Internal Structure of Icy Satellites of Jupiter

Oleg Kuskov,

Victor Kronrod

Vernadsky Institute of Geochemistry, Moscow

Europa Lander:
science goals and experiments
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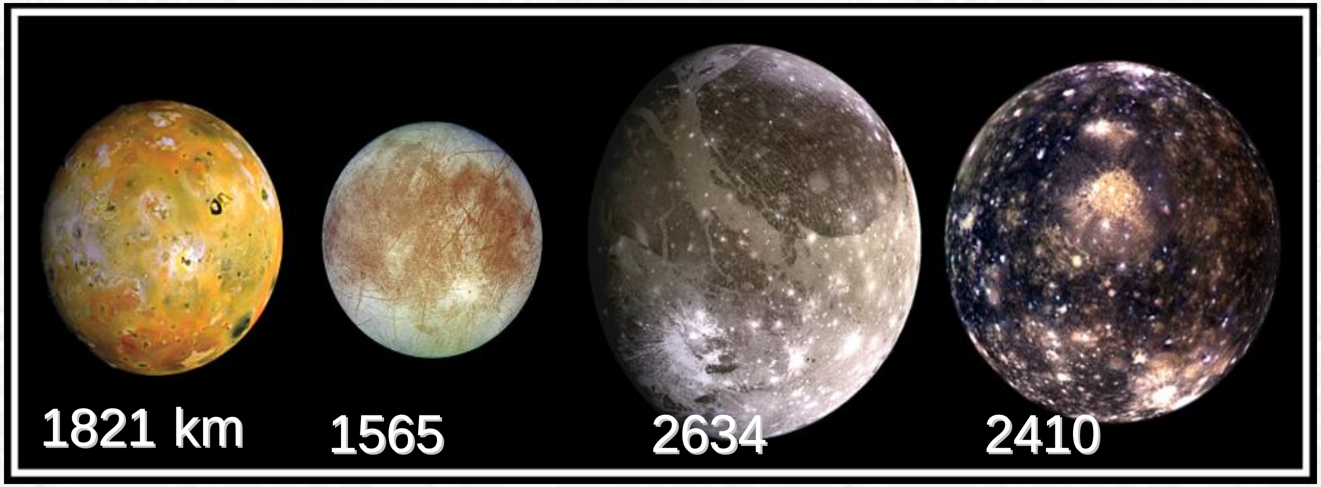
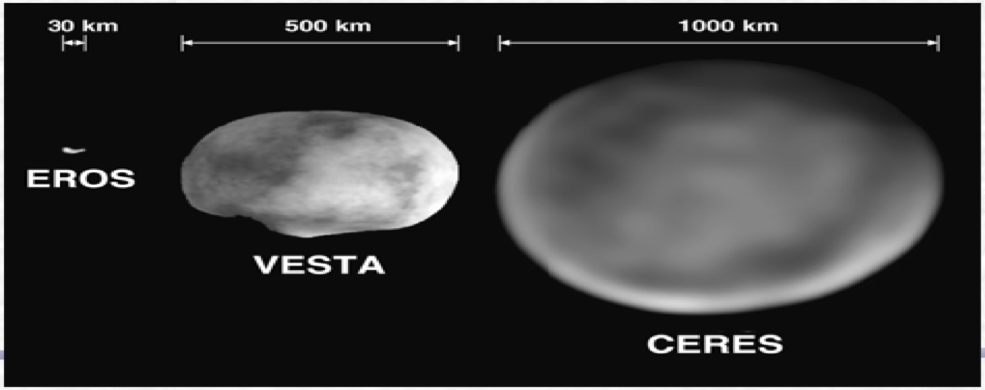
The Galilean satellites and large asteroids

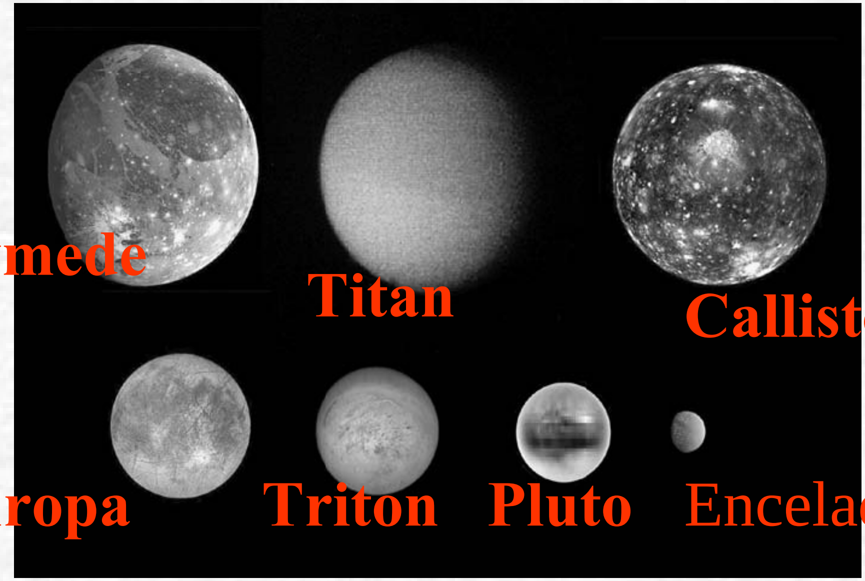


Ganymede and Callisto are the size of Mercury, and Io and Europa are the size of the Earth's Moon. Io, Europa and Ganymede are **differentiated** satellites and Callisto is a **partially differentiated** satellite.



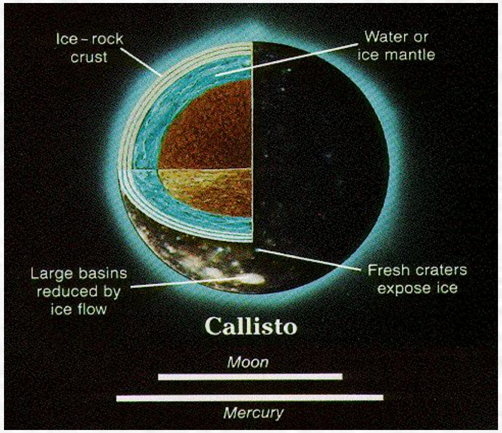
Outline

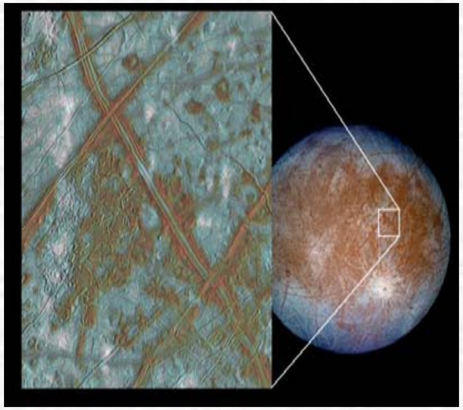
- Evidence for Ice/Water shell
- Methods of estimating interiors
  - Gravity and magnetic measurements, moment-of-inertia
  - Heat flow
  - Meteorites/chondrites
  - Thermodynamics,
  - Equations of state,
  - H2O phase diagram
- Summary

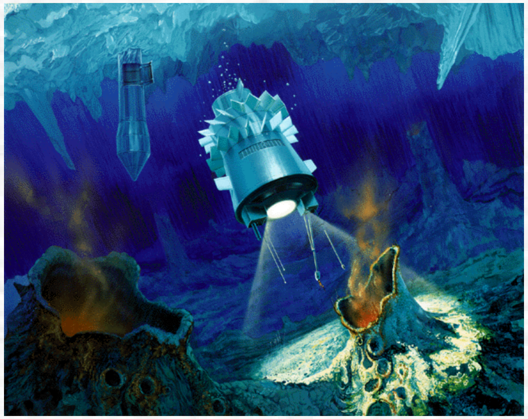


- The probable presence of liquid water beneath the outer ice crust is expected on these bodies.
- Internal structure and thermochemical evolution of the icy satellites are poorly known. The data obtained by the Galileo mission on the gravitational fields of the satellites made it possible to determine the radii, density and moments of inertia values, and to estimate the thickness of outer water-ice shells, core sizes and chemical composition.

