Introduction to Solar System Physics

Lecture course by
scientists from the Max Planck Institute for Solar System Research in Katlenburg-Lindau

summer semester 2009

Seminarraum Astrophysik, Mondays 10:15 - 11:45

Slides are found in:
http://www.solar-system-school.de/lectures.html

Topics and Lecturers

1.	Overview on the solar system	U. Christensen	20.04.
2.	Planetary atmospheres	D. Titov	04.05.
3.	Small bodies	H. Krüger	11.05.
4.	Planetary magnetospheres	N. Krupp	18.05.
5.	Planetary interiors	U. Christensen	25.05.
6.	Formation of planetary systems	D. Schmitt	08.06.
7.	Solar corona and solar wind	E. Marsch	15.06.
8.	Solar – terrestrial relations	J. Büchner	22.06.
9.	Solar interior and helioseismology	L. Gizon	29.06.
10.	Photosphere and Chromosphere	S. Solanki	06.07.
11.	Solar convection zone and magnetic field	M. Schüssler	13.07.

Credit points (3 ECTS) in the batchelor / master curriculum can be obtained after a written test at the end of the semester.

Overview on the solar system

Ulrich Christensen

The Sun

Solar influence on the Earth and other planetary bodies

The Planets

Satellites of the major planets

Small bodies (Asteroids, Comets, Meteorites)

Suggested reading

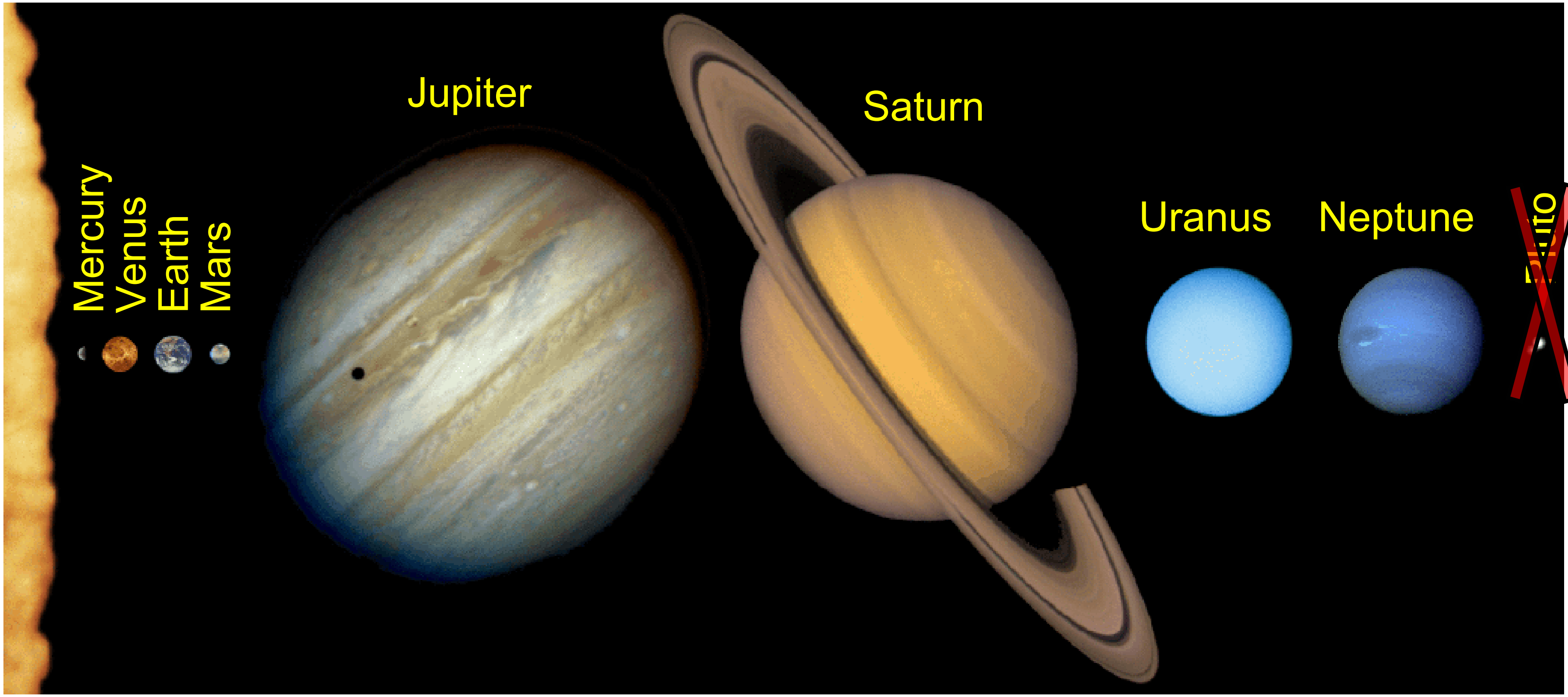
Lectures 1 and 4

De Pater, I., Lissauer, J.J., Planetary Sciences, Cambridge University Press, 2001.
(Modern introduction to most aspects of planetology at intermediate to advanced level).

Beatty, J.K., Chaikin, A. (Ed.), The new solar system, Cambridge Univ. Press, 4th ed., 1999. ***(Collection of chapters from various authors, many color images, mostly qualitative)***

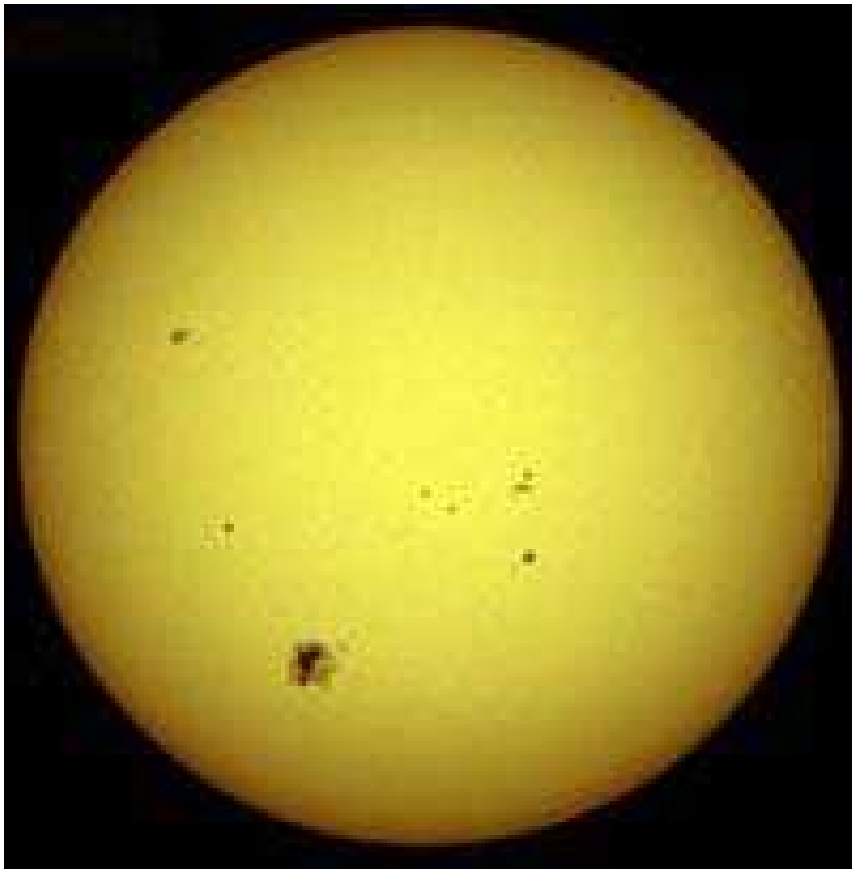
Stacey, F.D., Physics of the Earth, Brookfield Press, 3rd ed., 1992.
(Deals mainly with Earth's interior. Discusses concepts that are valid also for other planets and compares Earth with other planets. Intermediate to advanced level)

The family


Jupiter
Saturn
Mercury
Venus
Earth
Mars
Uranus
Neptune
Pluto


Ganymede 5262 km
Titan 5150 km
Mercury 4880 km
Callisto 4806 km
Io 3642 km
Moon 3476 km
Europa 3138 km
Triton 2706 km
Pluto 2300 km
Titania 1580 km

The sun: some basic facts



Radius: 696,000 km [109 x Earth]

Mass: 2×10^{30} kg [330,000 x Earth]

Mean density: 1410 kg/m^3 [1/4 x Earth]

Photosphere temperature: 5800 K

(photosphere ~100 km thick)

Energy flux: 63 MW/m^2

(at Earth distance 1370 W/m^2)

Rotation period: 25.4 days (25-30)

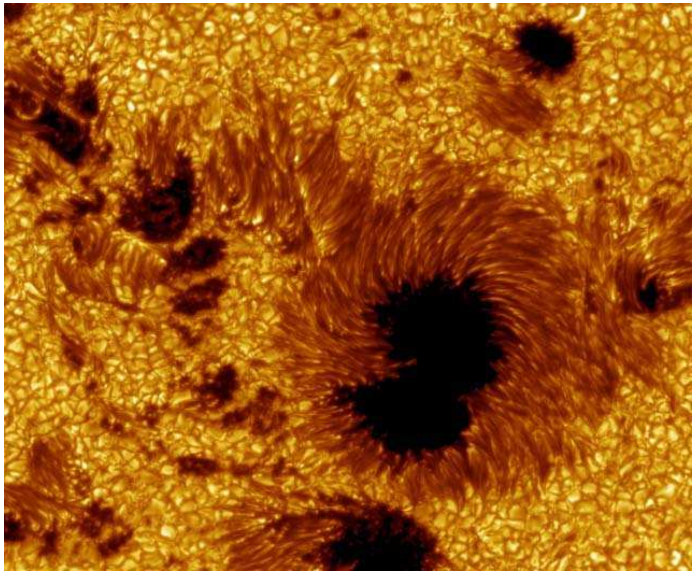
Composition near surface (spectroscopy):

