The Solar System Planets

RESOLUTION 5

Definition of a Planet in the Solar System

Contemporary observations are changing our understanding of planetary systems, and it is important that our nomenclature for objects reflect our current understanding. This applies, in particular, to the designation "planets". The word "planet" originally described "wanderers" that were known only as moving lights in the sky. Recent discoveries lead us to create a new definition, which we can make using currently available scientific information.

The IAU therefore resolves that planets and other bodies, except satellites, in our Solar System be defined into three distinct categories in the following way:

(1) A planet[1] is a celestial body that
- (a) is in orbit around the Sun,
- (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
- (c) has cleared the neighbourhood around its orbit.

(2) A "dwarf planet" is a celestial body that
- (a) is in orbit around the Sun,
- (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape[2],
- (c) has not cleared the neighbourhood around its orbit, and
- (d) is not a satellite.

(3) All other objects[3], except satellites, orbiting the Sun shall be referred to collectively as "Small Solar System Bodies".

1 The eight planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

2. An IAU process will be established to assign borderline objects into either dwarf planet and other categories.

3. These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies.

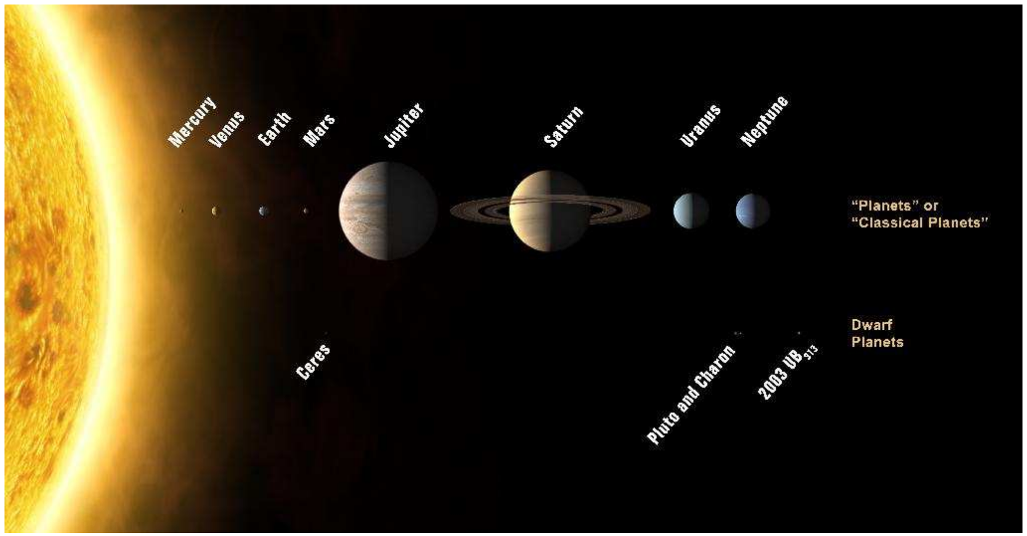
RESOLUTION 6

Pluto

The IAU further resolves:

Pluto is a "dwarf planet" by the above definition and is recognized as the prototype of a new category of Trans-Neptunian Objects[1].

1 An IAU process will be established to select a name for this category.



8 Planets and 5 dwarf planets: Ceres, Pluto, 2003 UB_{313} = Eris, Haumea, Makemake

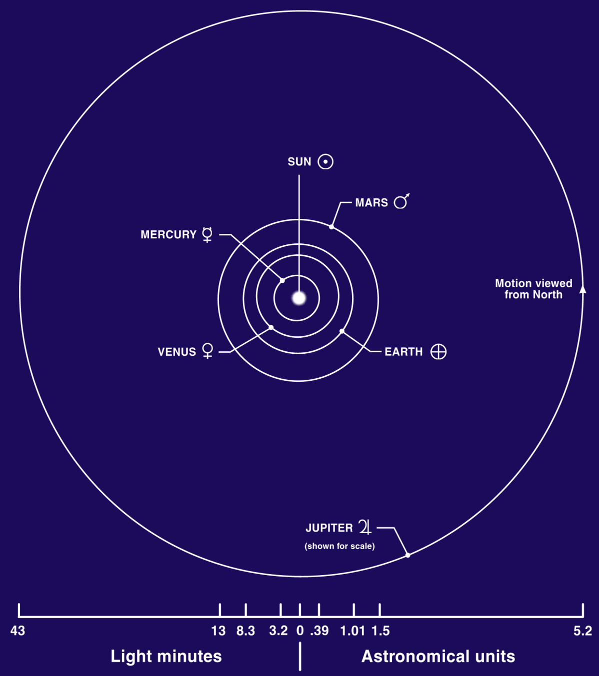
Overview

Division of Solar System into two major types of planets:

1. Inner "Terrestrial" Planets: Mercury, Venus, Earth/Moon, Mars:

   $\Longrightarrow$ all similar to Earth ("rocks").

   $\Longrightarrow$ *no moons* (Earth/Moon better called "twins")



The Inner Planets (SSE, NASA)

Overview

Division of Solar System into two major types of planets:

1. Inner "Terrestrial" Planets: Mercury, Venus, Earth/Moon, Mars:

   $\Longrightarrow$ all similar to Earth ("rocks").

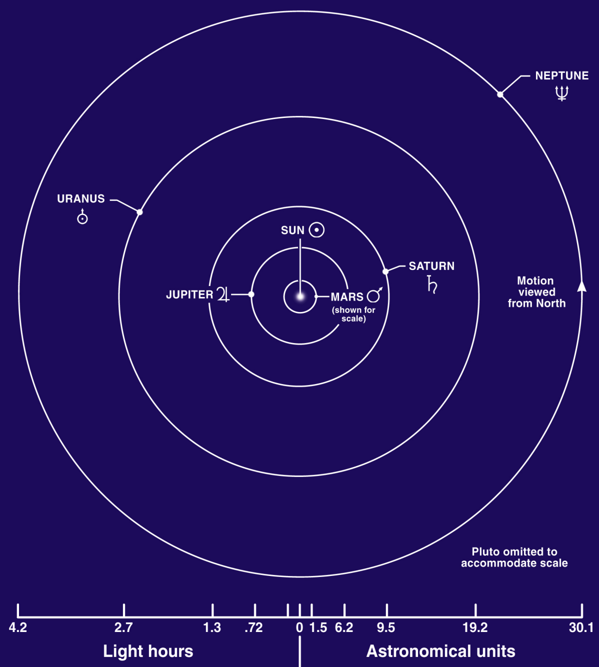
   $\Longrightarrow$ *no moons* (Earth/Moon better called "twins")

2. Outer Planets: Jupiter, Saturn, Uranus, Neptune:

   $\Longrightarrow$ "gas giants"

   $\Longrightarrow$ 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.



