ESS2222H

Tectonics and Planetary Dynamics
Lecture 8 – Other Solar System Planets

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Gaseous Planets

Gaseous Planets
Jupiter

Atmosphere

Jupiter's upper atmosphere **~90% hydrogen** and **~10% helium** by **volume** and **75% hydrogen** and **24% helium** by **mass** and **minor amounts** of **methane**, **water vapour**, **ammonia**, and **silicon-based** compounds and **very minor fractions** of **carbon**, **ethane**, **hydrogen sulphide**, **neon**, **oxygen**, **phosphine**, and **sulphur.** Wind speeds exceed 600 km/h.

Interior

The interior of Jupiter which includes small **rocky/icy core, metallic hydrogen, helium-neon layer, liquid hydrogen,** contains **~71% hydrogen, 24% helium, and 5% other elements** (by mass).

Magnetic field

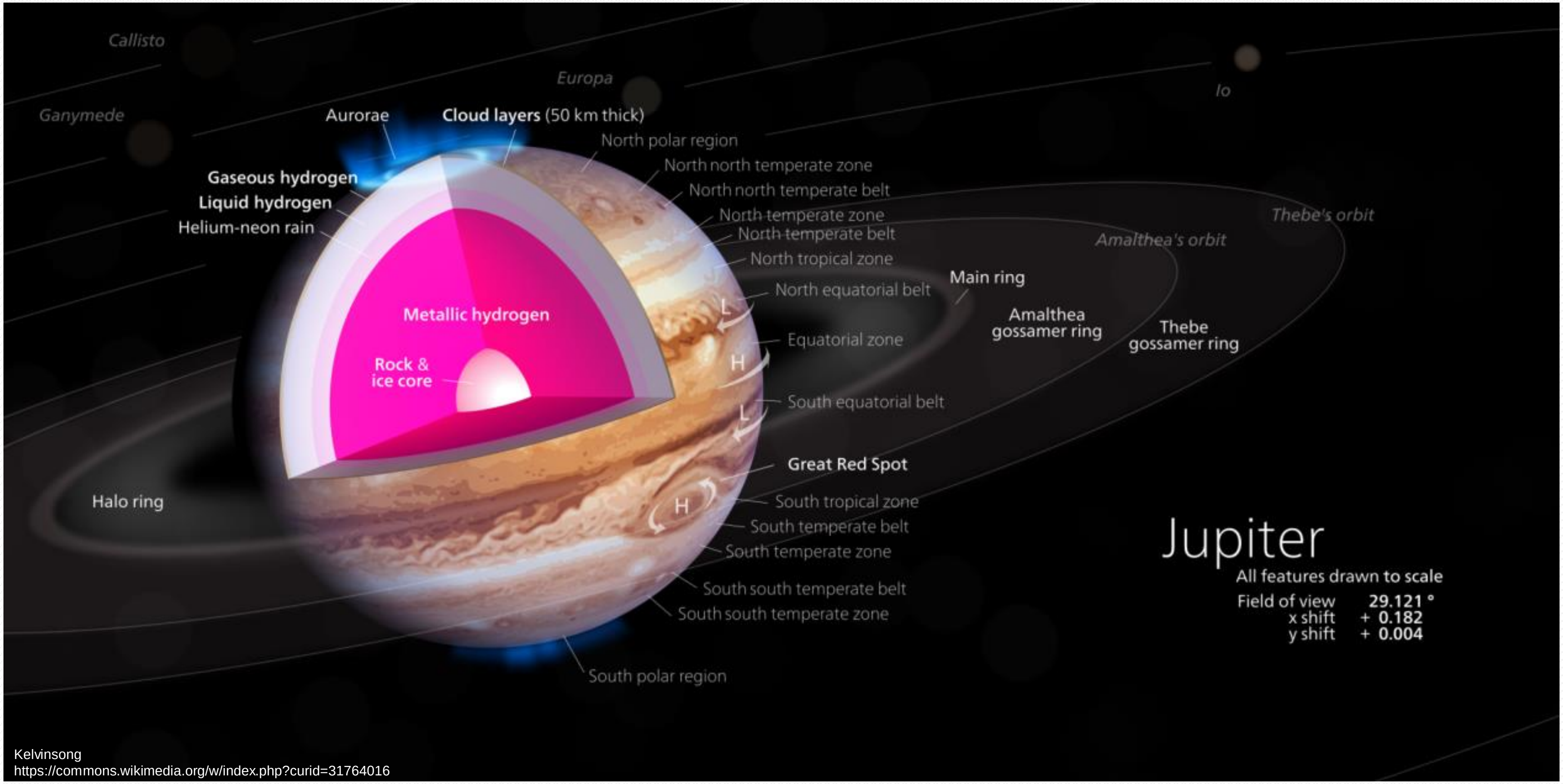
Jupiter's magnetic field is created by a **fluid dynamo** within circulating **metallic hydrogen liquid**. Unlike Earth the **north magnetic pole** is located in the **northern hemisphere** of Jupiter.

Mass: $1898.13 \times 10^{24}\ kg$
g: $23.12\ \ kg\ m/s^2$
Distance from Sun: 5.2 AU (mean)
Length of day: 9.9259 hrs
Radius (Eq): 71492 km
Radius (Pl): 66854 km

Gaseous Planets
Jupiter

Moons of Jupiter

Jupiter has **80 known moons**. They form a satellite system which is called the Jovian system. The most massive moons called Galilean moons are: **Io, Europa, Ganymede,** and **Callisto.**



Gaseous Planets
Uranus

Atmosphere

Tenuous atmosphere extends over **two planetary radii** from the nominal surface, (defined as of **1 bar pressure level**). Uranian atmosphere contains mainly **hydrogen**, **helium** and **methane**. Uranus is the **coldest** planet in solar system **(~49 K).** The speed of winds in its upper atmosphere reaches to 900 km/h in the direction of rotation.

Interior

Uranus is an **ice giant.** Uranus contains **water**, **ammonia** an **methane ices** in **mantle**, and a **rocky (silicate/iron–nickel) core.**

Magnetic field

Generated by currents at shallow depths by **water** and **ammonia dissociation** into positive and negative ions. $NH_3 + H_2O \leftrightarrow NH_4{}^+ + OH^-$

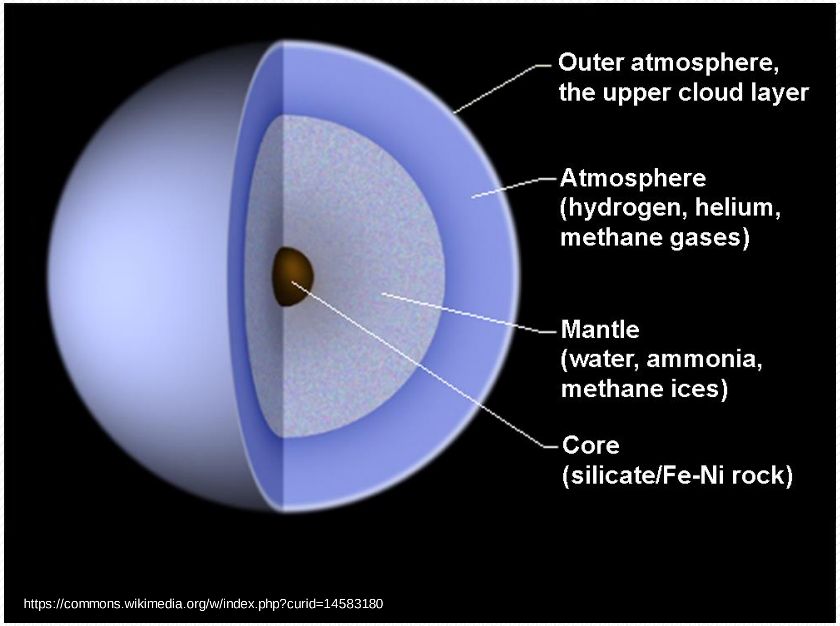
Mass: $86.811 \times 10^{24}\ kg$
g: $8.87\ \ kg\ m/s^2$
Distance from Sun: $19.20\ \mathrm{AU\ (meam)}$
Length of day: $17.24\ \mathrm{hrs}$
Radius (Eq): $25559\ \mathrm{km}$
Radius (Pl): $24973\ \mathrm{km}$

Gaseous Planets
Uranus

Moons of Uranus

Uranus has **27 known moons**. They are divided in three groups:

a) 13 inner moons
b) 5 major moons
c) 9 irregular moons



Gaseous Planets
Saturn

Atmosphere

Outer atmosphere of Saturn contains **~96.3% hydrogen** and **~3.25% helium** by volume. Trace amounts of **ammonia**, **acetylene**, **ethane**, **propane**, **phosphine**, and **methane** have been detected. Wind speeds can reach **1,800 km/h**. A pale **yellow** color of Saturn is due to **ammonia crystals** in its upper atmosphere.

Interior

Saturn's **rocky-(iron–nickel) core** is surrounded by a layer of **metallic hydrogen**, an intermediate layer of **liquid hydrogen** and **liquid helium**, and at the top a gaseous outer layer

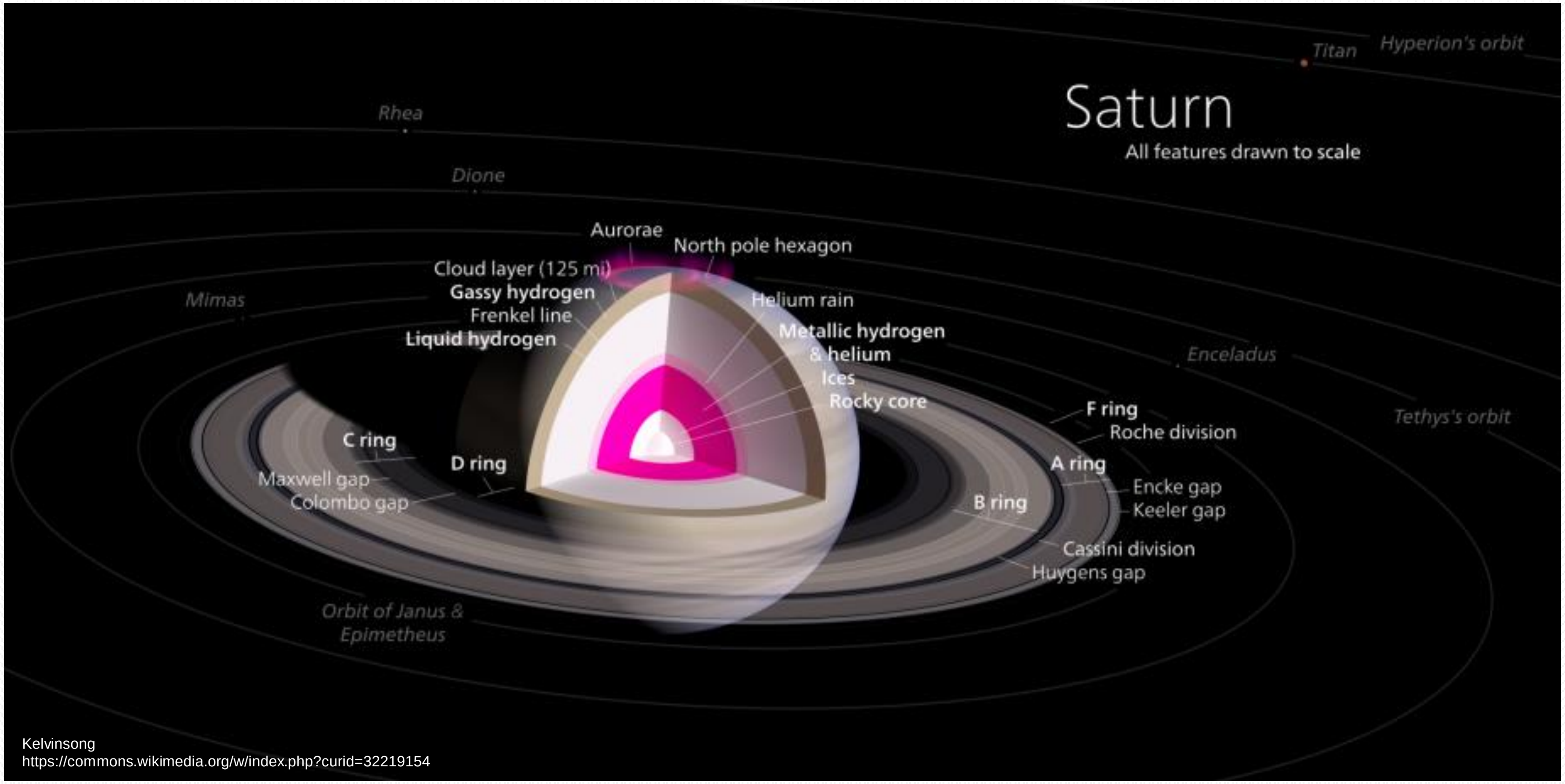
Magnetic field

Saturn's magnetic field is created by a **fluid dynamo** within circulating **metallic hydrogen liquid** above the core. Unlike Earth the **north magnetic pole** is located in the **northern hemisphere** of Saturn.