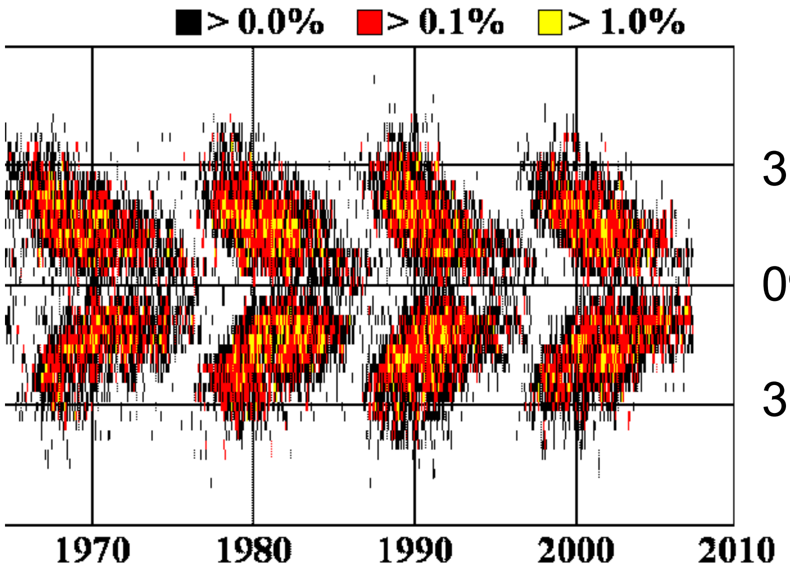
73% H

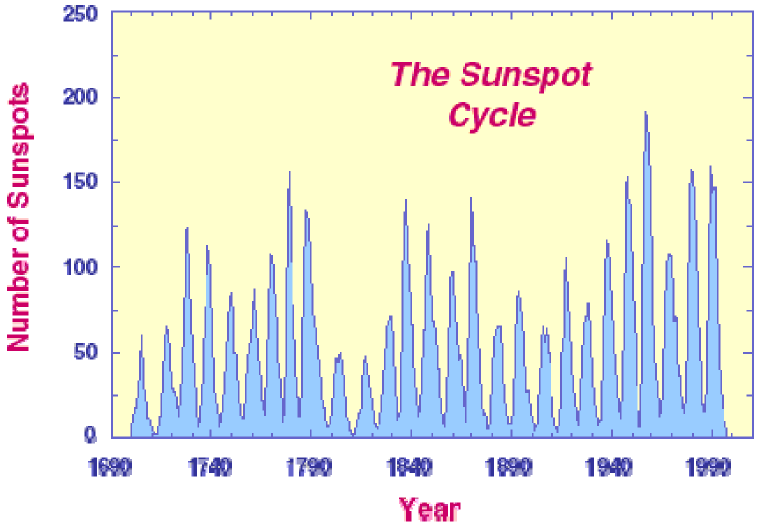
25% He

2% heavy elements (O, C, Fe, ...)

Sunspots







Sunspots in pairs or groups. Lifetime 1 – 50 d

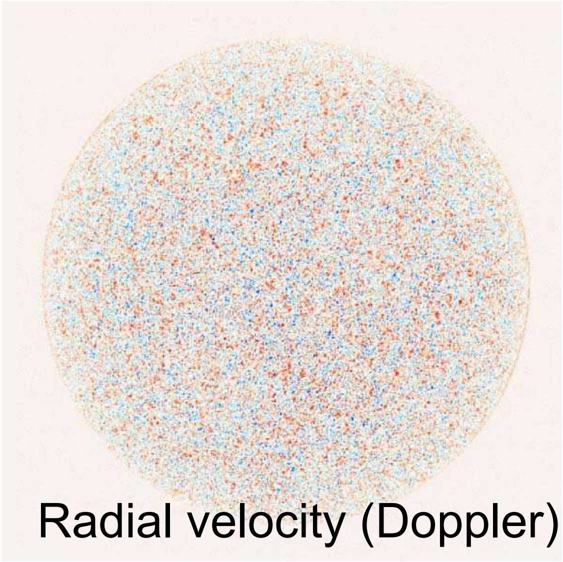
Sunspot cycle of 11 years (22 years)

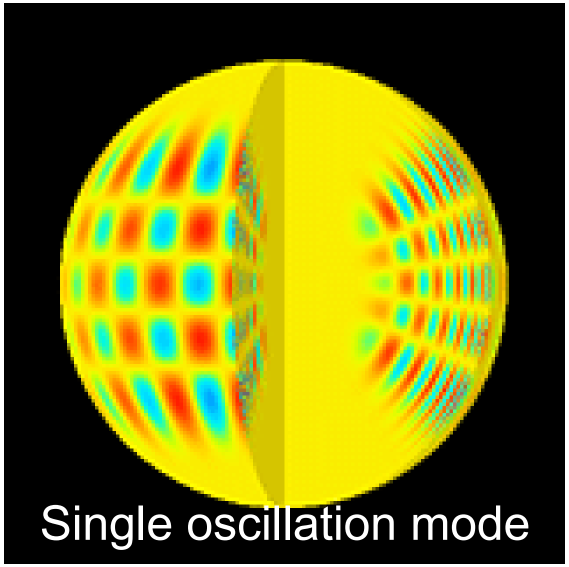
Sunspots between ±35° N/S, migrate equator-wards during cycle ("butterfly diagram")

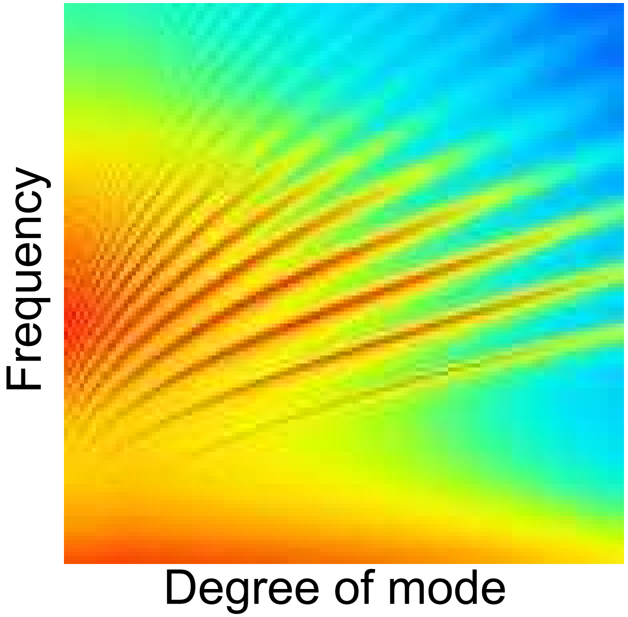
Magnetic field up to 0.5 T (5 kGauss = 1000 x Earth's surface field) [Zeeman effect]

Magnetic field suppresses convective heat transport (granulation)

Solar interior: helioseismology







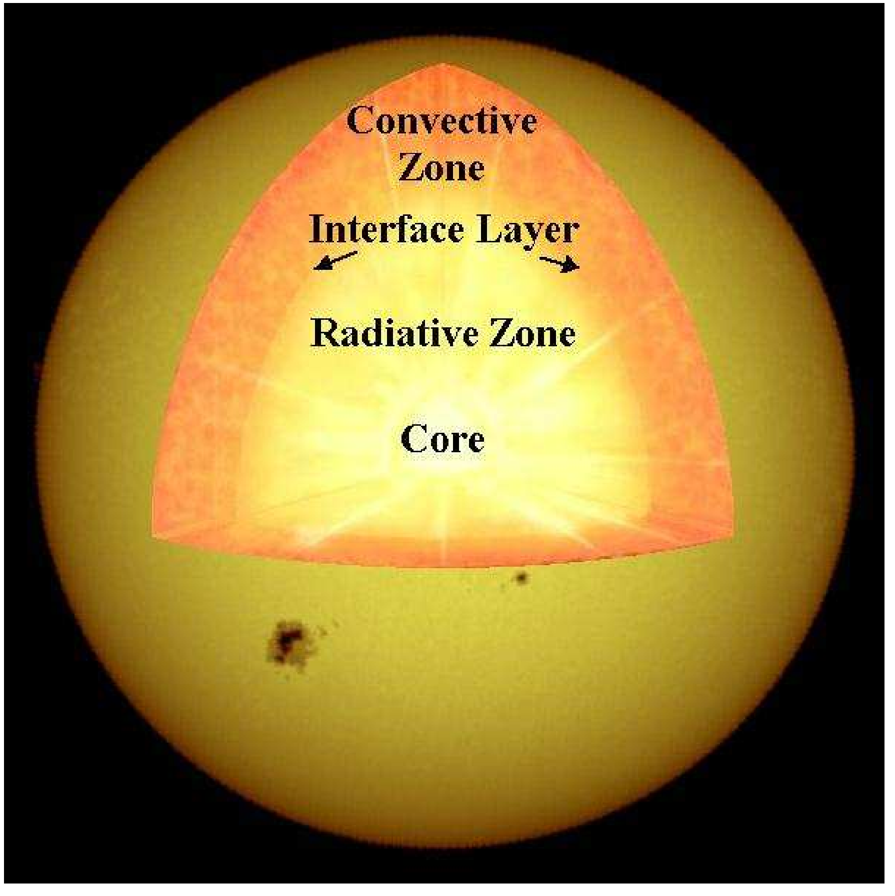
Models of the sun‘s interior based on theory and a data from helioseismology

Global helioseismology:

Radial motions at the sun‘s surface (from Doppler shift of spectral lines) are decomposed into free oscillation modes.

Each mode has a characteristic frequency that depends on the structure of the sun (and motions inside the sun)

Solar interior

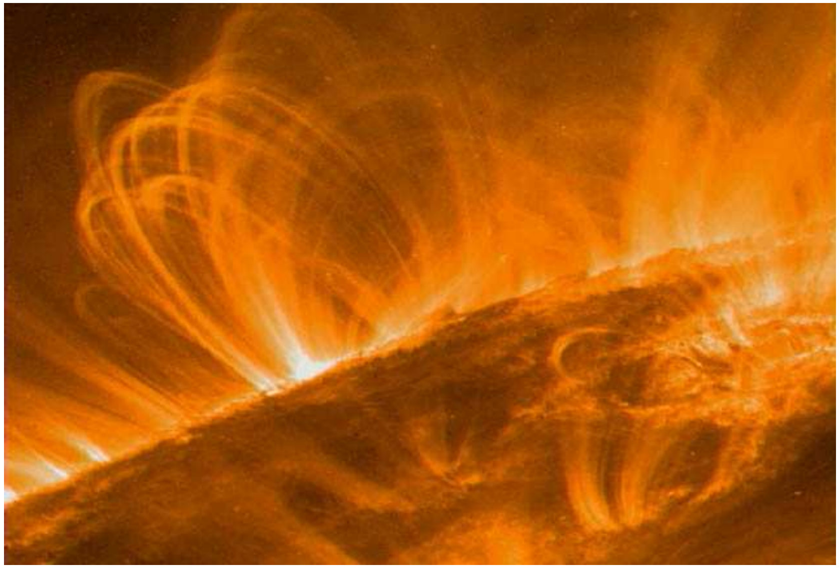


In the **core** (0-0.25 $R_\odot$) temperature is up to 15 million K.
Thermonuclear fusion creates energy mainly through the „pp-chain“ :
$4p \Rightarrow {}^4He^{++} + 2e^+ + 2\nu$ (+ 26.7 MeV)

In the **radiative zone** (0.25 - 0.7 $R_\odot$) the energy is transported outward by electromagnetic radiation.