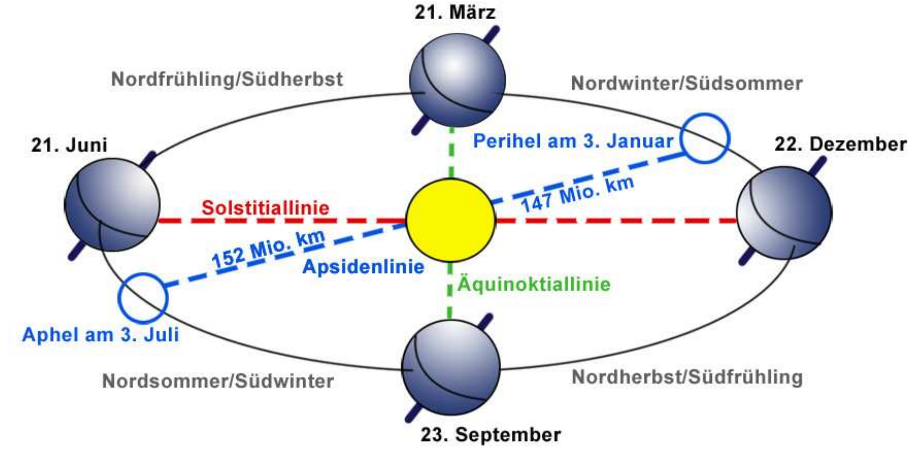
The Outer Planets (SSE, NASA)

Planets: Properties

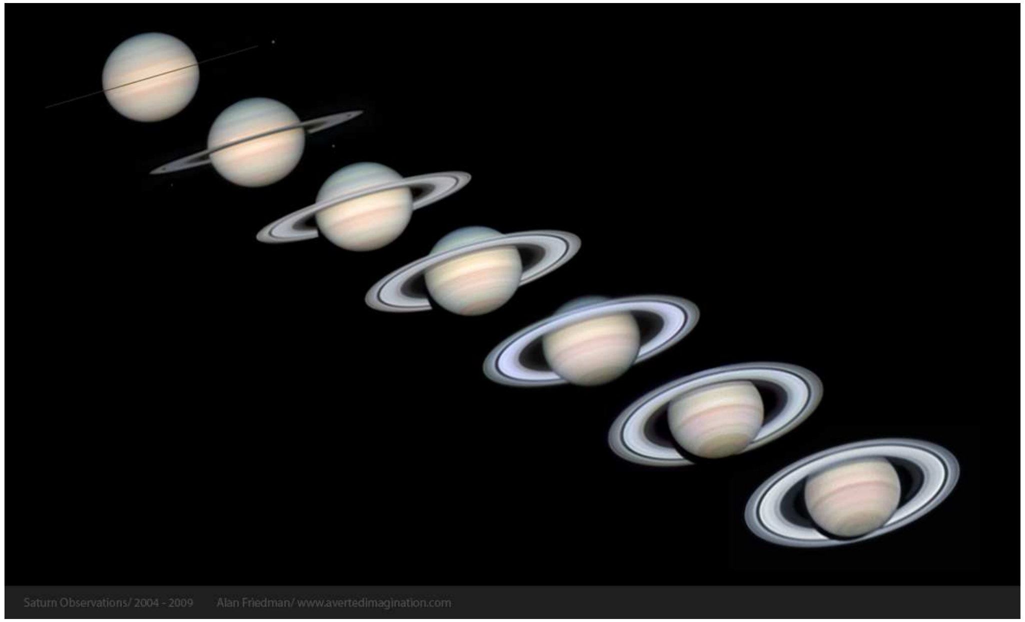
		a [AU]	P_{orb} [yr]	i [°]	e	P_{rot}	$M/M_{\oplus}$	$R/R_{\oplus}$
Mercury	☿	0.387	0.241	7.00	0.205	58.8 d	0.055	0.383
Venus	♀	0.723	0.615	3.40	0.007	−243.0 d	0.815	0.949
Earth	⊕	1.000	1.000	0.00	0.017	23.9 h	1.000	1.00
Mars	♂	1.52	1.88	1.90	0.094	24.6 h	0.107	0.533
Jupiter	♃	5.20	11.9	1.30	0.049	9.9 h	318	11.2
Saturn	♄	9.58	29.4	2.50	0.057	10.7 h	95.2	9.45
Uranus	⛢	19.2	83.7	0.78	0.046	−17.2 h	14.5	4.01
Neptune	♆	30.1	163.7	1.78	0.011	16.1 h	17.1	3.88
(Pluto	♇	39.2	248	17.2	0.244	6.39 d	0.002	0.19)

After Kutner, Appendix D;

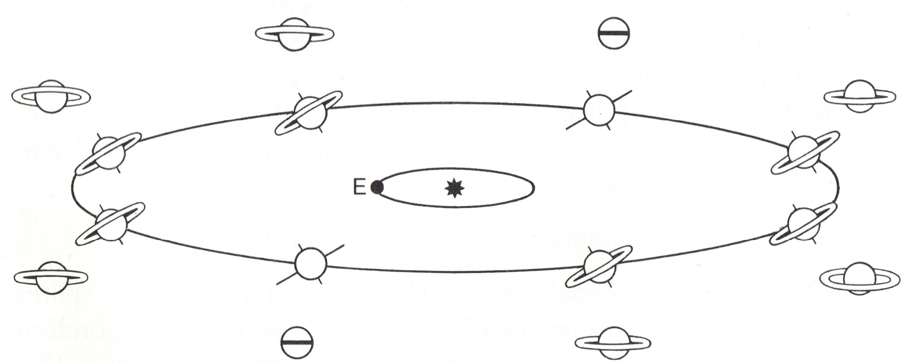
a: semi-major axis P_{orb}: orbital period i: orbital inclination (wrt Earth's orbit)
e: eccentricity of the orbit P_{rot}: rotational period M: mass
R: equatorial radius
1 AU $= 1.496 \times 10^{11}$ m.



