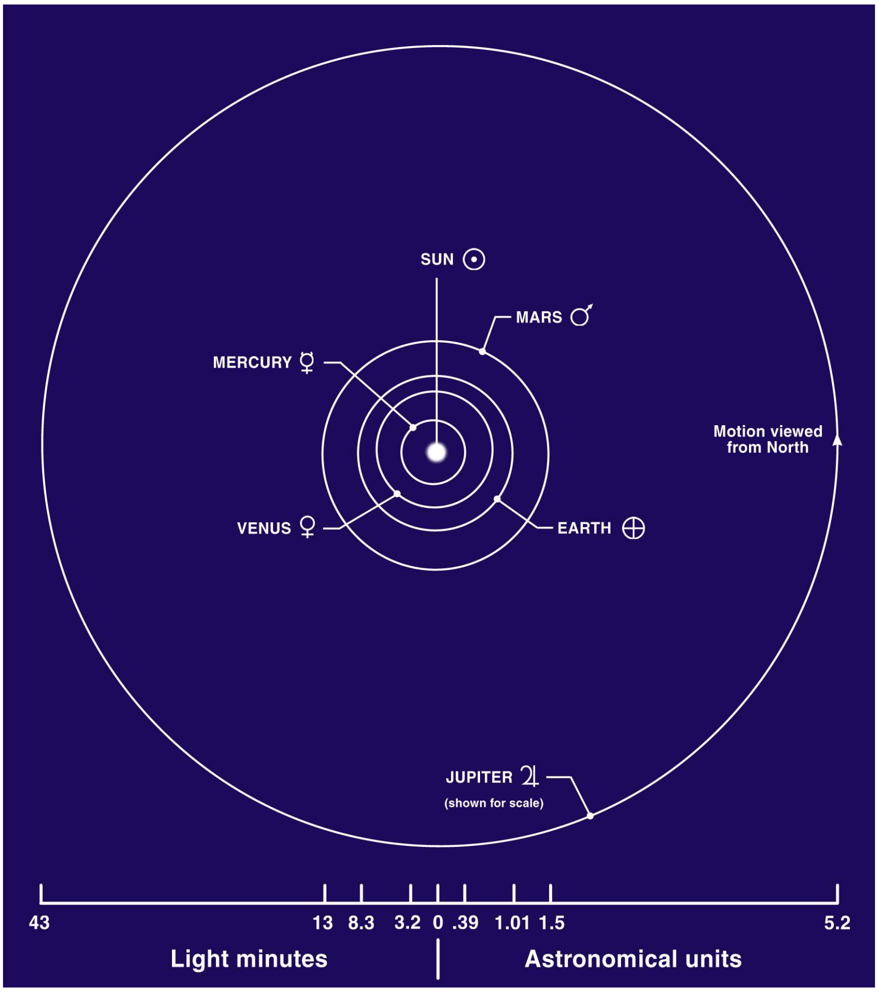
Overview

Division of Solar System into two major types of planets:

1. Inner "Terrestrial" Planets: Mercury, Venus, Earth/Moon, Mars:
   ⟹ all similar to Earth ("rocks").
   ⟹ *no moons* (Earth/Moon better called "twins")
   ⟹ Moons of
2. Outer Planets: Jupiter, Saturn, Uranus, Neptune:
   ⟹ "gas giants"
   ⟹ all have *extensive moon systems*

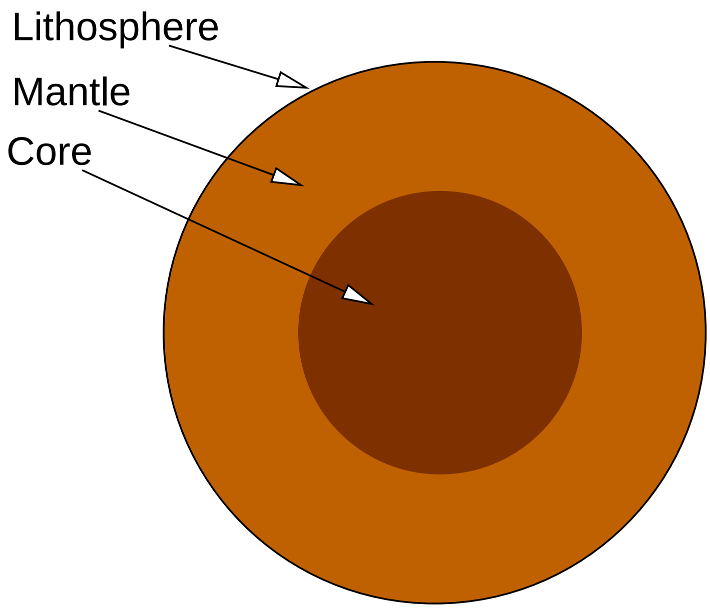
Although not planets (i.e., motion not around Sun), large moons of gas giants are very similar in structure to terrestrial planets.
Plan for this and next lecture:

1. Surfaces / Interiors of terrestrial planets
2. Atmospheric structure of gas giants (and terrestrial planets)



The Inner Planets (SSE, NASA)

Introduction, IV

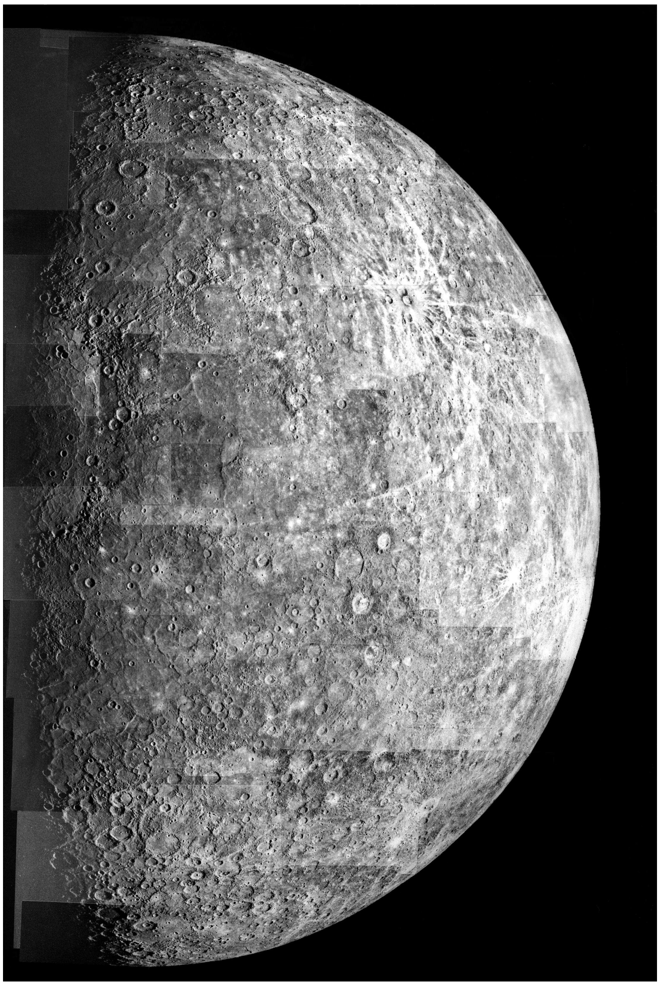


Structure of terrestrial planets:

- Core: high-density material (Fe)
- Mantle: plastic materials, hot (e.g., Earth: molten rocks)
- Lithosphere: rigid material, e.g., Silicates

Knowledge of structure important for, e.g.,

- origin of magnetic fields (thought to be caused by molten core $\Longrightarrow$ currents $\Longrightarrow$ B-field ("dynamo"). Details unknown).
- atmospheric composition (molten mantle $\Longrightarrow$ volcanism $\Longrightarrow$ CO_2, CH_4, . . .)



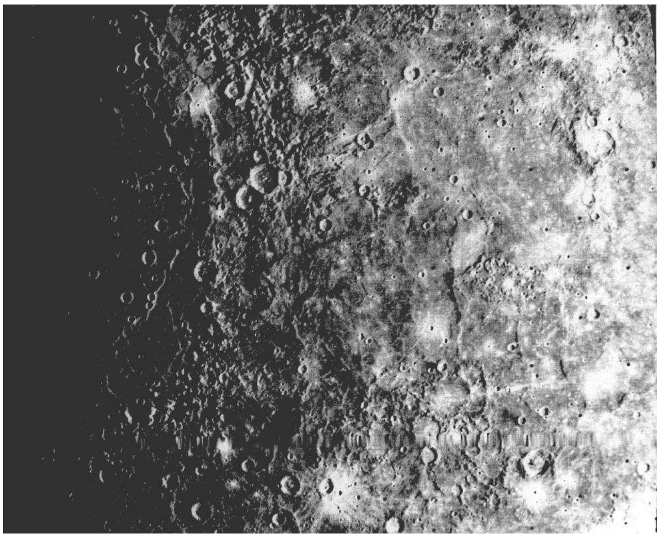
NASA

Mercury:

- not much larger than Moon
- densest of all terrestrial planets
- no evidence for atmosphere
- Rotation period: 59 d, $2/3$ of orbital period.
- surface: impact craters and tectonics
- Only information available is from Mariner 10 (three flybys, 1974/1975)
- ESA Mission Bepi Colombo, planned for $\sim$2012
- NASA mission "Messenger"

  (launched 2004 August 3, flyby 2008 and 2009, in orbit from 2011 on)

Major landforms: Large Structures



Caloris Basin (1300 km diameter) close to sub-solar point at perihelion

$\Longrightarrow$ hot ($T > 400$°C on day,
$T \sim -170$°C during night)

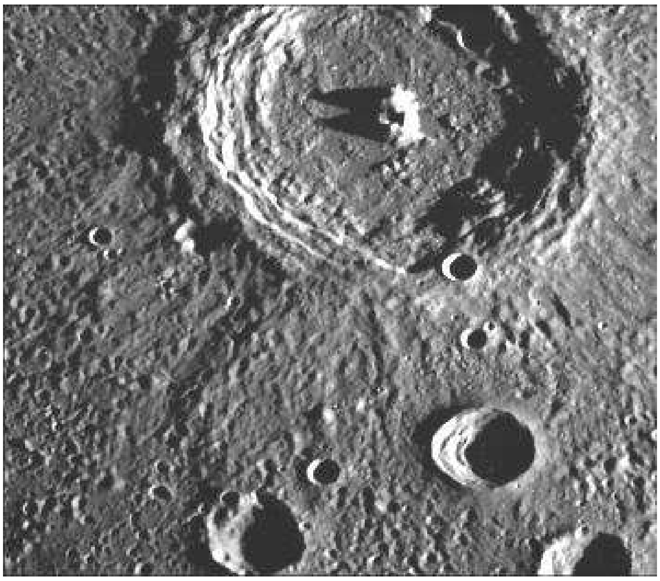
result of *large* impact event

Robinson, NWU / NASA

Hilly/lineated terrain antipodal to Caloris (120 km across)

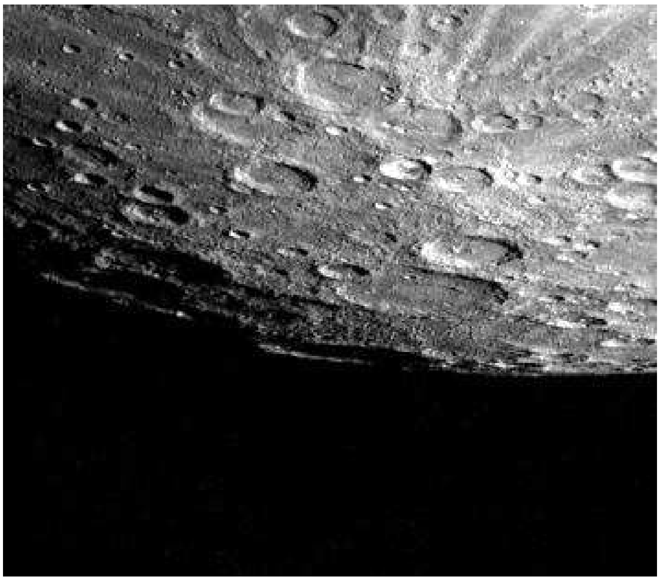
$\Longrightarrow$ effect of shock from Caloris impact.

Major landforms: Craters



NASA/JPL

Terraced craters, with central mountains.



S-Pole; NASA/JPL

50 km diam craters with rays (remains from impact)

Impact Craters, I

Physics of impact cratering:

Kinetic energy:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\cdot\frac{4}{3}\pi r^3 \rho v^2 = \frac{\pi d^3 \rho v^2}{12}$$

Important numbers:

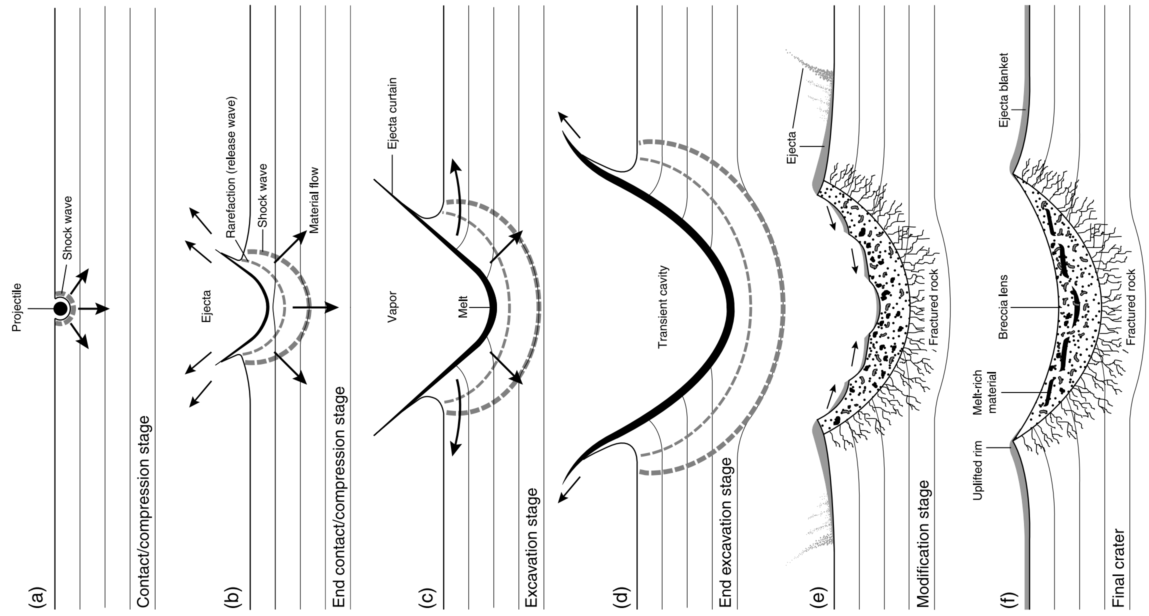
- Velocity of impact: several times orbital speed of planet
- Impacting body: rock or Fe, several meters to kilometers in size

Example:

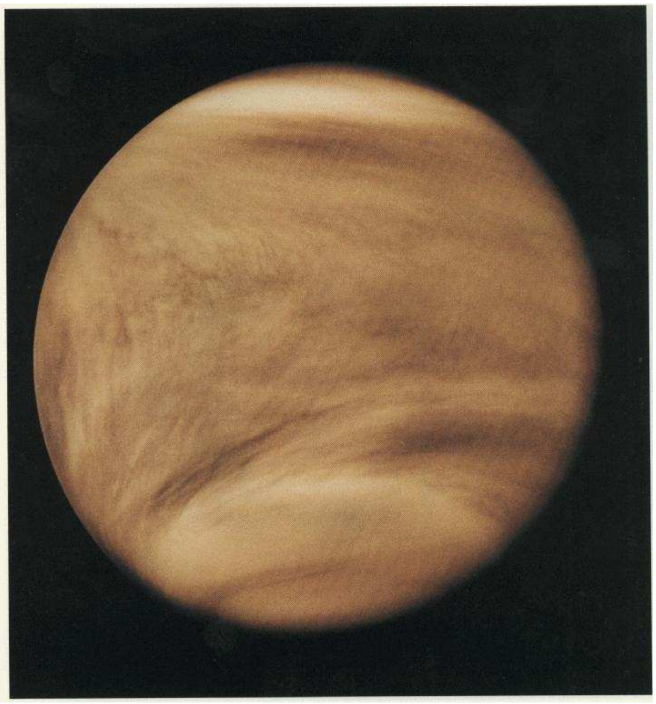
E.g., $v = 10\,\mathrm{km\,s^{-1}}$, $d = 25\,\mathrm{m}$, $\rho = 7900\,\mathrm{kg\,m^{-3}}$

$\Longrightarrow E = 3\times 10^{15}\,\mathrm{J}$ ($\sim$1 Megaton of TNT)

1 Megaton TNT is typical strength of US nuclear bombs [B-83 bomb],
UK's Trident bombs correspond to $\sim$0.3–100 kilotons TNT.