In the **convective zone** (0.7 - 1.0 $R_\odot$) the matter is too opaque for radiative transport. Convective motion of the conducting plasma generates magnetic field by a dynamo process in the convective zone and at the interface to the radiative zone (tachocline).

Regions above the photosphere

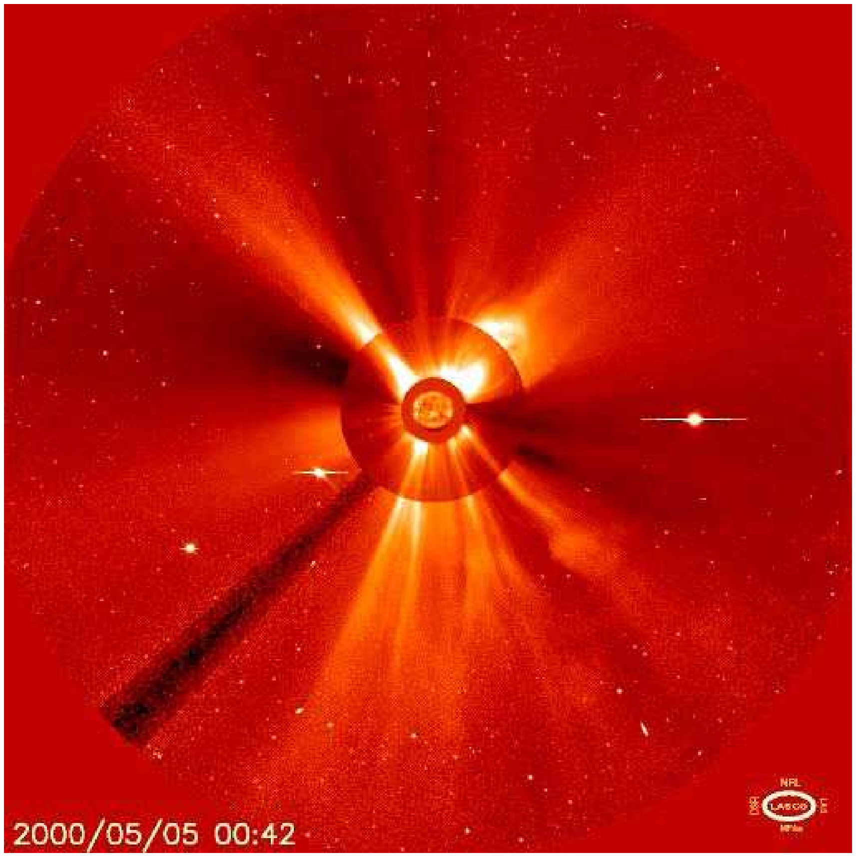


In the **chromosphere** (up to ~8000 km above the photosphere) the density drops by a factor 10^6, but the temperature rises again near its top to ~ 10^6 K.

The **corona** is visible at a total eclipse (and in artificial eclipses). Thin hot plasma (1- $2x10^6$ K) expands into space.

Images taken from satellites in the extreme ultraviolet (tracing emission lines from multiply ionized atoms) show the motion and ejection of plasma above the sun‘s surface. Plasma motion is strongly influenced by the sun‘s magnetic field.

Solar wind and coronal mass ejections

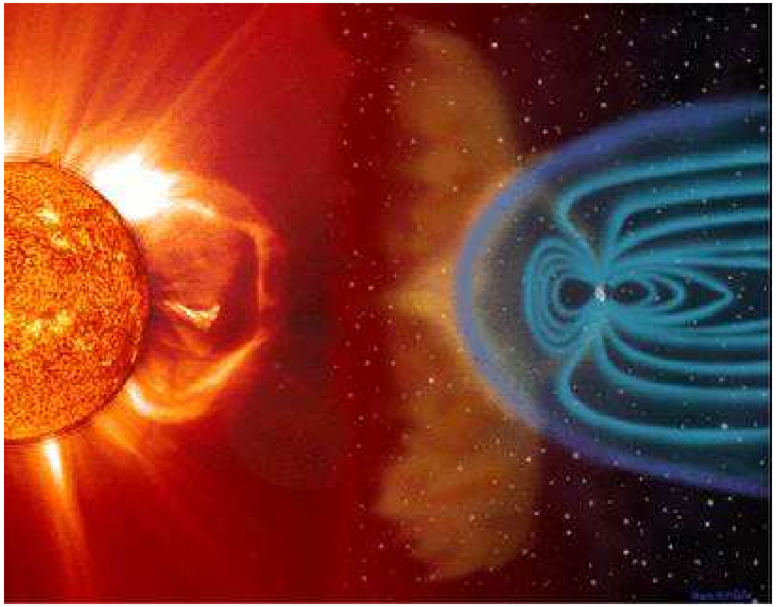


Images taken with the LASCO corono-graph on the SOHO spacecraft

The **solar wind** is a steady stream of particles (mostly protons and electrons) from the solar corona into space, with a typical velocity of 1000 km/sec. The solar wind carries magnetic field from the sun that is *frozen in*.

Solar flares / coronal mass ejections (CMEs) are violent eruptions near the solar surface, that are associated with strongly enhanced plasma flux, genera-tion of high energy particles (MeV to GeV) and X-rays. The magnetic field seems to play a major role in their formation.

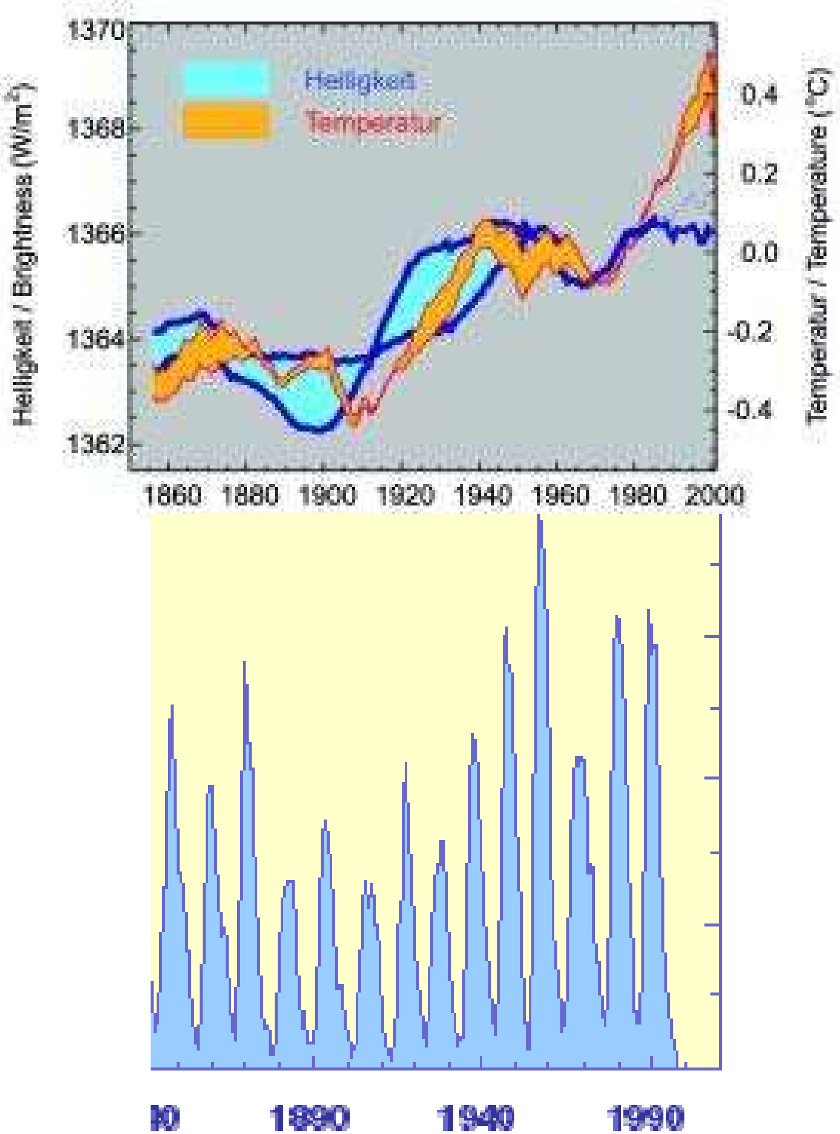
Magnetospheres / Space Weather



Intrinsic magnetic field of planet deflects stream of charged particles.
Closed cavity is formed (**magnetosphere**).
Planet's fieldlines confined by **magnetopause**.
Solar wind velocity supersonic $\Rightarrow$ **bow shock**.
Solar wind flows around the magnetosphere.
Earth: magnetopause is at $\sim 10 R_{Earth}$ in sunward direction; long anti-sunward tail.

When plasma cloud of a coronal mass ejection reaches Earth, magnetosphere strongly disturbed: Magnetic storm, aurorae (polar light).
Extreme events cause damage: failure of power lines (electromagnetic induction), damage of satellites by energetic particles.
Varying conditions of solar wind and energetic particle flux $\Rightarrow$ „**space weather**“.