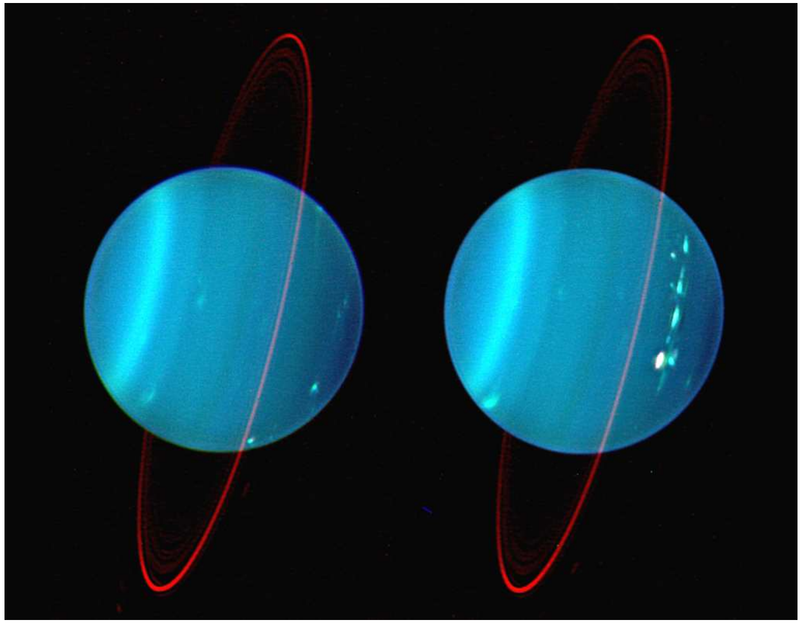
Earth orbit, inclination of the rotation axis and the seasons of the year.
Perihel: January 3. Sun is closest in northern winter.



2004-2009: Seasons on Saturn: 6 years of Saturns orbit.

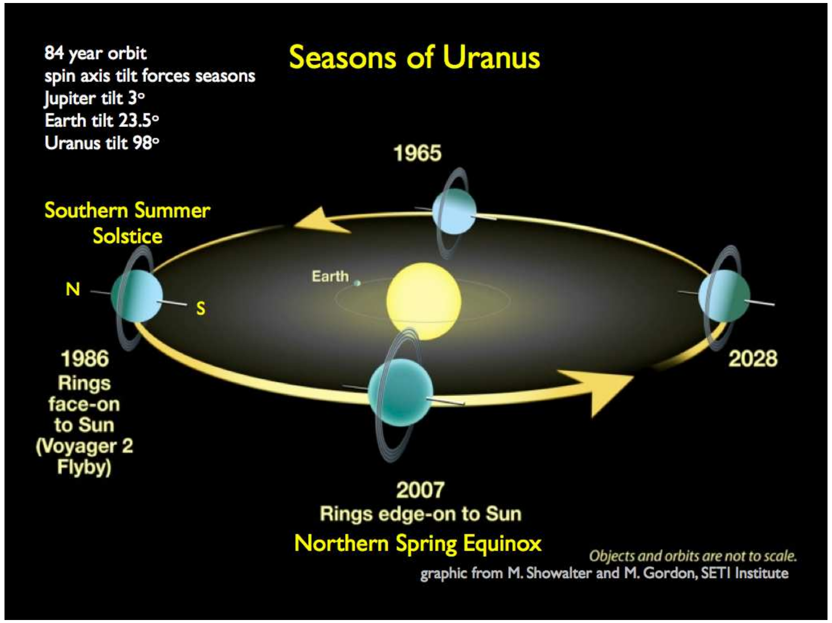


Seasons on Saturn
Kippenhahn: Unheimliche Welten



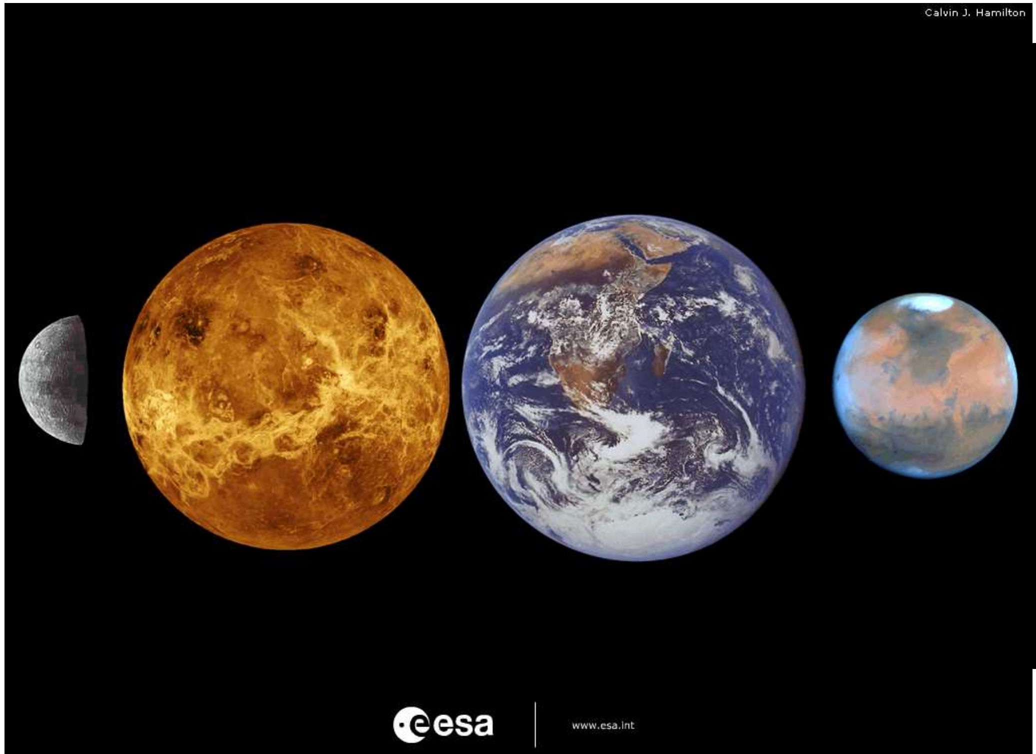
Uranus: rings and tilted rotation

Credit: Lawrence Sromovsky, (Univ. Wisconsin-Madison), Keck Observatory



Uranus: Seasons

Credit: Space Science & Engeneering Center (Univ. Wisconsin-Madison)

