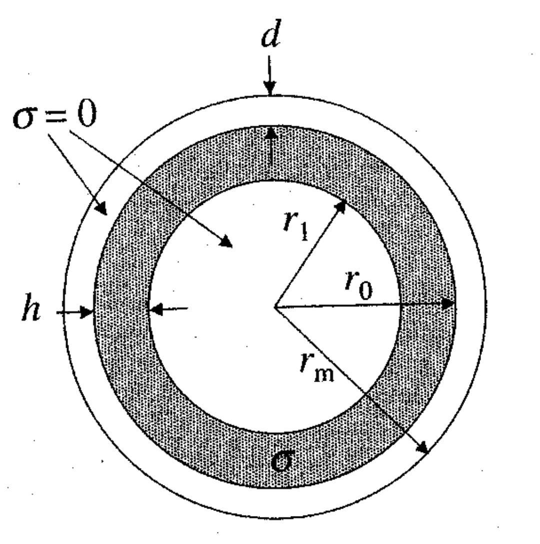
$\sigma > 22$ mS/m for arbitrary h,

$\sigma > 26$ mS/m for $h < 350$ km,

$h = 2$ km for $\sigma = 2.75$ S/m (salty water),

$d < 270$ km.

Conclusions for Europa



$A > 0.7$ requires:

$\sigma > 58$ mS/m for arbitrary h,

$\sigma > 72$ mS/m for $h < 200$ km,

$h = 3.5$ km for $\sigma = 2.75$ S/m (salty water),

$d < 175$ km.

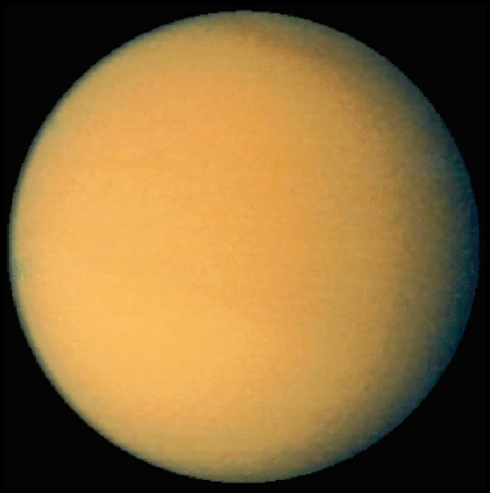
One currently assumed scenario: $d \approx 15$ km, $h \approx 100$ km.

Part 6: Titan

Under blue skys?

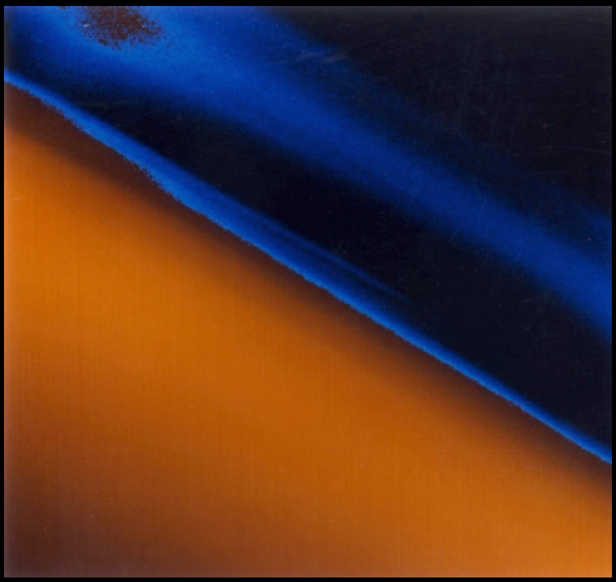
1944: Kuiper observes an atmosphere containing methane.