French, 1998, Traces of Catastrophe, LPI Contribution 954, p. 21



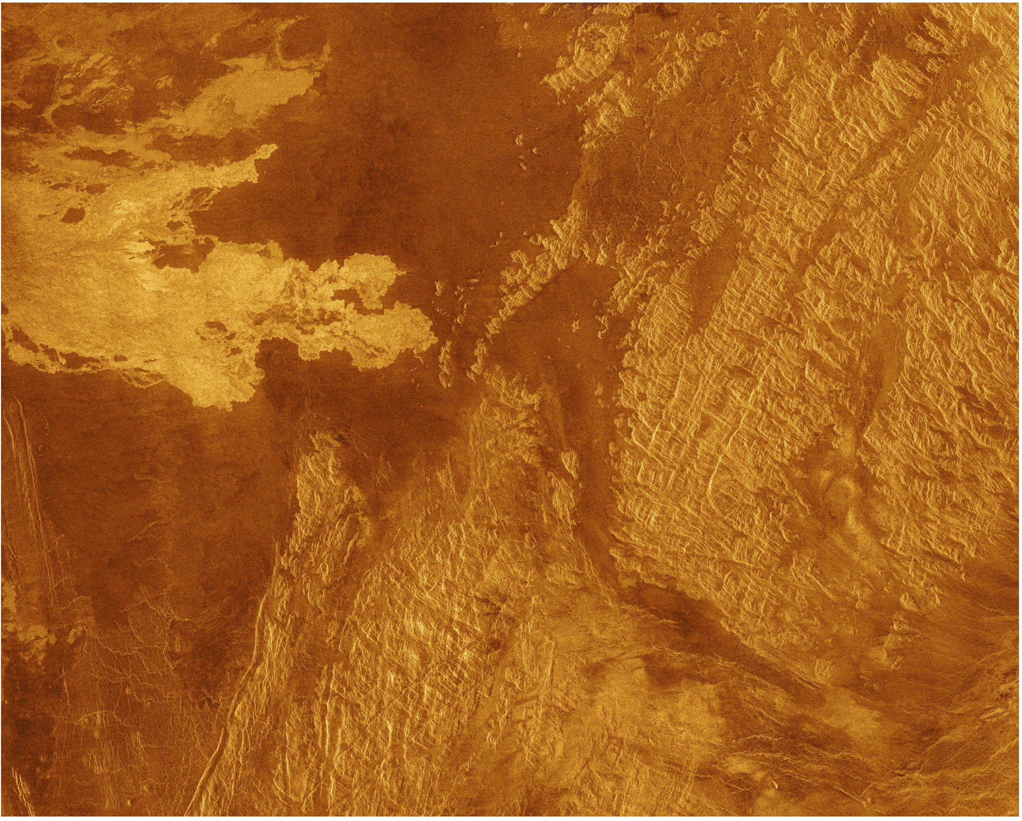
NASA, Pioneer Venus

Venus:

- similar size to Earth, similar structure
- insolation ∼2× Earth
- very slow rotation (243 d, retrograde; $\Longrightarrow$ no B-field)
- very dense atmosphere: surface pressure ∼90× Earth
- atmosphere: 96.5% CO_2, 3.5% N
  $\Longrightarrow$ strong greenhouse effect
  $\Longrightarrow$ surface temperature ∼460°C.
- acid rain (yes, sulphuric acid!)

Information mainly from radar surveying from Earth and from Magellan (1990–1994), plus images from Pioneer Venus Probe (1979). Several landings (Venera, 1975/1981)

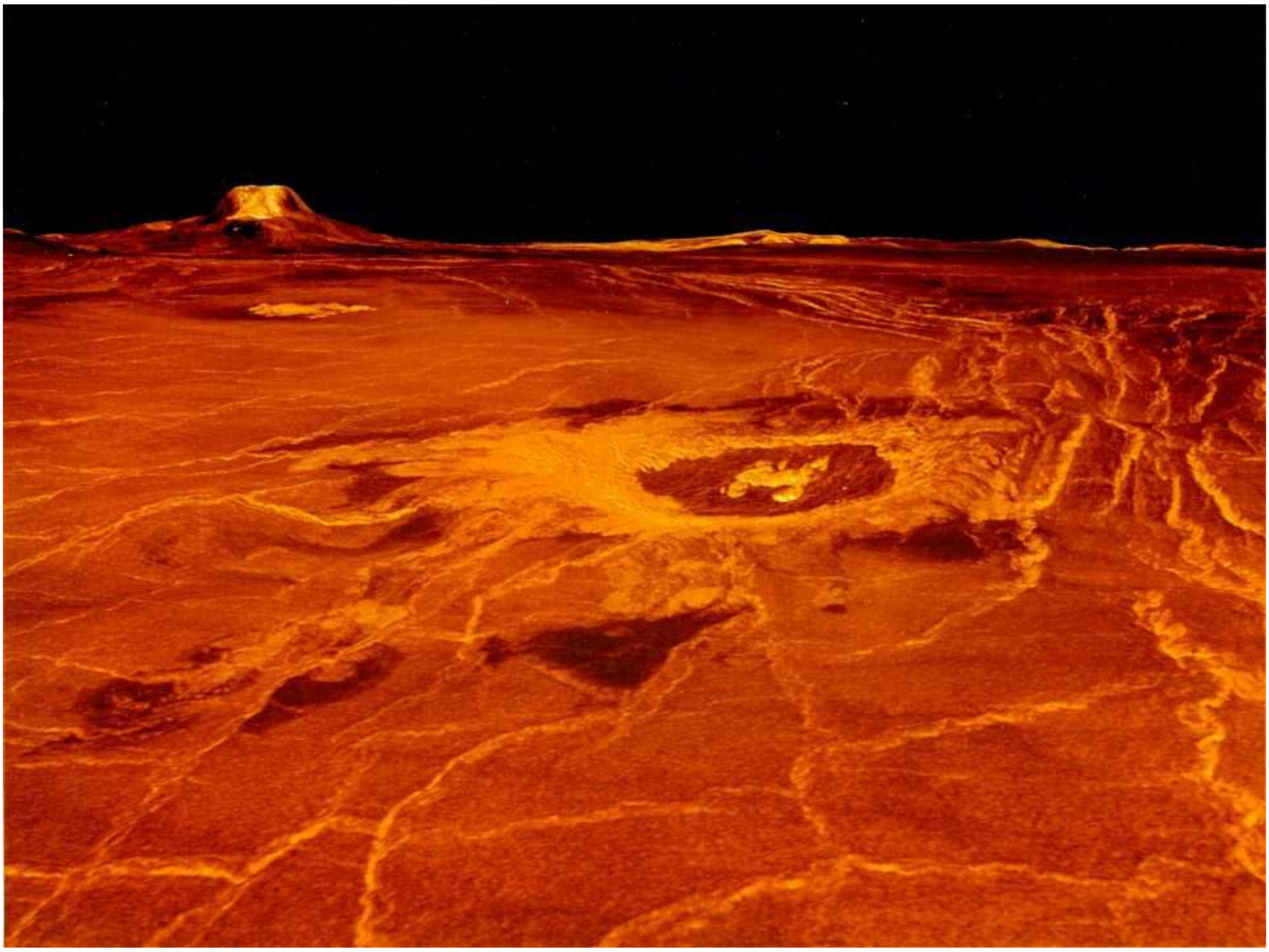
Major landforms



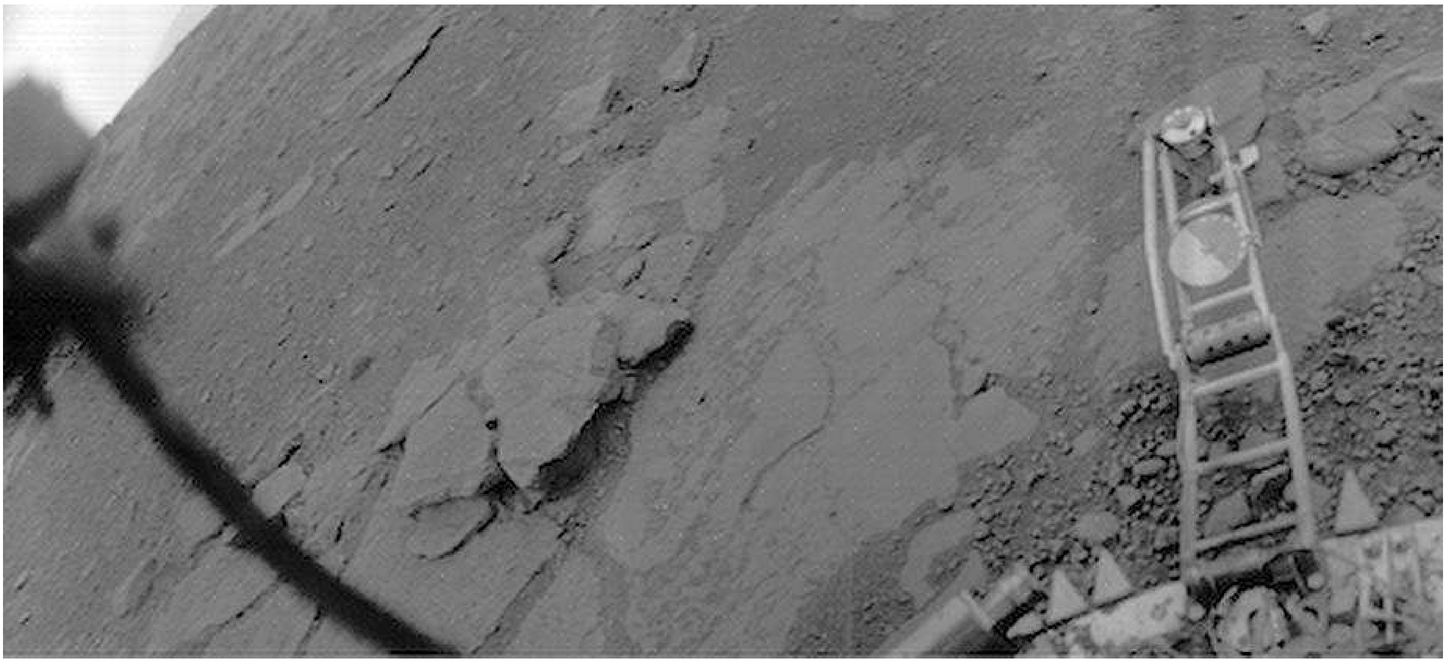
NASA, Magellan

$440 \times 350\,\mathrm{km}^2$ area in Eistla Regio, shows basic stratigraphy (sequence of geologic events): right half: old highlands, fractured structure (∼15% of surface), left part: lowlands, younger area, origin in former volcanism?

Craters (note: strong erosion $\Longrightarrow$ fewer craters overall)



Eistla Regio; heights exagerrated by factor 22.5



courtesy D.P. Mitchell

Venera 13 (3 March 1982): reanalysed image without camera distortion

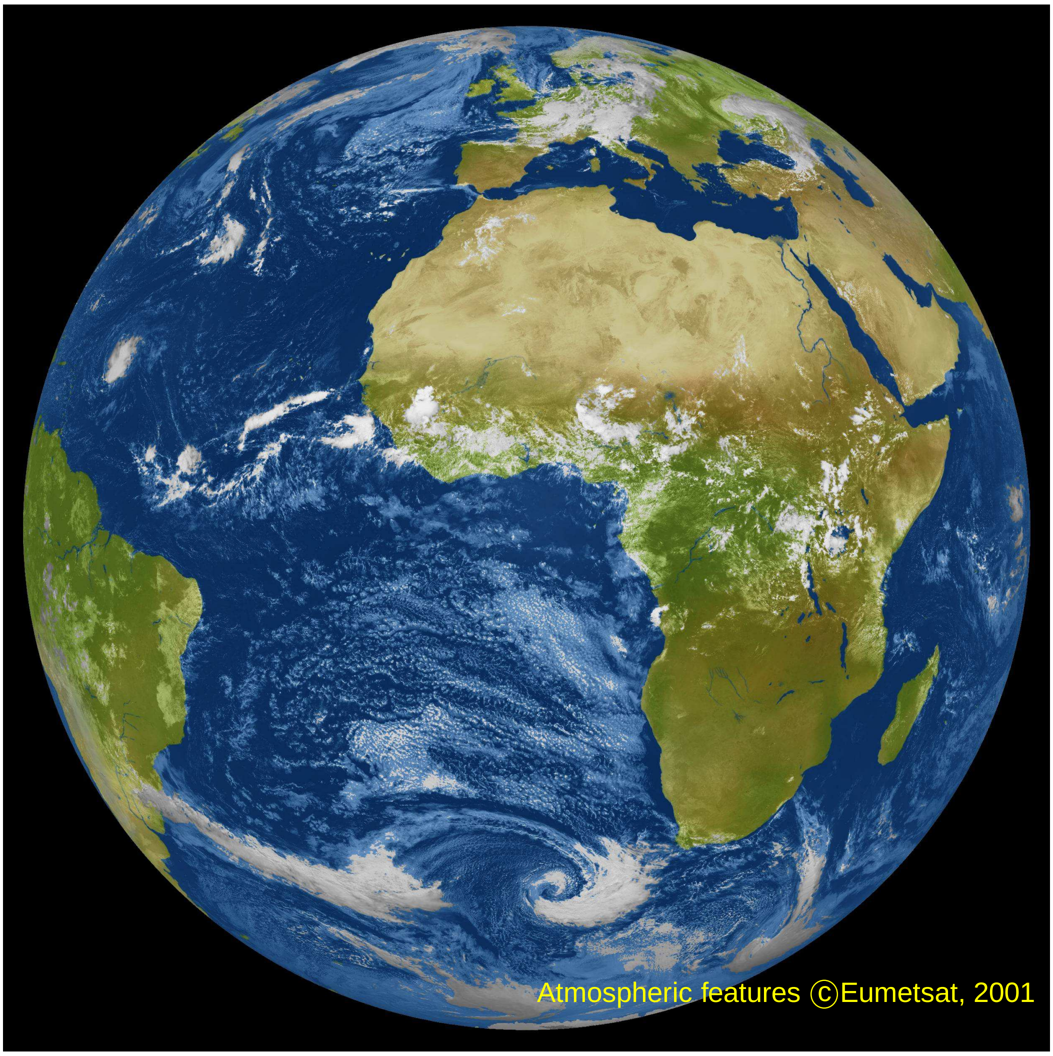
Earth:

- double planet system
- Earth surface: *dominated by plate tectonics, erosion*
- atmosphere: 80% N_2, 20%O_2
  $\Longrightarrow$ moderate greenhouse effect
  $\Longrightarrow$ surface temperature $>0^\circ$C.
- water present

Moon:

- very similar to Mercury, overall
- Mariae (plains from massive impacts) and impact craters
- Rotation synchronous to orbit around Earth

Earth/Moon, seen from Mars (NASA/Malin)