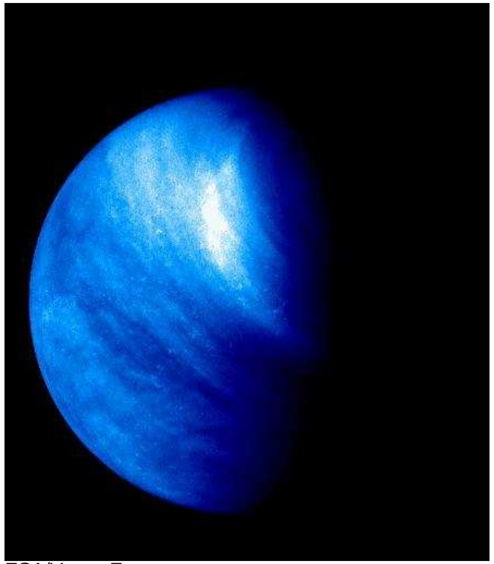


NASA/MESSENGER, 2008 Jan

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, flood volcanism
- Early information available from Mariner 10 (three flybys, 1974/1975)
- NASA mission Messenger

  (launched 2004, flybys 2008 and 2009, in orbit since 2011)
- ESA Mission BepiColombo, planned for $\sim$ 2016, arrival 2024



ESA/Venus Express

Venus:

- similar size to Earth, similar structure
- insolation $\sim 2\times$ Earth
- very slow rotation (243 d, retrograde; $\Longrightarrow$ no B-field)
- very dense atmosphere: surface pressure $\sim 90\times$ Earth
- atmosphere: 96.5% CO_2, 3.5% N
  $\Longrightarrow$ strong greenhouse effect
  $\Longrightarrow$ surface temperature $\sim 460^\circ$C.
- acid rain (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). Currently studied by ESA's Venus Express probe (launch April 2005, arrival April 2006, mission ongoing).

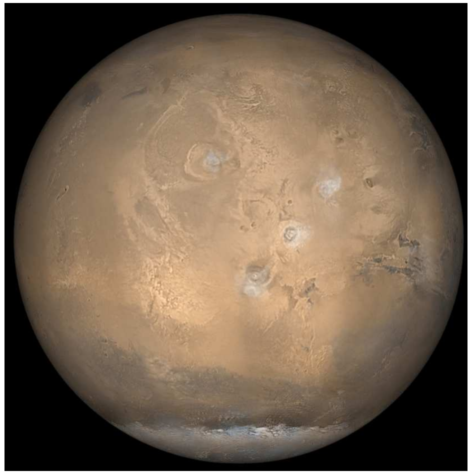
Earth/Moon, seen from Mars (NASA/Malin)

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

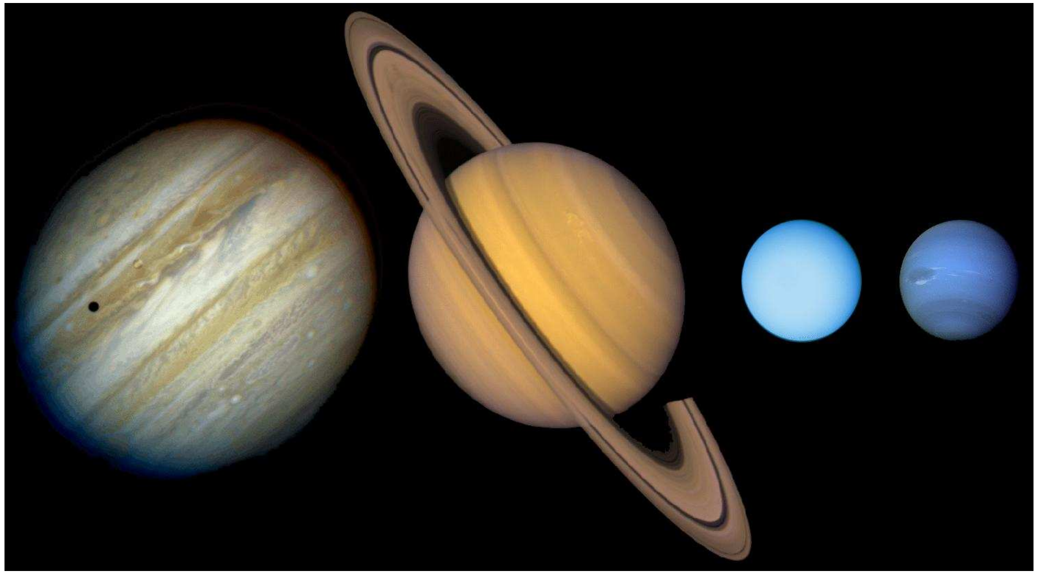


NASA, Mars Global Surveyor

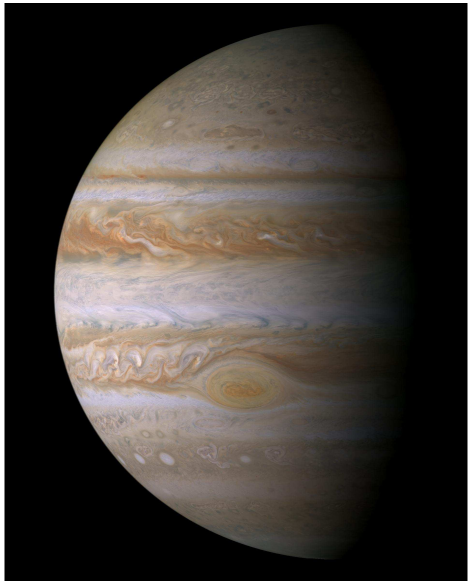
Mars:

- smaller than Earth
- very low density ($\langle\rho\rangle \sim 3\,\mathrm{g\,cm^{-3}}$)
  $\Longrightarrow$ small core, probably Fe and Fe_xS_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/accreted material)

Early Exploration through Mariner missions and Viking 1 & Viking 2 orbiters and landers in 1970s, recently, strong interest (NASA Mars Global Surveyor, ESA Mars Express, plus several landers. Rovers: Spirit/Opportunity/Curiosity). Currently best surveyed planet next to Earth.