Solar variability and climate

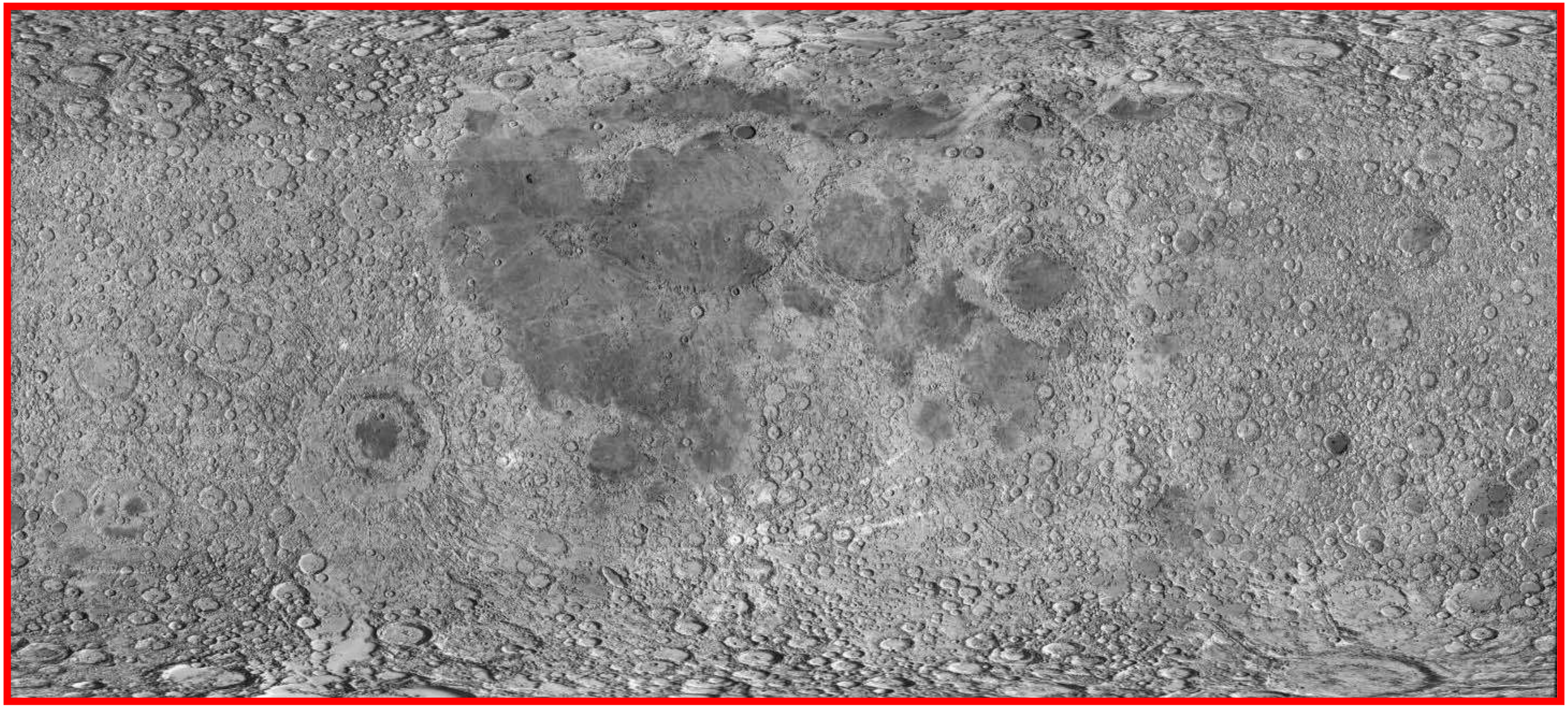


Solar radiation not strictly constant, (variation by fraction of a percent). Does this influence climate on Earth? Precise solar flux measurements only since ~1980 on satellites above atmosphere.

Total radiation changes with solar activity, expressed for example by sunspot number (even though sunspots are „dark“, total flux is higher when there are many sunspots).

Comparing solar flux inferred from average sunspot numbers and global temperature over the past 150 years suggests correlation until 1980. The most recent strong warming cannot be explained by solar activity.

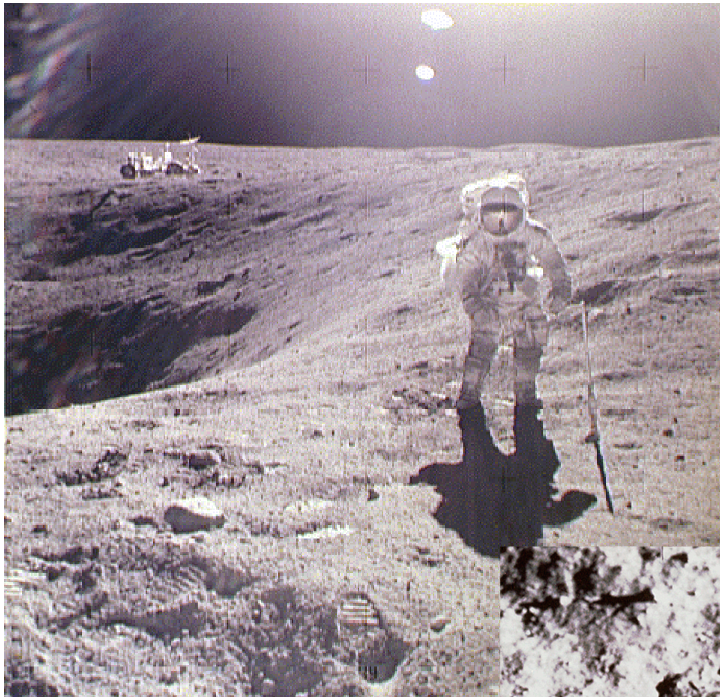
The Moon



Bright, heavily cratered, highland regions versus dark, smooth Mare regions with much lower crater density. Highland = primitive crust of the Moon, > 4 Gyr old. Mare = volcanic flood basalts filling impact depressions, 3.3 – 3.8 Gyr old.

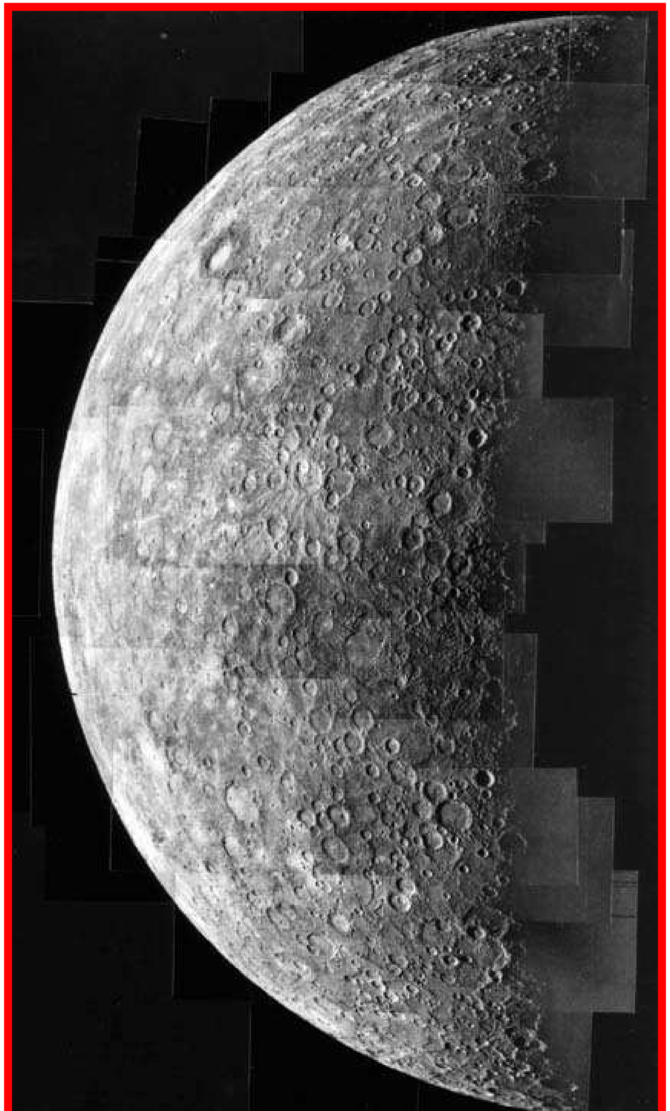
Crater density serves as measure for the age of the surface on planets from which we have no samples, with the moon taken for calibration.

Regolith



Planets without atmosphere are covered at their surface with a layer of **Regolith** = dust-sized particles of fragmented rock and (micro-)meteorites. Regolith is formed and „gardened“ by meteorite impacted and affected by energetic particles („space weathering“). The (fine) regolith is ~10 m deep.

Mercury



Radius = 2,400 km (38% Earth)

ρ_{mean} = 5440 kg m^{-3} (98% Earth)

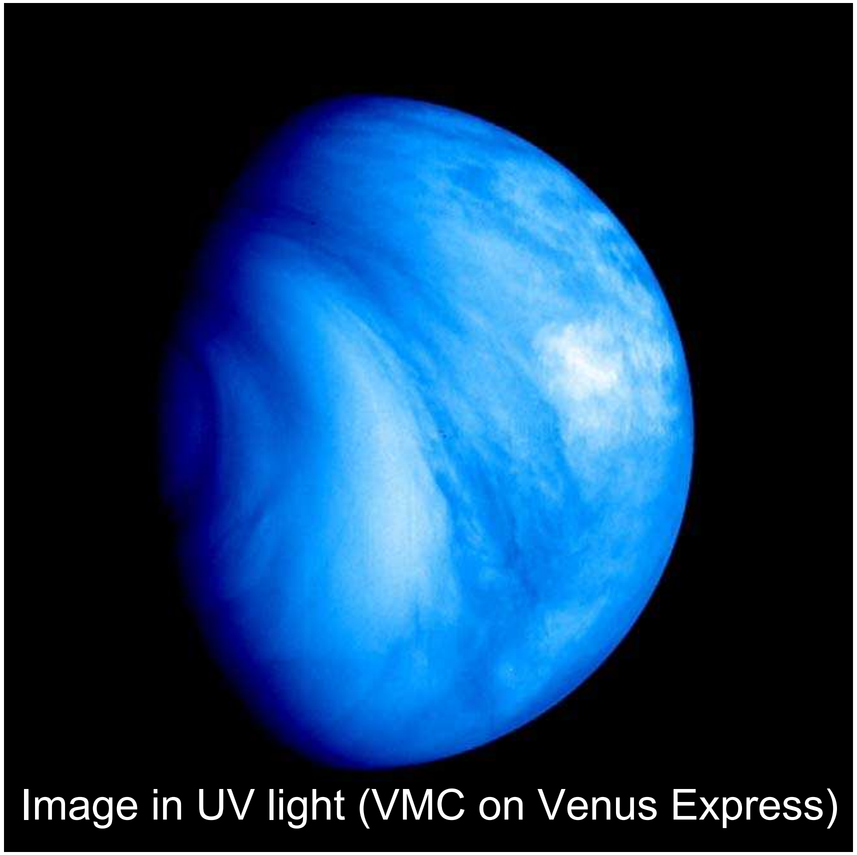
$T_{rot} \approx 59$ d = 2/3 T_{orbit}

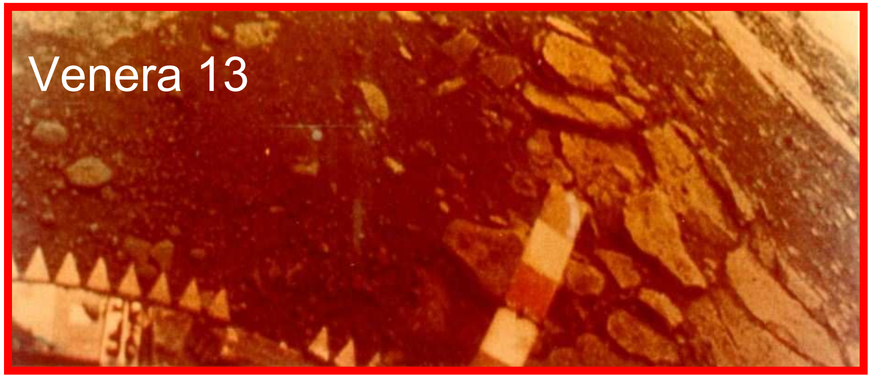
45% of Mercury's surface have been imaged in 1974/75 by Mariner 10. It is heavily cratered $\Rightarrow$ age > 4×10^9 yr.