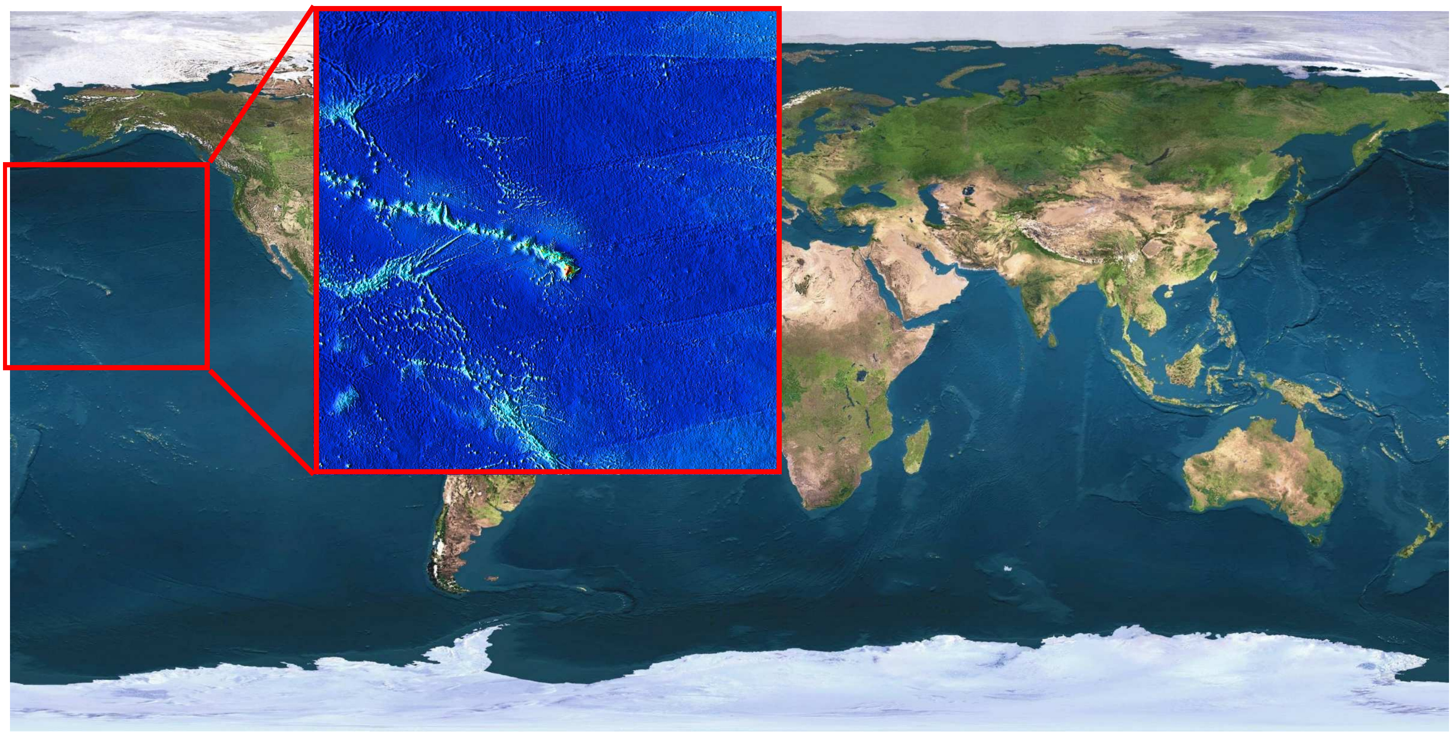


Atmospheric features ©Eumetsat, 2001

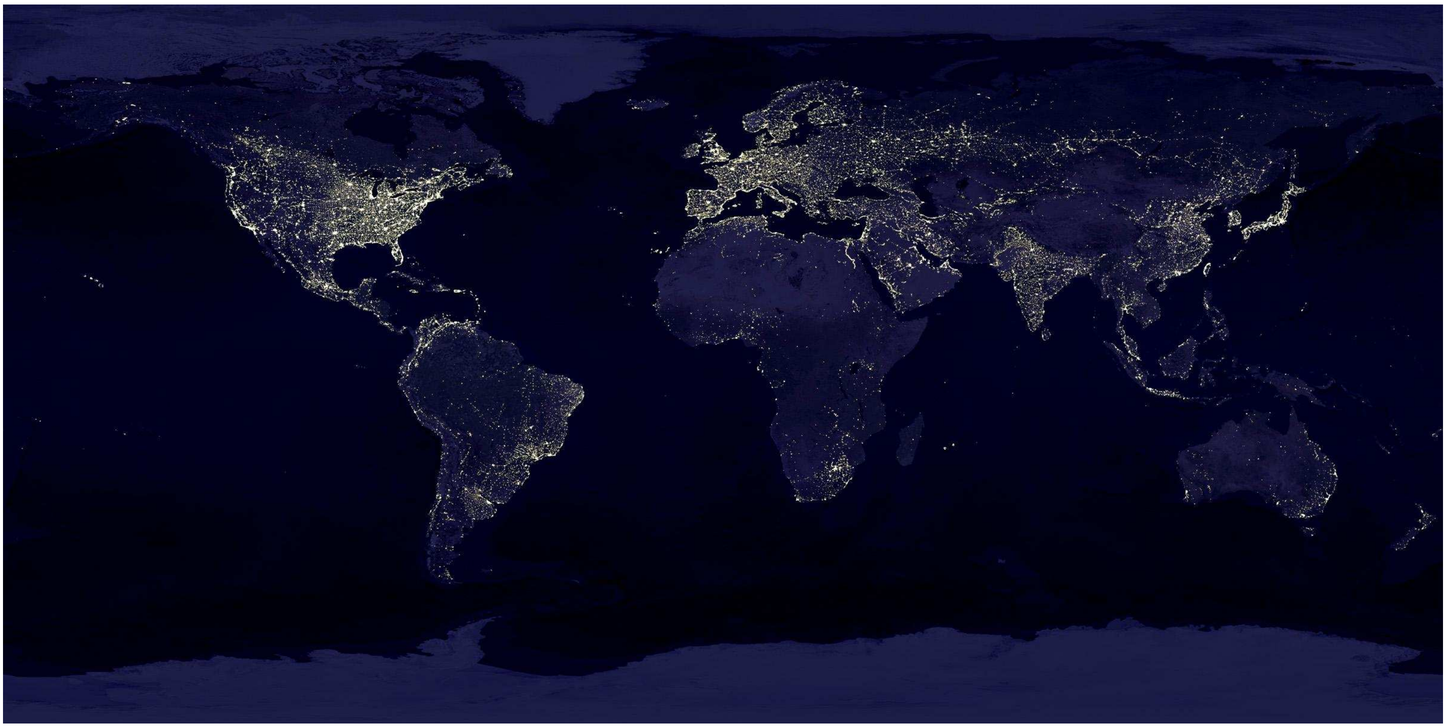
V. L. Sharpton

Earth: Wolf Creek Crater, Australia

Currently 172 confirmed impact structures on Earth

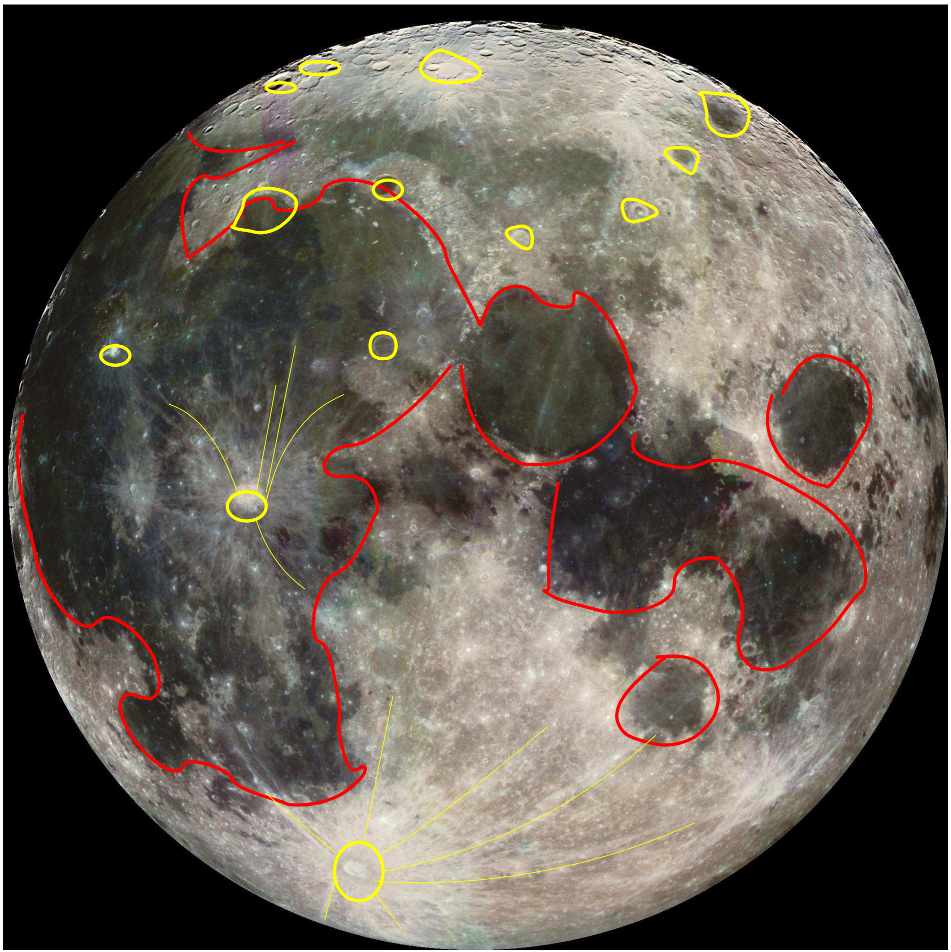


Evidence for plate tectonics (few craters!) , volcanism,. . .

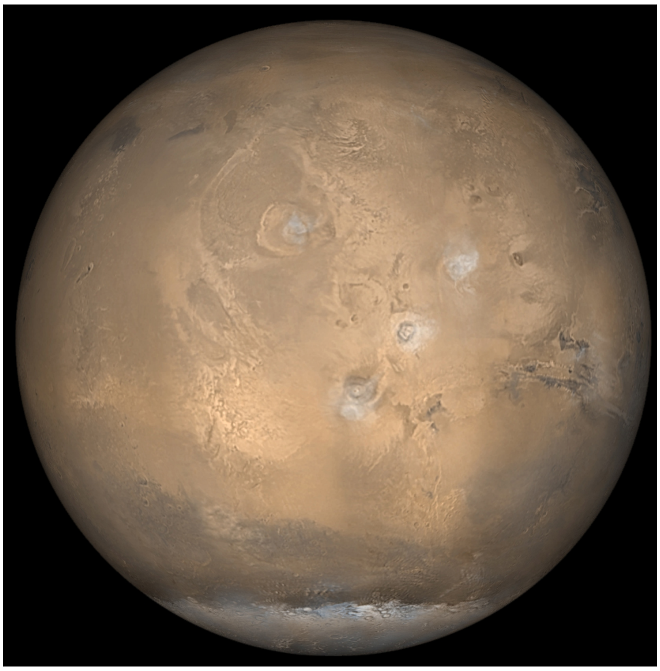


NASA

Evidence for life – note light pollution



Earth's Moon : surface dominated by mariae (large, dark lava basins) and craters (only most prominent shown).



NASA, Mars Global Surveyor

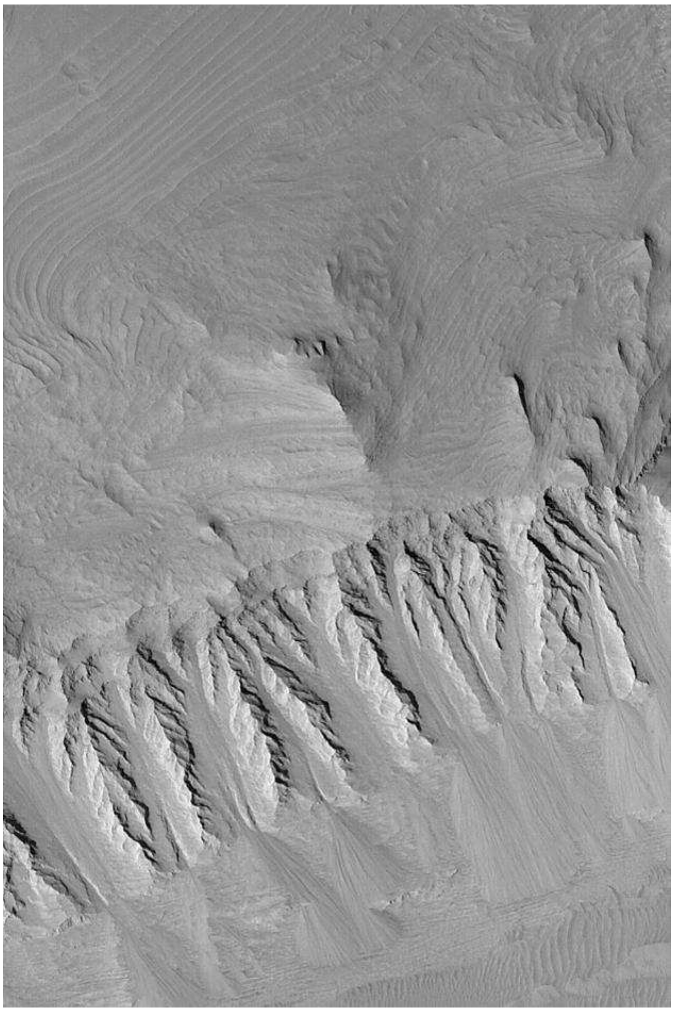
Mars:

- smaller than Earth
- very low density ($\langle\rho\rangle \sim 3\,\mathrm{g\,cm^{-3}}$)
  $\Longrightarrow$ small core, probably Fe and $\mathrm{Fe}_x\mathrm{S}_y$,
- polar caps, seasons
- thin atmosphere, clouds, fog,...
- water sublimes
  $\Longrightarrow$ no liquid water today
- Volcanism (large shield volcanoes
  $\Longrightarrow$ no (?) plate tectonics)
- atmosphere: 95% CO_2
  $\Longrightarrow$ weak greenhouse effect
- two moons (captured asteroids)

Early Exploration through Mariner missions and Viking 1 and Viking 2 orbiters and landers in 1970s, recently, strong interest (NASA Mars Global Surveyor [MGS], ESA Mars Express, plus several landers). Currently best surveyed planet except for Earth.

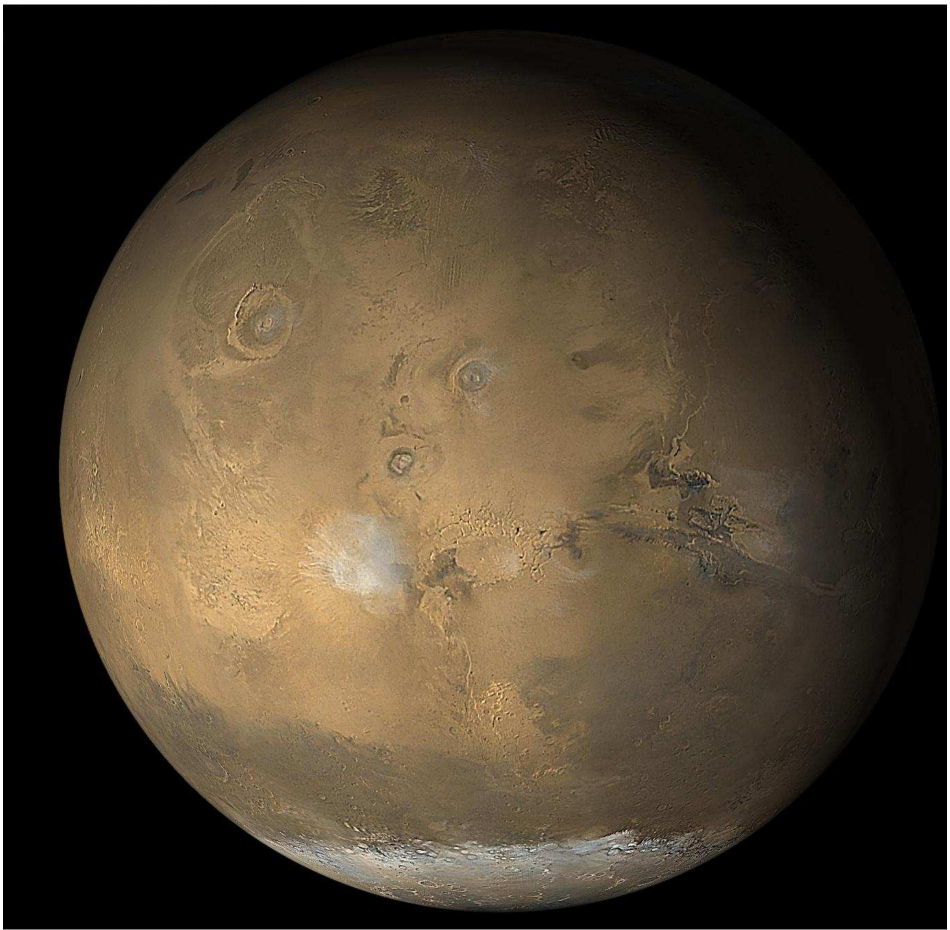
Mars: thin atmosphere (pressure on surface 1% Earth), but real seasonal variations.

Mars, 2005 Feb 7, NASA/Malin Space Systems



Rim of Valles Marineris
Sedimentary rocks, steep slope caused by faulting, possible location of fault two-thirds down the slope.

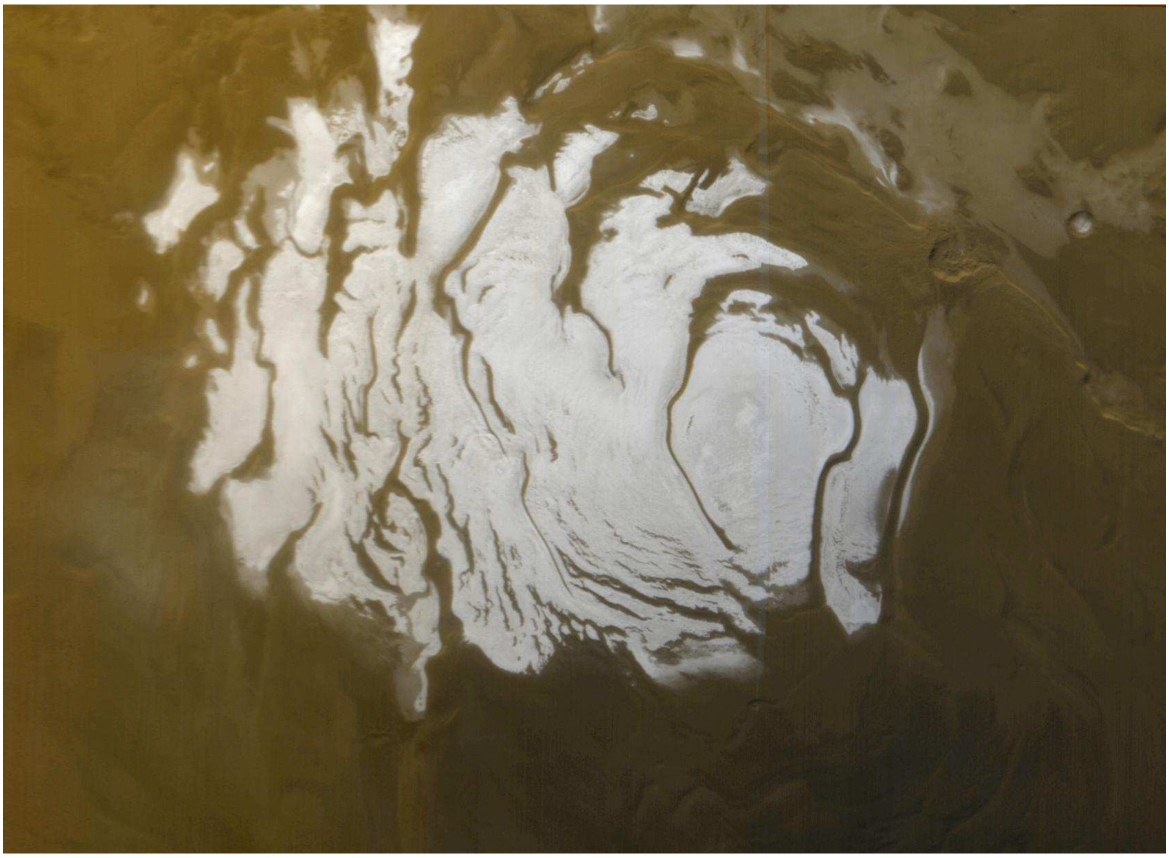
NASA MGS, 6 September 2003,
image: 3 km wide



Tharsis vulcanos: Large shield vulcanos, now extinct
$\Longrightarrow$ no plate tectonics $\Longrightarrow$ Mars interior is colder than Earth.