The jovian planets, ©C.J. Hamilton

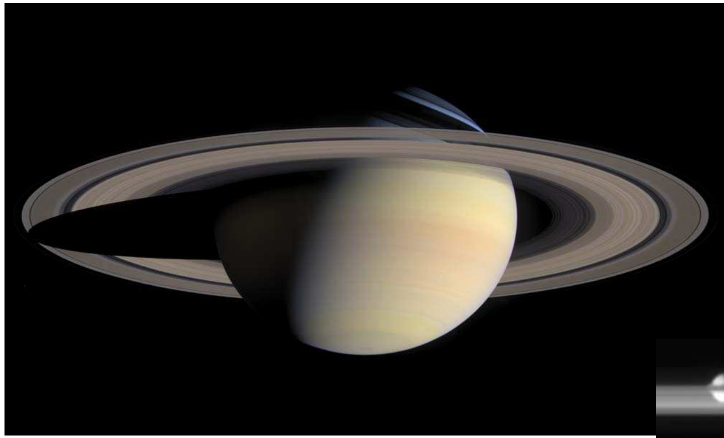


NASA/ESA, Cassini-Huyghens

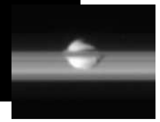
Jupiter:

- 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 9 h 50 m at equator, 9 h 55 m at poles)
- strong magnetic field
- four major “Galilean” moons plus 63 small ones (as of Oct 2014; captured asteroids)

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



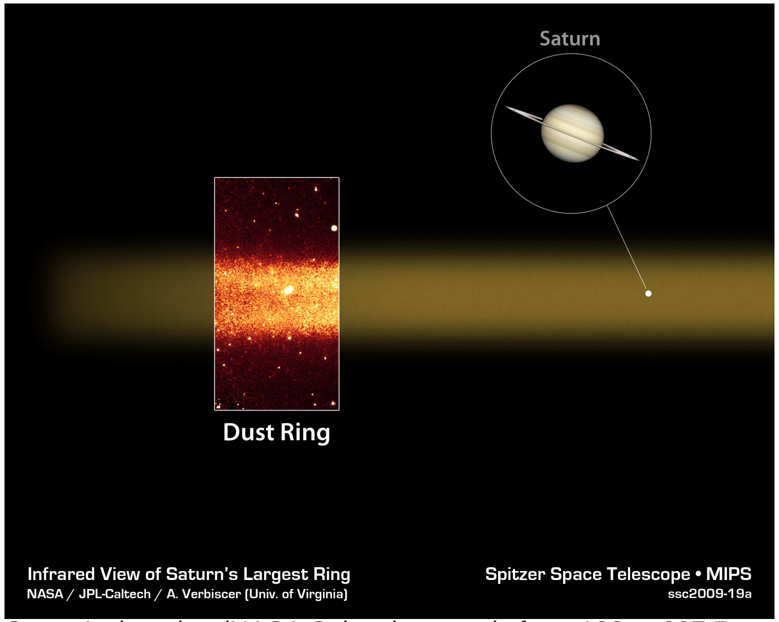
NASA/ESA Cassini, 2004 Oct.



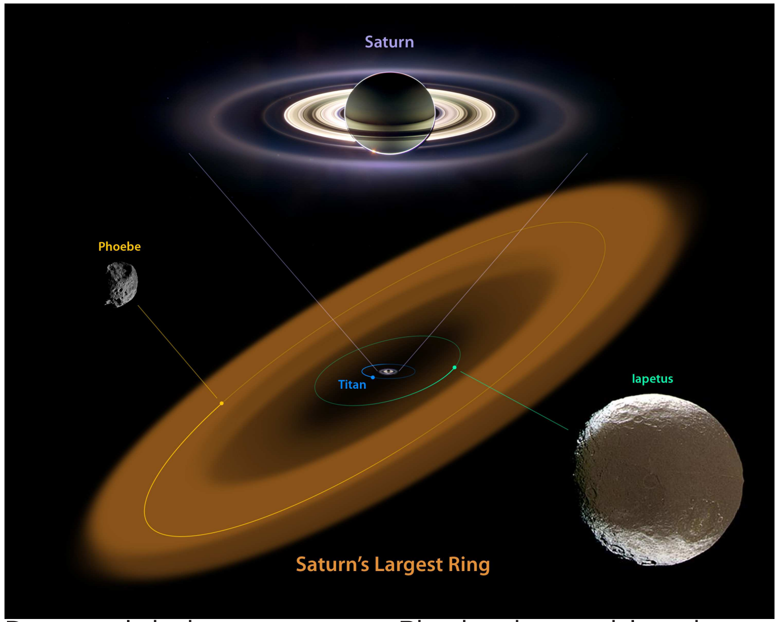
NASA/ESA Cassini

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
- seven major moons plus 55 small ones (as of Oct 2014; mainly captured asteroids)
- Early Exploration in 1970s with Pioneer 11 and 12 and the Voyager probes.
  Studied since 2004 by NASA/ESA Cassini-Huygens project (duration until 2017)



Saturn's dust ring (NASA Spitzer): extends from 128 to 207 R_S, 40 R_S thick. (Verbiscer et al. 2009, Science October 22)



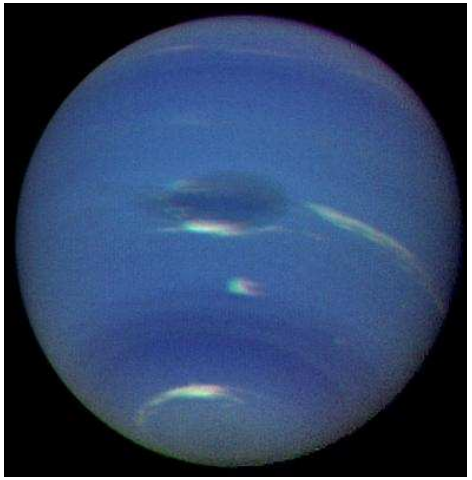
Dust supply by impacts on moon Phoebe, dust particles migrate inwards and are swept up by Iapetus