The main questions





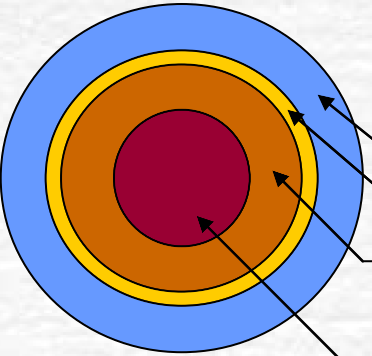


- Is there a water ocean beneath the iced surface?
- How deep is the ocean?
- How thick is the ice shell?
- Is Callisto differentiated / partially differentiated /undifferentiated satellite ?
- What is the thermal and chemical structure of the Galilean moons?
- Is there life???

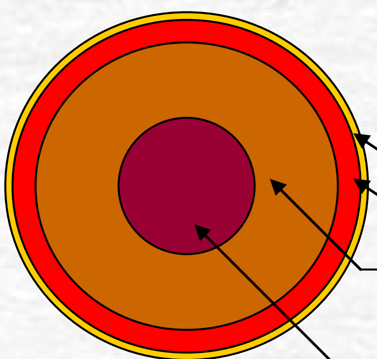
Models of the Satellites

Europa

Ganymede

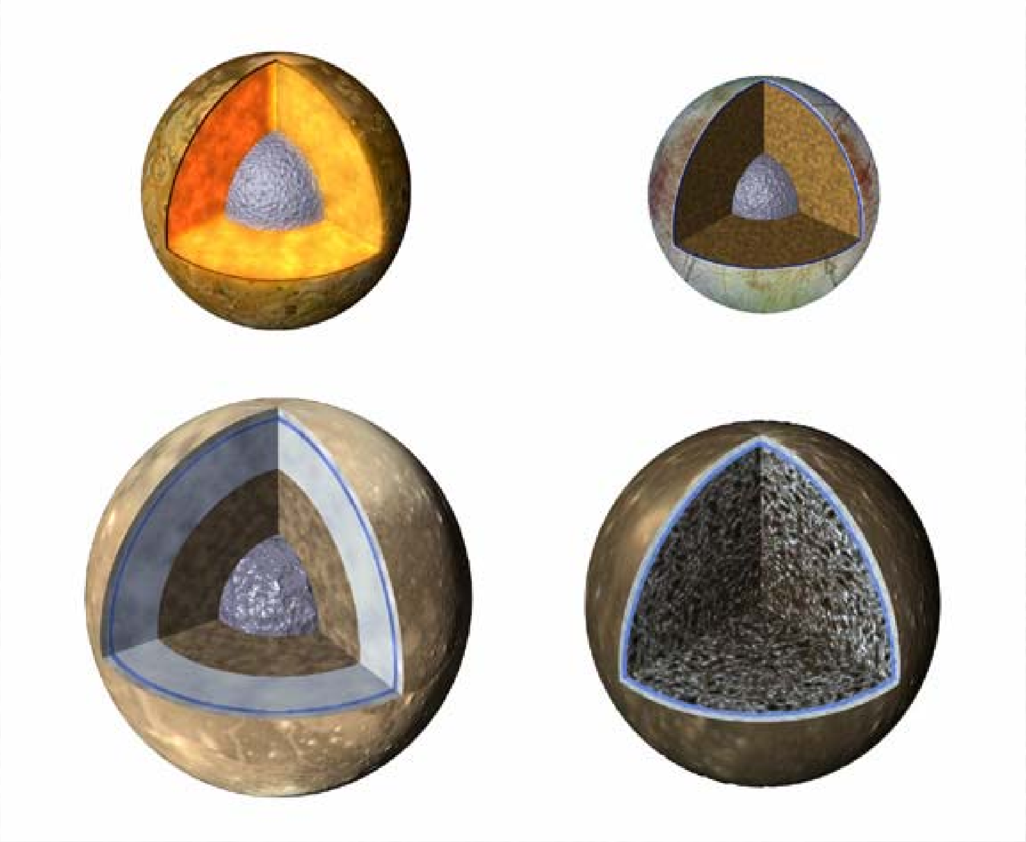


Io



- **Leaving aside the details, we consider models of the internal structure of the satellites, including an ice (water-ice) layer and a rock-iron core. Rock-iron cores of Europa and Ganymede consist of crust, mantle and Fe-FeS core.**
- **In contrast, Io consists of crust, asthenosphere, silicate mantle and Fe-FeS core.**

Major Aims



We present the results for determining

- (1) the thickness of an ice-water shell,
- (2) the satellite chemistry - (Fe/Si) ratio and metallic iron content,
- (3) the Fe-S core sizes and masses.

Mass and moment-of-inertia values are used to model the internal structure of the satellites.

- Ordinary and carbonaceous chondrites are taken as representatives of nebula matter

Approach

- We assume a three-layer model: water-ice shell, silicate mantle, and metallic core consistent with the values of mass and moment of inertia
- Core models: Fe-10 wt%S-core for ordinary (H, L, LL) chondrites, and
- Fe-FeS and FeS (troilite)-core for carbonaceous (CI, CM, CV) chondrites.

- For phase equilibrium calculations in the system Na_2O-TiO_2-CaO-FeO-MgO-Al_2O_3-SiO_2, the Mie-Gruneisen equation of state of minerals and free-energy-minimization technique were used.

  Phase diagram of H2O

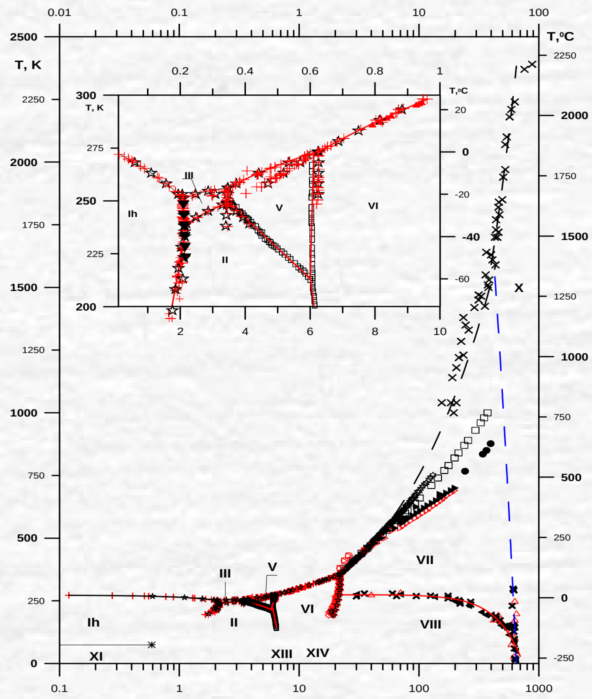
- The core radii and masses are found by the Monte-Carlo method.