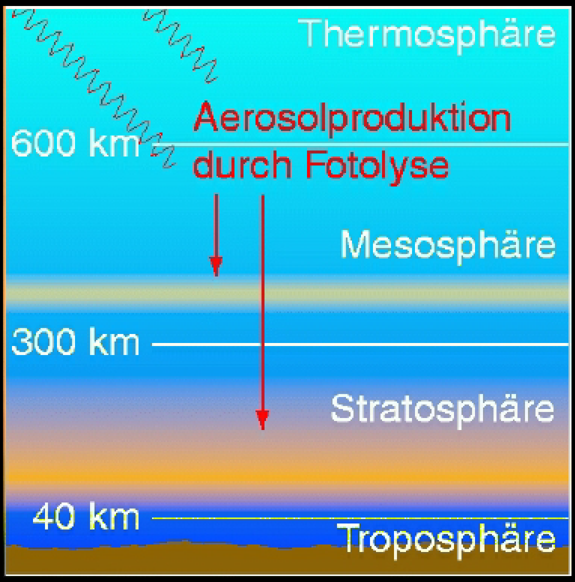
Titan's atmosphere



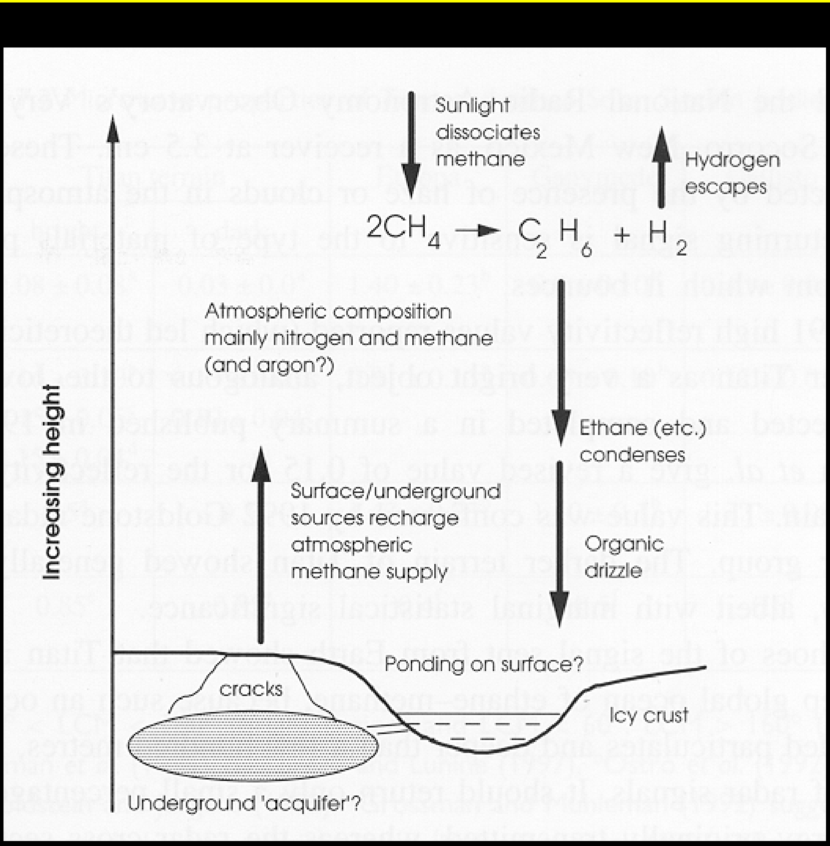
Surface pressure:	1.5 bar
Temperature:	93 K
Composition:	$> 90\,\%$ N_2, Argon, CH_4

Aerosol layers





The methane “cycle”



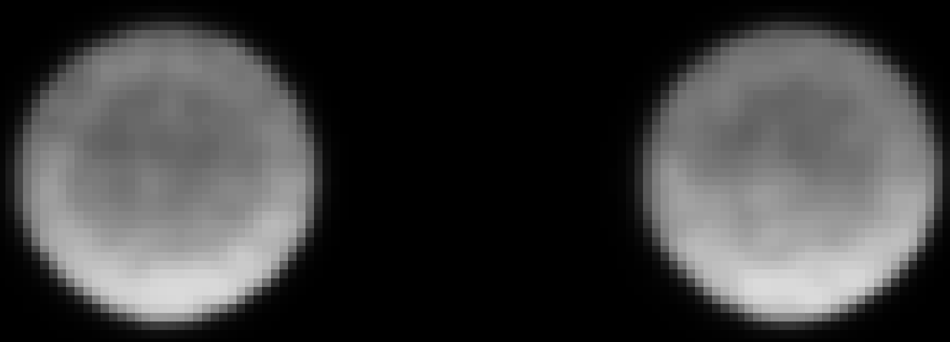
An ethane-methane ocean?