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 Oct 2014; captured asteroids)

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



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), 12 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)

Surface structures: Craters

Moon: Crater Copernicus

Impact Craters

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

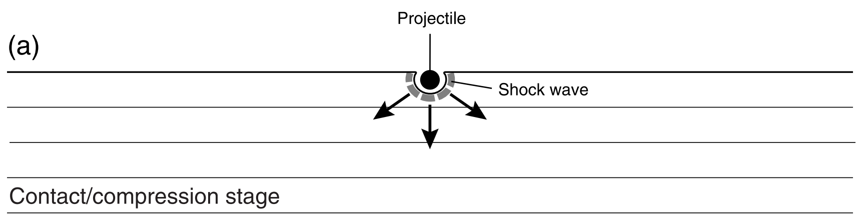
Example:

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

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

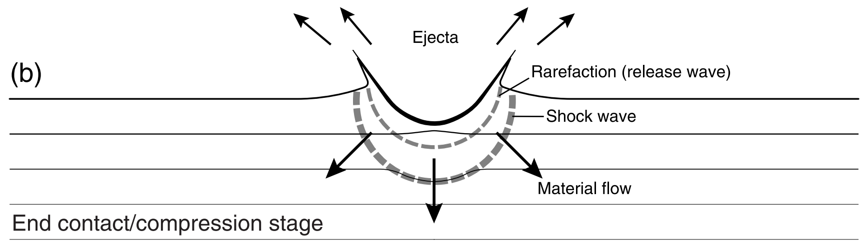
1 Megaton TNT is typical strength of US nuclear bombs [B-83 bomb]

Impact Craters



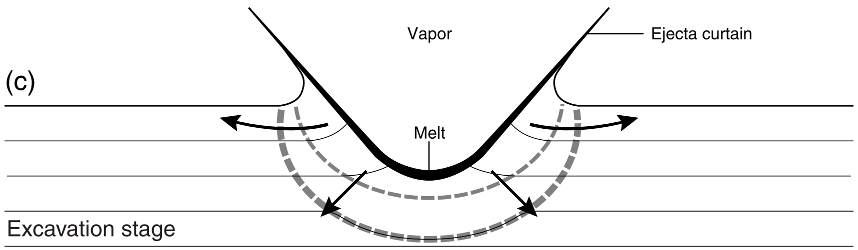
French, 1998, LPI Cont. 954

Impact Craters



French, 1998, LPI Cont. 954

Impact Craters



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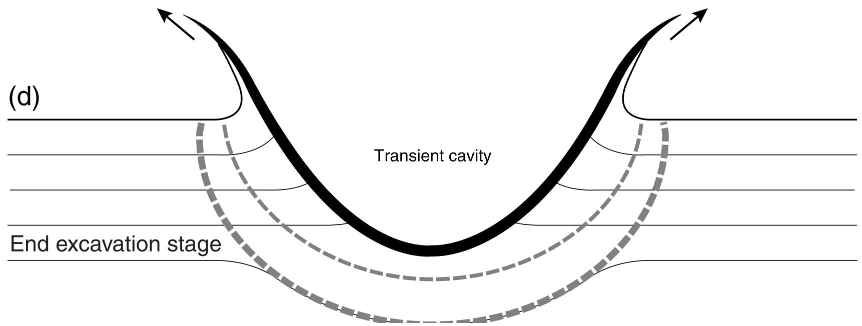
Impact Craters



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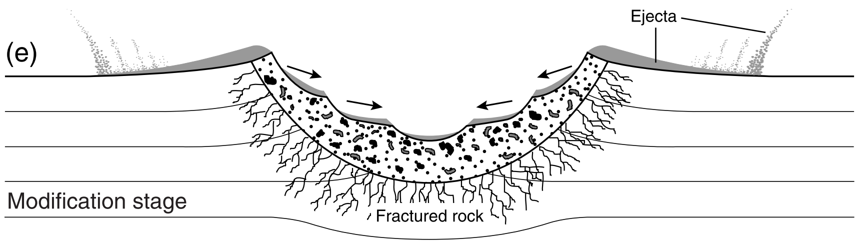
Impact Craters



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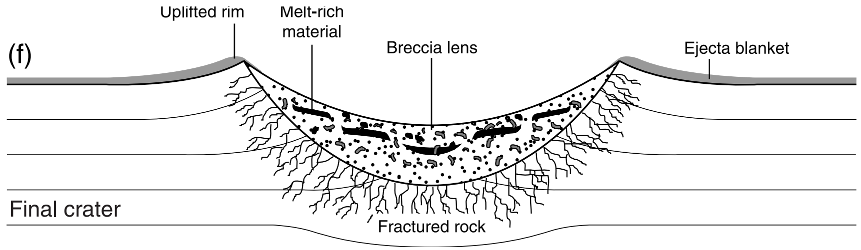
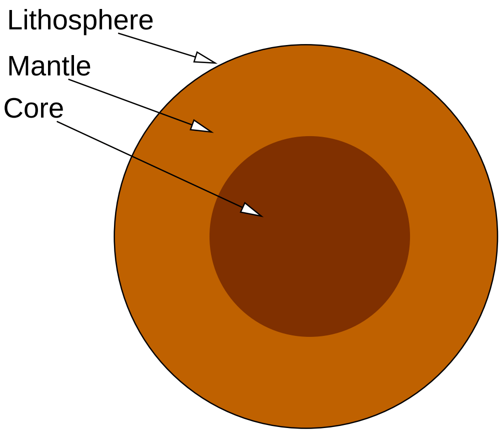
Impact Craters