Mass: $568.32 \times 10^{24}\ kg$
g: $10.44\ \ kg\ m/s^2$
Distance from Sun: $9.5\ \mathrm{AU\ (meam)}$
Length of day: $10.656\ \mathrm{hrs}$
Radius (Eq): $60268\ \mathrm{km}$
Radius (Pl): $54364\ \mathrm{km}$

Moons of Saturn

Saturn has **83 moons** (only 13 of them with diameters larger than 50 km), ranging from tiny **moonlets** (tens of meters across) to **Titan** (larger than Mercury). Seven largest moons have ellipsoidal shape, but only **Titan** (second largest moon in solar system after Jupiter's Ganymede) and possibly **Rhea**, are in hydrostatic equilibrium.



Gaseous Planets
Neptune

Atmosphere

Atmosphere of Neptune is mainly composed of **hydrogen** and **helium**, with traces of **hydrocarbons** and possibly **nitrogen**, **ices** of **water**, **ammonia** and **methane**. Its **blue color** is due to the methane in the atmosphere (**deeper blue** compared to **Uranus**). Wind speeds approaches 2100 km/h

Interior

Neptune is an **ice giant.** Its core is likely composed of **iron-nickel** and **silicates** and its **mantle** consists of **water**, **ammonia** and **methane ices.** Silicates and nickel–iron rocks form the Neptunian core.

Magnetic field

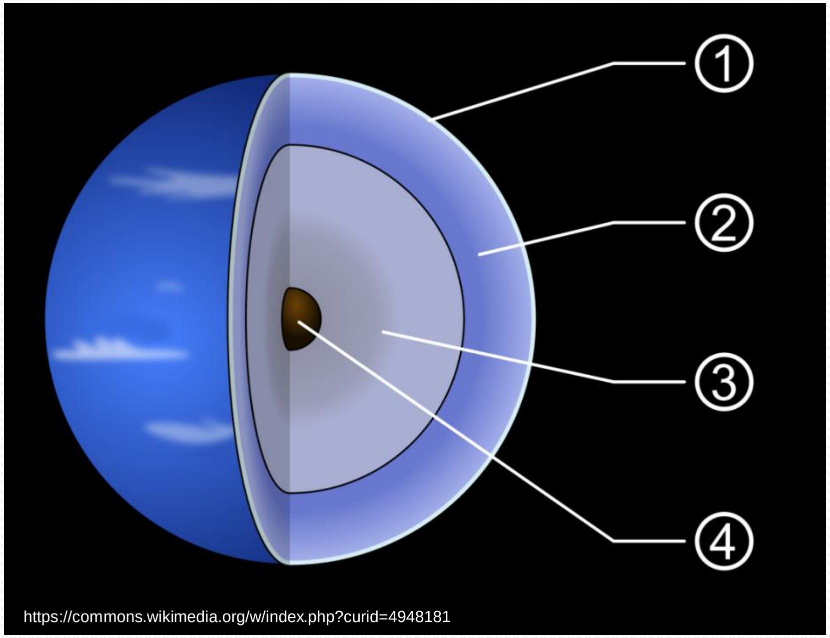
Generated by currents by **water** and **ammonia dissociation** into positive and negative ions. $NH_3 + H_2O \leftrightarrow NH_4{}^+ + OH^-$ (Uranus, Neptune, Pluto, and the outer solar system, Elkins-Tanton).

Mass: $102.409 \times 10^{24}\ kg$
g: $11.15\ \ kg\, m/s^2$
Distance from Sun: 30 AU (meam)
Length of day: 16.11 hrs
Radius (Eq): 24764 km
Radius (Pl): 24341 km

Gaseous Planets
Neptune

Moons of Neptune

Neptune has **14 known moons.** The largest and the second largest are **Triton** and **Nereid**, respectively.



Dwarf Planet

Pluto

Dwarf Planet

Defined by the International Astronomical Union (IAU), a dwarf planet is a celestial body orbiting the Sun, massive enough so that its shape is the consequence of gravitational forces, **but has not cleared its neighbouring region of other objects.**

Criteria of the IAU for a full-sized planet

a) Orbiting around the Sun
b) Massive enough to be in **hydrostatic equilibrium** (nearly round shape)
c) Ability of **clearing** the **neighbour objects** around its orbit.

Pluto

Atmosphere
A tenuous atmosphere consisting of **nitrogen**, **methane**, and **carbon monoxide**, are with their **ices** on Pluto's **surface.**

Interior
Pluto has a **large silicate core** with **liquid water ocean mantle** and **water ice crust**.

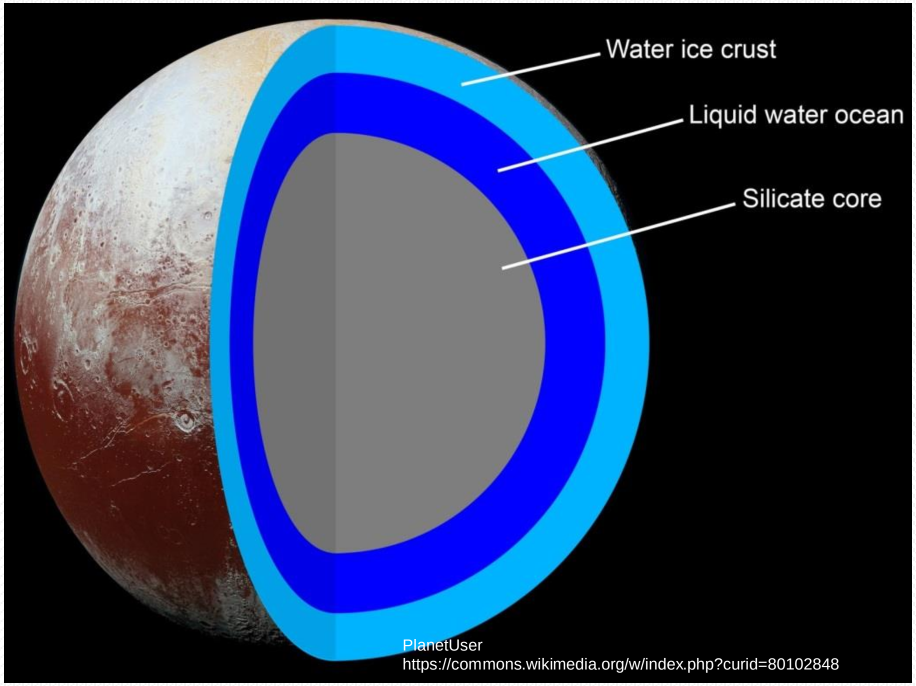
Magnetic field
No magnetic field.

Mass: $0.01303 \times 10^{24}\ kg$
g: $0.62\ \ kg\ m/s^2$
Distance from Sun: $39.5\ \mathrm{AU\ (meam)}$
Length of day: $153.282\ \mathrm{hrs}$
Radius (Eq): $1188\ \mathrm{km}$
Radius (Pl): $1188\ \mathrm{km}$

Pluto

Moons of Pluto

Pluto has **five natural moons.** By distance from Pluto, they are **Charon** (the largest), **Styx**, **Nix**, **Kerberos**, and **Hydra**. Charon is mutually tidally locked with Pluto (**Pluto–Charon** sometimes is considered a **double dwarf planet**).



Galilean Moons
Moons of Jupiter

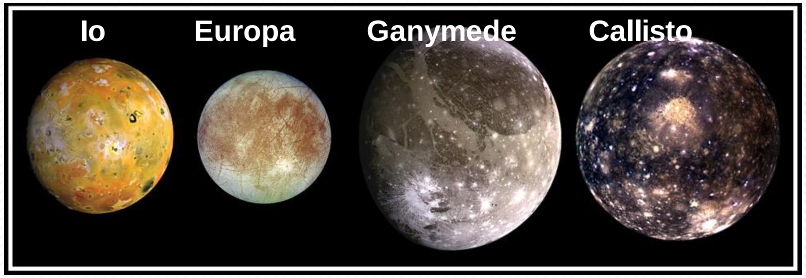
Moons of Jupiter

Galilean Moons

Jupiter has more than 80 moons, four of them are large which are called Galilean moons: **Io, Europa, Ganymede**, and **Callisto**.

Bulk Parameters

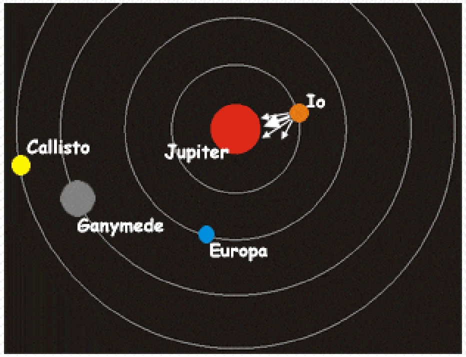
	Mass (10^{20} kg)	Radius (km)	Mean Density (kg/m^3)
Io	893.2	1821.5	3530
Europa	480.0	1560.8	3010
Ganymede	1481.9	2631.2	1940
Callisto	1075.9	2410.3	1830



Orbital Parameters

	Semi-major axis (10^3km)	Orbital Period (days)	Rotation Period (days)	Inclination (degrees)	Eccentricity
Io	421.8	1.769138	S	0.04	0.004
Europa	671.1	3.551181	S	0.47	0.009
Ganymede	1070.4	7.154553	S	0.18	0.001
Callisto	1882.7	16.689017	S	0.19	0.007

S: indicates synchronous rotation - the rotation period is the same as the orbital period



Moons of Jupiter
Ganymede

Atmosphere

A **thin** oxygen atmosphere of O, O_2, and possibly O_3. Atomic hydrogen (H) is a minor atmospheric constituent.

Interior

Metallic solid inner core (iron) and **liquid** outer core (iron & iron sulphide), **rocky** mantle, **icy** outer layers with different **crystal structures.**

Magnetic field

Ganymede is the **only moon** known to have a **magnetic field**.

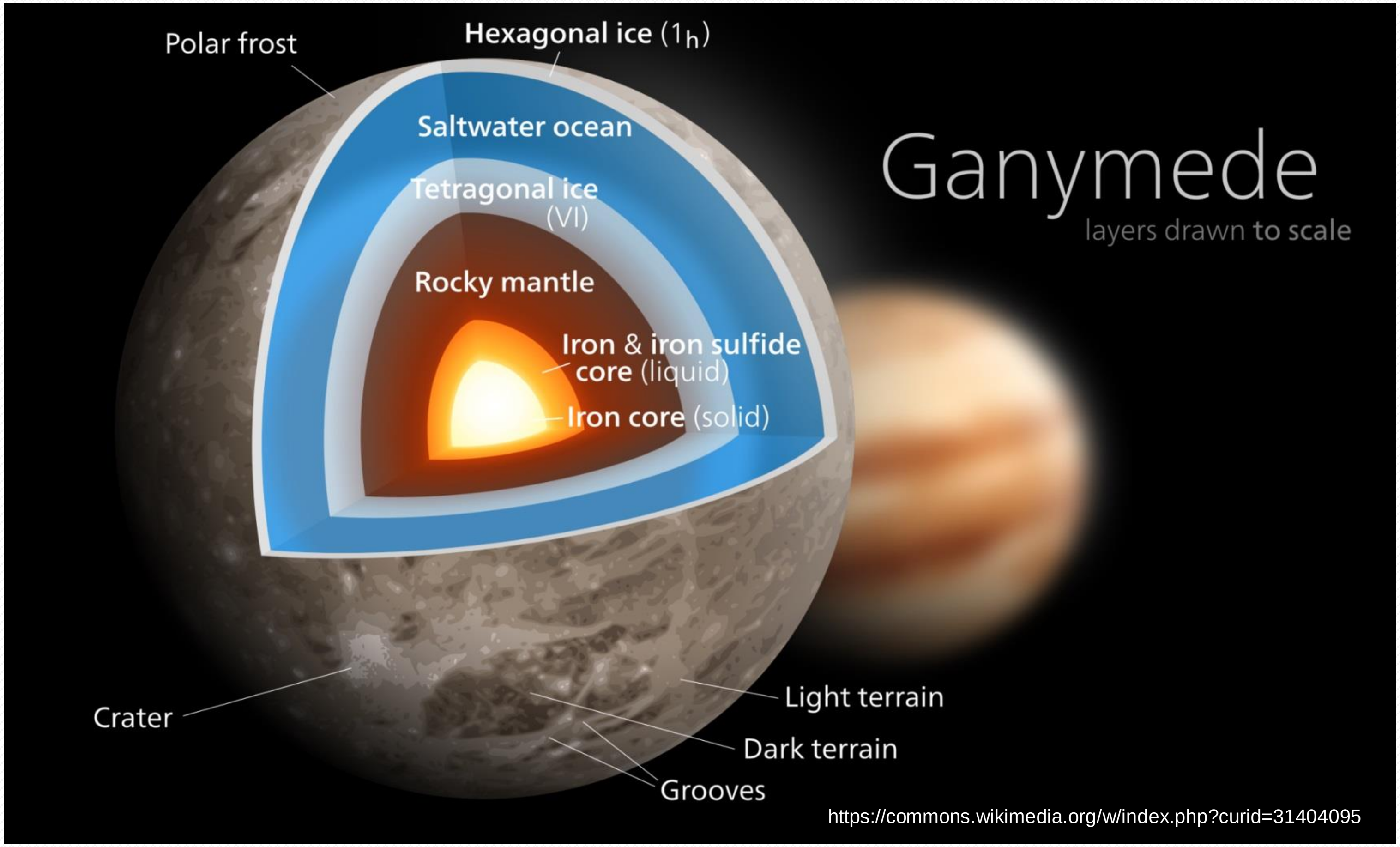
Orbital resonance

Ganymede orbits Jupiter in roughly **seven days** and is in a **1:2:4** orbital **resonance** with the moons **Europa** and **Io**, respectively.