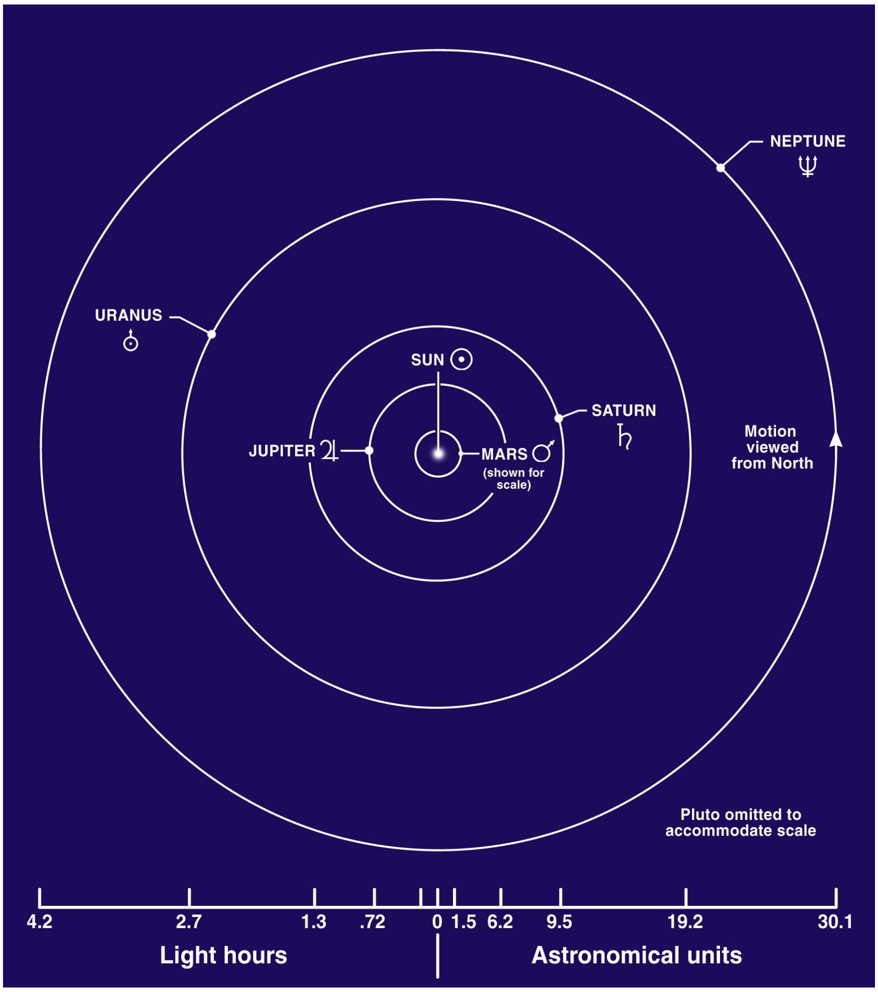
Don Davis/NASA

Viking lander 2: frost (water ice) in early morning
(*very* thin layer [$<$ 0.1 mm])

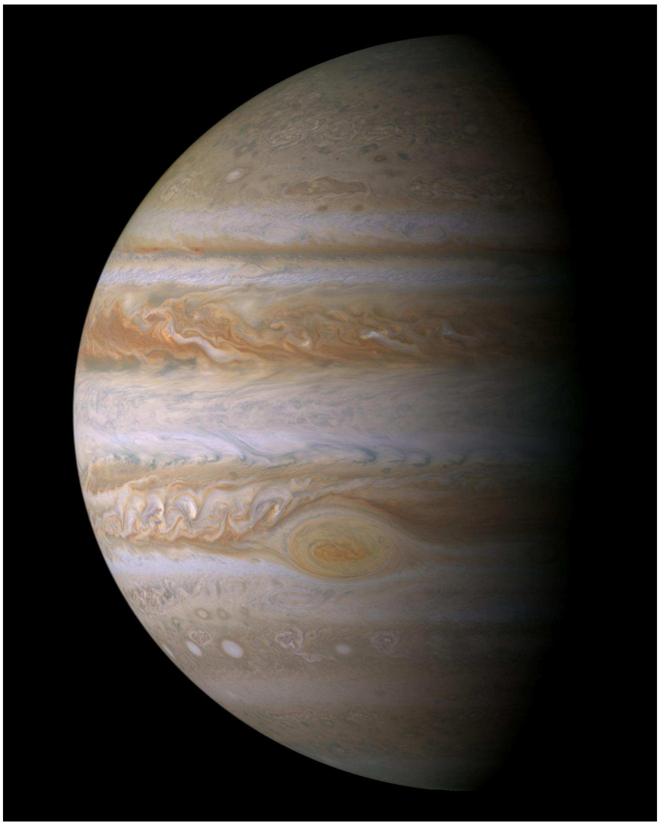


NASA/JPL/MSSS

Mars' Polar Caps: Mainly CO_2 ice ("dry ice"), grows and shrinks with seasons.



The Outer Planets (SSE, NASA)

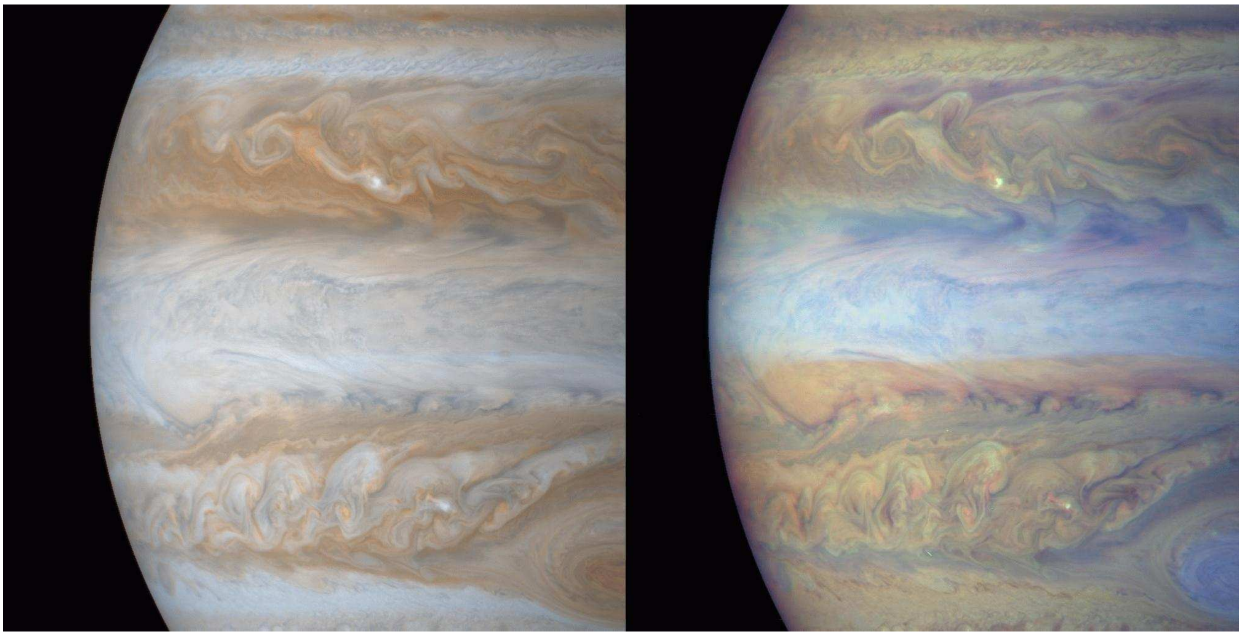


NASA/ESA, Cassini-Huyghens

Jupiter:

- Largest planet in solar system
- rapid rotation $\Longrightarrow$ severely flattened, banded atmosphere (Coriolis force), Great Red Spot
- strong magnetic field (strong radio emission)
- atmosphere: 75% H, 24% He (by mass), very close to solar
- differential rotation (rotation period 9h50m on equator, 9h55m on poles).
- strong magnetic field
- four major “Galilean” moons plus 59 small ones (as of Jan. 2005; all are captured asteroids)

Early Exploration 1970s through Pioneer 11 and 12, and then through the Voyager probes. Extensively studied by NASA’s Galileo project (ended 2003 Sep 14).



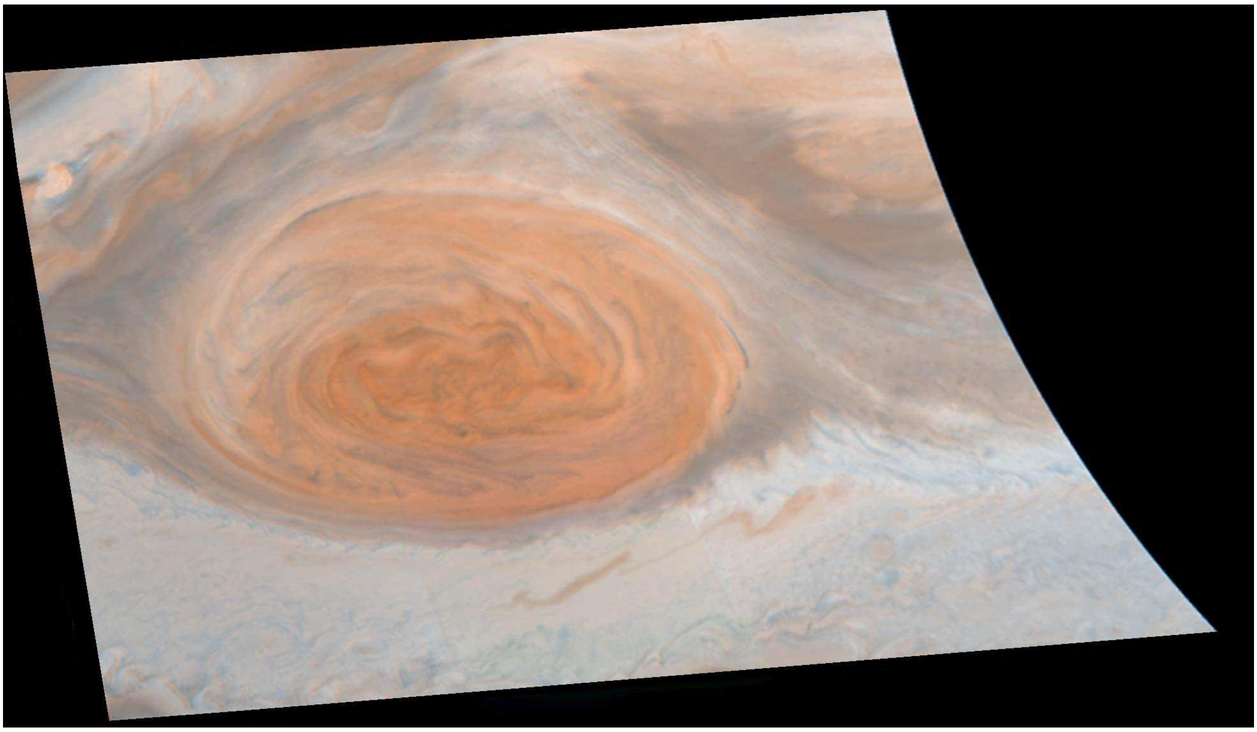
NASA/JPL,

Cassini, 2000 Dec 31

Jupiter: true color image; colors likely from trace content of organic compounds in atmosphere

false color image,
red: waterclouds,
dark spots: deep hot spots

Overall atmospheric structure: three layers:
Ammonia – ammonia hydrosulfide (NH_4HS) – water ice/water (deepest)

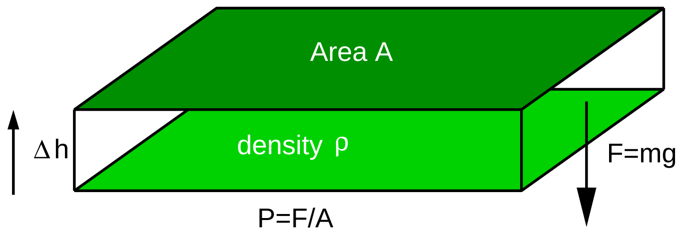


Great Red Spot
NASA Galileo, 1996 June 26

Great Red Spot: Storm System, $\sim 2\times$ Earth diameter, exists since more than 300 years, 8 km above and 10° cooler than surrounding region (rising high pressure region), rotates counterclockwise (Coriolis force on Southern hemisphere).

Jupiter, IV

Structure of atmosphere defined through hydrostatic equilibrium:



Force on area A by slab of gas of area A and density ρ:

$$F = mg = \rho V g = A h \rho g$$

Such that pressure becomes

$$P = \frac{F}{A} = \rho h g$$

where g gravitational acceleration.

For thin atmosphere (g constant): Decrease of P when going upwards by Δh:

$$\Delta P = -\rho g \Delta h \quad \text{and for } \lim_{\Delta h \to 0}: \quad \frac{\mathrm{d}P}{\mathrm{d}h} = -\rho g$$

Jupiter, V

For (ideal) gas: relationship between density and pressure ("equation of state") given by

$$P = (\rho/m)kT$$

where T: Temperature (K!), m: average mass per gas particle, k: Boltzmann's constant $k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$. Therefore:

$$\frac{\mathrm{d}P}{\mathrm{d}h} = -\left(\frac{mg}{kT}\right) P$$

For isothermal atmosphere separation of variables (see handout) gives

$$P(h) = P_0 \exp\left(-\frac{mg}{kT} \cdot h\right) = P_0 \exp\left(-\frac{h}{H}\right)$$

The pressure in the atmosphere thus decreases exponentially, the characteristic height scale of the decrease is given by the scale height H.

On Earth, $H \sim 9\,\mathrm{km}$.

Separation of variables is a standard technique for solving boundary conditions such as the equation of hydrostatic equlibrium,

$$\frac{\mathrm{d}P}{\mathrm{d}h} = -\left(\frac{mg}{kT}\right)P$$

In order to obtain P as a function of height, h, we need to solve this differential equation with the boundary condition that for $h = 0$, $P = P_0$.

First, divide by P and integrate both sides of the equation with respect to height:

$$\int_0^h \frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}h}\,\mathrm{d}h = -\int_0^h \left(\frac{mg}{kT}\right)\mathrm{d}h$$

we can now substitute $P(h)$ for h on the left hand side. Using the chain rule gives

$$\int_{P_0}^{P(h)} \frac{\mathrm{d}P'}{P'} = -\int_0^h \left(\frac{mg}{kT}\right)\mathrm{d}h$$

such that

$$\ln\left(\frac{P(0)}{P(h)}\right) = -\left(\frac{mg}{kT}\right)h$$

and exponentiating then gives

$$P(h) = P_0 \mathrm{e}^{-(mg/kT)h}$$

This method is called "separation of variables" since people often jump from the first (linear) equation to the third one in one step, by "separating the dependent from the independent variable":

$$\frac{\mathrm{d}P}{\mathrm{d}h} = -\left(\frac{mg}{kT}\right)P \quad\Longrightarrow\quad \frac{\mathrm{d}P}{P} = -\left(\frac{mg}{kT}\right) \quad\Longrightarrow\quad \int_{P_0}^{P(h)} \frac{\mathrm{d}P'}{P'} = -\int_0^h \left(\frac{mg}{kT}\right)\mathrm{d}h$$

Jupiter, VI

In general, gas giants have very different properties from terrestrial planets:

- average density low, e.g.,
  - Jupiter: $\langle\rho\rangle \sim 1.3\,\mathrm{g\,cm^{-3}}$
  - Saturn: $\langle\rho\rangle \sim 0.7\,\mathrm{g\,cm^{-3}}$

  (compare to terrestrial planets: $\langle\rho\rangle \sim 5.5\,\mathrm{g\,cm^{-3}}$; water has $\rho = 1\,\mathrm{g\,cm^{-3}}$).
- elemental composition similar to stars (by mass):
  - 75% H
  - 24% He
  - 1% rest ("metals")

$\Longrightarrow$ expect fundamentally different internal structure!

Jupiter, VII

Structure of a gas giant from equation of hydrostatic equilibrium:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho(r)\frac{GM(r)}{r^2}$$

To solve, need to know $\rho(r)$, $M(r)$ $\Longrightarrow$ complicated, but doable if properties of material are known.

To guesstimate the central pressure, one can show for a planet of radius R:

$$P_{\text{central}} = \frac{2\pi}{3}G\langle\rho\rangle^2R^2$$

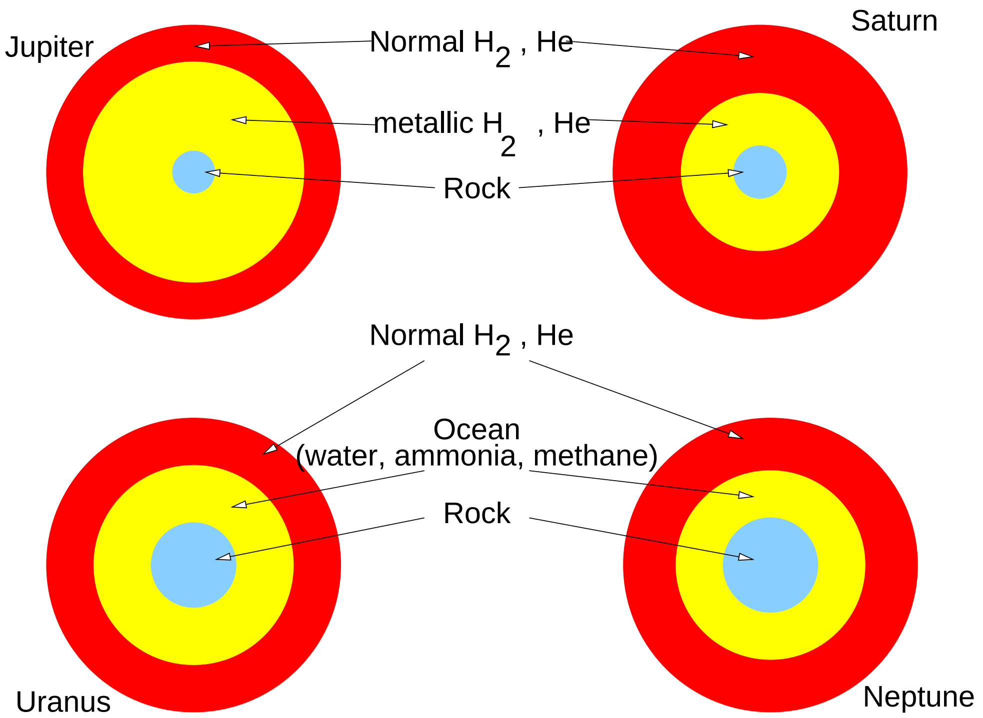
(see handout for derivation).