Weak global magnetic field
$\Rightarrow$ dynamo in fluid iron core.

Messenger mission (first flybyes in 2008) and Bepi Colombo (launch 2013) contribute strongly to enhance knowledge.

Venus





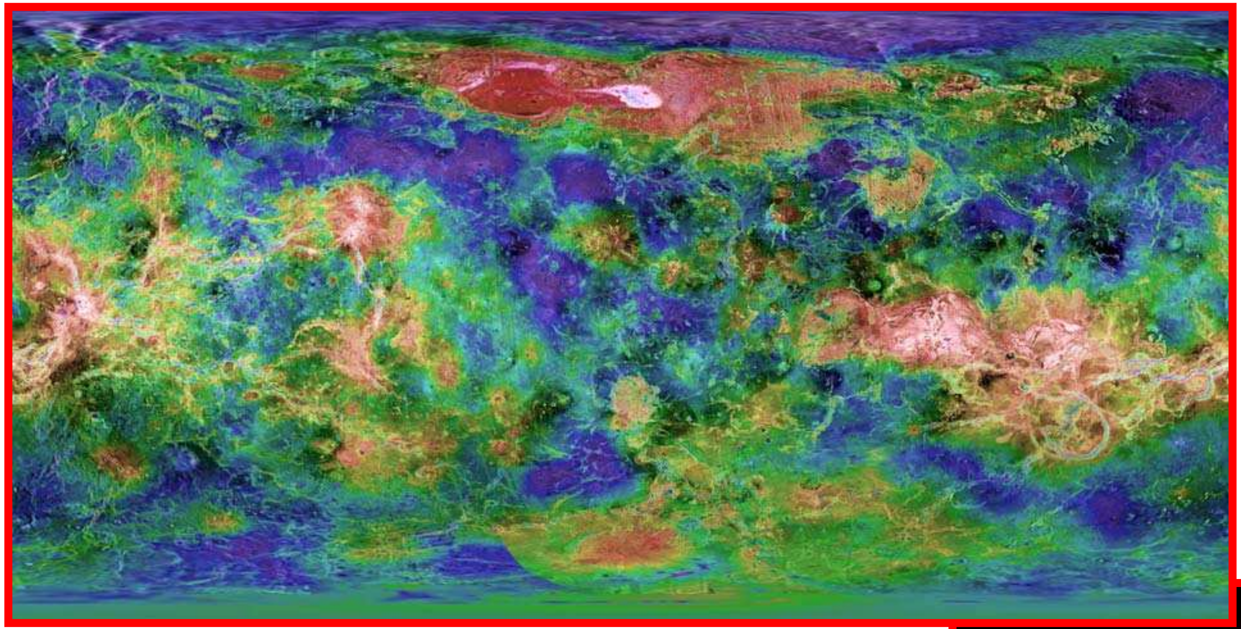
Radius: 6080 km (95% R_{Earth})
Slow rotation: T = 225 d, retrograde

Atmospheric pressure: 90 bar
Temperature: 450^{o}C

Main constituent: CO_2 (95%)
Clouds: H_2SO_4 droplets

Surface: Basaltic rocks

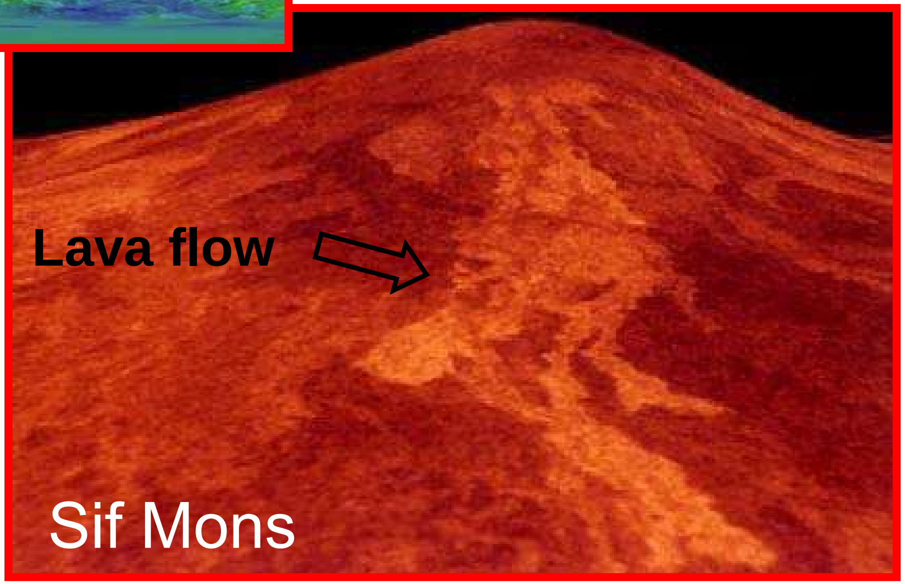
Venus: Topography & volcanism



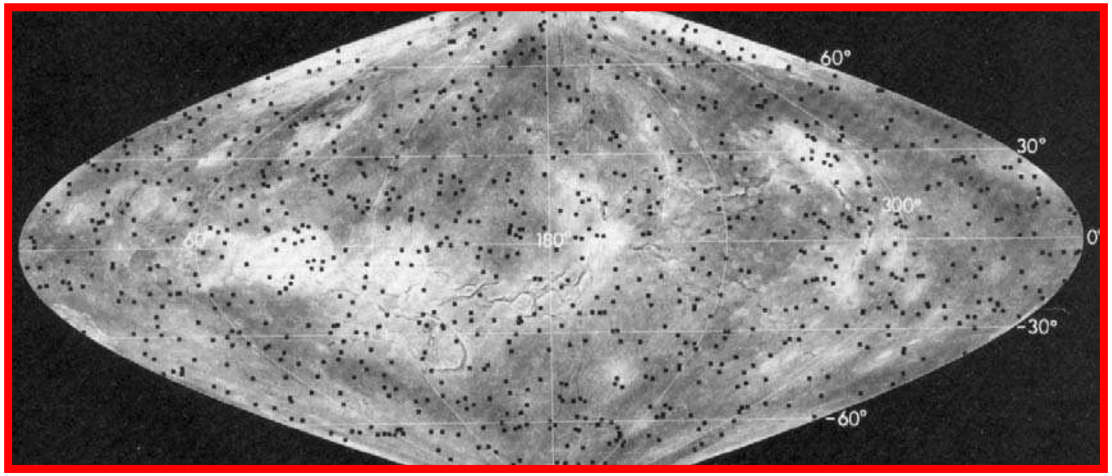
Global topographic map
(radar altimetry by Magellan mission)

No bimodal height distribution (as in case of Earth) $\Rightarrow$ no continent – ocean dichotomy). No clear signs of plate tectonics.

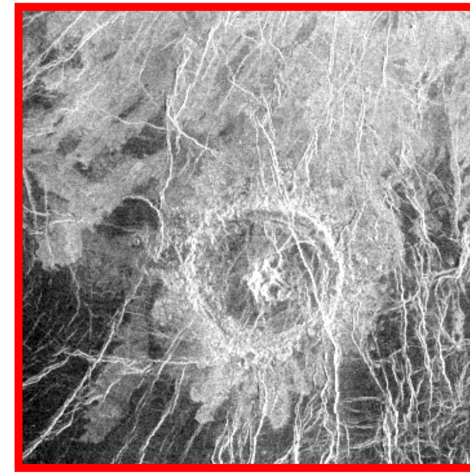
Many signs of volcanism.



Venus: Cratering



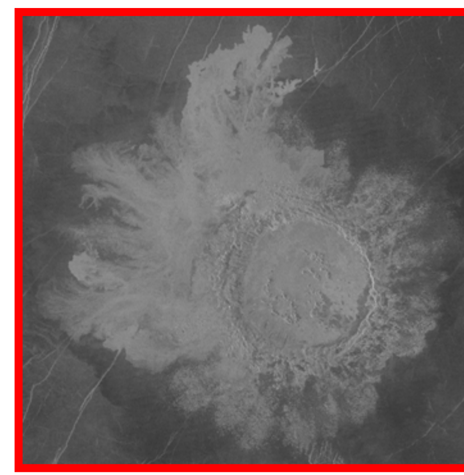
Global distribution of impact craters



Overprinted crater (rare)