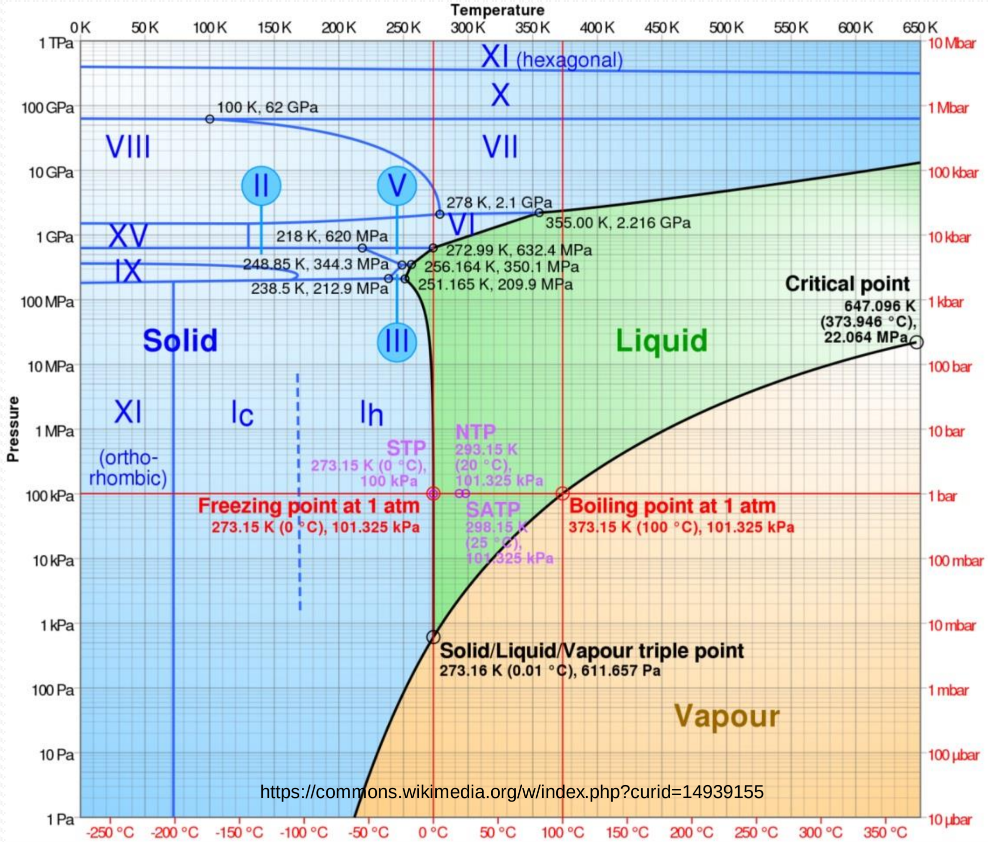
Moons of Jupiter
Ganymede

Ganymede

Ganymede is the **largest** and most massive of the Solar System's moons. The **9th-largest** object (including the Sun) of the Solar System.



Moons of Jupiter
Ganymede



Phase diagram of water

Moons of Jupiter
Europa

Atmosphere

A very **thin** atmosphere, composed primarily of **oxygen**.

Surface

Europa is the **smoothest** known object in the Solar System. Its surface is striated by **cracks** and **streaks** (possibly generated **by the stresses of the tidal effects** of Jupiter), but craters are relatively few.

a) The **red** color of the **cracks** may potentially be due to water ice mixed with hydrated salts and **magnesium sulphate** or **sulphuric acid**.

b) Organic macromolecular solid material has also been assumed for the colored regions on Europa's surface (Borucki et al., 2002).

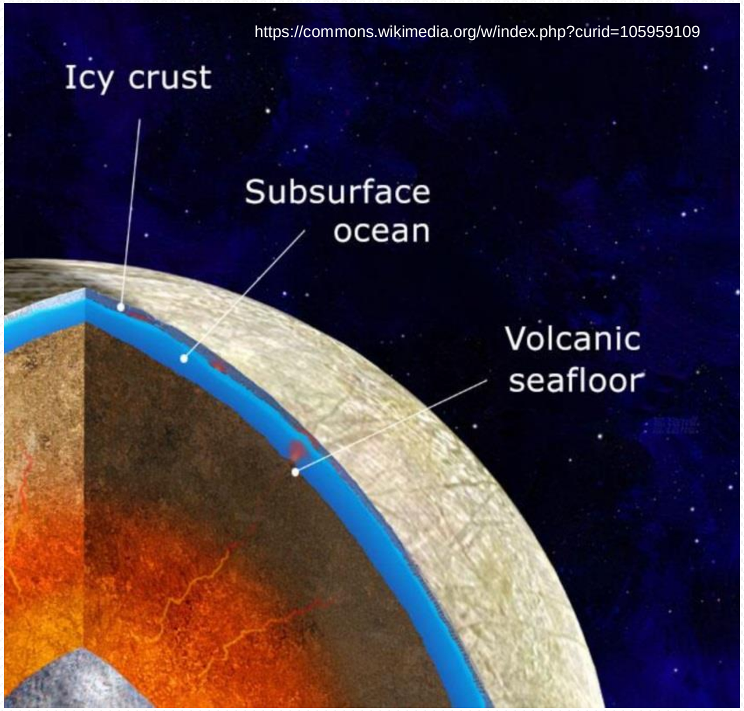
Interior

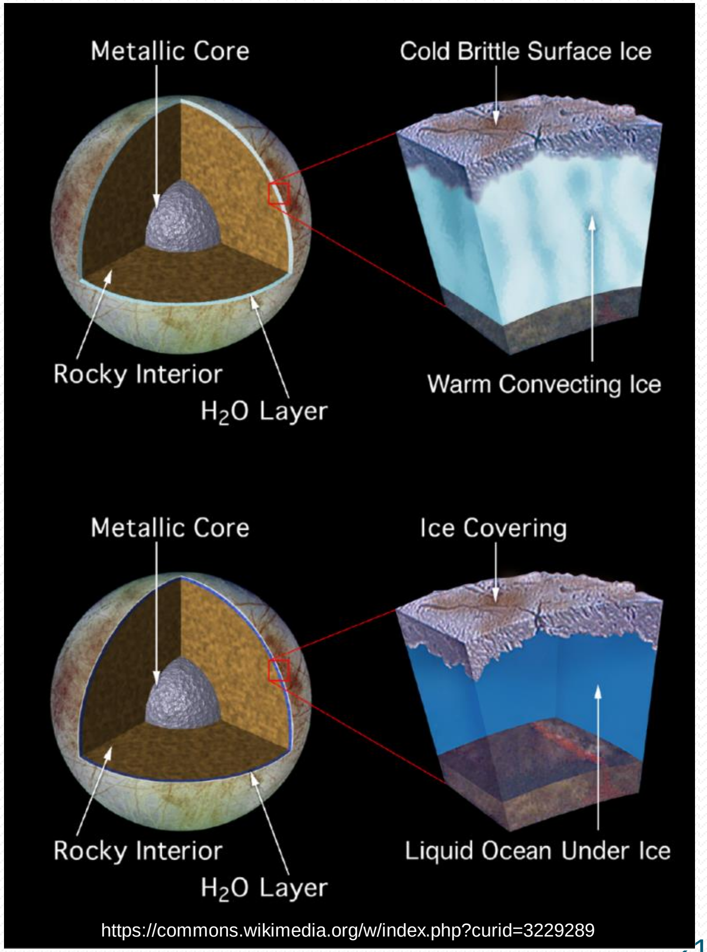
Probably an **iron–nickel** core, **rocky mantle**, **icy crust** with **possible water ocean** below.

Moons of Jupiter
Europa

Europa

Europa is the **smallest** of the **four Galilean** moons orbiting Jupiter, and the **sixth-largest** moon in the **Solar System**.





Moons of Jupiter
Europa

Heating

Tidal heating caused by Jupiter and **radiogenic** heating from mantle. This can keep **ocean** below the icy crus in **liquid state**.

Magnetic field

An induced magnetic field through interaction with Jupiter's, which suggests the presence of a subsurface conductive layer (Phillips & Pappalardo, 2014).

Moons of Jupiter
Callisto

Atmosphere

A **thin** atmosphere composed of **CO_2** and probably molecular oxygen **(O)** as well as by a rather intense ionosphere.

Interior

Rocky and metal core, with **outer different icy layers**. Callisto's gradual accretion and the **lack of tidal heating** meant **prevented rapid** differentiation. The **slow convection** in the interior of Callisto led to **partial differentiation**: possibly the formation of a **subsurface ocean** and **a small, rocky core** (Spohna & Schubert, 2003).

Magnetic field

No internal magnetic field. **Perturbations of the external magnetic fields** associated with Jupiter’s inner magnetosphere in the vicinity of both Europa and Callisto were interpreted as **induced magnetic fields**, generated by the moons (which requires the **existence** of **eddy currents** to flow within the moons, **i.e., subsurface liquid oceans**). (Khurana et al., 1998).

Moons of Jupiter
Callisto

Callisto

Callisto is the **second-largest moon of Jupiter**. It is the **third-largest moon in the Solar System** after Ganymede and Saturn's largest moon Titan, and the largest object in the Solar System.

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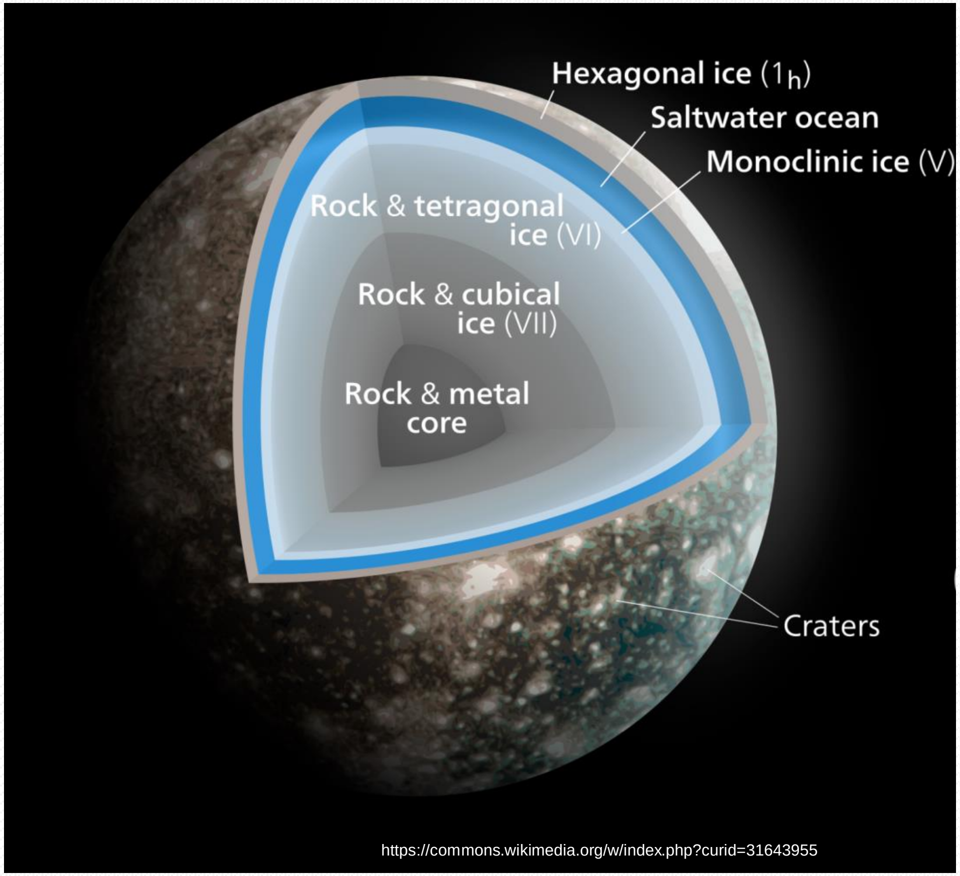

Moons of Jupiter
Io

Atmosphere

An extremely **thin** atmosphere consisting mainly of sulphur dioxide **(SO_2),** with minor constituents of sulphur monoxide **(SO),** sodium chloride **(NaCl),** and atomic sulfur and oxygen **(O).** The atmosphere has **significant** variations in **density** and **temperature** with **time** of day, **latitude**, **volcanic activity,** and surface **frost abundance**.