French, 1998, LPI Cont. 954

Interiors: Terrestrial Planets

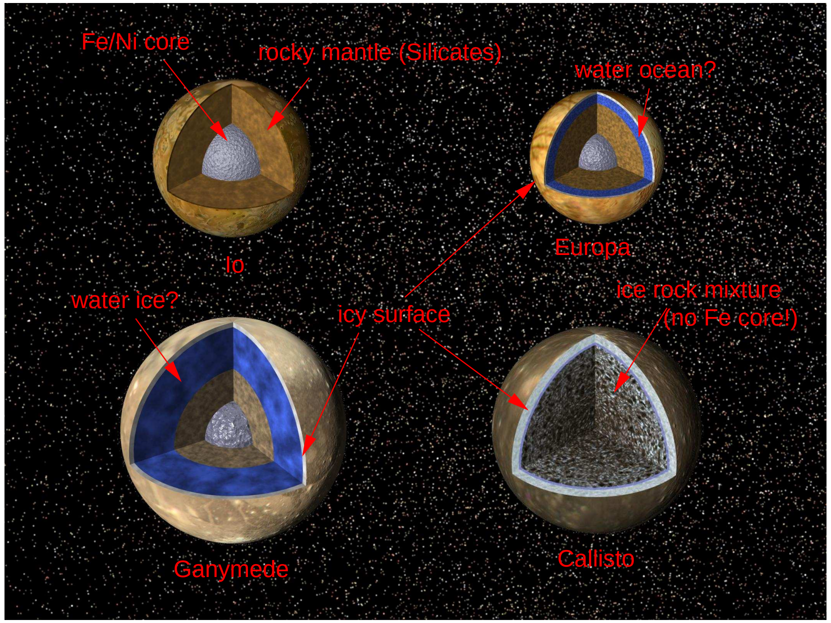


Structure of terrestrial planets:

- 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,...)



Structure of Jupiter's Galilean Moons similar to terrestrial planets
(but some also have very thick ice layer on top)

Structure: Gas Giants

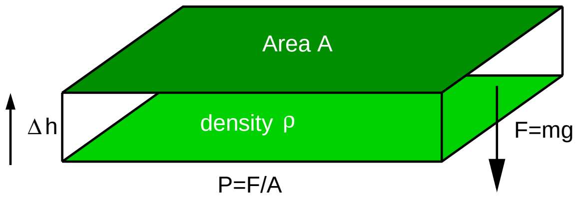
In general, gas giants have very different properties from terrestrial planets:

- 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!

Hydrostatic Equilibrium



Gas giants: structure defined by equilibrium between gravitation (downwards) and buoyancy (”Auftrieb”, upwards): hydrostatic equilibrium.

Force excerted by material with density ρ sitting on top of an area A:

$$F = mg = \rho V g = Ah\rho g \quad \text{where} \quad g = \frac{GM(r)}{r^2} \quad \Longrightarrow \quad P = \frac{F}{A} = \rho h g \qquad (4.1)$$

where $M(r)$: mass contained within radius r.

Change in pressure between two points separated in radius by Δr:

$$\Delta P = \rho(r)g(r)(h+\Delta r) - \rho(r)g(r)h \quad \xrightarrow{\lim_{\Delta r\to 0}} \quad \frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2} \qquad (4.2)$$

This is the equation of hydrostatic equilibrium.

Structure: Gas Giants

Structure of a gas giant from equation of hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2} \qquad (4.2)$$

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

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

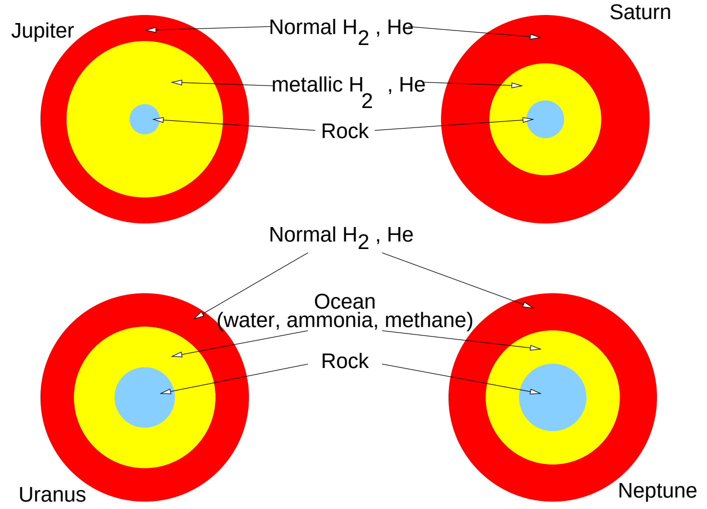
$$P_{\text{central}} = \frac{2\pi}{3}G\langle\rho\rangle^2 R^2 \qquad (4.3)$$

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

Structure: Gas Giants



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

Formation of the solar system

Facts to be explained:

- planetary orbits all lie almost in the same plane, parallel to the Sun's equator, almost circular
- all planets orbit counterclockwise, in the same direction as the solar rotation
- prograde rotation (except Venus & Uranus)
- planets have 0.15% of the total mass, but 98% of the total angular momentum of the solar system
- (planetary distances obey the empirical Titius-Bode law:

$$a_n = 0.4 + 0.3 \times 2^n \tag{4.4}$$

  for $n = -\infty, 0, 1, \ldots, n = 3$: asteroid belt (Ceres)), a_n in AU
- terrestrial and giant planets are physically and chemically different
- satellite systems resemble miniature solar systems in structure

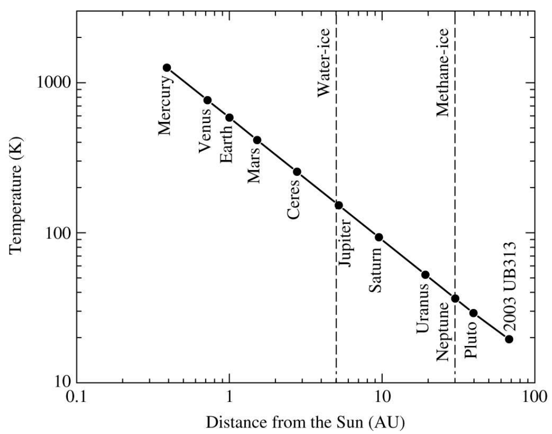
Nebula Hypothesis

- A cloud of interstellar gas and/or dust collapses under its own gravity.
- During collapse gas heats up and compresses in the center.
- A protostar is formed and the rest of the gas orbits/flows around it.
  $\Longrightarrow$ accretion disk
- Metal, rock and ice (only far from star) condense as gas cools.
- The dust particles collide with each other and form larger particles.
- Once the larger of these particles get big enough to have a nontrivial gravity, their growth accelerates $\Longrightarrow$ run away growth.
- ≈1 Myrs after the nebula cooled, star generates a very strong solar wind and sweeps away the gas left in the protoplanetary nebula.
- The "planetesimals" would slowly collide with each other and become more massive.
- Eventually, after 10 to 100 Myrs planets are in stable orbits
  $\Longrightarrow$ solar system formed.