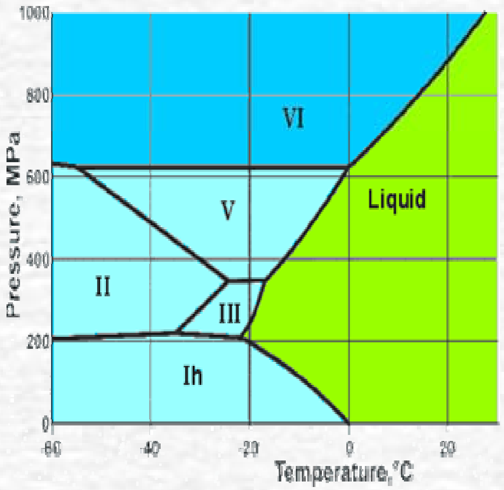
Mathematical model

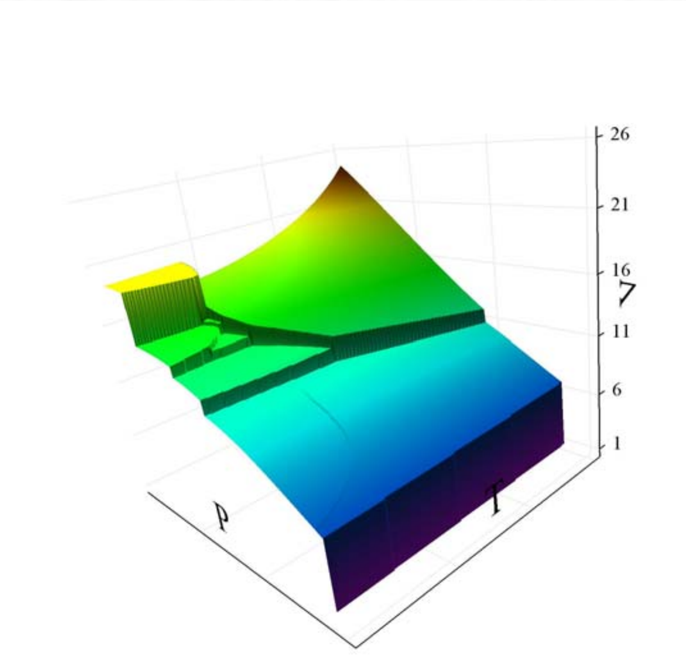
- **The known parameters**
  - **moment of inertia and mass**
  - **+ chemistry of chondrites + thermodynamics**
- **The density of the mantle mineral assemblages is calculated from the silicate fraction of ordinary and carbonaceous chondrites.**

- **The unknown parameters**
- **The distribution of density**
- **The radius of Fe-FeS core**
- **The thickness of the crust**
- **The thickness of the water-ice shell**
- **The $Fe_{(tot)}$/Si ratio in the rock-iron core**
- **The distribution of temperature**

H_2O Phase Diagram





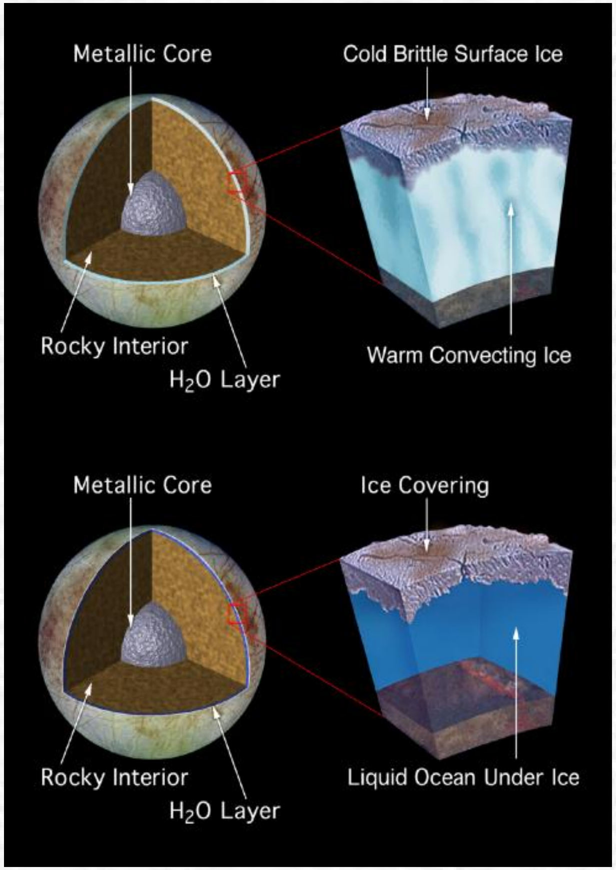


- These figures illustrate the stability fields of high-pressure ices and possibility of the existence of a liquid-water ocean on the icy satellites, because the melting temperature of ice-I decreases with pressure up to the triple point.

Europa - Second major satellite from Jupiter, Smallest of the Galileans (a little smaller than Earth's Moon)
ρ =2.989 g/cm^3, R= 1565 km, I/MR^2 =0.346$\pm$0.005

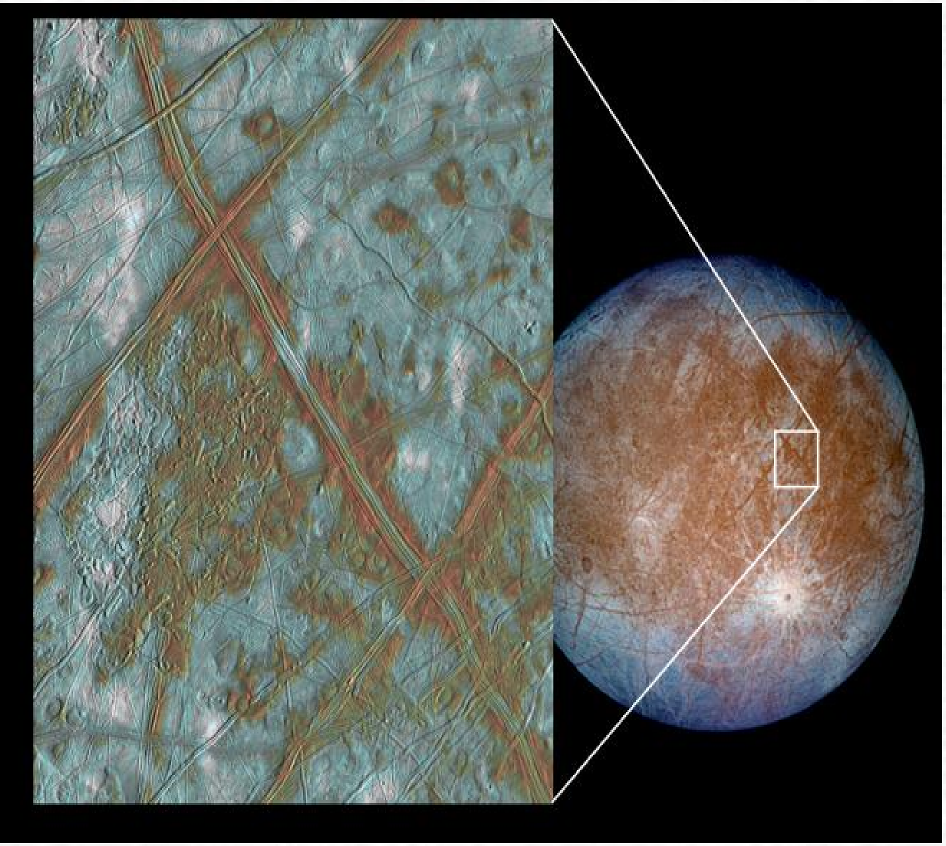
The main facts

- Ice-cracks on Europa's surface consistent with either "warm-ice" or water beneath the surface
- Moment-of-inertia values (Anderson et al., 1998)
- Magnetometer data from Galileo mission confirm presence of water (Kivelson et al., 2000)



- Geophysical and geochemical constraints are used to model the internal structure of Europa for three first-order parameters (none of which is known):
- (1) the thickness of an outer water-ice shell;
- (2) the chemical composition - the ratio of total iron to silicon (Fe_{tot}/Si), FeO content, and metallic iron content;
- (3) the core sizes and masses.