Plug in numbers for Jupiter: $R = 70000\,\text{km}$, $\langle\rho\rangle = 1.3\,\text{g}\,\text{cm}^{-3}$, get $P_{\text{central}} = 1.2\times 10^{12}\,\text{Pa}$ (10× Earth).

At this pressure: existence of metallic hydrogen (i.e., electrons can move freely around).

more detailed computations: metallic hydrogen from 14000–45000 km away from center

Jupiter, VIII



Note: relative sizes of planets not to scale! Also rotational flattening not taken into account.

The following is for your education only and its knowledge will not *be assessed in any way!*

To obtain information on the pressure structure of any gravitationally supported static body we can again use the *concept of hydrostatic equilibrium* already used for estimating the structure of atmospheres,

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho(r)g(r)$$

here, r is now the radial distance from the planetary centre. In contrast to atmospheres, the acceleration g depends on the position, $g = g(r)$. It is easy to show that

$$g(r) = \frac{GM(r)}{r^2}$$

where $M(r)$ is the mass of the planet contained within the radius r:

$$M(r) = \int_0^r \frac{4\pi}{3}\rho(r)r^2\mathrm{d}r$$

(interpretation: integrate over onion shells of thickness dr and density $\rho(r)$; the mass in each of these shells is $(4\pi/3)\rho(r)\mathrm{d}r$, summing over all onion shells gives the above answer).

To solve the equation of the hydrostatic equilibrium one needs to know the equation of state. Unfortunately, this equation of state is generally much more complicated than for gases and often only roughly known. One can estimate, however, the order of magnitude for the pressure within a planet. In order to do so, we assume that the density is the same throughout the planet, and that it equals the planet's average density $\rho(r) = \langle\rho\rangle =$ const.. This is o.k. to an order of magnitude. Under this assumption,

$$M(r) = (4/3)\pi r^3\langle\rho\rangle$$

such that the equation of hydrostatic equilibrium reads

$$\frac{\mathrm{d}P}{\mathrm{d}r} = \langle\rho\rangle^2 G(4/3)\pi r$$

Differential equations looking like this are called separable. They can be solved “separation of variables”, as we already did when computing the structure of an isothermal atmosphere.

First integrate both sides of the equation from $r = 0$ to the surface of the planet at $r = R$:

$$\int_0^R \frac{\mathrm{d}P}{\mathrm{d}r}\,\mathrm{d}r = \int_0^R \langle\rho\rangle^2 G(4/3)\pi r\,\mathrm{d}r$$

To integrate the left hand side of the equation, substitute $r \longrightarrow P(r)$ where $P(r)$ is an unknown function (the pressure as a function of radius r). Luckily enough, we only need to know its values at $r = 0$ and $r = R$ (the “boundary conditions”). By definition of the surface of the planet, the pressure at $r = R$ will be $P(R) = 0$ to very good accuracy, while the pressure at $r = 0$ is the (unknown) central pressure, $P(0) = P_\mathrm{c}$. Therefore

$$\int_0^R \frac{\mathrm{d}P}{\mathrm{d}r}\,\mathrm{d}r = \int_{P_\mathrm{c}}^0 \mathrm{d}P = -P_\mathrm{c}$$

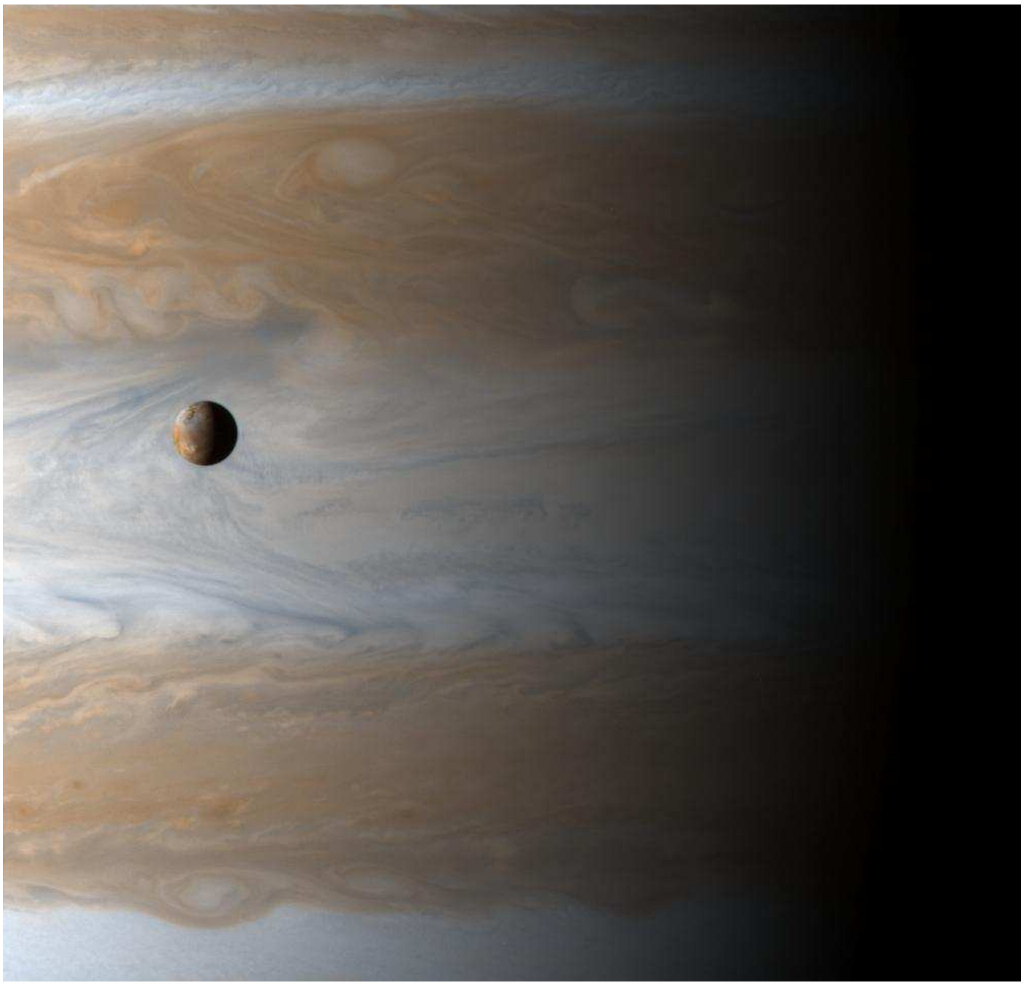
The right hand side of the equation is easily found as well:

$$\int_0^R \langle\rho\rangle^2 G(4/3)\pi r\,\mathrm{d}r = -\langle\rho\rangle^2(4\pi/3)G\int_0^R r\,\mathrm{d}r = -\langle\rho\rangle^2(4\pi/3)GR^2/2 = -\frac{2\pi}{3}\langle\rho\rangle^2 R^2$$

Putting everything together gives

$$P_\mathrm{c} = \frac{2\pi}{3}\langle\rho\rangle^2 R^2$$

As a rule of thumb, this formula gives central pressures that are correct to better than a factor of 10 compared to the detailed theory.



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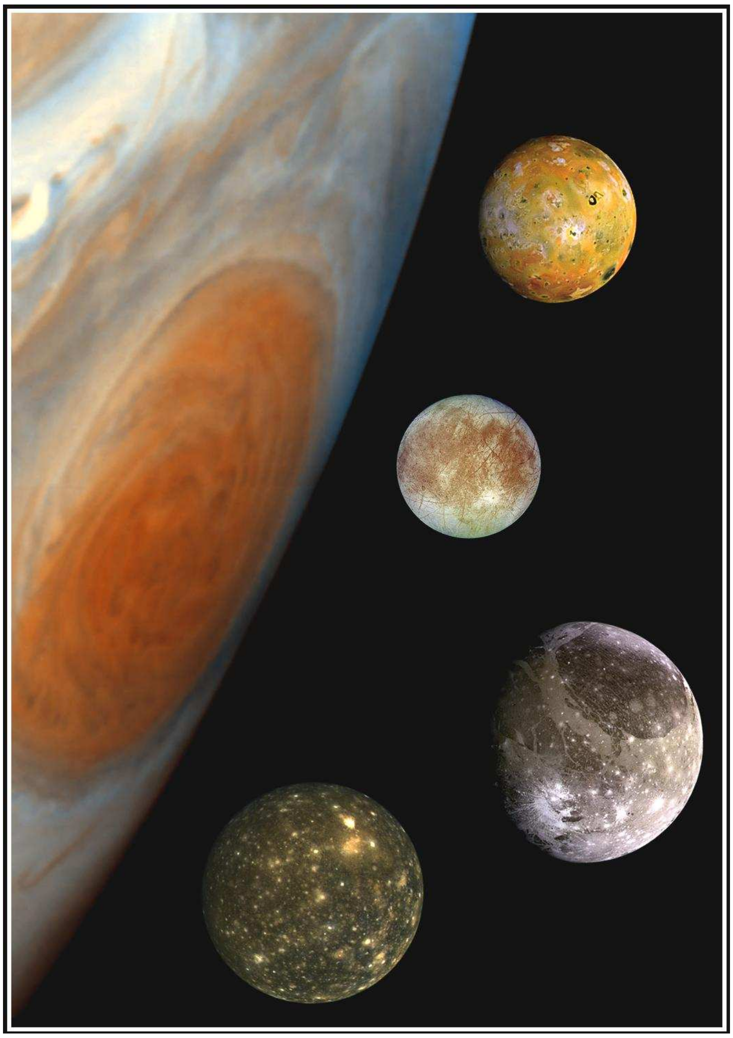
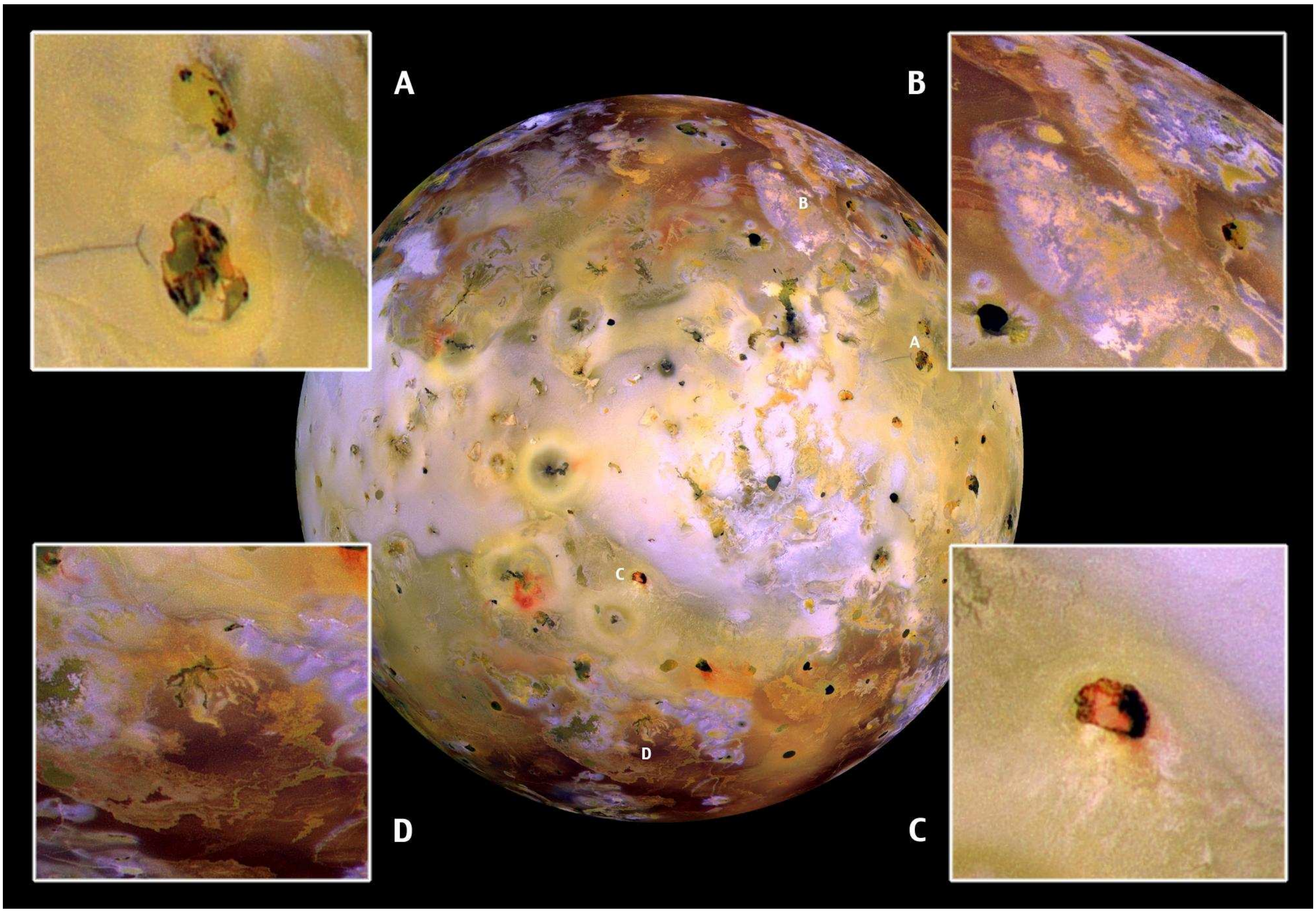
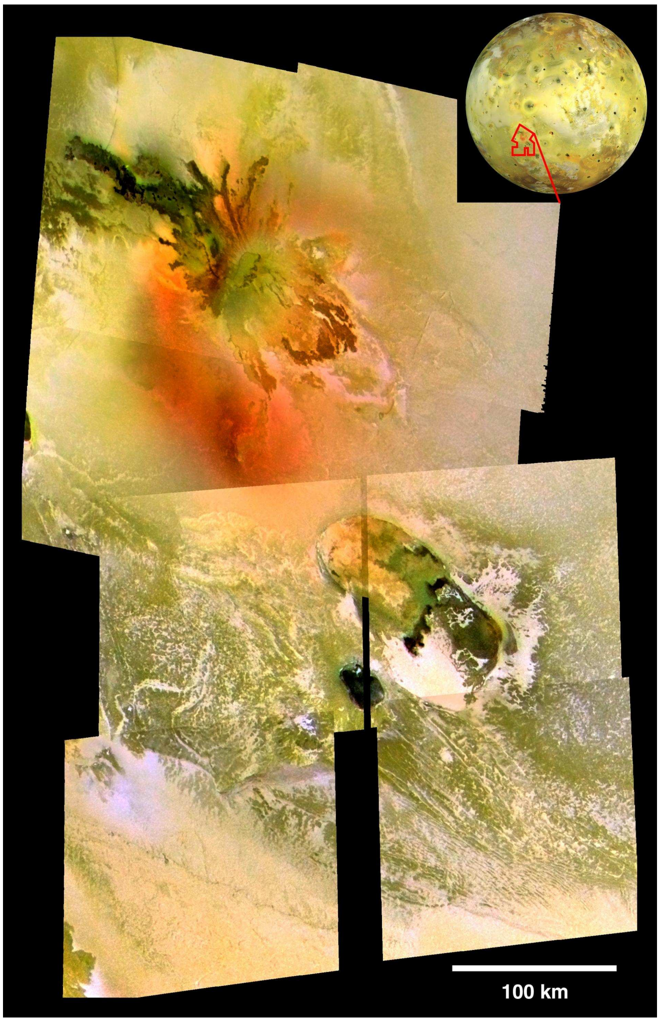


Montage of Jupiter and Galilean Moons: top to bottom: Io, Europa, Ganymede and Callisto.