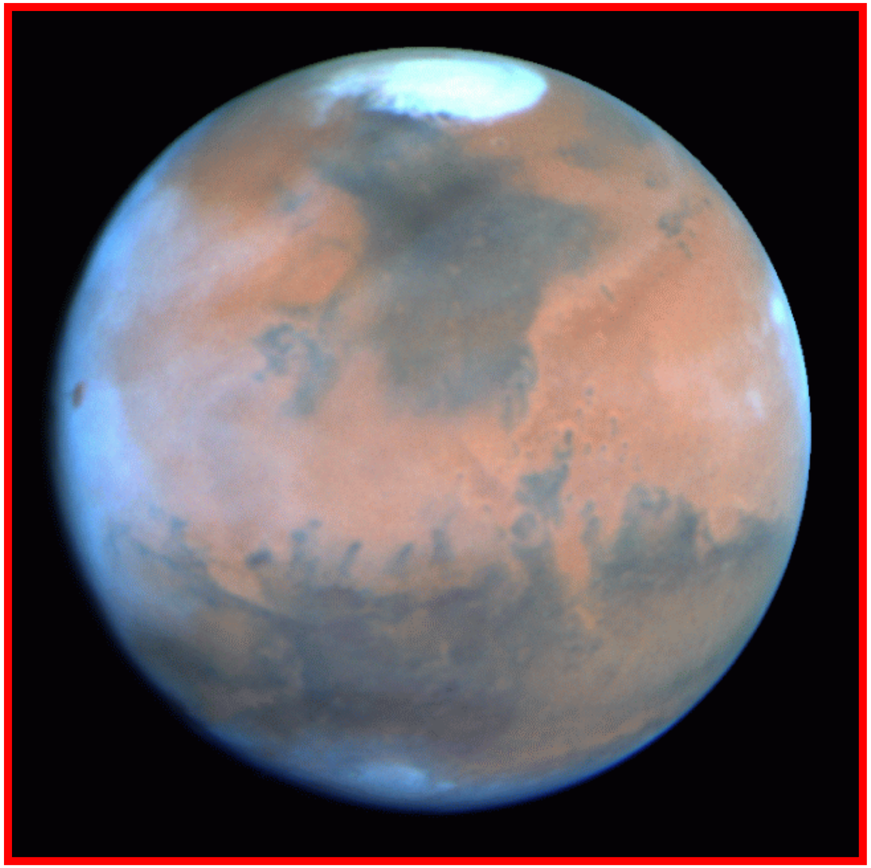
Crater density statistically uniform $\Rightarrow$ different surface units have similar age.
Crater density much lower than on Moon / Mercury $\Rightarrow$ surface age ≈ 500 Myr.
Few craters are tectonically overprinted or embayed by lava flows.

Global re-surfacing event (flooding by lavas) about 500 Myr ago ?



Normal crater

Mars

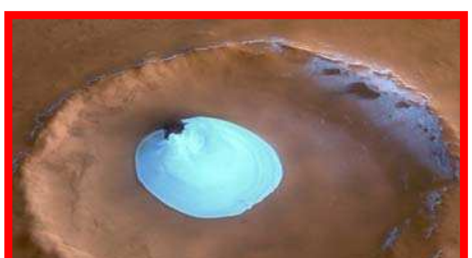


Radius: 3370 km (53% Earth)

Rotation period: 24 h 56 min

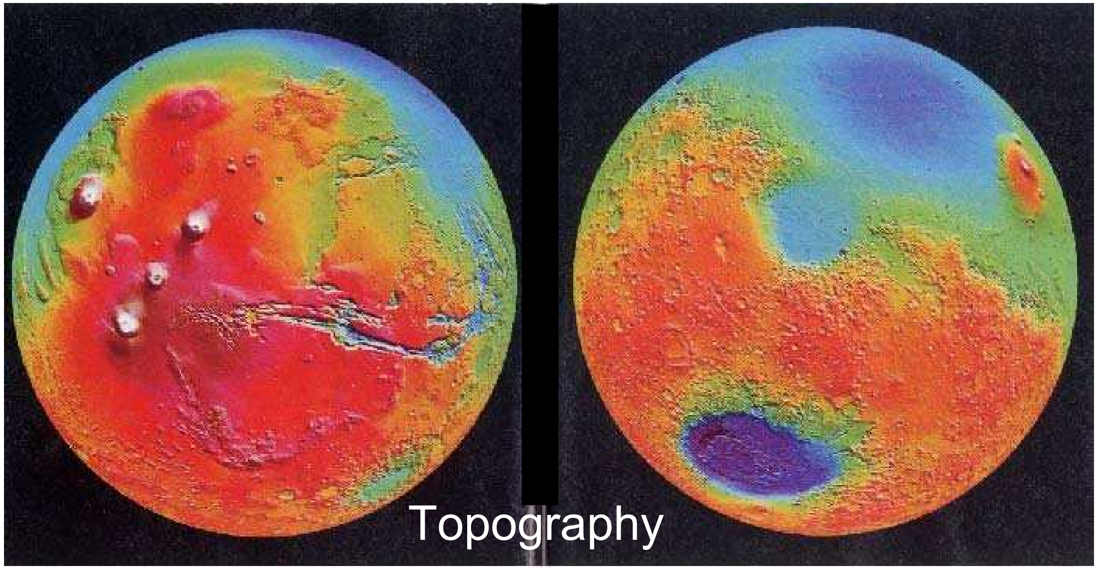
CO_2-atmosphere: 6 mbar, -40°C

Seasonal condensation of CO_2 in polar regions.



Running water in early history.
Water ice present in polar regions

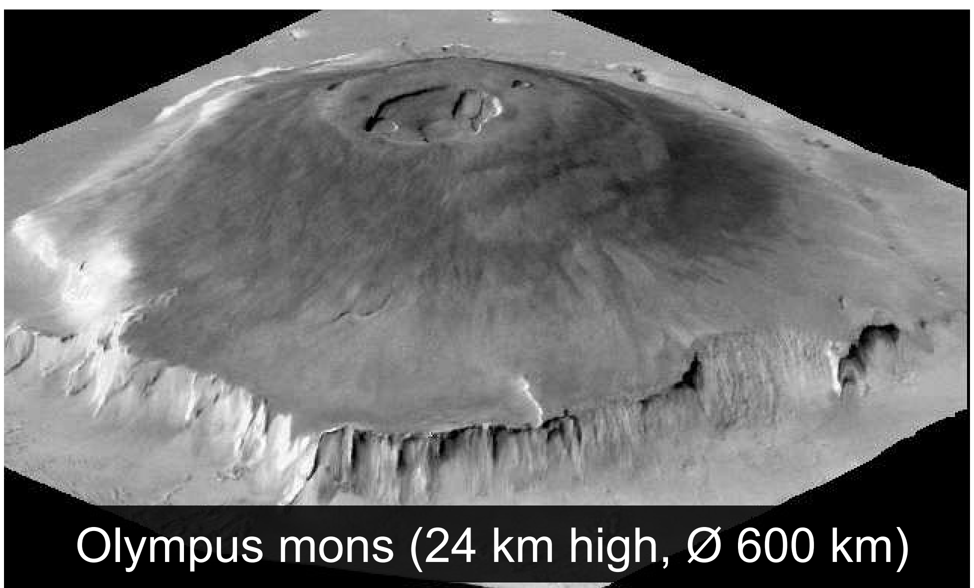
Mars: Topography & Volcanism



Southern highlands: heavily cratered: > 4 Gyr old

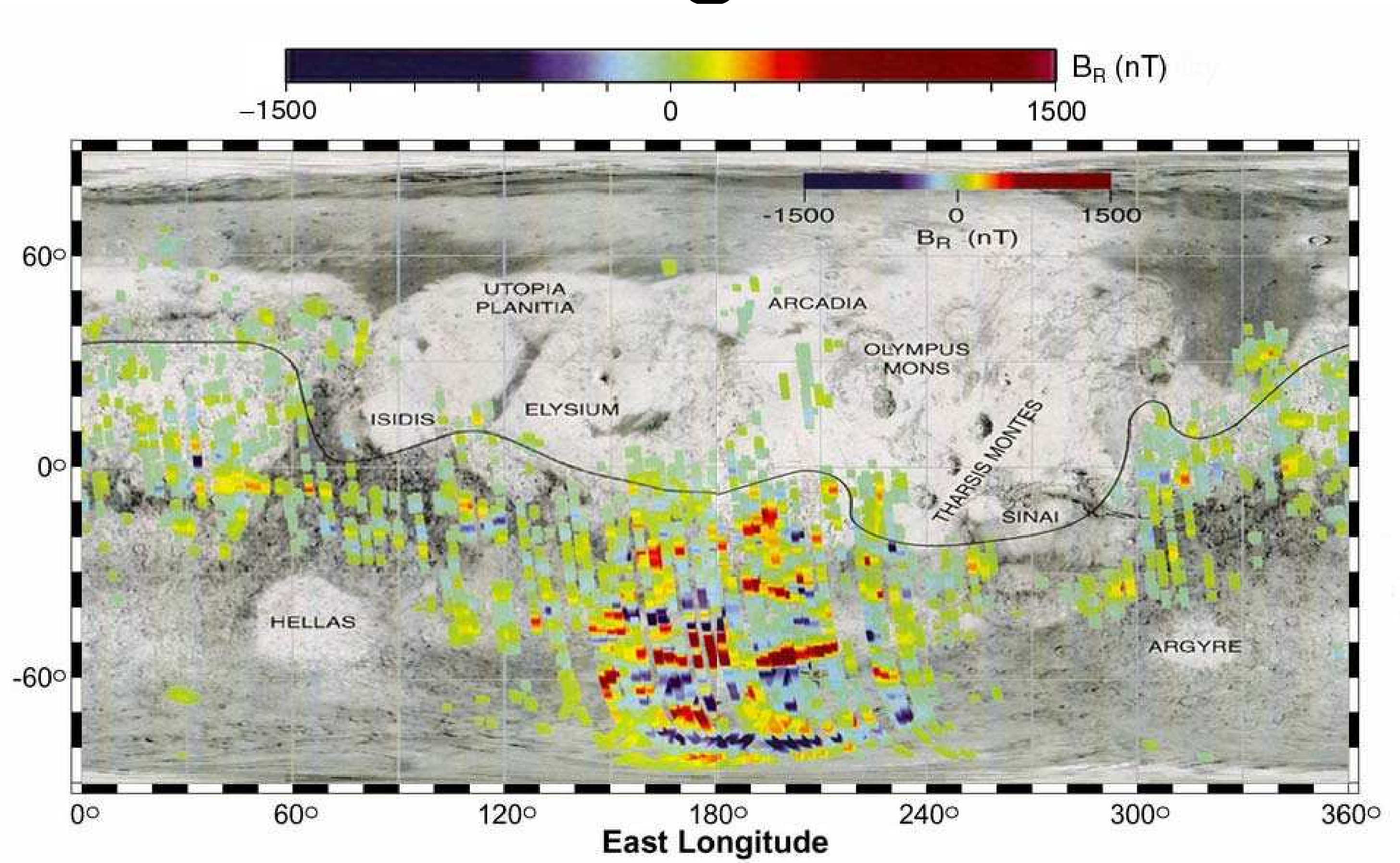
Northern lowlands: 2 – 4 Gyr (a few regions very young)

Tharsis bulge with giant volcanoes (2 – 4 Gyrs)



High resolution images allow to detect very small craters. Their scarcity in parts of the Olympus Mons Caldera suggest that volcanism is not extinct.