- A source to resupply the methane destroyed by photolysis is needed.
- Over geologic time, the ocean composition evolves to become more ethane-rich.
- In detailed numerical models, the ocean depth ranges from 500 m to 10 km.
- Recent radar observations indicate a specular reflection like from a liquid surface.

No *global* ocean!

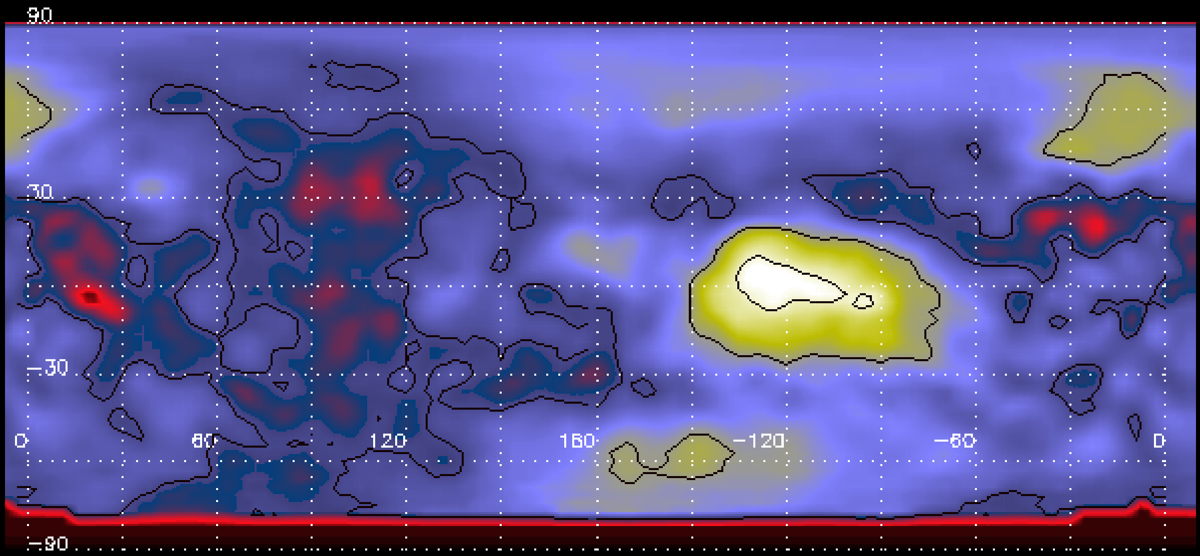
- Titan is in Laplace resonnance on an eliptical orbit (like the Galilean moons).
- Tidal forces on a global shallow ocean (less than 100 m deep) would have dissipated the eccentricity long ago.
- Of course, this assumes that the eccentrcity was not introduced recently by a large impact.
- The tidal argument can be overcome if the ocean is confined in basins.
- The most compelling evidence against a global ocean comes from near-infrared surface images . . .