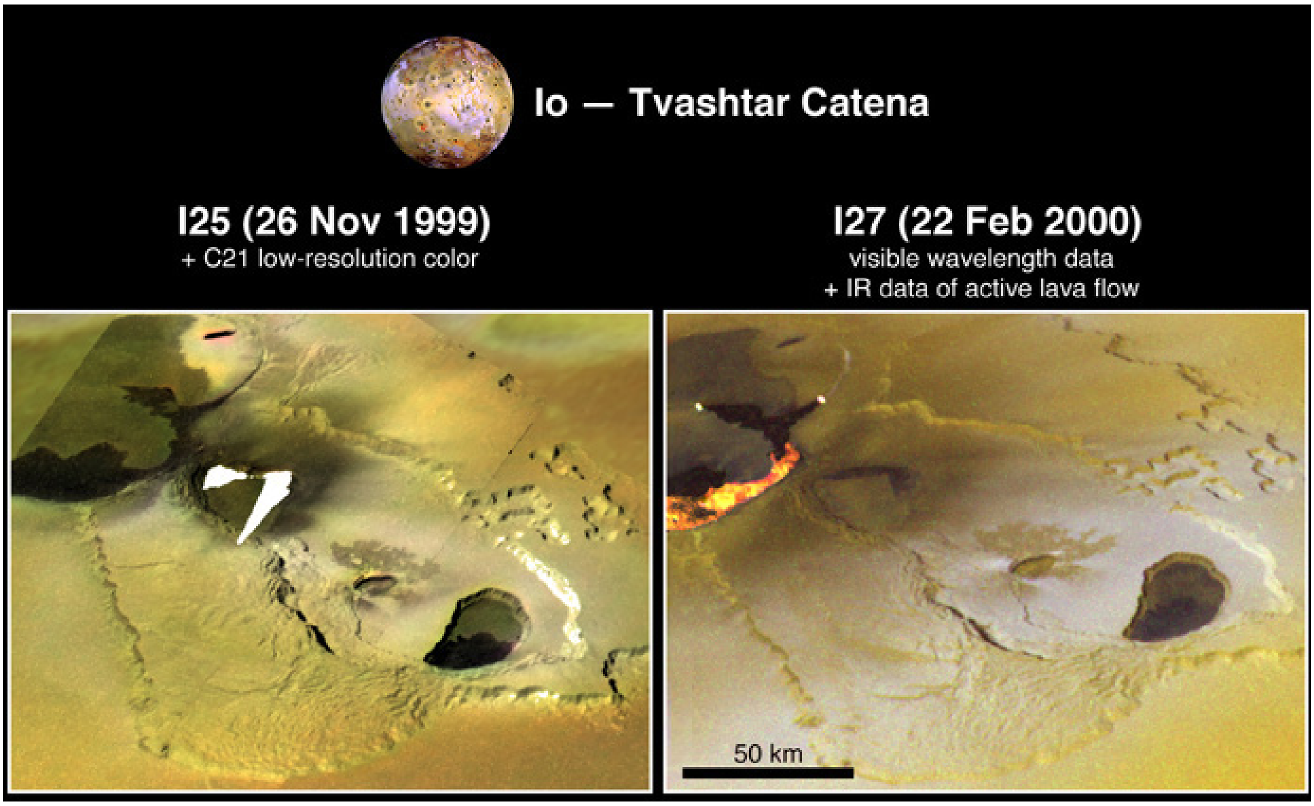
(N.B.: All Galilean moons tidally locked to Jupiter – always same side is facing Jupiter)



Jupiter’s moon Io – the vulcano moon (Diam. 1821 km [Earth moon: 1738 km])

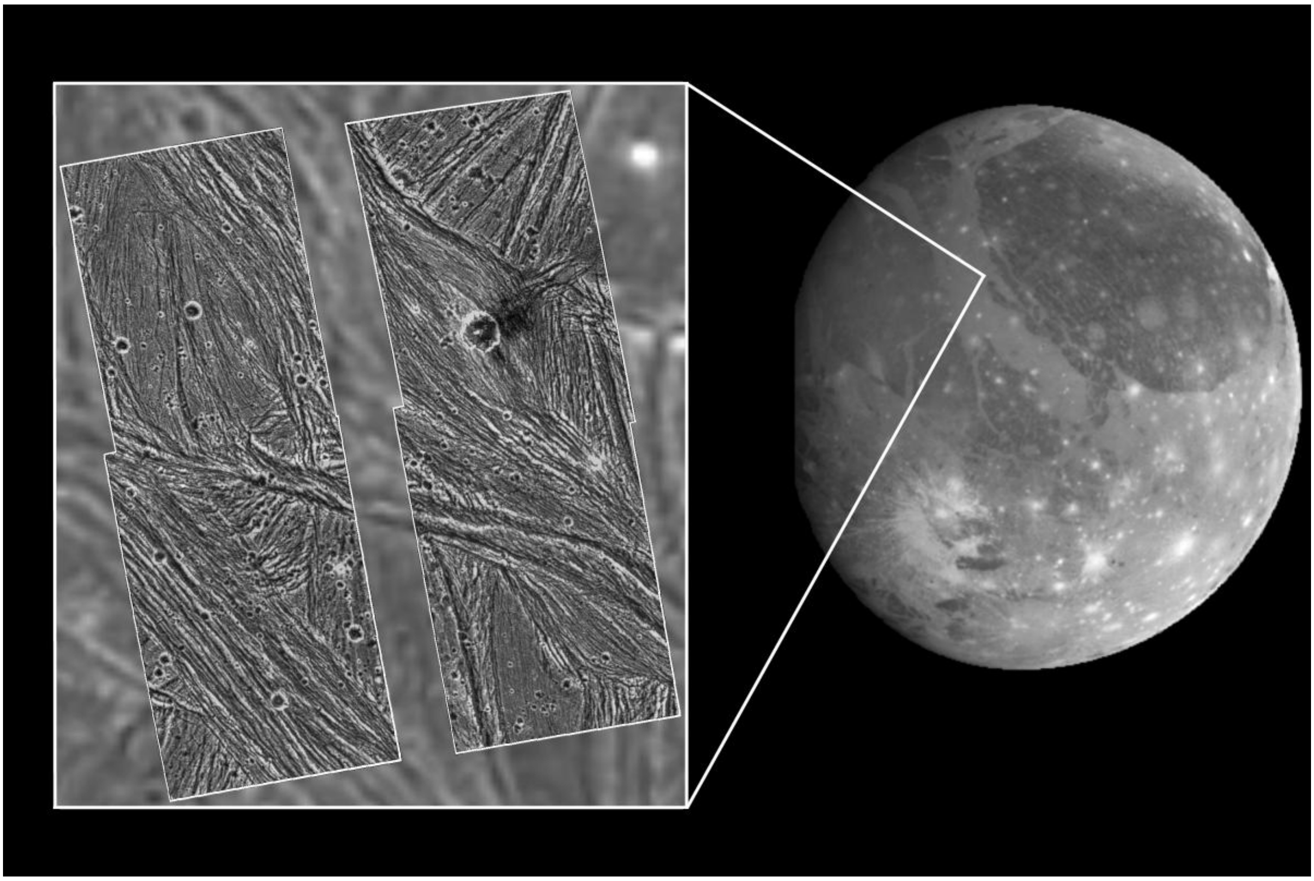


Active vulcanoes on Io (interior heated by tidal forces from Jupiter), color due to large contents of sulphur and sulphur oxides in lava. Height of vulcanoes: 6 km or higher



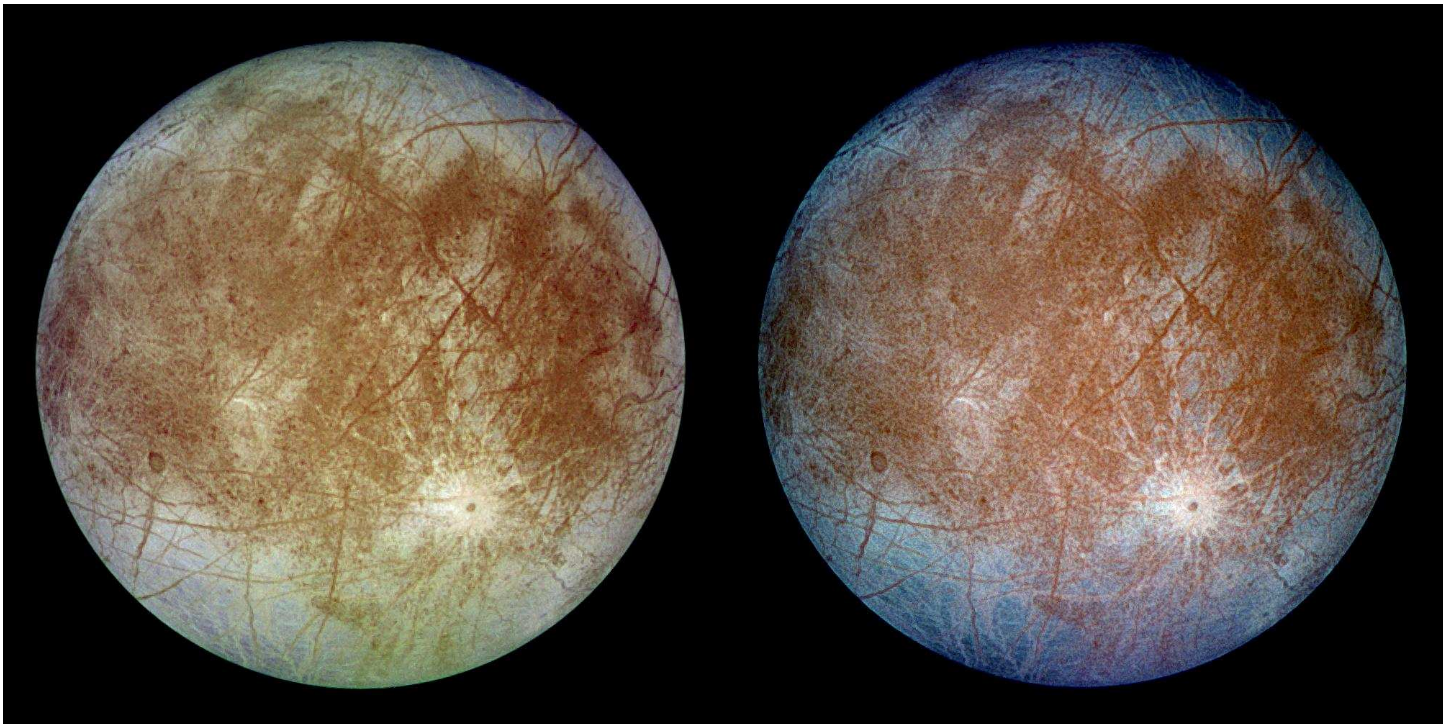
curtains of lava fountains [white: overexposed]
NASA Galileo, 1999 Nov 26

High temperature volcanism (2000 K; hotter than on Earth [1700 K]!)



NASA Galileo / DLR, inset: 120×110 km

Ganymede – icy surface, ice hills and valleys, craters
Radius: 2634 km (∼ Mercury!)

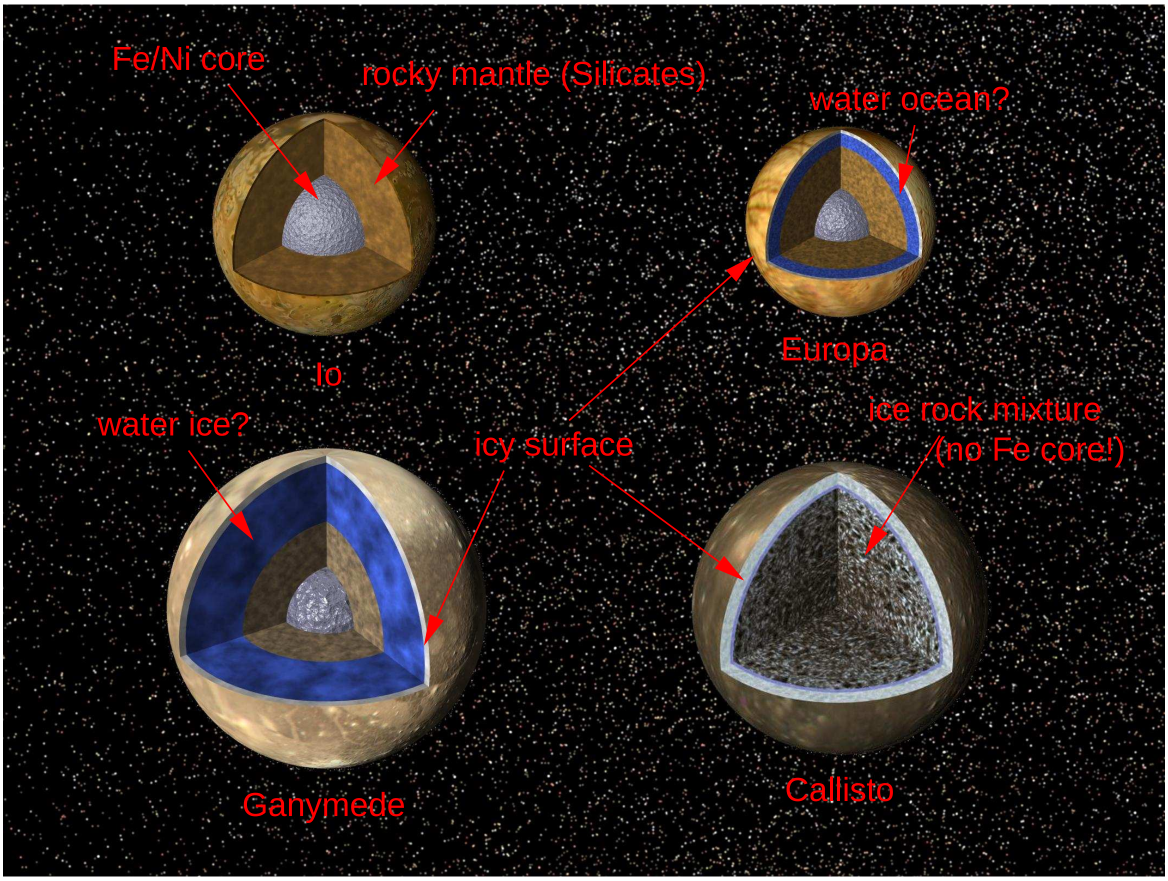


NASA Galileo / DLR, 1996 September 7

Europa – icy surface with ridges (colors: different kinds of ice)
Radius: 1565 km ($\sim$ Earth Moon)
possibility of water ocean below surface

Callisto: “pock faced”,
mainly impact craters.
white: ice
dark: ice-poor material

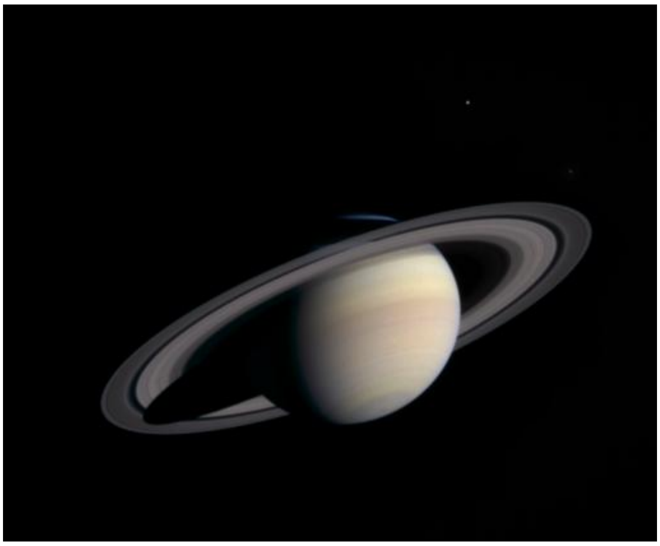
Radius: 2406 km (similar
to Mercury!)



Structure of Jupiter’s Galilean Moons similar to terrestrial planets

(but some also have very thick ice layer on top)

There are more terrestrial “planets” than one might think!

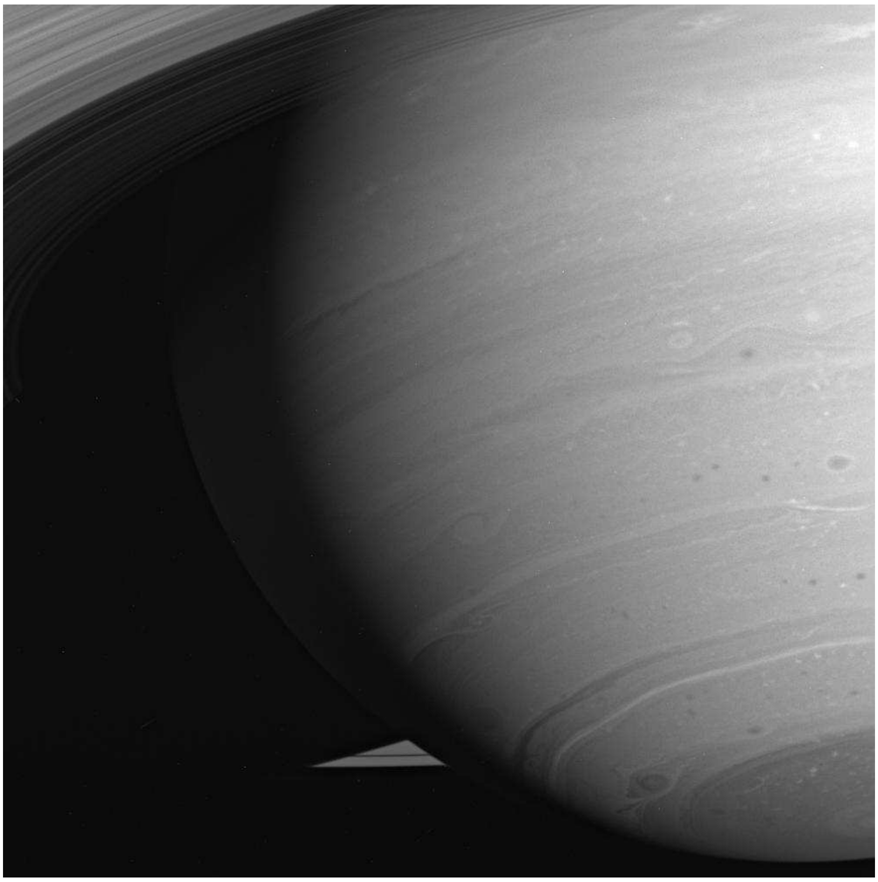


Saturn:

- similar to Jupiter, slightly smaller
- rapid rotation $\Longrightarrow$ flattened, banded atmosphere
- atmosphere: 75% H, 24% He (by mass), molecules etc. similar to Jupiter
- Rings!
- six major moons plus 27 small ones (as of Jan. 2005; mainly captured asteroids)