Interior

Models based on the **Voyager** and **Galileo** measurements of Io's **mass**, **radius**, and **quadrupole gravitational coefficients** (measure of mass distribution) suggest that Io's interior is **differentiated** between a **silicate-rich crust** and **mantle** and a **molten iron- or iron-sulphide-rich core** (Anderson et al., 1996).

Magnetic field

The Jupiter's magnetic field through the Io's ionosphere induces an electric current, which in turn creates an **induced magnetic field** within Io's interior, probably generated within a partially molten**, silicate magma ocean 50 kilometers beneath Io's surface** (Kerr, 2010).

Moons of Jupiter
Io

Io

Io is the **innermost** and **third-largest** of the **four Galilean** moons of the planet Jupiter (slightly larger than the Earth's moon.

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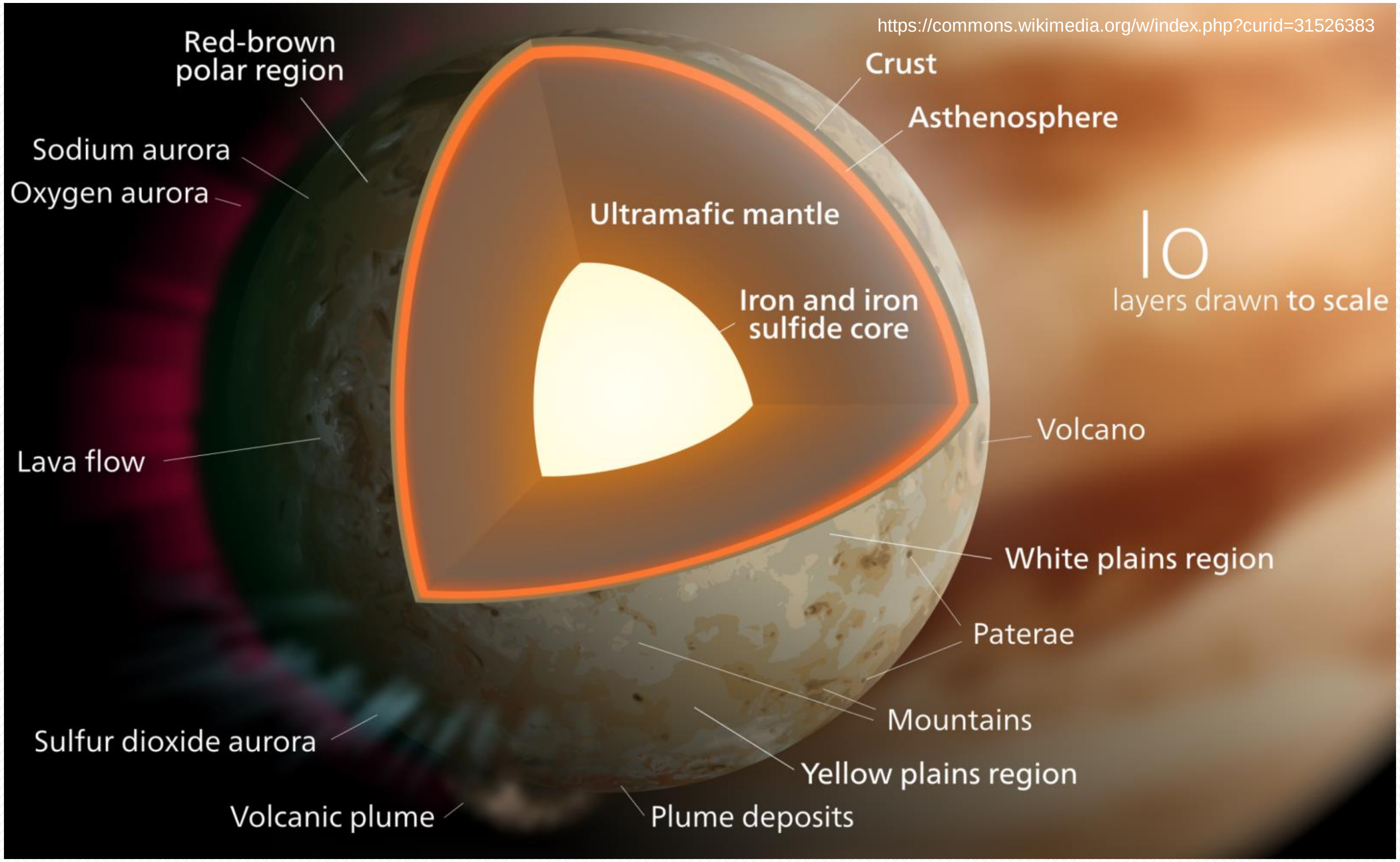
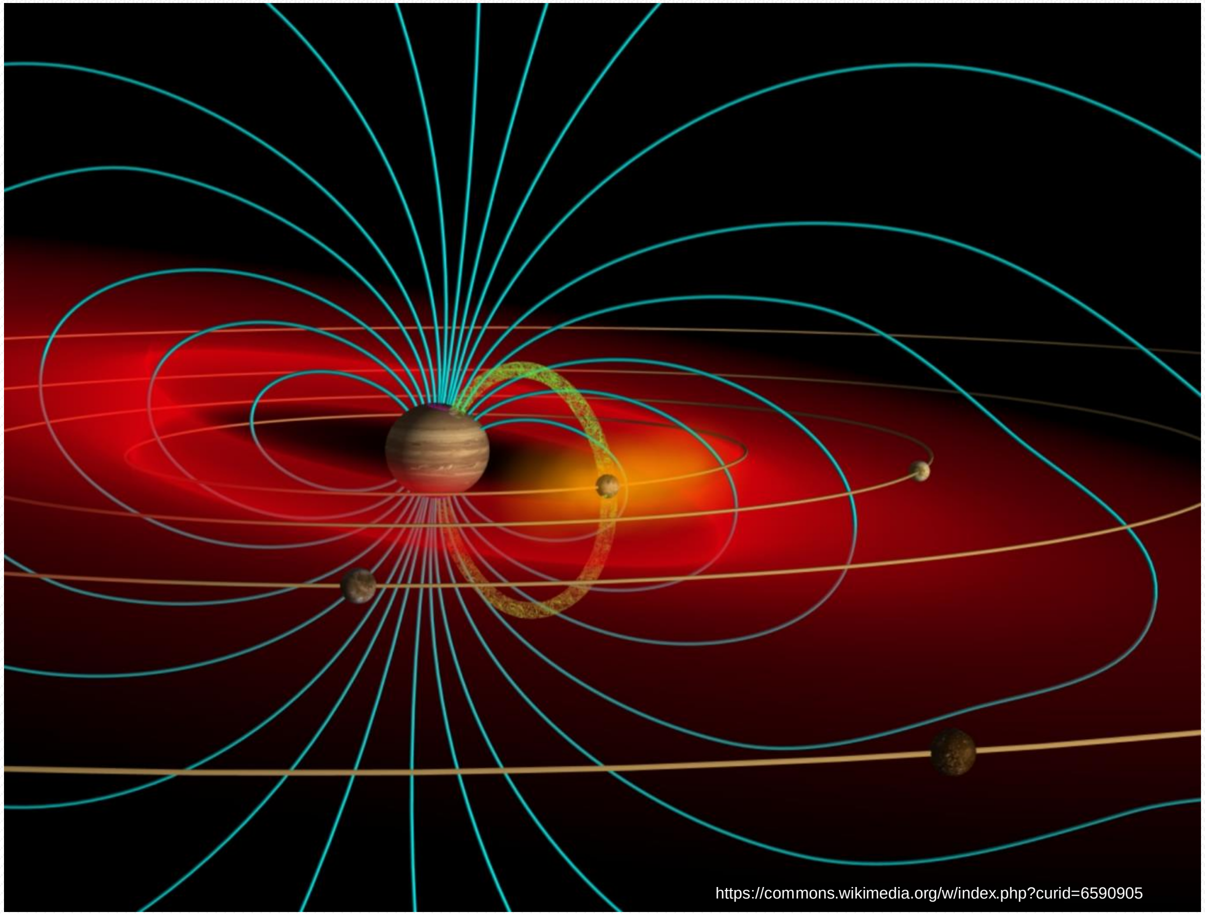


Moons of Jupiter
Io

The **magnetosphere** of Jupiter **sweeps up** gases and dust from Io's thin atmosphere at a rate of **1 tonne per second** (Lopes & Spencer, 2007).



Tectonic Activates in Io

Moons of Jupiter
Io

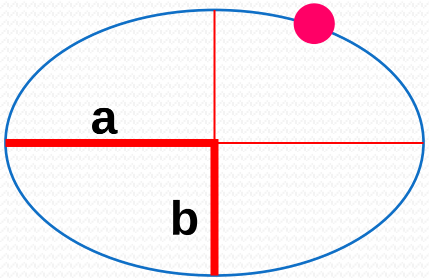
Volcanism and Tidal Heating

Io is **remarkable** for its **extensive volcanism** and **extreme interior tidal heating**.

The **volcanic activity** of Io originate s from **tidal dissipation** in its interior. The heat is generated by the stresses in the interior caused by the **gravitational attraction** of **Jupiter**, **coupled** with the gravitational pull of Io's neighbouring moons-**Europa** , **Callisto**, and **Ganymede** (Yoder and Peale, 1981; Ross and Schubert, 1985,1986; Segatz and Spohn, 1988). There exists a **slight eccentricity** in Io's orbit (Lieske, 1980), which is due to the orbital resonance with Europa and Ganymede which is referred to as a **Laplace resonance**.

$e = \sqrt{1 - \frac{b^2}{a^2}}$ *eccentricity*

$e = 0.0041$ *for Io*

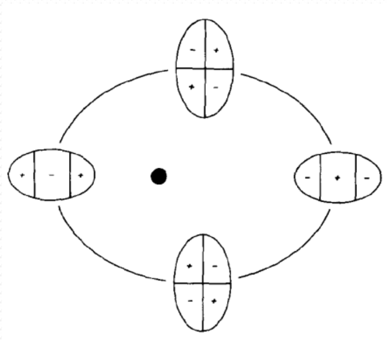


Moons of Jupiter
Io

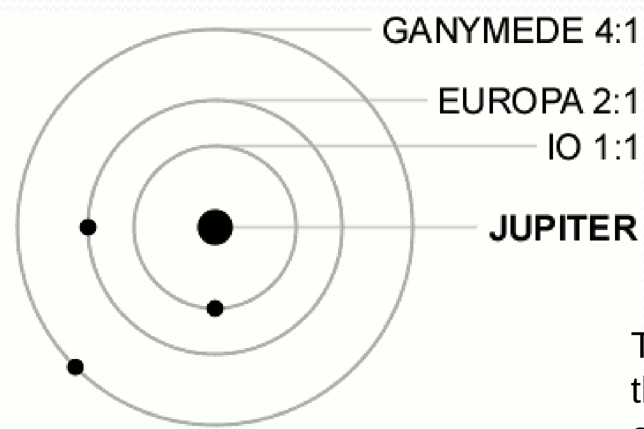
This **eccentricity** causes the **tide-raising** potential of Jupiter on the **surface of Io** to oscillate. The tidal effects at Io's surface could cause a rise and fall of approximately **100 m** which is **more than five times in** excess of the **highest ocean tides on Earth**. The **distribution of tidal dissipation** depends on the **internal structure** of Io.