Titan in the Hubble Space Telescope

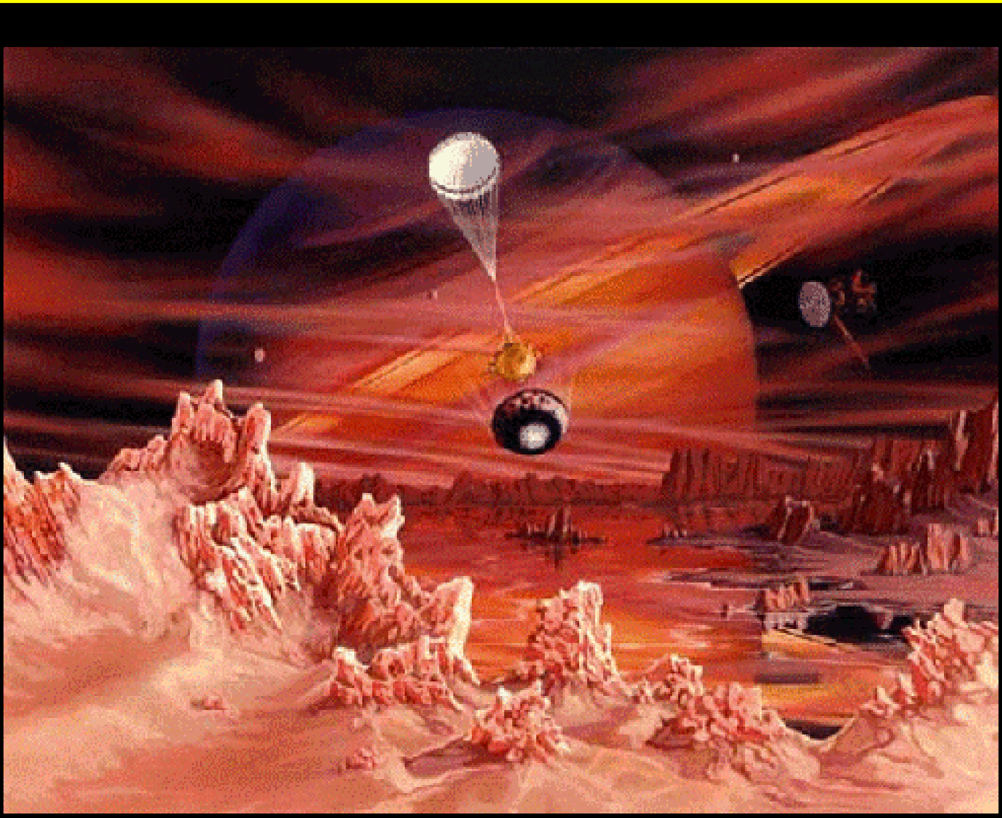


Near-infrared images of two hemispheres.