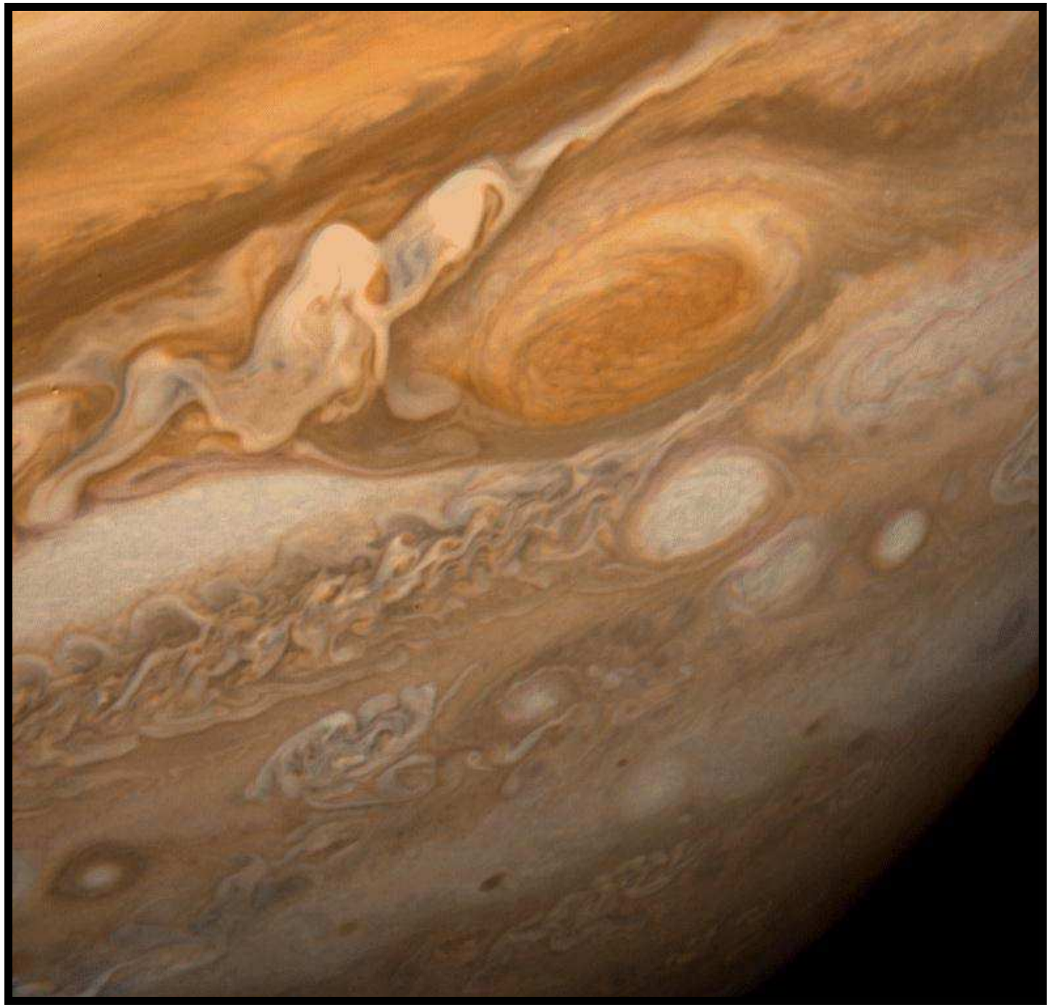
Mars: Magnetic field



MGS/Magnetometer

No global magnetic field, but strong local magnetic „anomalies" in parts of the southern highlands $\Rightarrow$ did Mars have an early, now extinct, dynamo ?

Jupiter: a gas giant



Radius: 71,400 km (11 x Earth)

Mean density: 1330 kg m^{-3}

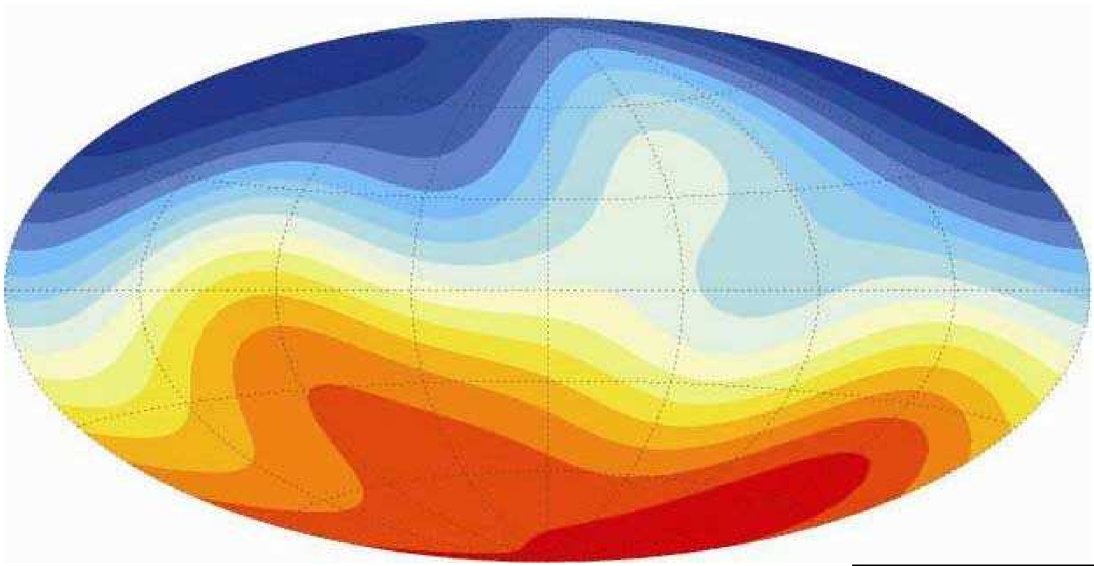
Rotation period: 10 h

Atmospheric composition: 85% H_2, 14% He, small amounts of NH_3 and other components forming clouds

Very dynamic atmosphere

Emitted energy 70% higher than absorbed sunlight $\Rightarrow$ 5 W/m^2 internal heat flow

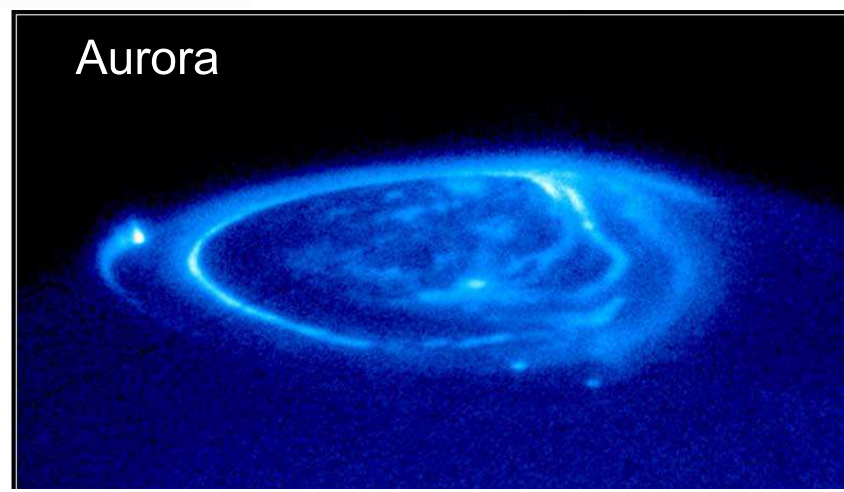
Jupiter: magnetic field



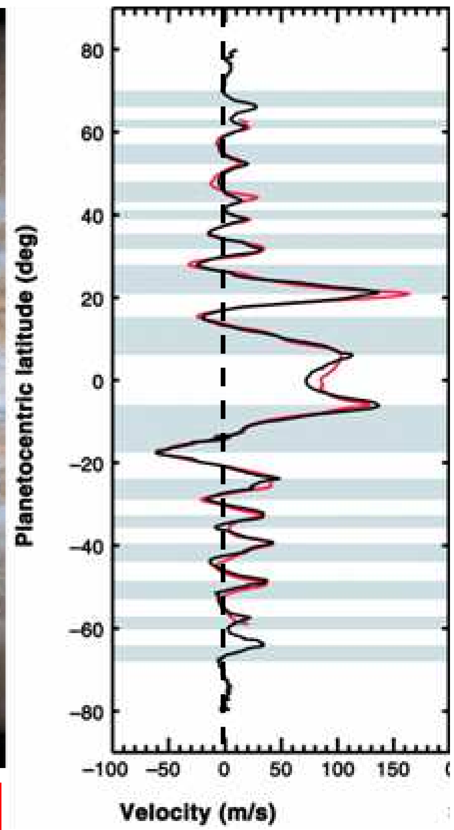
Radial field component at Jupiter‘s surface

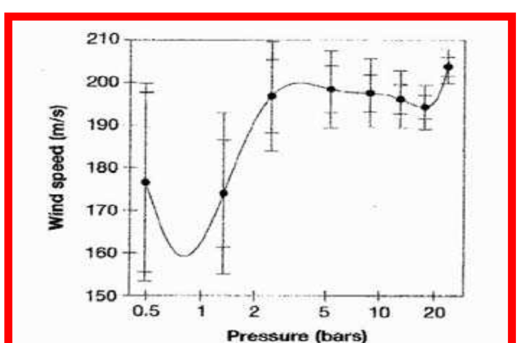
Dipole-dominated magnetic field
Field strength 10x Earth‘s field
Tilt of dipole ≈ 10^o

⇒ Active dynamo in Jupiter



Jupiter: zonal flow





Strong zonal winds are associated with the latitudinal zones and bands, with velocities up to 150 m/sec, alternating in direction. The zonal velocity is larger than the velocity of the superimposed eddies. Wind speed and pattern has hardly changed in 25 yr.