Laplace Resonance

In celestial mechanics, orbital resonance occurs when orbiting bodies exert regular, periodic gravitational influence on each other, usually because their orbital periods are related by a ratio of small integers.



(Spohn et al., 1988)



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The three-body Laplace resonance exhibited by three of Jupiter's Galilean moons. Conjunctions are highlighted by brief color changes

Moons of Jupiter
Io

Surficial Features

- Io is a triaxial ellipsoid in shape with: a = 1830.0 km, b = 1818.7 km, and c = 1815.3 km.

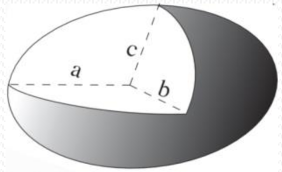
- The Ionian surface topography is defined in terms of deviations from the surface of this ellipsoid that minimize the variance in elevation differences (Ross et al., 1990).

- Signatures of widespread **volcanic resurfacing** in the recent geologic past.

- **Visible** and near infrared mapping spectrometer **(NIMS),** observation reveals the **existence** of **volcanic plumes** and **lava flows** reaching temperatures of approximately **1800 K** (McEwen et al., 1998b; Lopes-Gautier et al., 1999).

- The **high-temperature lavas** suggest a predominantly **silicate character** of Io volcanism (McEwen et al., 1998a,b).

- **Despite** Io's **pervasive volcanism, only 4%** of the Ionian regions of high topographic relief are **volcanic in origin**. From **96** selected Ionian mountains (out of **143**) for which sufficiently high resolution imaging exists**, 3** seem to be **volcanic, 92** appear to be edifices constructed **by other tectonic events** (Jaeger et al., 2003).



Moons of Jupiter
Io

Topography

Three distinct type of topography may be identified:

I - Elevations of the **north** and **south** poles which are moderately **high (~0.9 km)** and **low (~-0.3 km),** respectively.

II - Topography in the **equatorial** region which consists of **four alternating** long wavelength **high** and **low** regions **(max. ~1.1 km).**

III - Distributed **short wavelength** topography (few hundred meter) that is well **correlated** with the observed **surface heat flux.**

IV – High mountains exceeding **17 km**.

Moons of Jupiter
Io

Topography Formation

Problems

- The formation of the Ionian topographic highs is **not well understood.**

- The tectonic features are **obscured** by **lava flows** and **sulphurous-plume deposits** which rapidly **(1 cm/yr on average)** resurface its lithosphere (Johnson et al., 1979; Blaney et al., 1995; Phillips, 2000).

High Montes

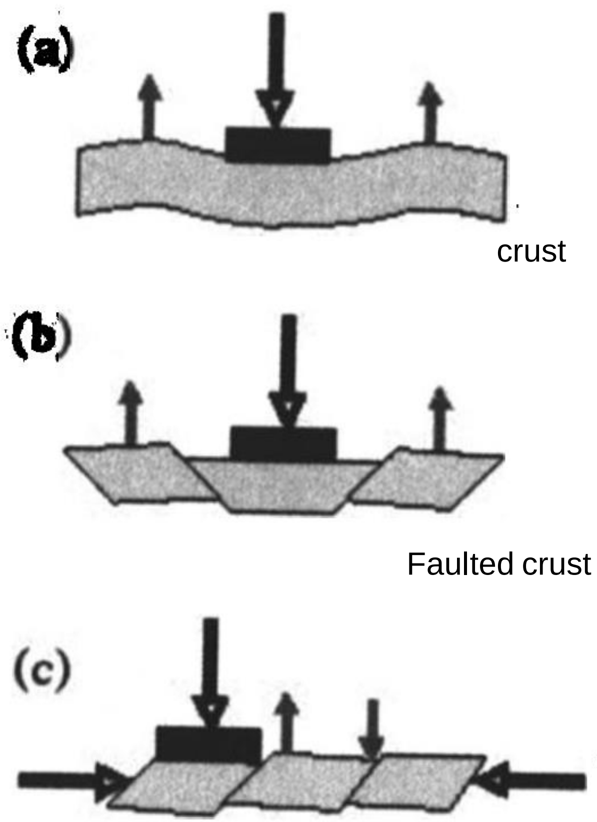
Moons of Jupiter
Io

- The **mountains** are expected to have been **initiated tectonically** (Turtle et al., 2001; Jaeger et al., 2003).

- One possibility for the initiation of **mountain formation** might be in response to the **global compression** caused by the **high rate of global subsidence** associated with this high rate of resurfacing (Turtle et al., 2001). The **cold crust** is **deflected downward** by the load associated with the volcanic resurfacing, causing **shortening and isostatic compensation and uplift** (Schenk and Bulmer, 1998). The observed mountain elevations could conceivably be explained by lithosphere thicknesses ranging from **13 km to 80 km** (Jaeger et al., 2003). Since the lithosphere is generally under compression, the magma is expected to ascend along tectonic faults, thereby relieving the compression (Keszthely i et al., 2004; Jaeger et al., 2003).

Moons of Jupiter
High Montes – Numerical Models

Volcanic load

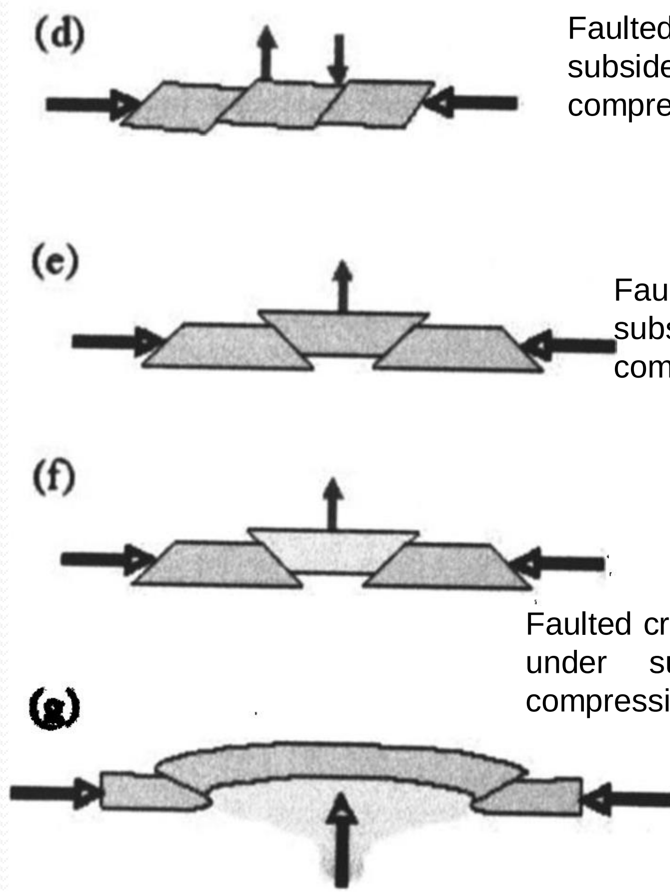


crust

Faulted crust

Crust under subsidence-induced compression

Resurfacing: 0.1-10 cm/yr
Johnson et al. (1979)



Faulted crust under subsidence-induced compression

Faulted crust under subsidence-induced compression

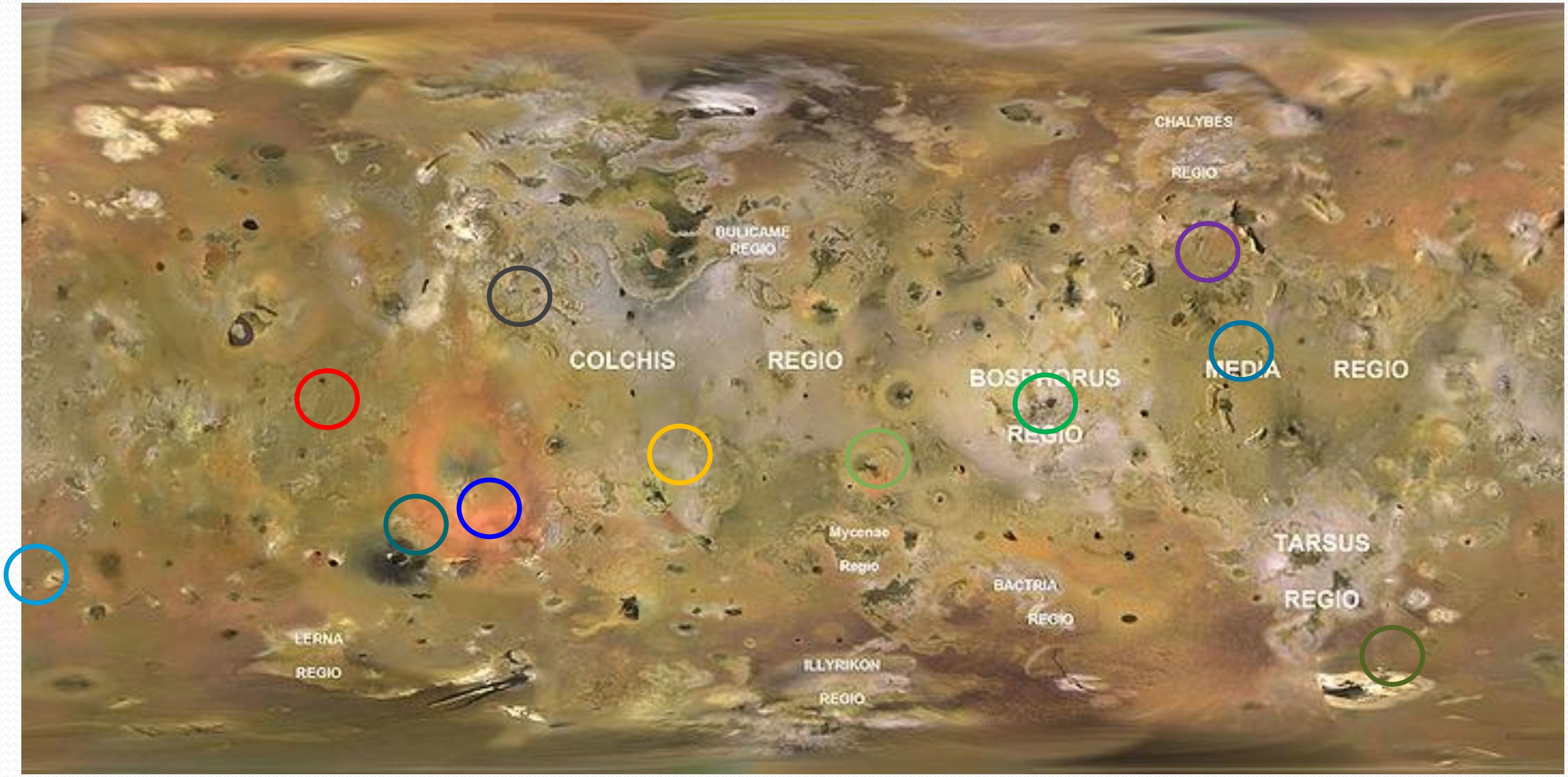
Faulted crust (lower density) under subsidence-induced compression

Crust under subsidence-induced compression with mantle upwelling

Turtle et al., 2001

Moons of Jupiter
Io

High Montes-Isolated Structures



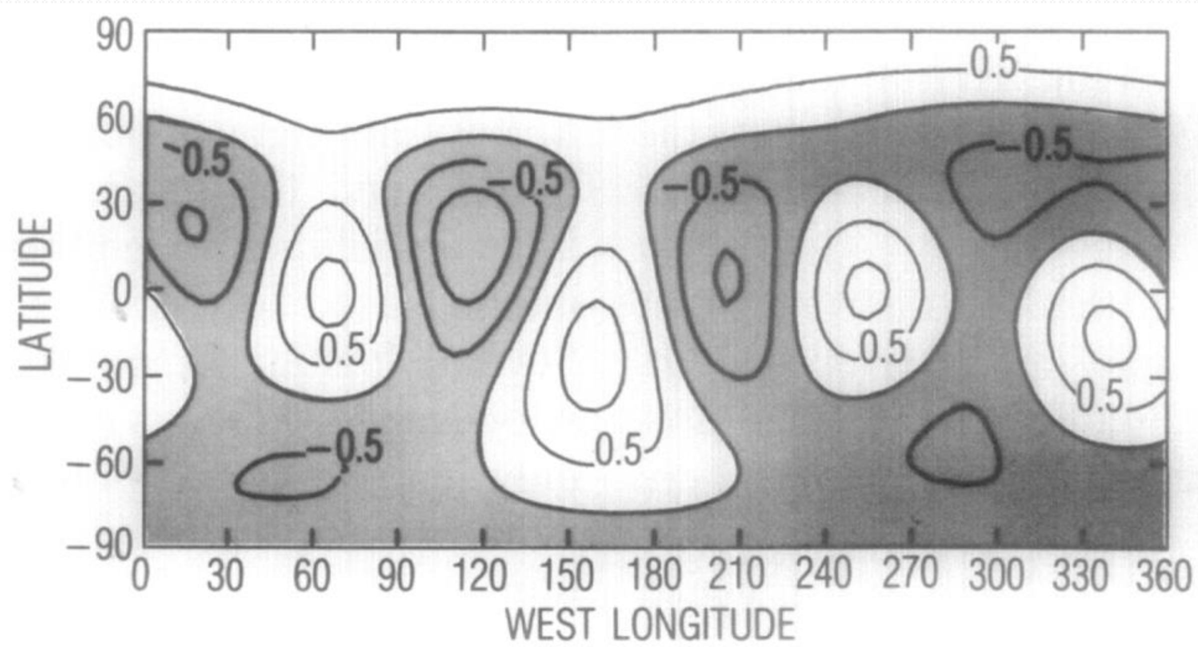
Boösaule: 17.5-18.2 km
Capaneus: 9.2-9.5 km
Caucasus: 10.6 km
Dorian: 8.5-9.2 km
Egypt: 10 km
Euboea: 10.3-13.4 km
Gish Bar: 9.7-11 km
Haemus: 10.8 km
Hi'iaka: 11.1 km
Ionian Sea: 12.7 km
Tohil: 9-9.4 km
Others: < 9 km