Map of the surface



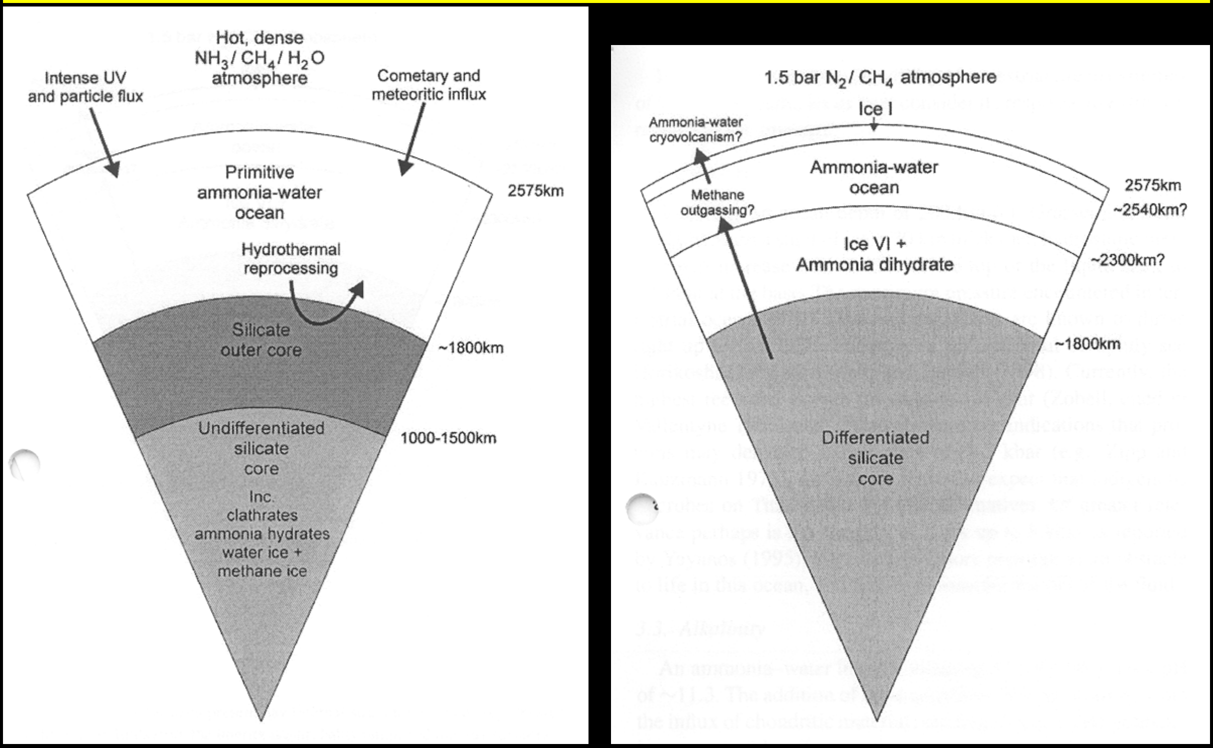
Cassini/Huygens: Landing on Titan



Primordial amonia-water surface ocean

- Titan formed in an ammonia–methane-rich circum-planetary nebula.
- During the first 10^8 years, there was a warm (> 300 K) environment.
- Ammonia was dissociated to generate a thick N_2 atmosphere.
- As the ocean cools down, it is roofed over by Ice I, while at the base high-pressure Ice IV and ammonia dihydrate cristallize.

Evolution of an ammonia-water ocean



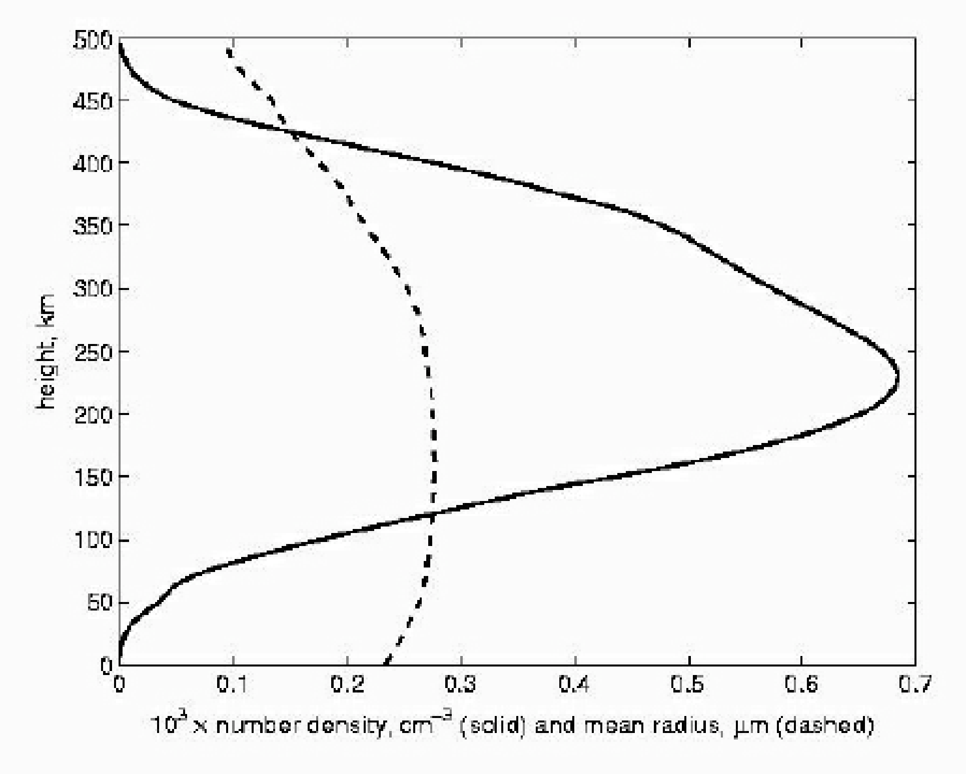
Illustrations from Fortes (1999), Icarus *146*, 444–452.