Europa



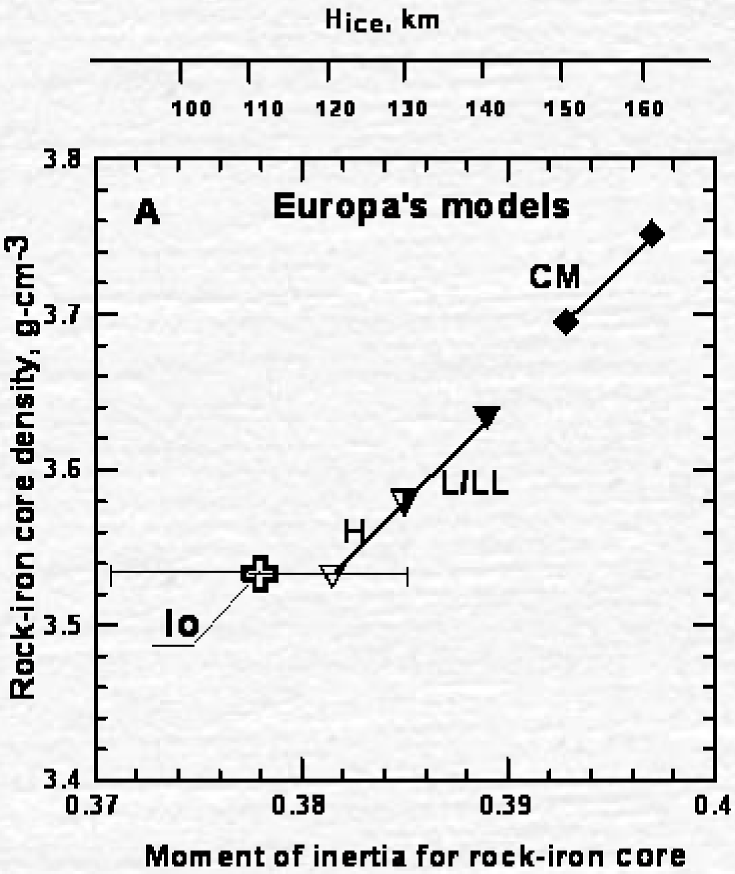
- Morphology features are the best evidence that Europa has or had a subsurface ocean. The lines represent tectonic features, such as cracks and rifts, and ridges.

- The characteristic feature of Europa is the probable presence

of liquid water beneath the outer ice crust, which gave rise to attractive hypothesis on the existence of extraterrestrial forms of primitive life.

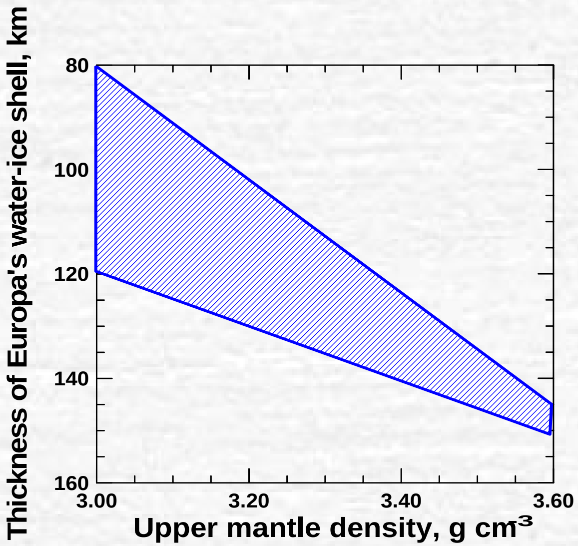
The existence of a water ocean on Europa was supported by magnetic measurements obtained with *Galileo*.

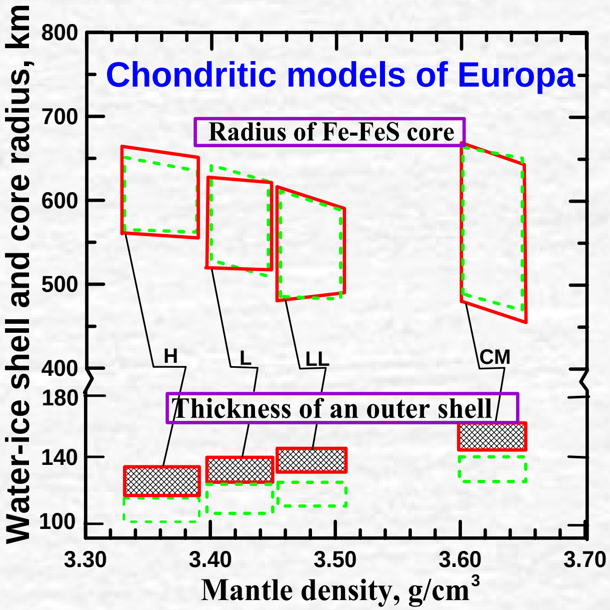
Moment of inertia values for the rock-iron core of Europa vs the rock-iron core density



- The models of the rock-iron core (chondritic mantle + central Fe-10% S core for ordinary chondrites or FeS core for carbonaceous chondrites) are consistent with the total mass and moment of inertia for Europa ($M = 47.99 \cdot 10^{21}$ kg, $I^{\circ}/MR^2=0.346\pm0.005$) at varying thickness of the outer water-ice shell, *H*(ice).
- The cross denotes the mean density and moment of inertia for Io (Anderson et al., 2001) and shows that H/L/LL chondritic models of Europa's rock-iron core with $H(H_2O)$ = 100-140 km are closer to the position of anhydrous Io than C-chondritic models.

Europa: Thickness of an outer shell and core sizes





A geophysically permissible thickness of the Europa's shell lies between 80 and 160 km.

Any thickness of the outer shell beyond the range obtained is incompatible with the constraints on the mass and moment of Europa.