Long Wavelength Topography

Moons of Jupiter
Io

Long Wavelength Topography

The **long wavelength** component of topography of Io, defined in these terms, consists of four alternating high and low regions near the equator, spaced roughly equidistant in longitude (Gaskell et al., 1988). The maximum amplitude of this long wavelength equatorial topography is approximately **1.1 km** (Ross et al., 1990). The north and south poles are moderately high **(0.9 km)** and low **(0.3 km)** in elevation respectively (Ross et al., 1990).



Long wavelength topography (Ross et al., 1990)

Moons of Jupiter
Io

Model Based on Isostatic Adjustment

Some previous numerical studies that rely on **isostatic adjustment** and the assumption of isostatic compensation of the long-wavelength topography and **ignore** the impact of **convection** on surface topography (Ross et al., 1990):

a) The Thermal Swell Model

1- **Composition** of the **lithosphere** an d the **asthenosphere** are **assumed** to be **the same**

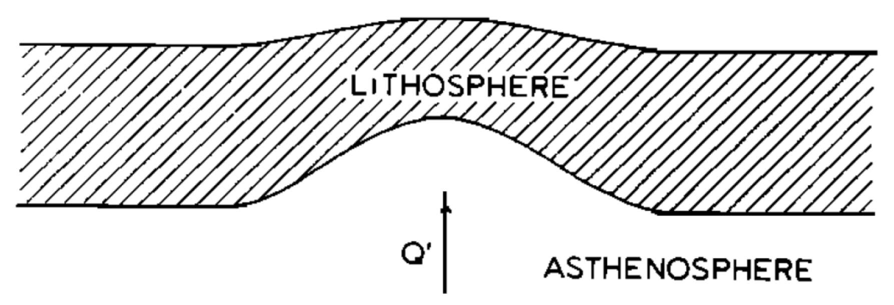
2- The density contrast between the thermal lithosphere and asthenosphere is assumed to be **1.6%** (Gaskell et al., 1988).

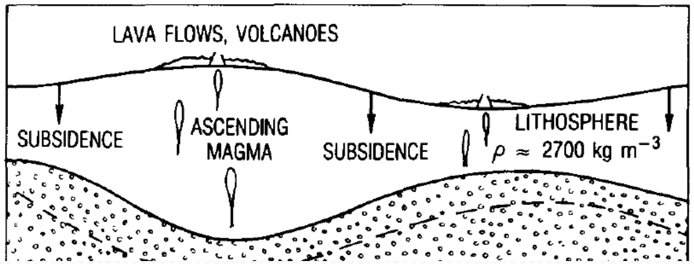
3 - The model results show that there is a **positive correlation** between the **heat flow** and **topographic elevation**.

b) The Differentiated Lithosphere Model

1 - The lithosphere is assumed to be **lower** in density by **7%.**
2 - The model results show that In model the **heat flow** and **topography** are **anti-correlated.**

Their calculations are based on heat flow calculations with assumed rates of tidal dissipation in a viscous **asthenosphere** and deep **mantle** (which are assumed to account for **2/3** and **1/3** of the heating respectively).



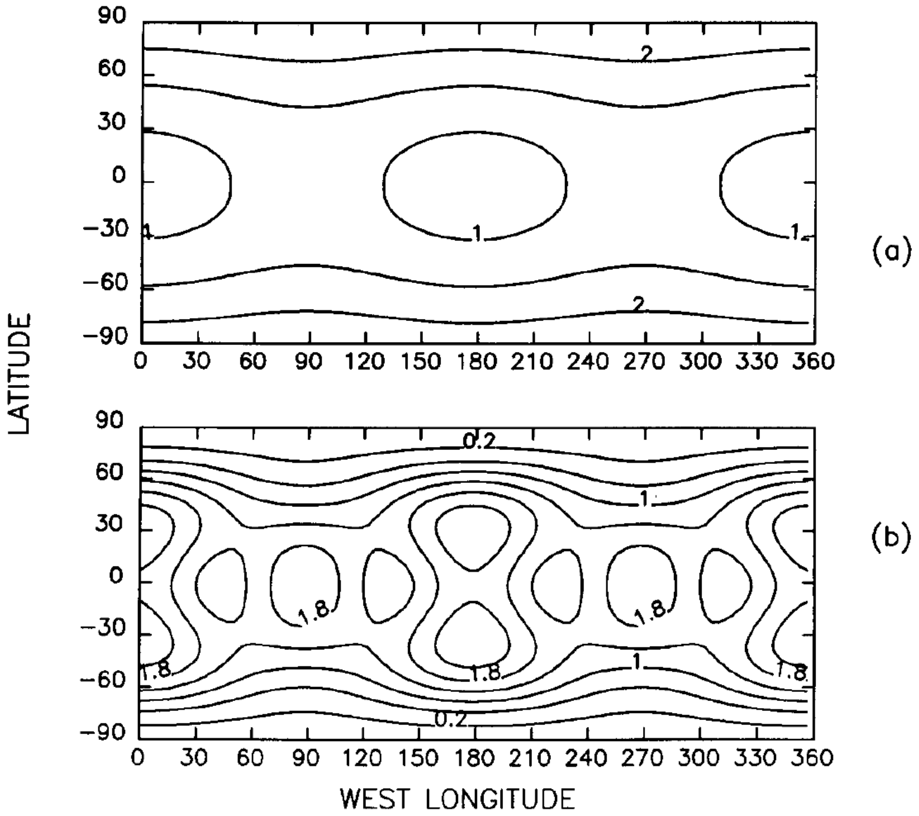


$\rho = 2900\ km\, m^{-3}$

(a) (Ross et al., 1990) **(b)**

Moons of Jupiter
Io

a) Deep mantle tidal dissipation
b) Asthenosphere tidal dissipation



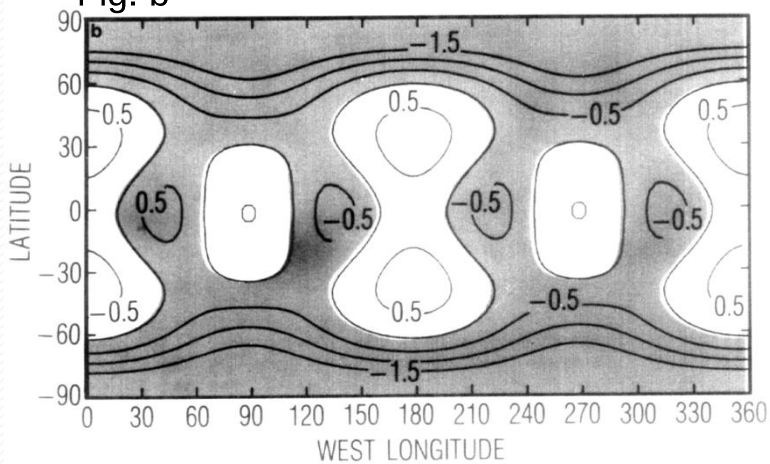
Contour map of the radially integrated tidal dissipation (in W m $^{-2}$) for the deep-mantle Io model (a) and the asthenosphere Io model (b). Total dissipation equals 60 TW (Ross et al., 1990).

Moons of Jupiter
Io

Both Model Can be Acceptable

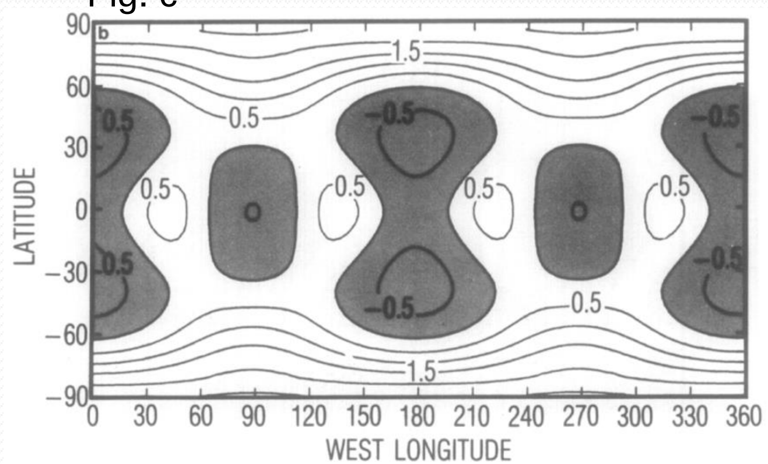
These two model topographies can show positive correlation with the observed long wavelength topography of Io **(Fig. a)** if they are rotated longitudinally by -25 and 25 in the case of the **thermal swell** lithosphere model topography **(Fig. b)** and the **differentiated** lithosphere model topography **(Fig. c)** (Ross et al., 1990).