Hypothesis of a contemporary subsurface ammonia-water ocean

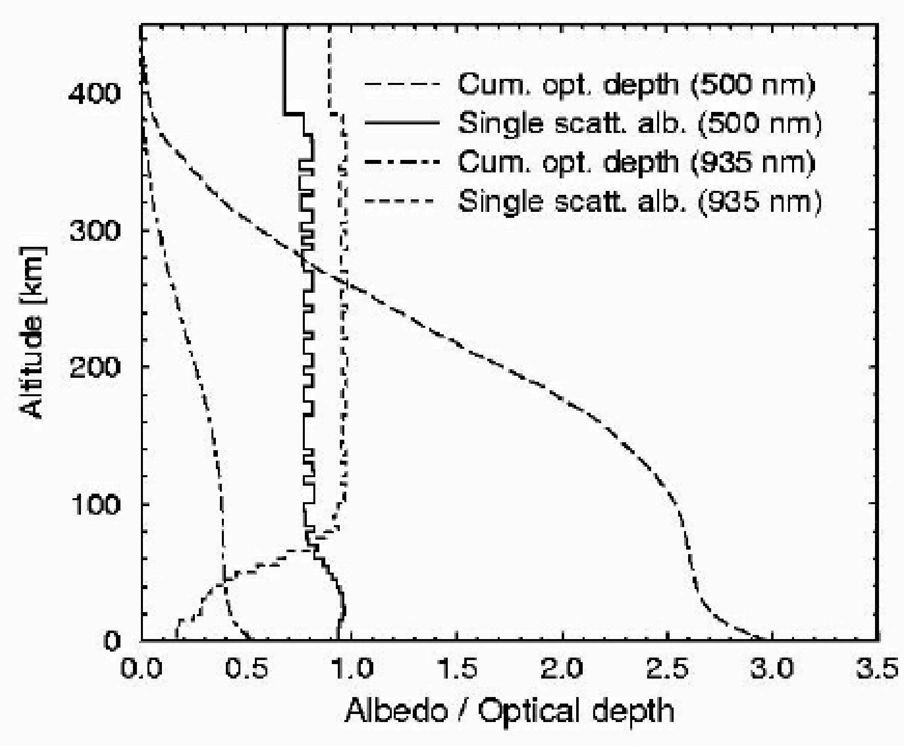
Depth :	≈ 200 km
Temperature:	235–240 K
Presure:	1–4.5 kbar
pH:	10.5–11.4

Such an ocean could be detected by the Cassini mission (whereas any biological activety can not).

Microphysical modeling of aerosol formation



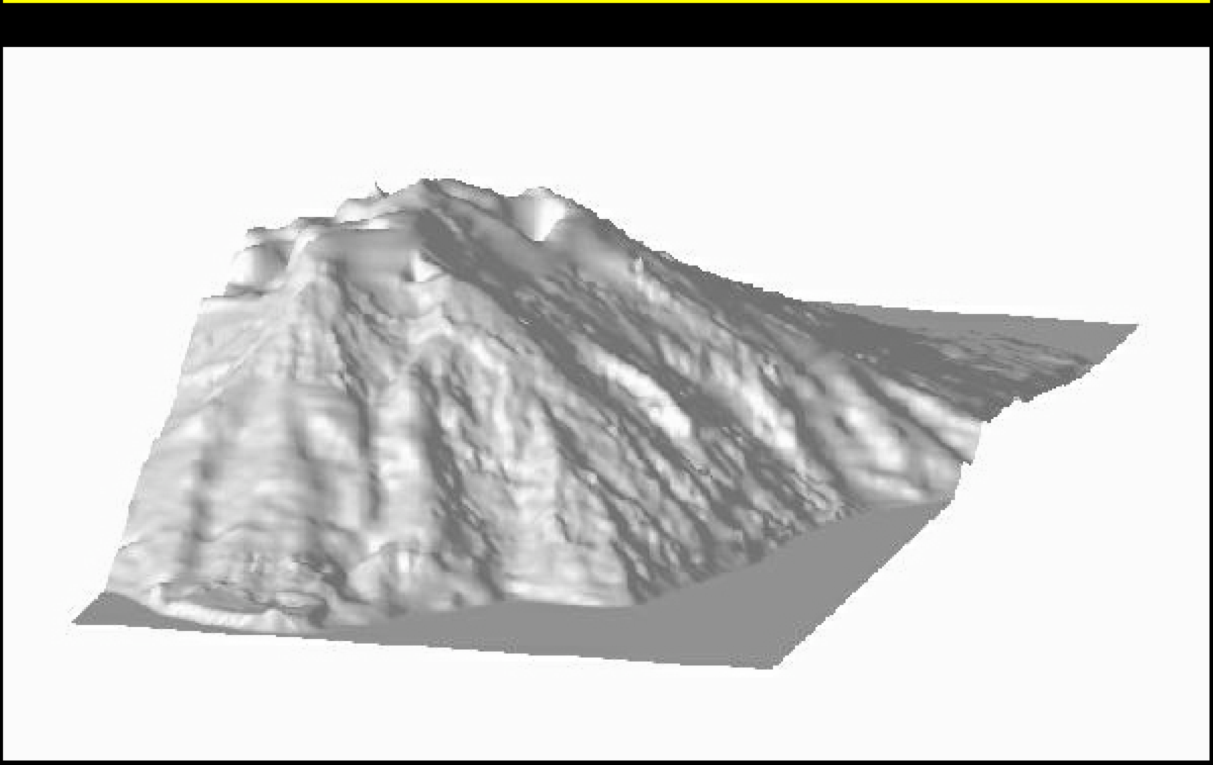
Optical properties of the model atmosphere