R_E, km	R(Fe-S) core, km	H(ice), km	M_{ice},%
1565	450-670	100-160	6-8

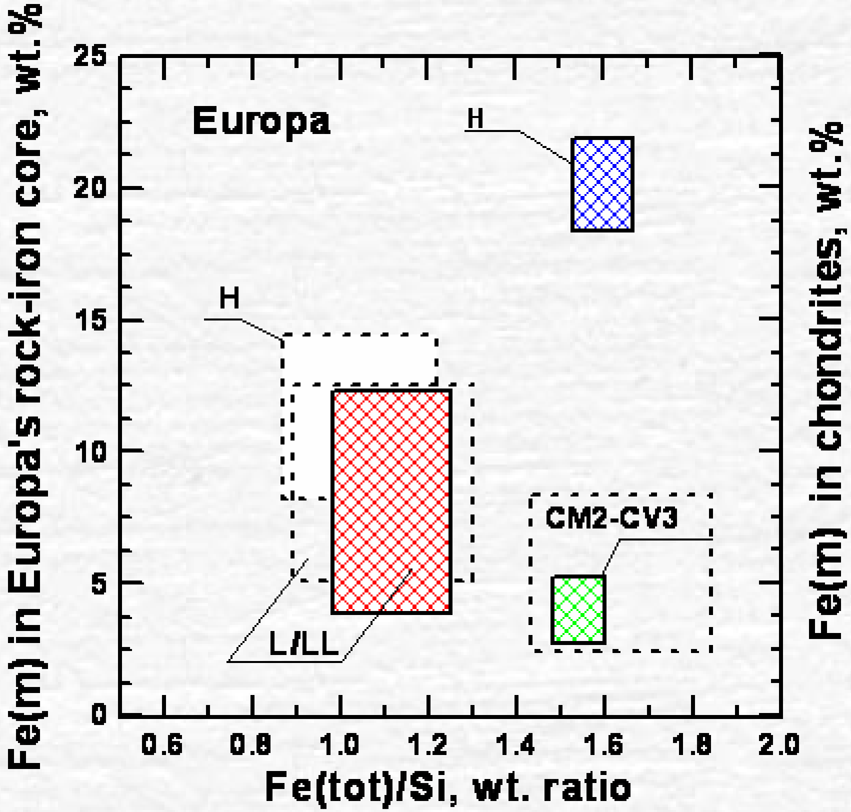
Thickness of an outer water-ice shell depends on the presence of a crust (dashed lines) and density of a chondritic mantle:

100-140 km – H/L/LL;

130-160 km – C chondrites.

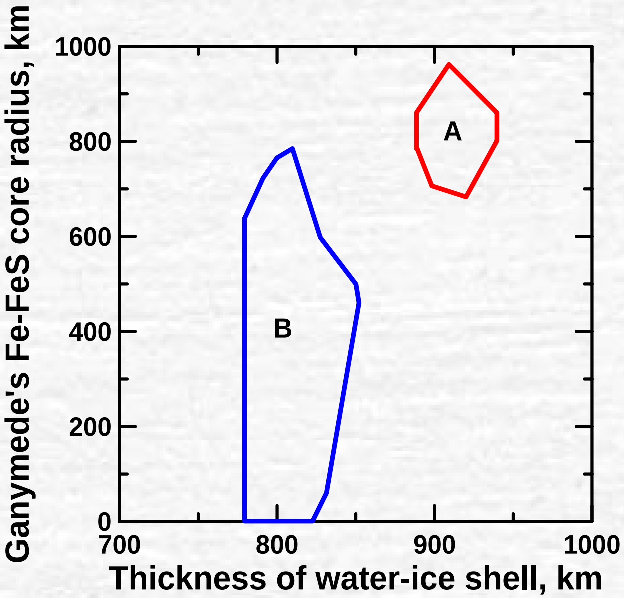
Europa contains 6-8% of H_2O and has a core (R=450-670 km).

Element ratios for the chondritic models of Europa



- Element ratios for Europa (empty boxes) and chondrites (shaded boxes). The boxes outline an allowed Fe/Si ratio and content of metallic iron in chondrites and satellite.
- Europa's major element composition matches the bulk composition of L/LL chondrites.
- H and C (probably) chondritic materials may be excluded for Europa's bulk compositions.

GANYMEDE – Biggest of the Solar system satellites



- Two alternative models of an outer shell are considered.

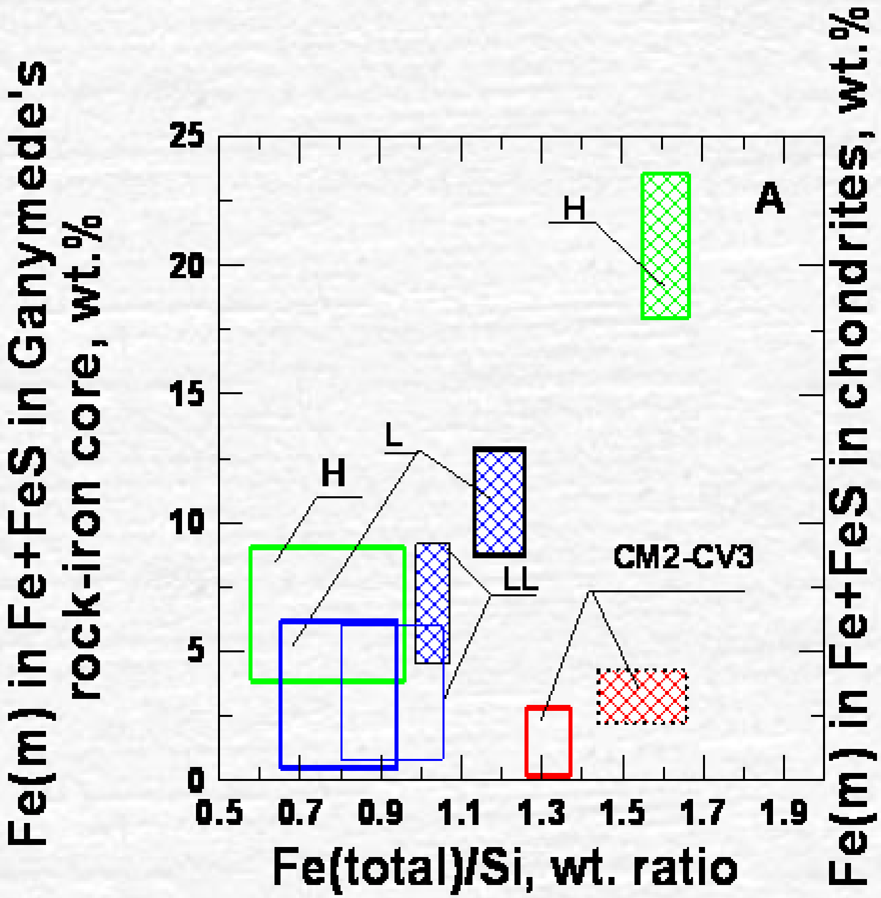
Model (A) - an outer shell is completely composed of the high-pressure ice phases (no water is present) - 890-920 km thick.

Model (B) - below a shell of ice-I (30-120 km thick), a liquid layer of 230-140 km thick may exist. The water-ice thickness in model (B) is 780-850 km.

The content of H2O in Ganymede's outer envelope is **46-48%** of the total mass.

- **R(Fe-FeS-core) = 800-950 km**

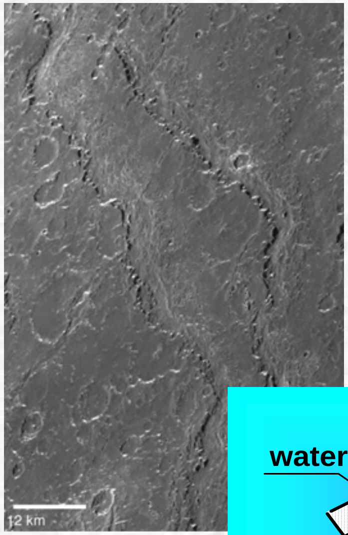
Element ratios for the chondritic models of GANYMEDE