Fig. b



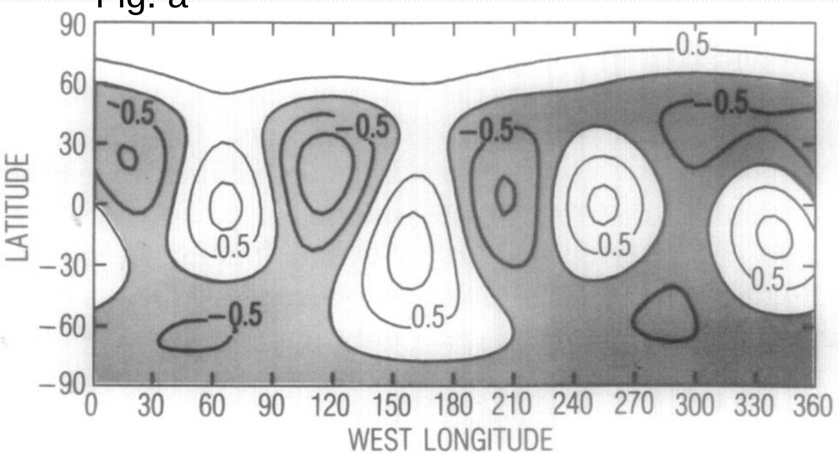
Thermal swell model

Fig. c



Differentiated model

Fig. a

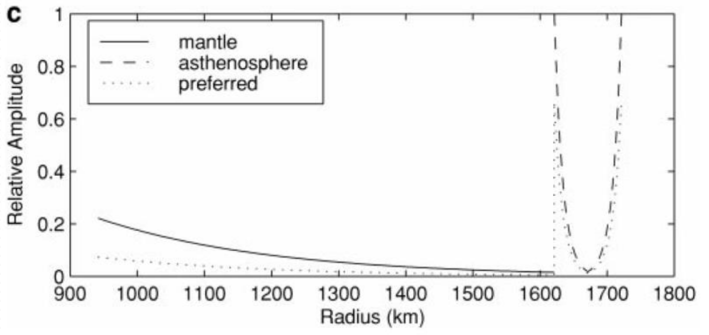


Long wavelength topography

Moons of Jupiter
Long Wavelength Topography

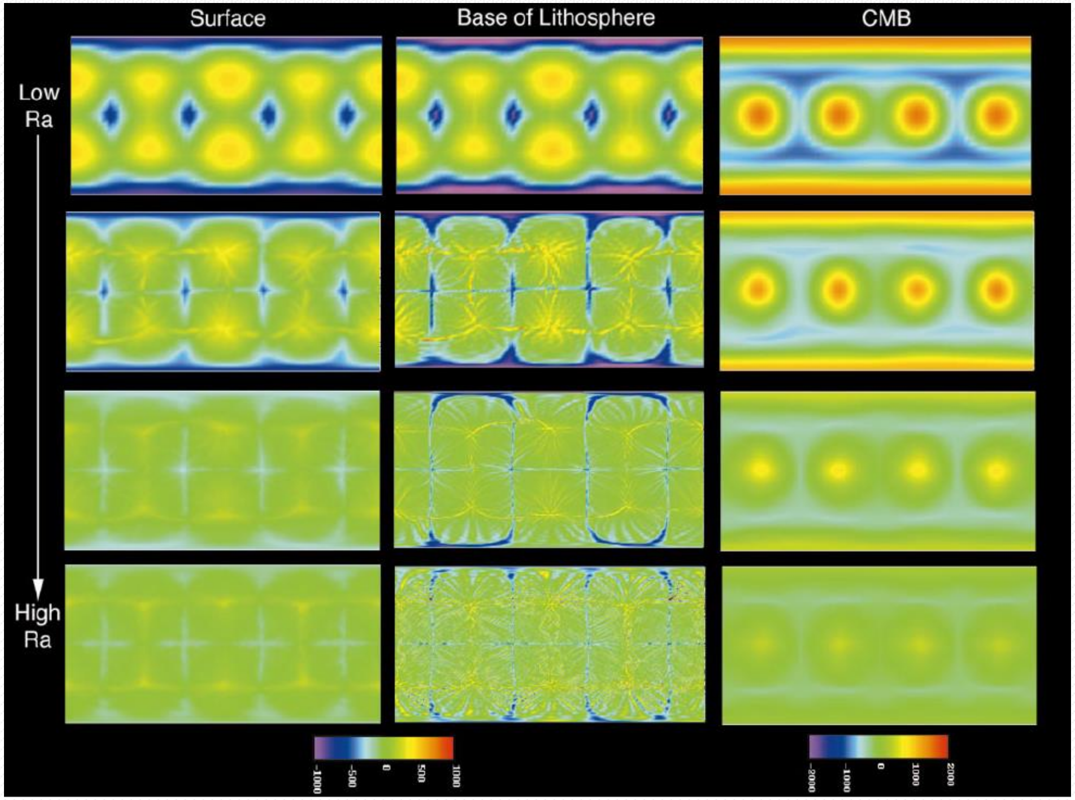
The **differentiated** lithosphere model suggests a **zonal rotation** toward the **smaller longitudes**. Such a zonal rotation could conceivably occur due to an **exchange** of **spin angular momentum** between the **lithosphere** and **asthenosphere**.

Io – Results from Numerical Models
Scaling to the Lower Rayleigh Numbers



The radial distribution of heating for all mantle (solid line), all asthenosphere (dashed line), and preferred (combined: 2/3 asthenosphere and 1/3 mantle heating) modes (dotted line). Curves have the correct relative amplitude.

$$\frac{\eta_{asth}}{\eta_{mant}} = 0.01$$



Variations in surface, base-of-lithosphere and CMB heat fluxes for the preferred models with combined heating, a permeable asthenosphere–mantle boundary, and Ra_H increasing in factors of 10 from 2:5 x 10^4 (top row) to 2:5 x 10^7 (bottom row). The color bar is in W/m^2 (Takley et al., 2001).

Short Wavelength Topography Predictions from the Numerical Models

Io – Results from the Numerical Models

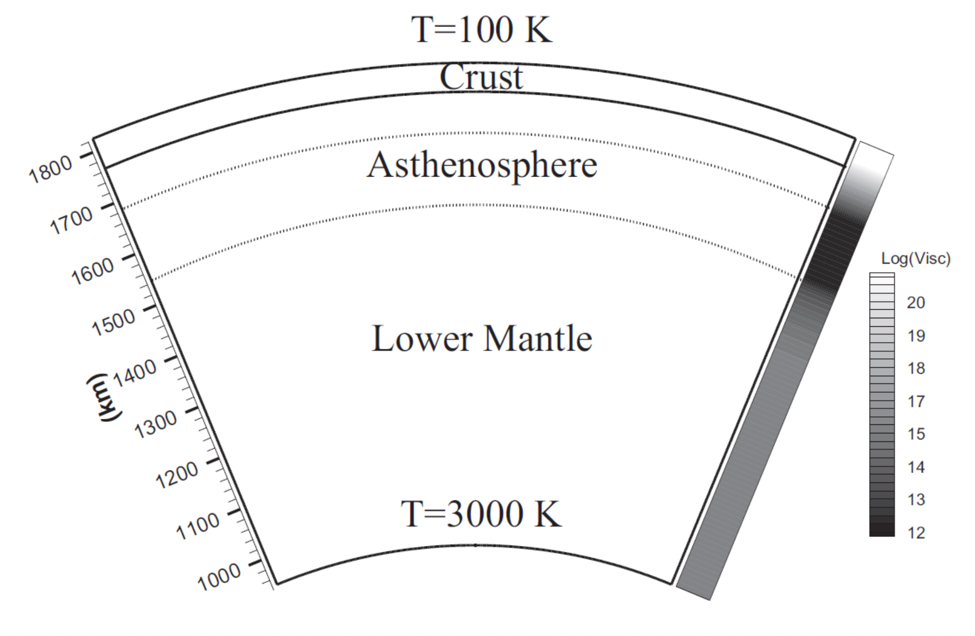
Model setup

Tidal Heating

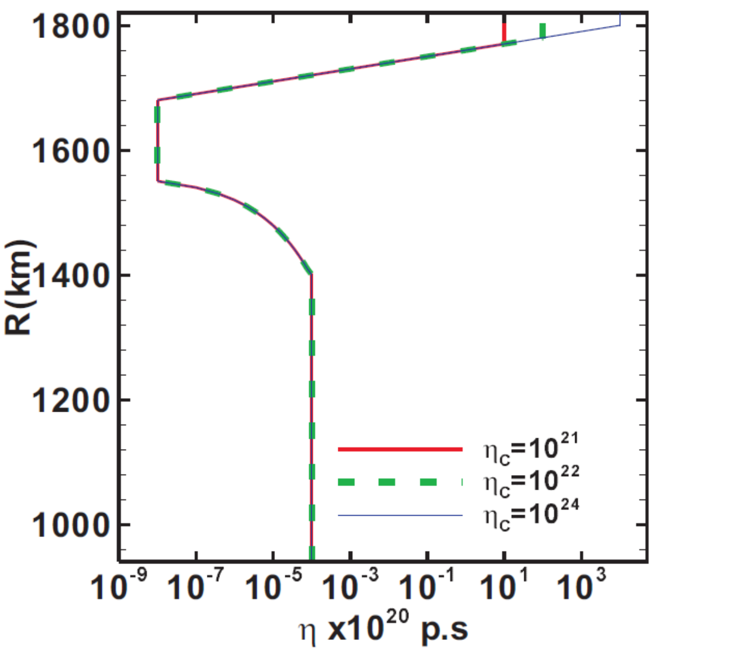
$$H(r) \sim \frac{0.4}{r^4}, \quad r < r_{asb},$$

$$H(r) \sim \frac{3}{1-\exp(-6)}\{\exp(-6z) + \exp[-6(1-z)]\}, \quad r_{asb} < r < r_{ast},$$

$$z = \frac{r_{ast} - r}{r_{ast} - r_{asb}},$$

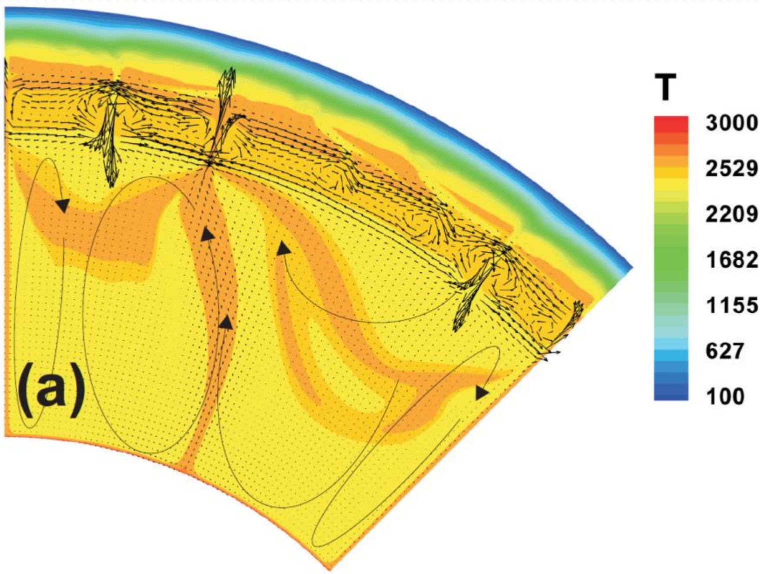


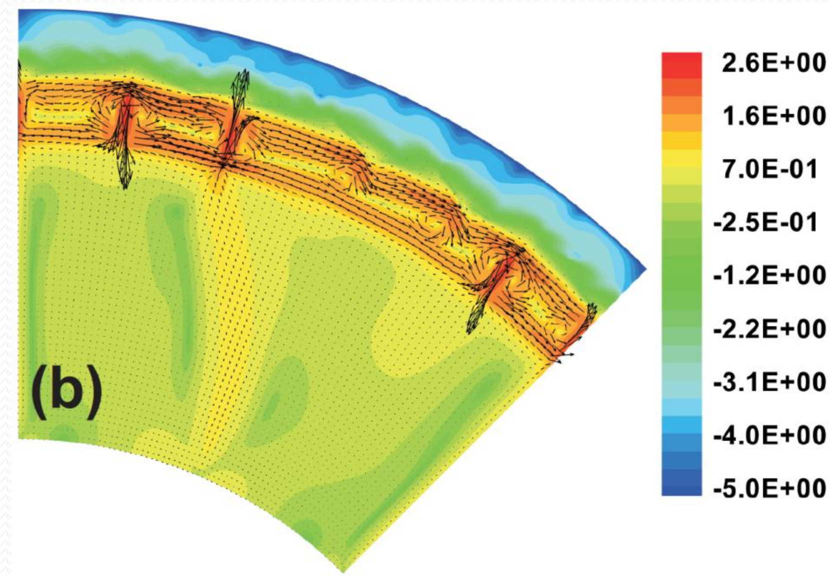
Model Setup

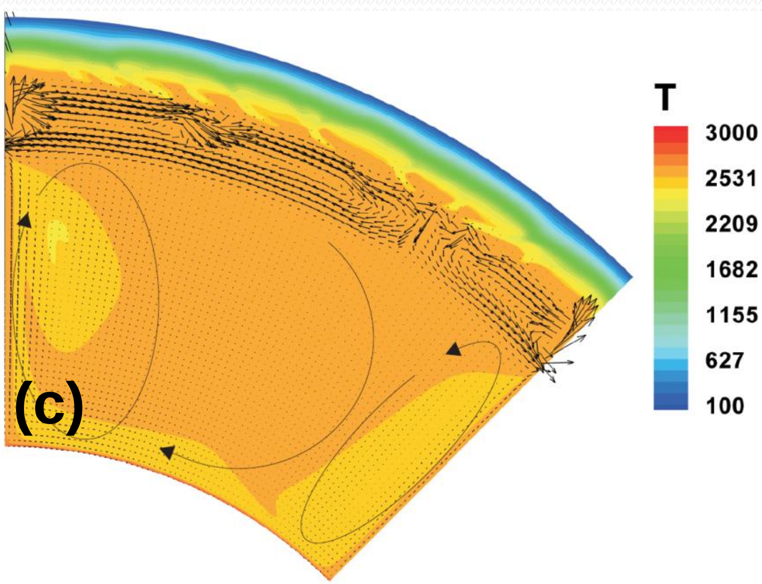


Radial Viscosity (Shahnas et al., 2007)

Io – Results from the Numerical Models







(a) Snapshot of the temperature field (K) with superimposed velocity arrows at a statistically steady state, (b) the logarithm of the velocity field (m/yr) with the superimposed velocity arrows, (c) Snapshot of the temperature field at a later time in which some of the small scale convection cells have merged to form relatively larger cells.