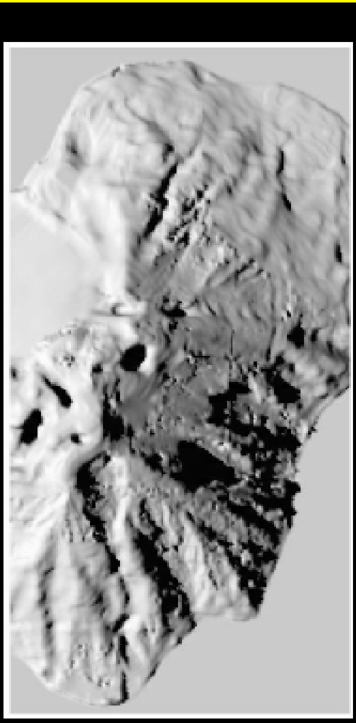
View at top of atmosphere

View at the surface

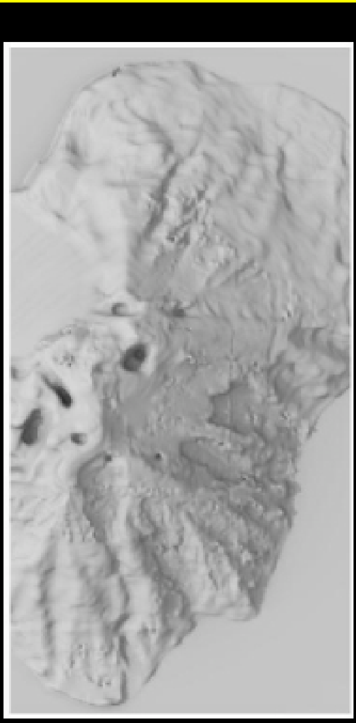
Stromboli Island as example surface structure



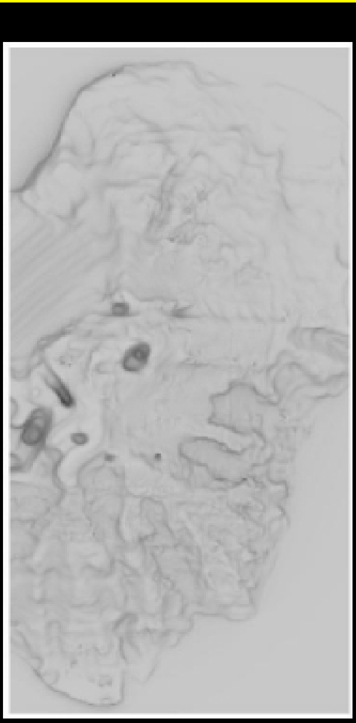
Different illuminations



Point light



Titan sky



Isotropic

Stromboli Island under Titan's sky