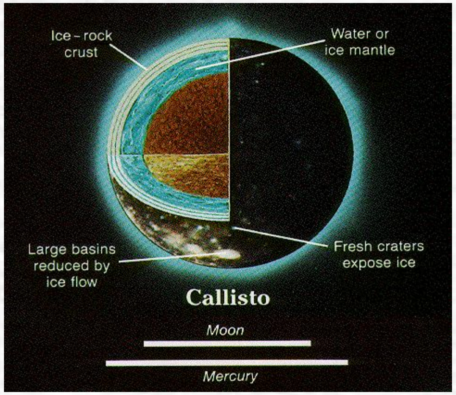


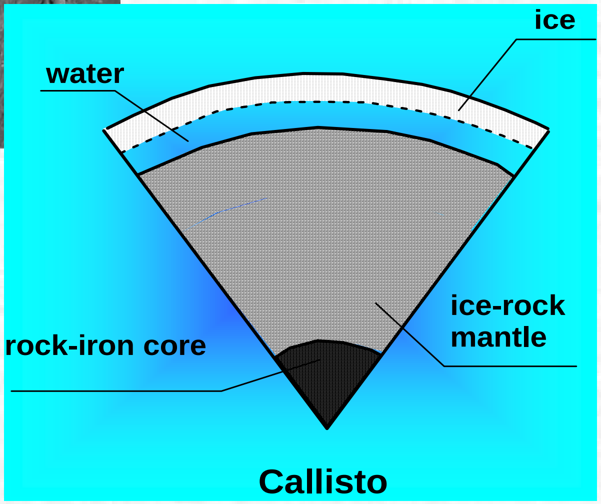
- Element weight ratios Fe_{tot}/Si vs $Fe_m+Fe_m(FeS)$ for chondritic models of Ganymede's rock-iron core (empty boxes) derived from the geophysical constraints in comparison with those in chondrites (shaded boxes).
- **Bulk composition of the rock-iron core of Ganymede may be described by the composition close to the L/LL chondrites.**
- Geochemical constraints show that H and C chondritic matter was not the building material of the rock–iron core.

Callisto

R=2410 km, I*=0.3549, ρ=1.834 g/cm3

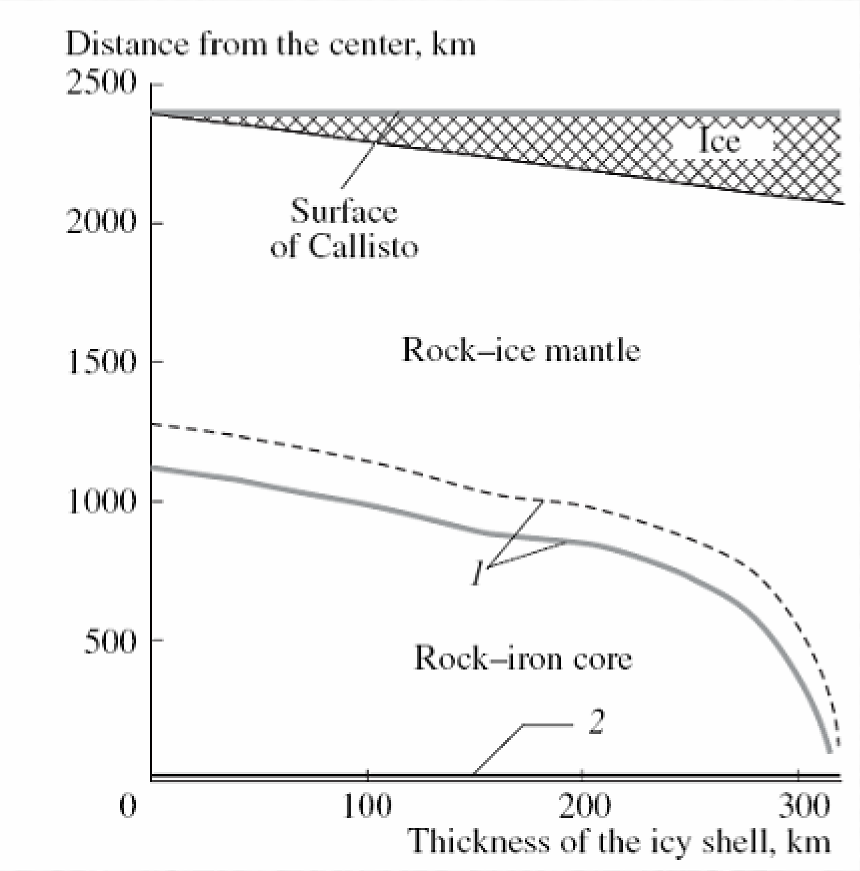






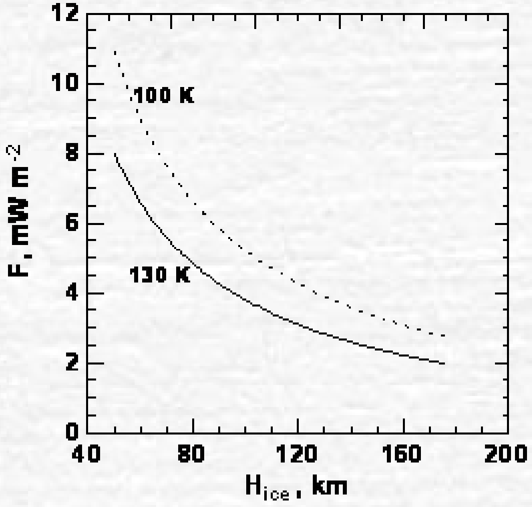
- We consider a six-layer model of Callisto consisting of an ice layer, a water ocean, a three-layer ice-rock mantle, and a rock-iron core. The major uncertainty in the internal structure of Callisto is related to the equation of state of rock-iron material, because its density can vary from low (hydrous silicates + Fe-FeS alloy) to high values (anhydrous silicates + Fe-FeS alloy). Taking into account the considerations from the constitution of Europa and Ganymede, we accept that the composition of the rock-iron material of Callisto is similar to the bulk composition of L/LL type chondritic material containing up to 10-15% of iron and iron sulfide.

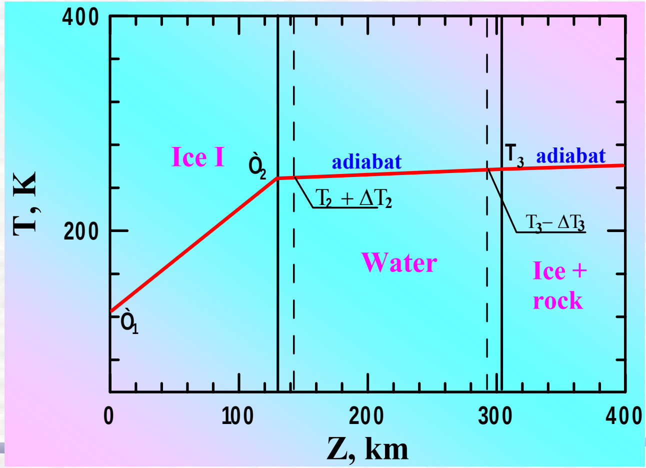
Model of Callisto with a continuous icy shell – ocean is completely frozen



- In general, Callisto can consist of three chemically different layers: an icy lithosphere, a rock–ice mantle, and an ice-free rock–iron core.
- The maximal thickness of the icy lithosphere is 320 km.
- Two-layer models of Callisto are possible: (1) an outer icy lithosphere and a rock–ice mantle (without a central rock–iron core), (2) an outer rock–ice shell and a central ice free rock–iron core (without an icy lithosphere).
- One-layer model of Callisto with constant ice concentration from its surface to the center is not realistic.
- A two-layer model composed of an icy lithosphere and a dry rock–iron core contradicts the constraints on the moment of inertia.