First discussed by I. Kant in 1755

Nebula Hypothesis

Condensation of dust and ices

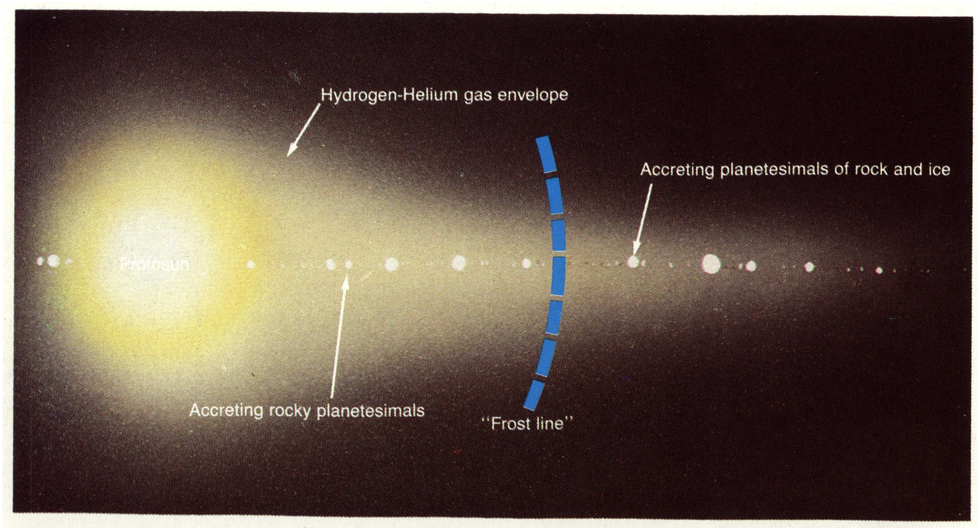


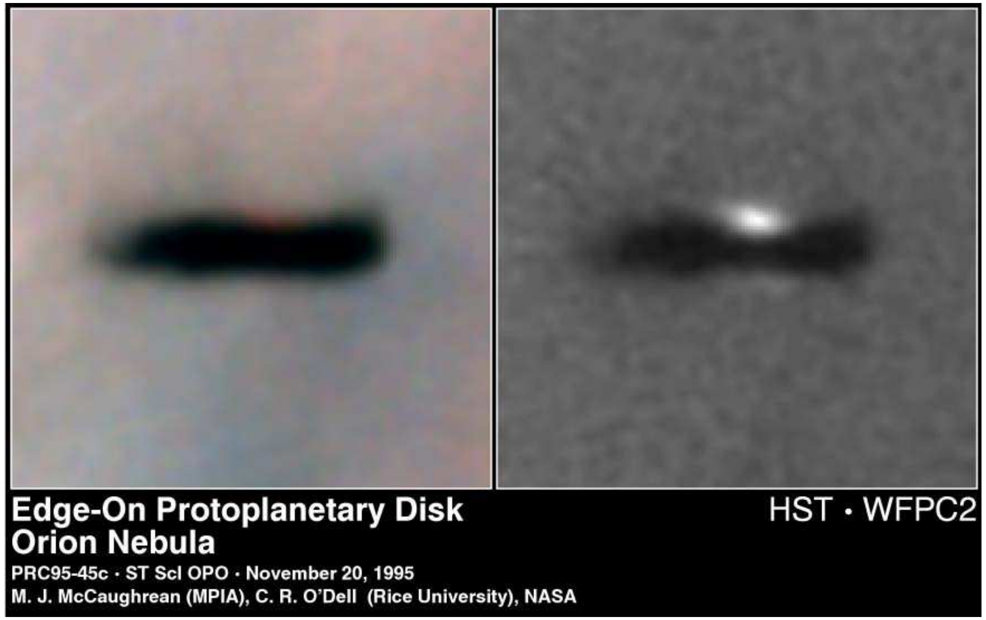
Temperature gradient in the early solar nebula (Carroll & Ostlie)

Chemical differentiation according to temperature:

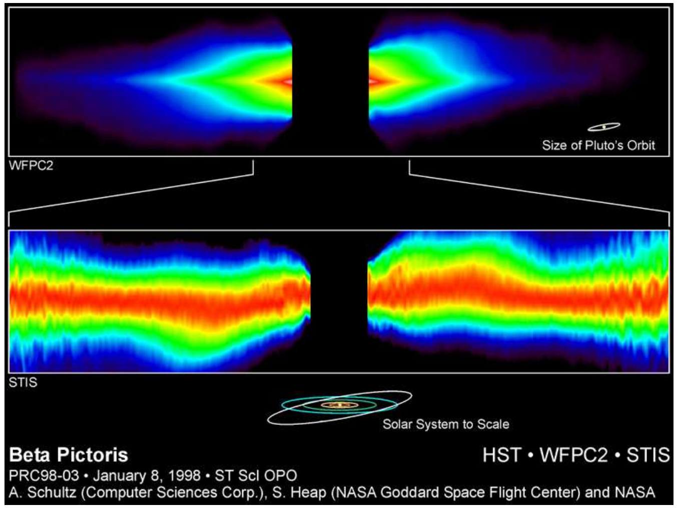
- $T > 1500$ K: Fe, Ni, CaO, AlO condense
- 1500 K $> T >$ 1000 K: Silicates (e.g. feldspar)
- 1000 K $> T >$ 800 K: FeS
- 800 K $> T >$ 500 K: Metallic Oxides
- $T < 150$ K: Water ice

The frostline





Disk around the young star β Pic



"False color" image shows gradations in the brightness of the disk, which scatters the starlight. Warps in the disk might be caused by the gravitational pull of one or more unseen planets.