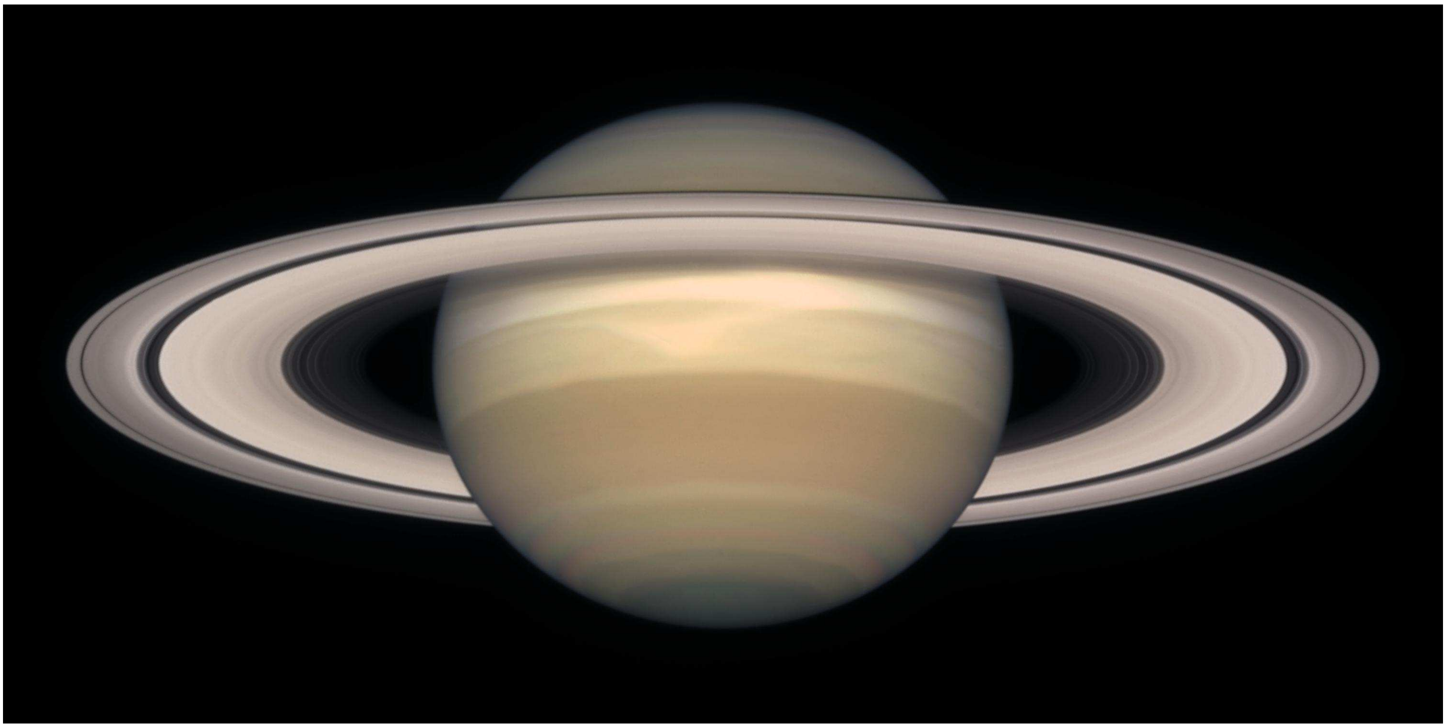
NASA Cassini, 2003 Dec.

Early Exploration 1970s through Pioneer 11 and 12, and then through the Voyager probes.
Studied since 2004 July 1 by NASA/ESA Cassini-Huygens project (duration: four years)



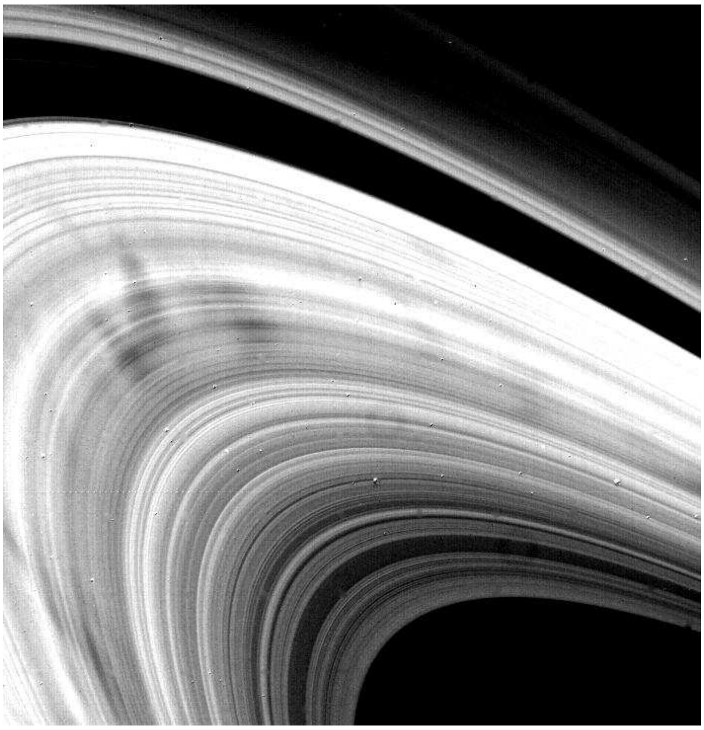
NASA/ESA Cassini, 2005 July (polarised IR light)

Saturn: Similar atmospheric structure as Jupiter



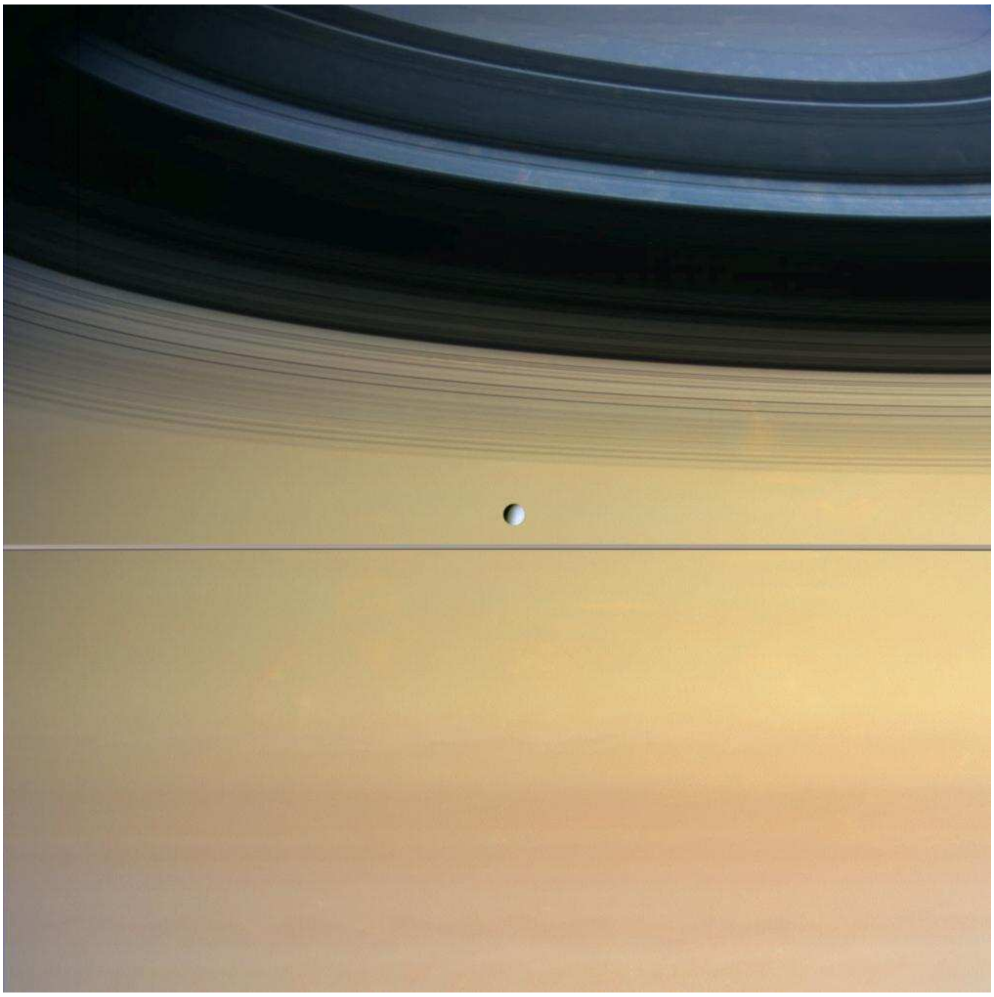
NASA HST, 1999 October

Rings: equatorial plane, thin (few km high, 71000–140000 km from centre);
gaps due to gravitational effects of outer moons (widest gap: Cassini's division);
speed of rings agrees with 3rd Kepler ($\Longrightarrow$ individual particles!)

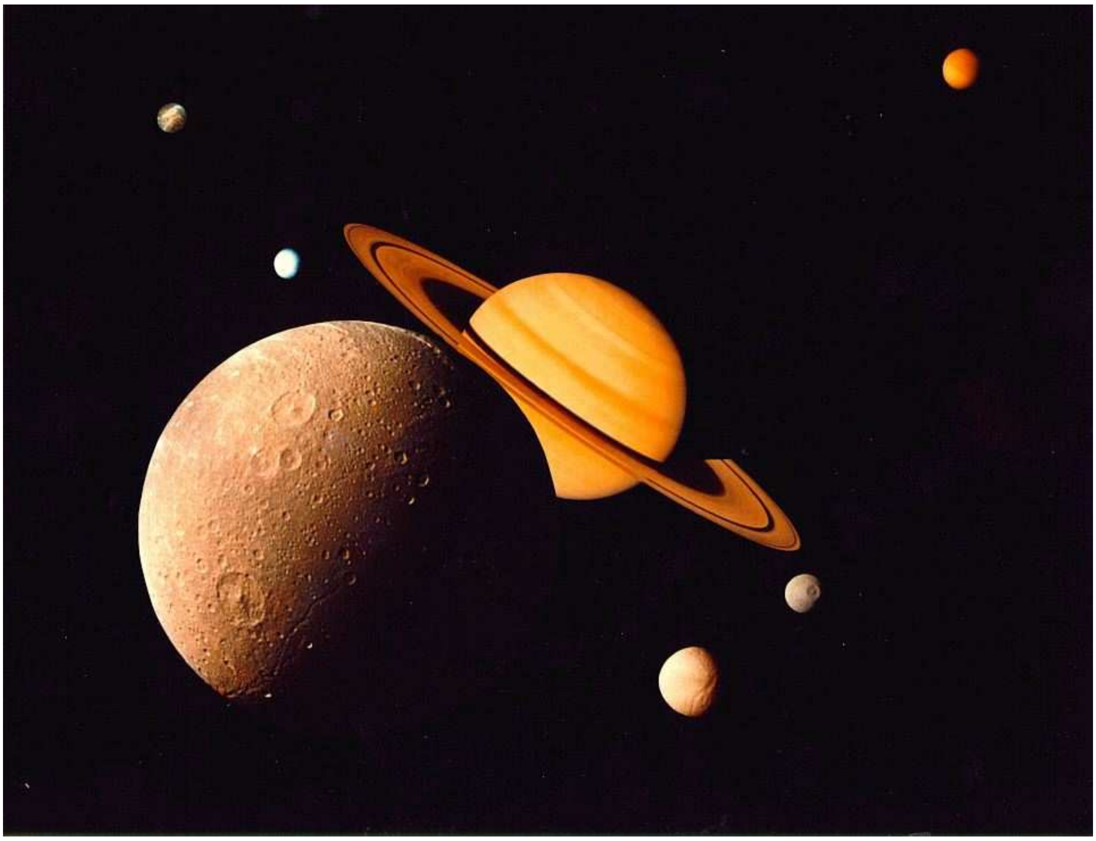


NASA Voyager 2, 1981 August 22

Rings: equatorial plane, thin (few km high, 71000–140000 km from centre);
gaps due to gravitational effects of outer moons (widest gap: Cassini's division);
speed of rings agrees with 3rd Kepler ($\Longrightarrow$ individual particles!)



Dione, Rings (edge on), and ring shadows on Saturn

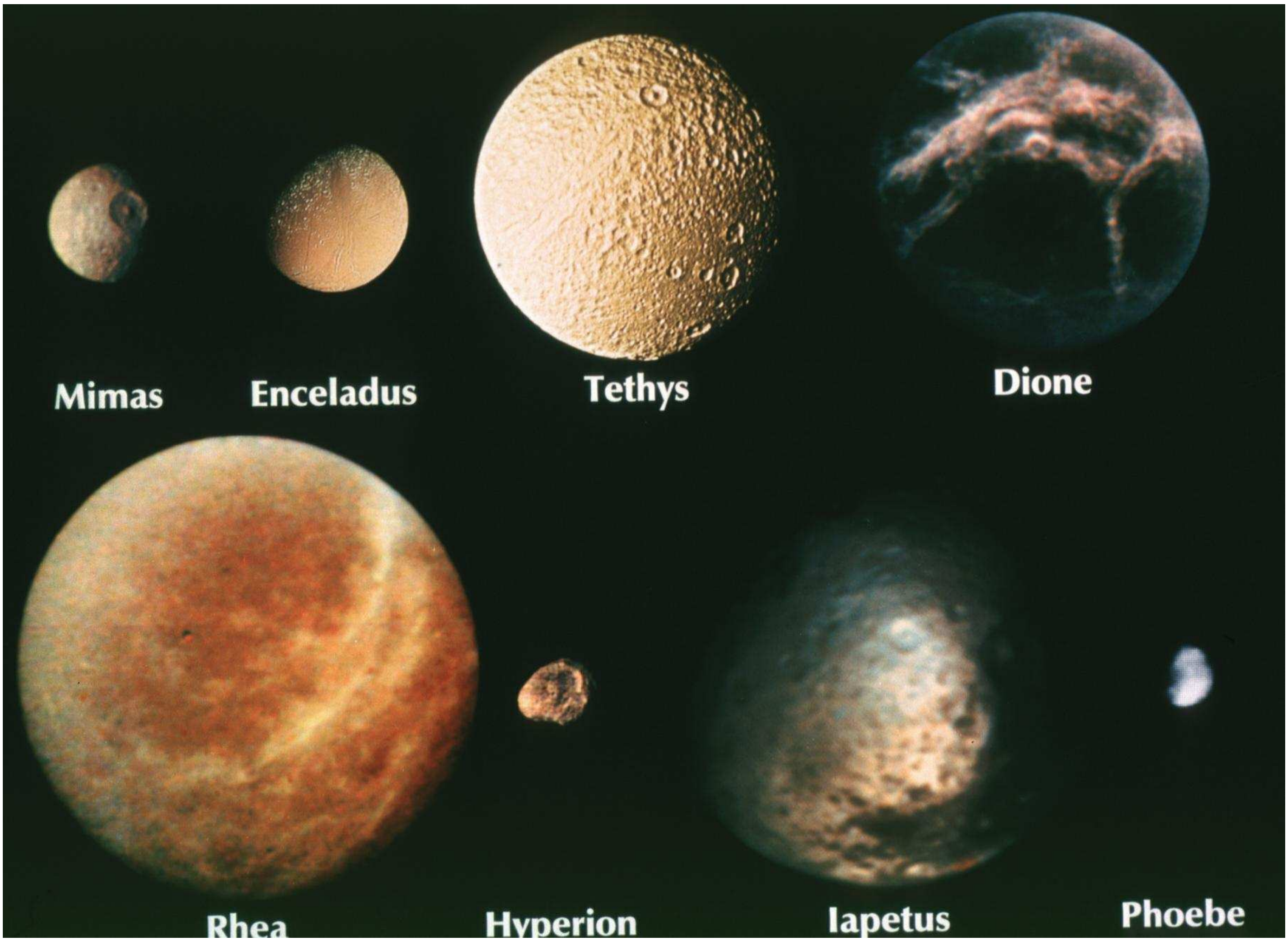


NASA Voyager (montage)

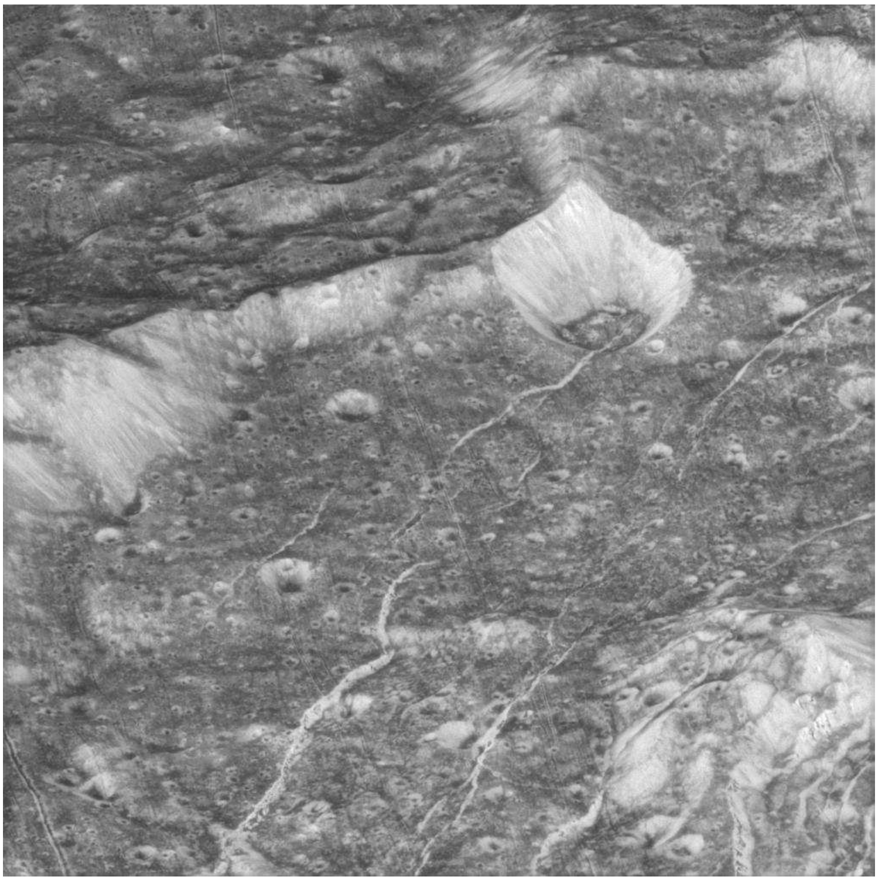
Six major moons, typically $\langle \rho \rangle \sim 2\,\mathrm{g\,cm^{-3}}$