Thickness of the icy crust versus the heat flow from the surface of Callisto

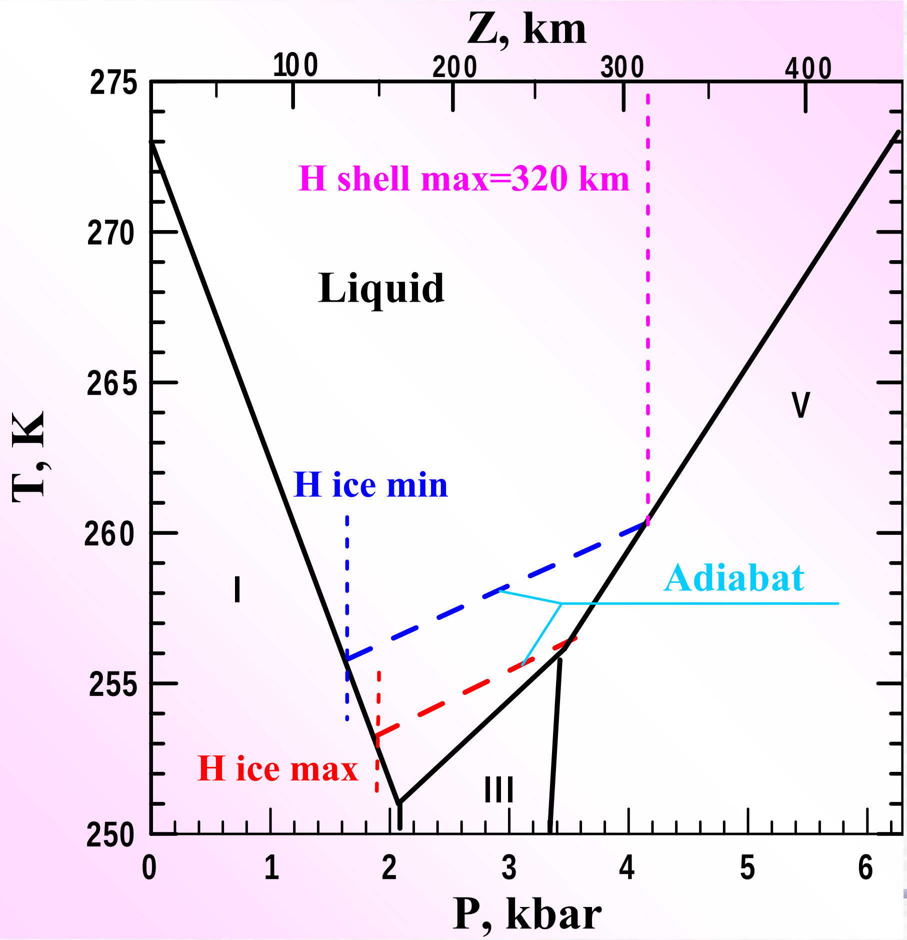




- The maximal pressure at which the water layer can exist corresponds to a depth of ~176 km. Depending on the surface temperature, the heat flux through the crust of such a thickness varies from
- ~2 (T = 130 K) to 2.7 (T = 100 K) mW/m^2 .
- If the heat flux from the satellite exceeds these values, there should be water beneath the ice layer. At present, the heat flows expected from the satellite are estimated as 3.3–3.9 mW/m^2 (Mueller and McKinnon, 1988), indicating that there can be an ocean beneath the ice-I layer.

The permissible thickness of Callisto's water-ice shell

F = 3.3-3.7 mW/m²



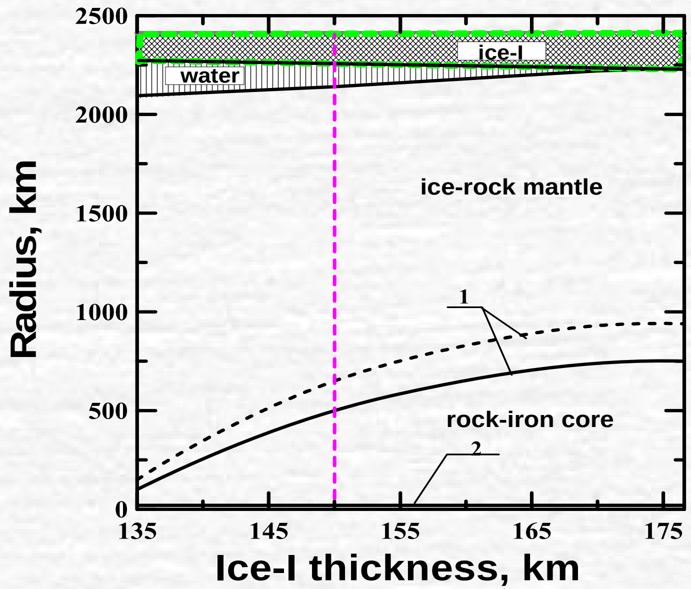
- **The distribution of temperature was calculated from the condition of conductive heat transfer in the ice-I layer, and the T-profile in the stability fields of water and high-pressure ices goes along the adiabat.**
- **The heat flow values are in the range of 3.3-3.7 mW/ m². In this case the geophysically permissible thickness of ice-I crust is 135-150 km, and the thickness of the underlying internal ocean is between 120 and 180 km.**

A model of Callisto with an internal ocean

- Callisto consists of an ice layer, a water ocean, a rock-ice mantle, and a rock-iron core free of ice.

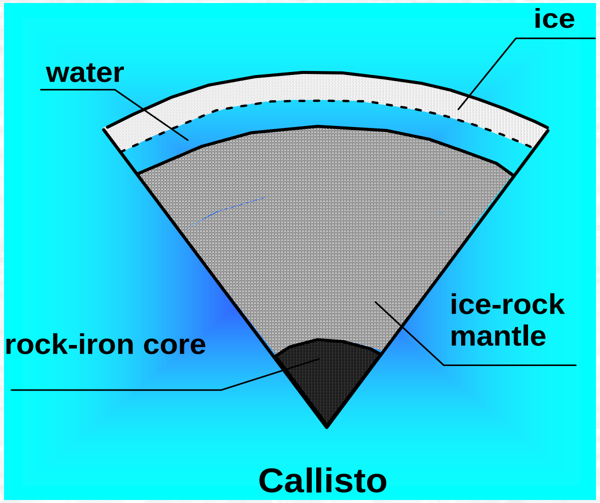
- Because Callisto is only partially differentiated, a layer of a mixture of high-pressure ices and rock-iron material (ice-rock mantle) must exist between the outer shell and the rock-iron core.

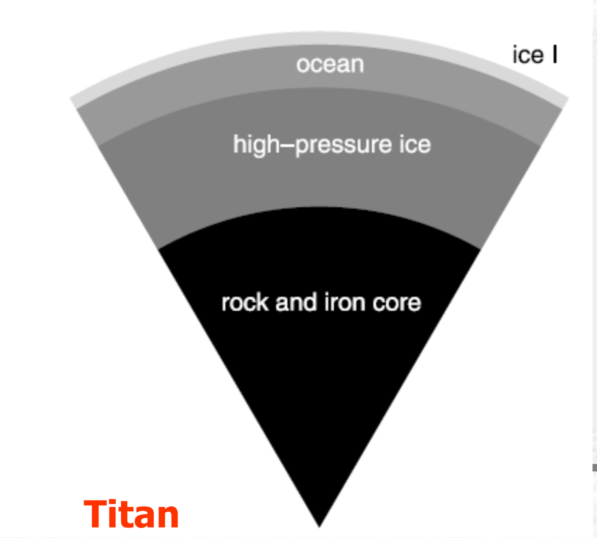
The total thickness of the outer shell is 270-315 km, the thicknesses of the ice crust is ~150 km and that of the ocean is ~120-180 km.