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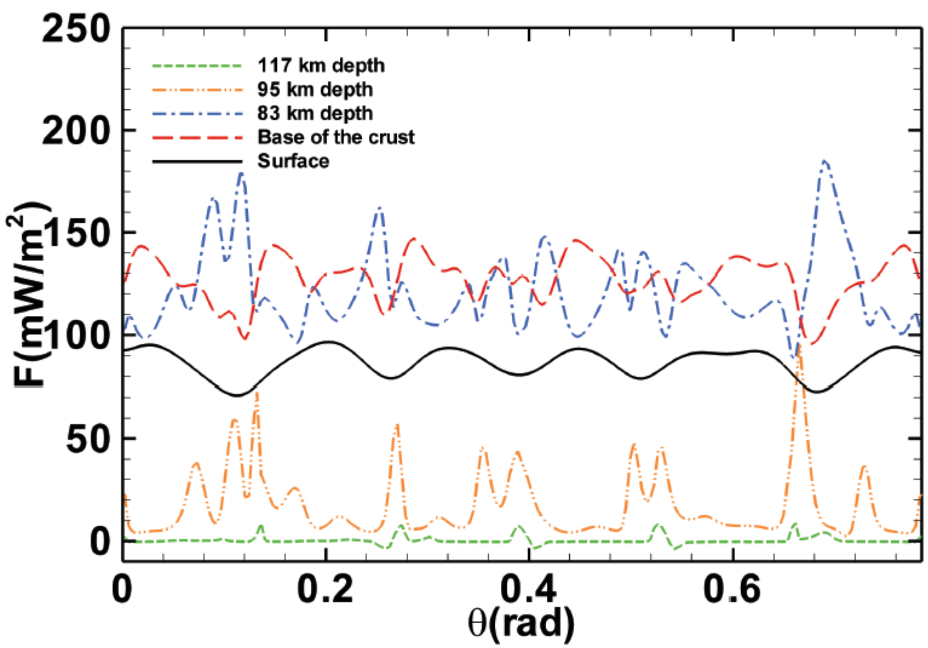
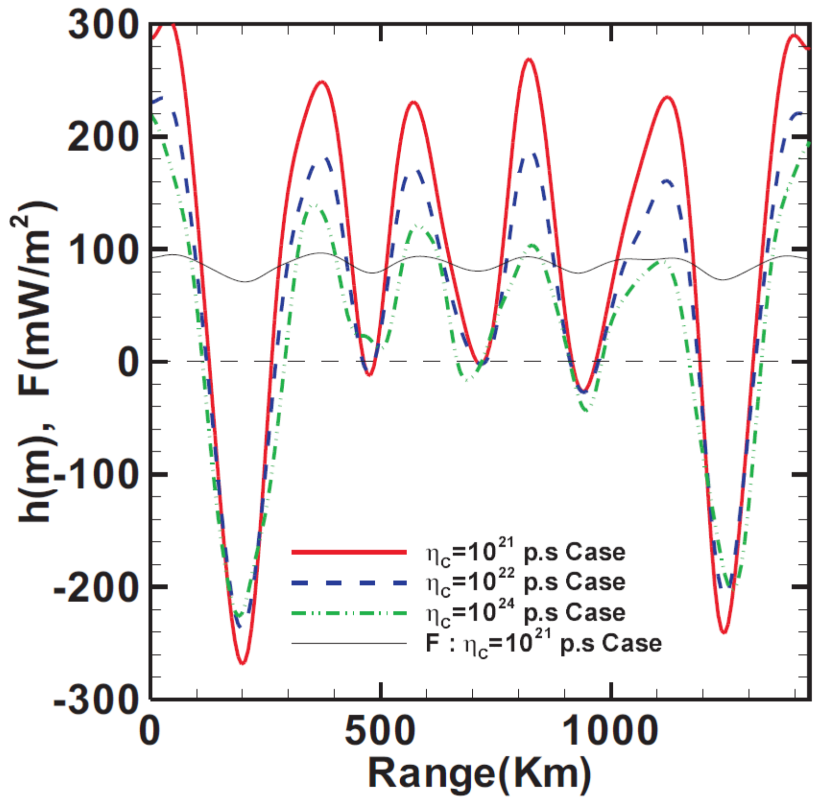
Io – Results from the Numerical Models

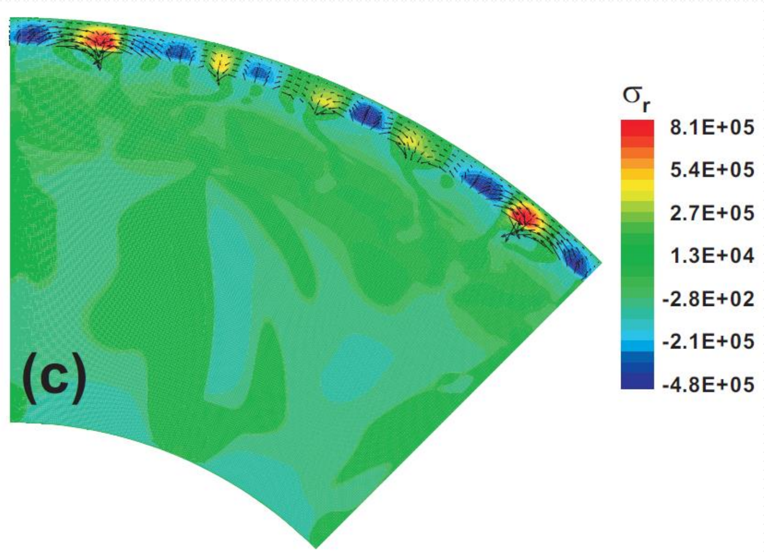


Heat fluxes at different depths for the main model (50 km crust) at the statistically equilibrium state of the model.

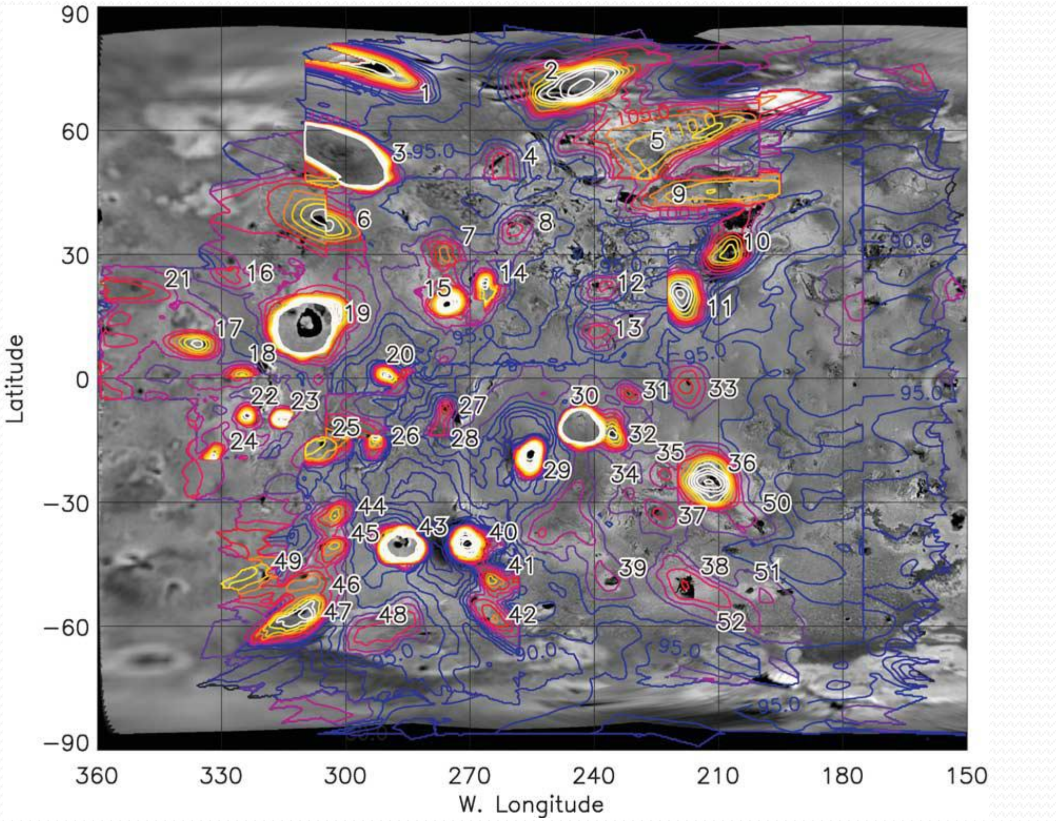


Surface topography for the models with different crust viscosities and heat flux for the original model with 50 km crustal thickness, after 2 Myr evolution. The topography has an average 280 km wavelength and is highly correlated with the surface heat flux.

Io – Results from the Numerical Models

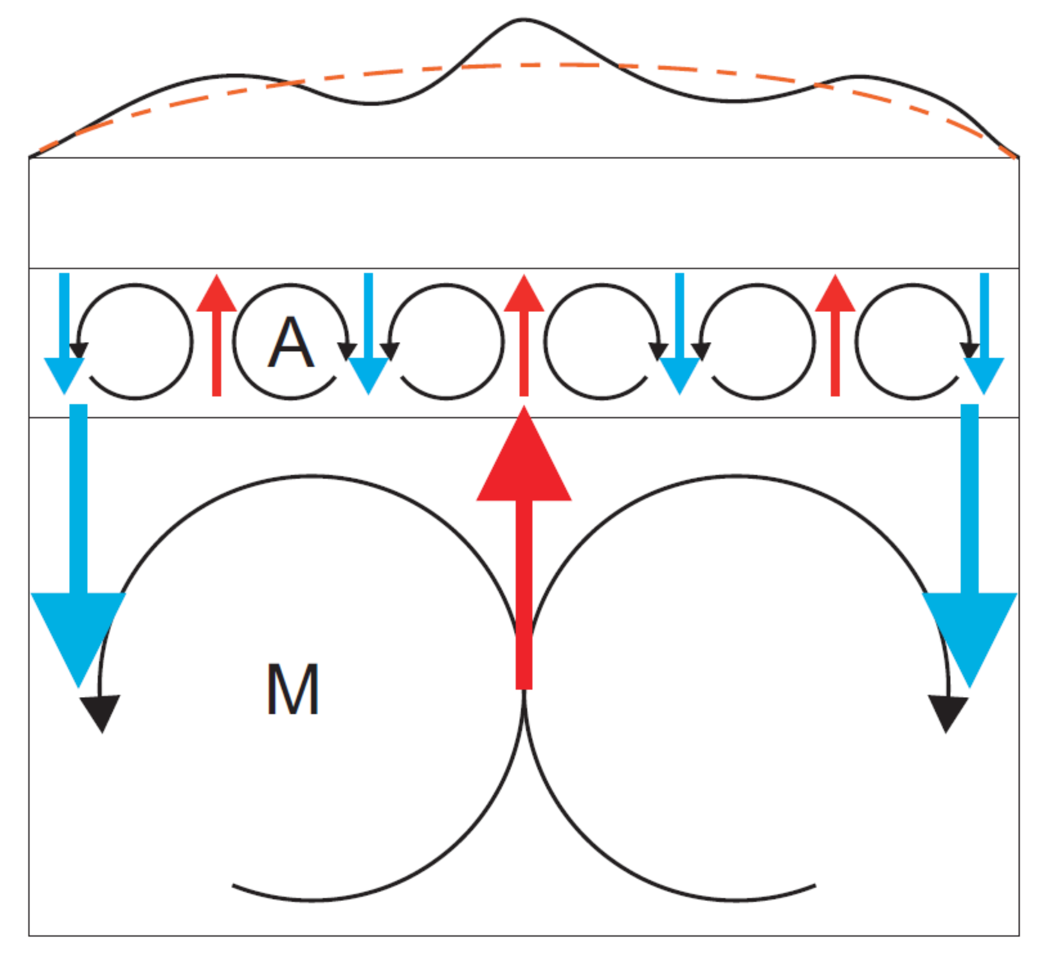


Deviatoric normal stress field (Pa) for the snapshot shown in (a) with the superimposed velocities near the surface.



Map* of night-time effective temperature in photopolarimeter–radiometer (PPR) open filter, superimposed on an SSI map of Io. Hot spots observed near Io's limb are elongated perpendicular to the limb when projected onto the map. Contour interval is 2.5 K, and contours above 130 K are omitted to avoid hiding the sources of the brightest hot spots. Figure is taken from Rathbun et al., (2004).

Io – Results from the Numerical Models



Io – Results from the Numerical Models

These numerical models suggest that **a layered intra-lithospheric small-scale convection (LILSSC)** in the asthenosphere of Io **can explain** the short wavelength heat flow distribution on the surface of Io.

LILSSC-theory in conjunction with a **differentiated lithosphere** (or large mantle plumes) **may explain** the expected Ionian surface topography, where the **short wavelength topography** arising from **LILSSC** is **modulated** on the **long wavelength topography** component.

This **small scale convection-induced surface topography,** however, cannot exceed **few hundred meters in high**. **Other tectonic events** must be **responsible** for the formation of **high Ionian Montes**. And other tectonic processes should be considered.