$\Longrightarrow$ mainly ice (60–70%), with smallish rocky cores

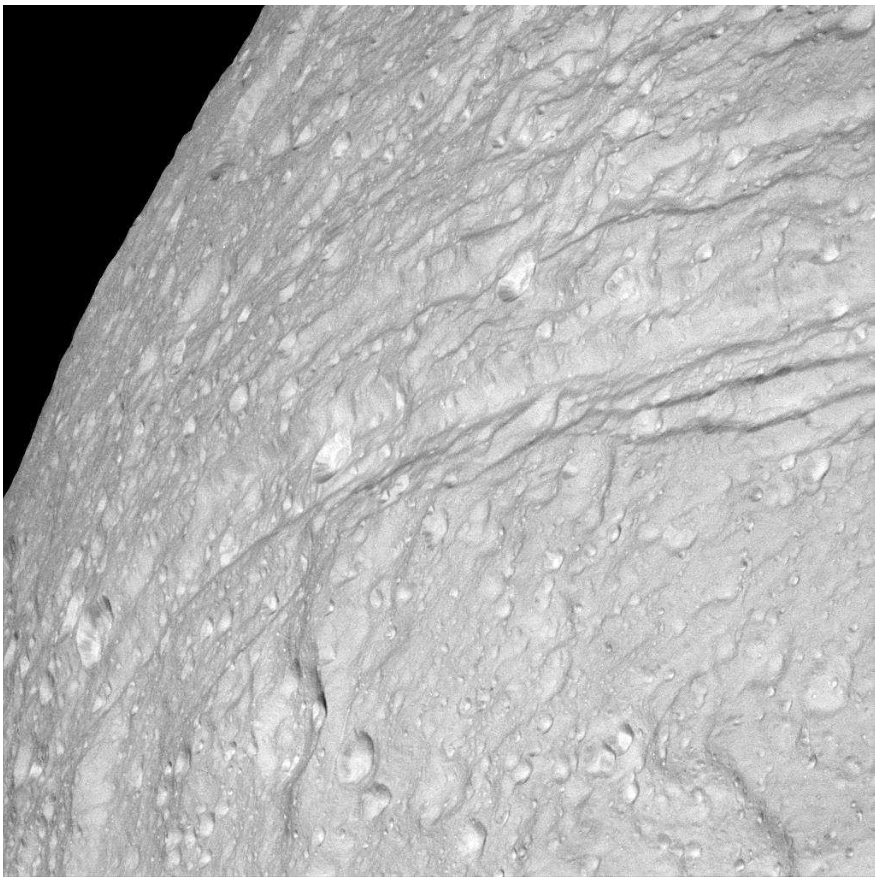
As with Jupiter, small moons are captured asteroids.



X



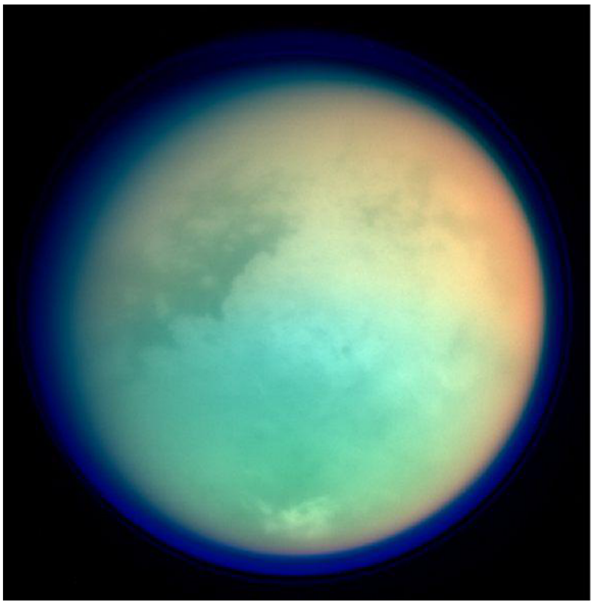
Dione (surface detail, 23 km wide, 2005 Oct.) – note craters and *fractures*)
Saturn’s moons are icy moons, similar to Jupiter’s Galilean moons



Tethys (2005 September; surface detail, ∼500 km wide)

Density of Tethys ∼ Water ice, so (if existent) its rocky core is small

NASA Voyager

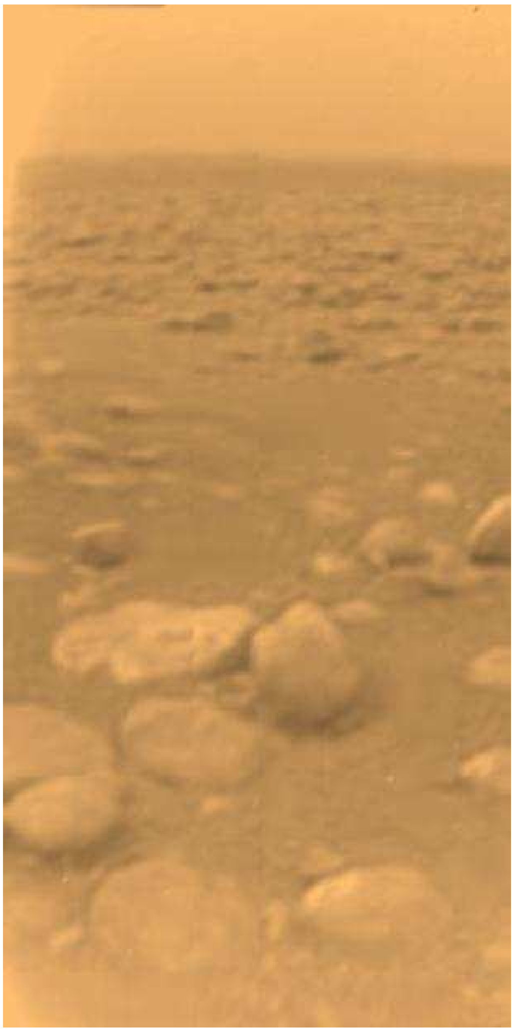


27.10.2004, false colour IR/UV; NASA/ESA

Titan: dense atmosphere, 99% nitrogen, 1% methane, some hydrocarbons, thought to be similar to primordial atmosphere of Earth.

Radius: 2575 km (∼ Mercury!)

ESA probe *Huygens* landed on Titan on 2005 January 14



Surface of Titan
(2005 January 14):
methane ice rocks strewn
over icy surface.

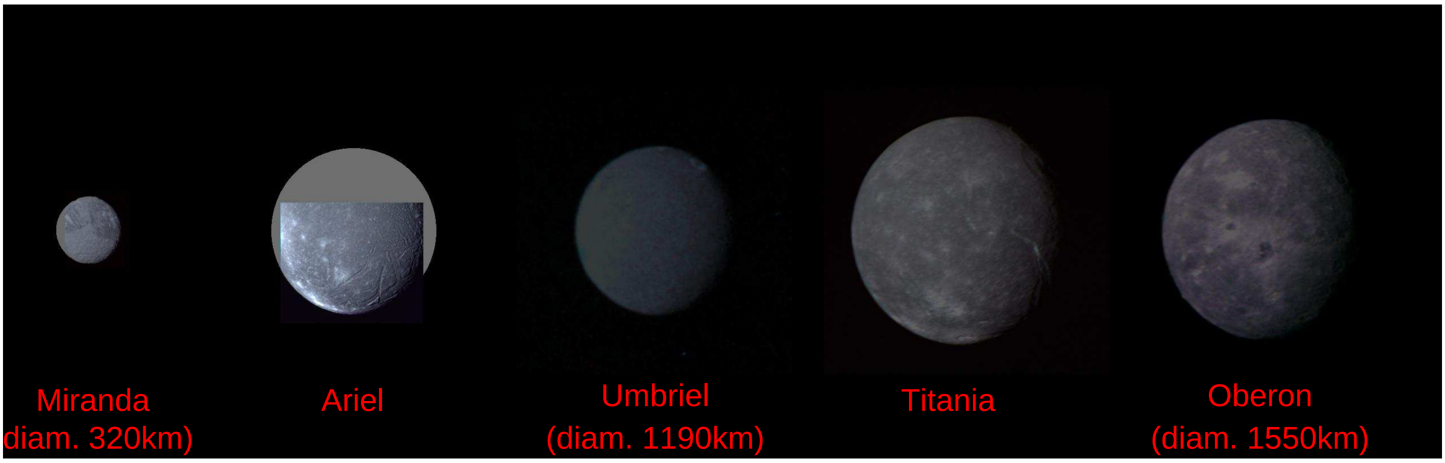
NASA Voyager 2, 1986 Jan 10

Uranus:

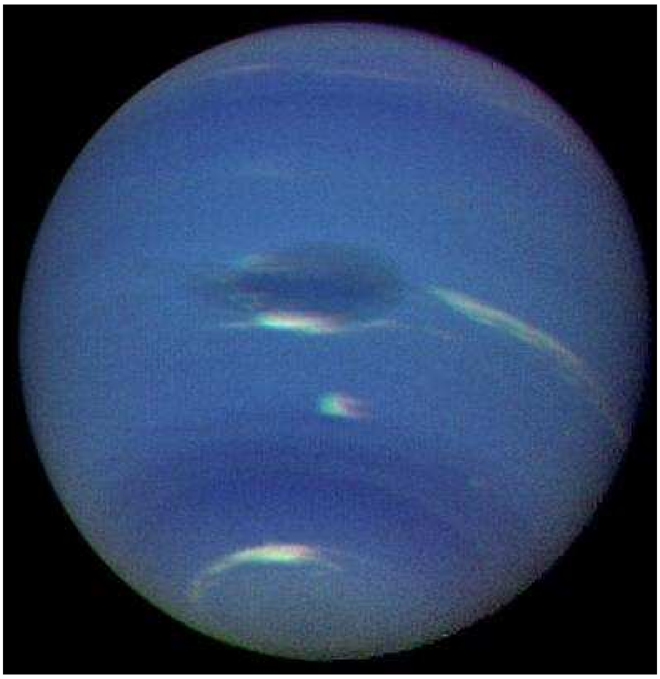
- atmosphere cold (59 K = −214°C) $\Longrightarrow$ ammonia has frozen out
- methane, hydrogen, and helium detected so far (less He than expected from Jupiter and Saturn!) $\Longrightarrow$ bluish color
- inclination of rotation axis: 98° (“rolling on ecliptic plane”).
- small ring system
- five major moons in equatorial plane plus 22 small ones (as of Jan. 2004; captured asteroids)

Flyby of Voyager 2 in 1986 January, since then only remote sensing via Hubble Space Telescope (HST) and ground based instruments.

HST Image (image enhanced) of Uranus ring system,
plus evidence for banded atmosphere and clouds



major satellites have $\langle\rho\rangle \sim 1.3\text{–}2.7\,\mathrm{g\,cm^{-3}} \Longrightarrow$ rocks and ice

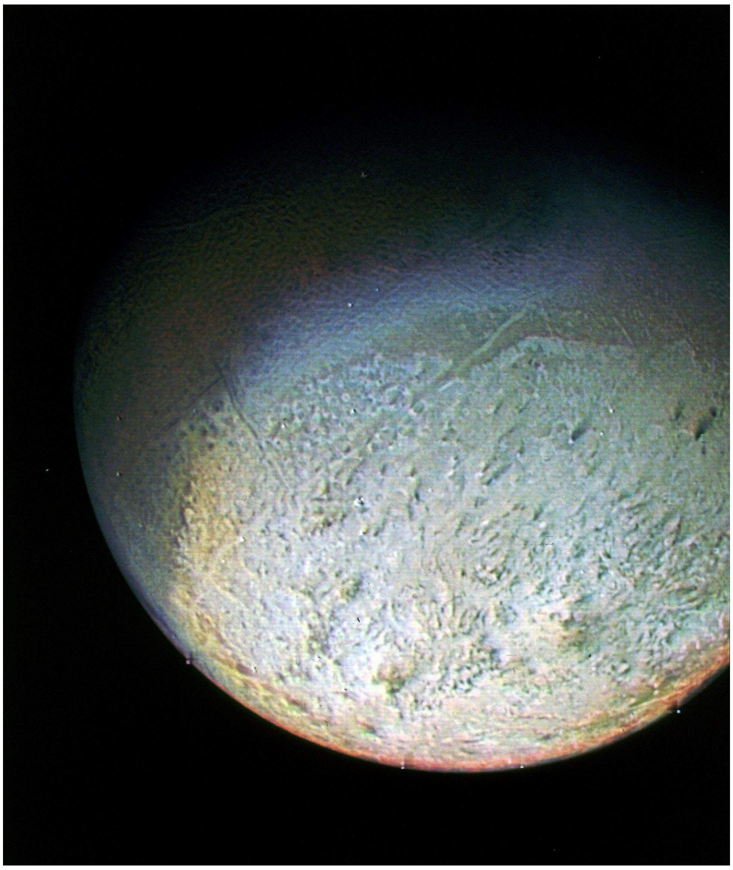


NASA Voyager 2

Neptune:

- atmosphere similar to Uranus, but more active; bright methane clouds above general cloud layer
- ring system (5 individual rings)
- Two major moons (Triton, 2720 km diameter(!) and Nereid 355 km), 11 captured asteroids

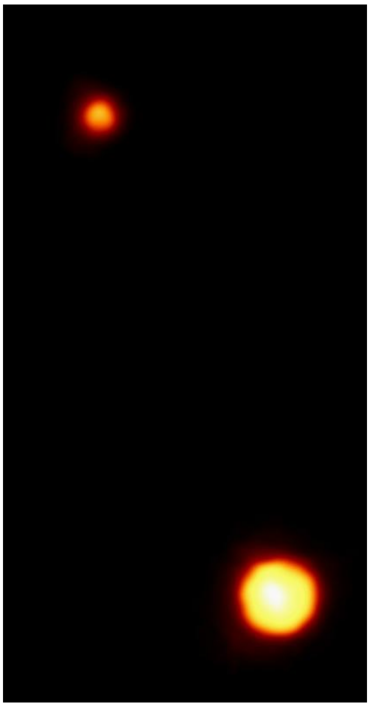
Flyby in 1989 August by Voyager 2, only HST since then (showed in 1995 that dark spot has vanished, detected new storm system)



NASA/Voyager 2

Triton: ice cap of frozen methane (freezing point 90 K) and frozen nitrogen (freezing point 60 K). Few impact craters $\Longrightarrow$ young surface $\Longrightarrow$ volcanism (dark spots in picture; nitrogen geysers with $T \sim 70\,\mathrm{K}$)

Only three volcanically active bodies in solar system: Earth, Io, and Triton.

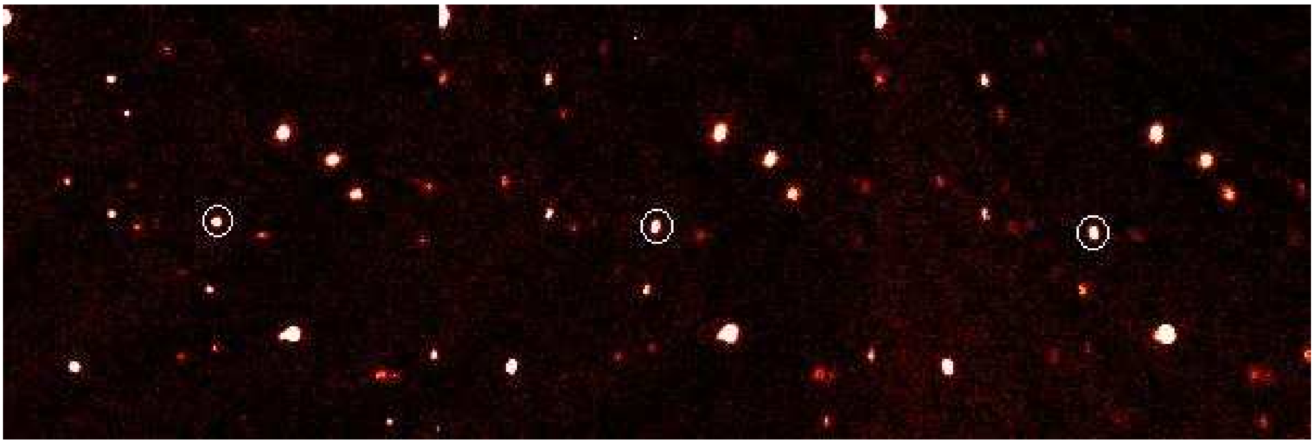


NASA/ESA HST

Pluto/Charon:

- discovered 1930
- double planet system (Pluto: $D = 2320\,\text{km}$, Charon: $D = 1270\,\text{km}$), 2 smaller moons
- planet nature debated

Kuiper belt: similar to asteroid belt, $>$70000 objects outside Neptune in 30–50 AU region; largest further members currently known: Quaoar ($D = 1200 \pm 200\,\text{km}$), Ixion ($D = 1060 \pm 165\,\text{km}$), Varuna ($D = 900 \pm 140\,\text{km}$), 2002 AW197 ($D = 890 \pm 120\,\text{km}$), see `http://www.ifa.hawaii.edu/faculty/jewitt/kb.html`



M. Brown et al. (Caltech)

2003 UB_{313}, discovered 2005: distance $\sim$100 AU,
brightness similar to Pluto
$\Longrightarrow$ has to be larger than Pluto, unless it is 100% reflective (unlikely)!