ρ(Fe-Si) g/cm3	H(ice-I) km	H(wat) km	H(ice+wat)
3.15	135-150	120 -180	270-315
3.62	135-150	120-165	270-300

Models of Icy Satellites

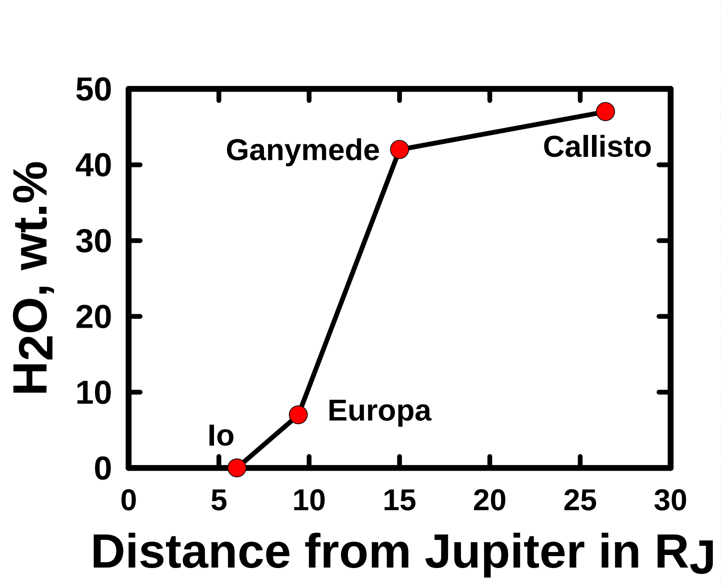




Ganymede

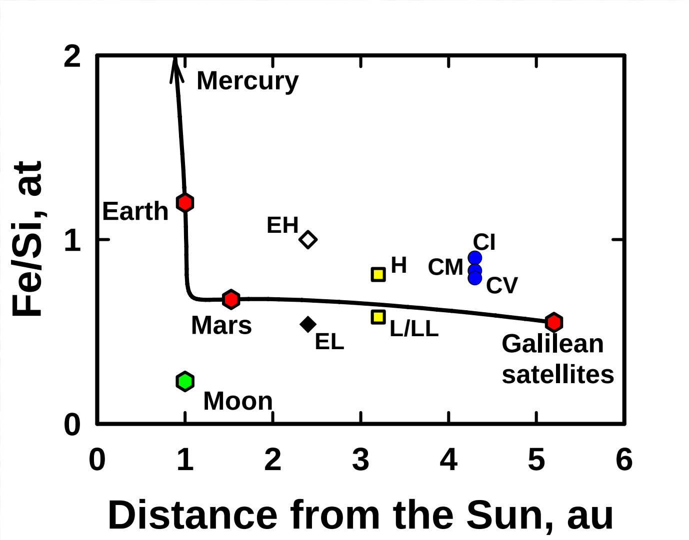
Water-ice shell, km	Callisto (Kuskov, Kronrod, 2005)	Titan (Sohl et al., 2003)	Ganymede (Kuskov, Kronrod, 2001)
Ice crust	150	70	120
Ocean	150	220	140
Water+ices-V-VI	0	600	600
Total thickness of H2O shell	300	900	800-900

Amount of H2O in the satellites



- Ice-free Io
- Europa ~6-8% of H2O.
- The water and ice content in Ganymede is between 46-48%.
- The total amount of H2O in Callisto is found to be 49–55 wt%.

Fe/Si ratio and chemical composition in the protojovian nebula



- The Fe/Si ratio varies from 4.5 for Mercury to 0.5 for the Galilean satellites.
- Geophysical and geochemical constraints show that the bulk compositions of the rock-iron cores of the Galilean satellites are similar and may be described by the composition close to the L/LL chondrites. Fe/Si ratio for C-chondrites is ~0.85. These results indicate that the jovian satellites did not form from C-chondritic material.

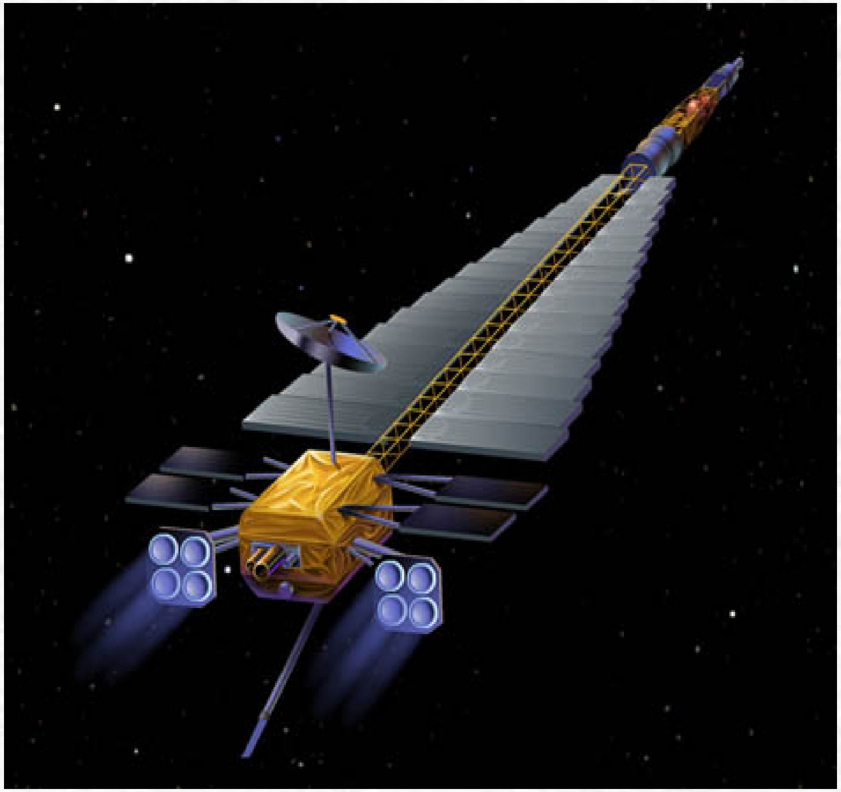
Planetesimals composed of the L/LL types of ordinary chondrites could be considered as analogues of building material for the rock–iron cores of the Galilean satellites.

Isochemical composition of Io, Europa, Ganymede and Callisto

$Fe_{tot}/Si \sim 0.5$; $(FeO)_{mantle} \sim 16$ wt.%

Similarity of bulk composition of the rock–iron cores of the inner and outer satellites implies low temperatures in the protojovian nebula and the absence of iron–silicon fractionation.

Conclusions



- (1) We have constructed models of Europa, Ganymede and Callisto based on *Galileo* measurements and cosmochemical constraints on the composition of chondrites.

  (2) Chemistry of the satellites and the amount of H2O are estimated. Fe/Si ratio is close to that of the L/LL chondrites. The results indicate that the jovian satellites did not form from C-chondritic material.

  (3) H2O-content: Europa - 6-8%, Ganymede and Callisto – 46-55%.

  (4) The results of modelling support the hypothesis that Callisto may have an internal liquid-water ocean.

- (5) Rock-iron material forming the Galilean satellites may reflect the chemical composition of the solar nebula at the radial distance of Jupiter.

Thank you for your attention!