Two competing concepts for the origin of the zonal flow:

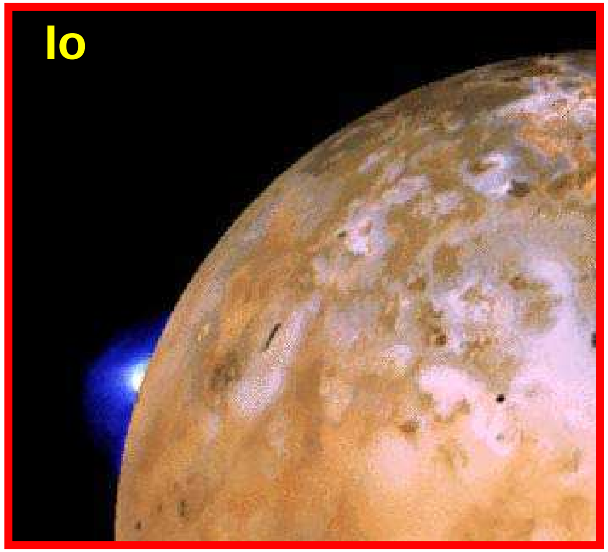
(1) Meteorological phenomenon of a shallow atmospheric layer, powered by solar heat.

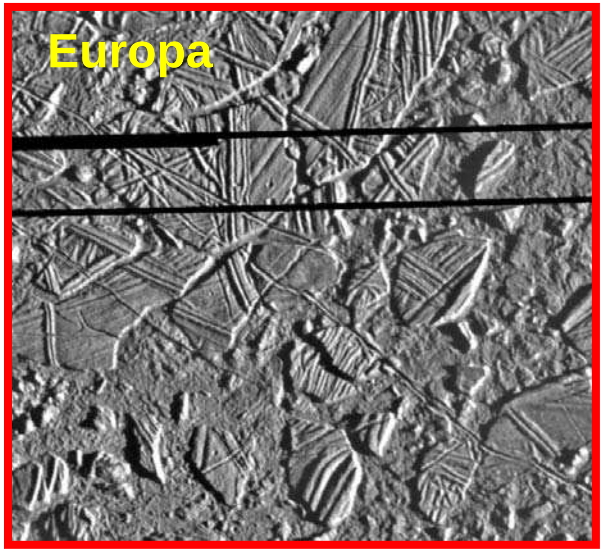
(2) Expression of convection in the deep interior, driven by Jupiter‘s internal heat.

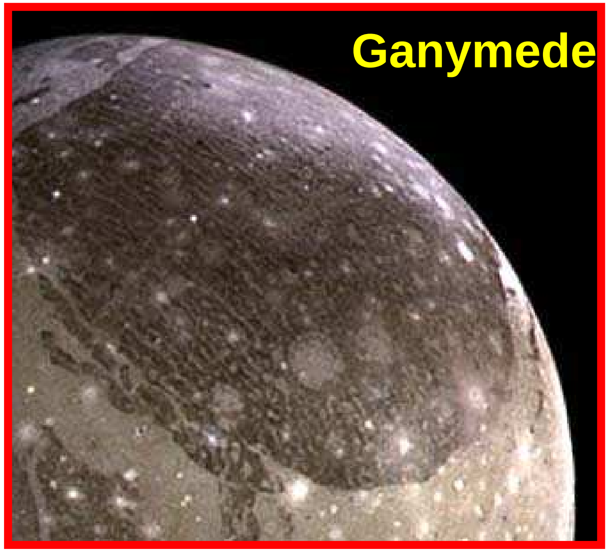
Observation by the Galileo probe that the wind speed does not decrease with depth below the cloud deck (up to the 20 bar pressure level) supports 2nd hypothesis.

Galilean Satellites

Galilean satellites: surfaces







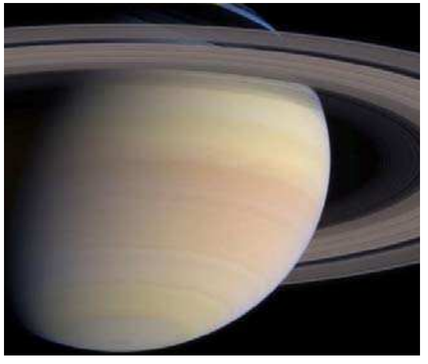
Io - No impact craters. Volcanically most active object in solar system. Heat flow 2 W/m^2 (20 x Earth), supplied by tidal friction from large tides (~30 m) excited by massive Jupiter.

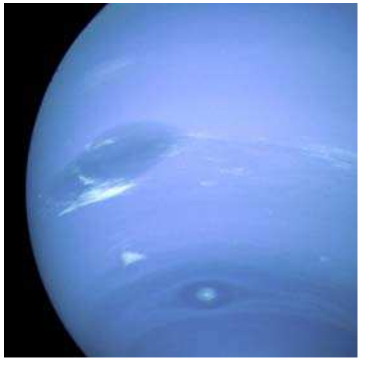
Europa - Very few impact craters. In some places fractured surface looking like pack-ice rafts that drifted on fluid substratum. Active interior, surface 50 Myr old (?)

Ganymede & Callisto
Many impact craters (surface age > 4 Gyr). Impacts removed dark surface material and excevated bright interior. Surface material ice (+ dust).

Saturn, Uranus, Neptune

	Saturn	Uranus	Neptune
ρ [kg m^{-3}]	704	1290	1650
R [km]	60,200	25,900	24,800

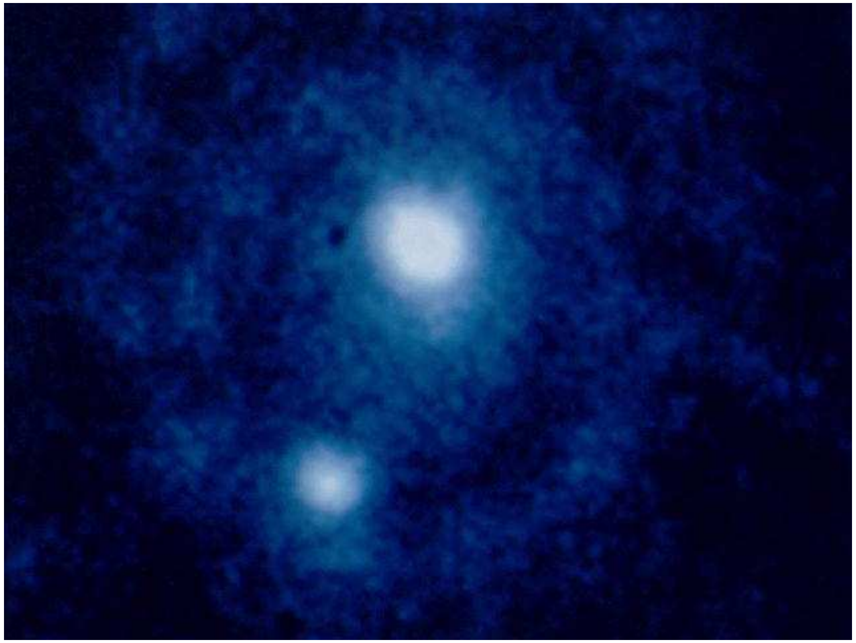




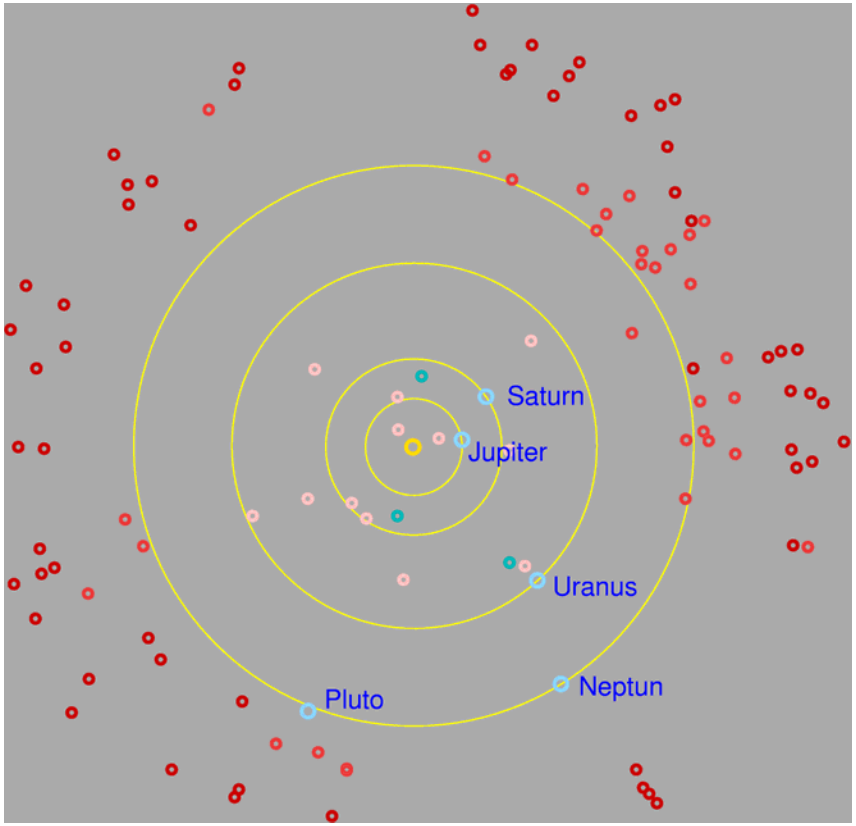
Saturn is the little brother of Jupiter: Mainly composed of H+He; strong alternating zonal jet flow at the surface; magnetic field very axisymmetric.

Uranus and **Neptune** are different: Surface CH_4 in addition to H+He. Smaller size but higher mean density than Saturn $\Rightarrow$ must consist mainly of denser components. Strong zonal wind flow retrograde at equator.

Pluto and Kuiper belt

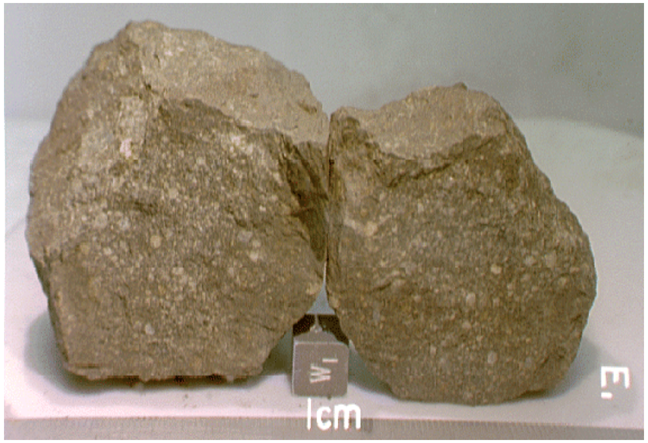


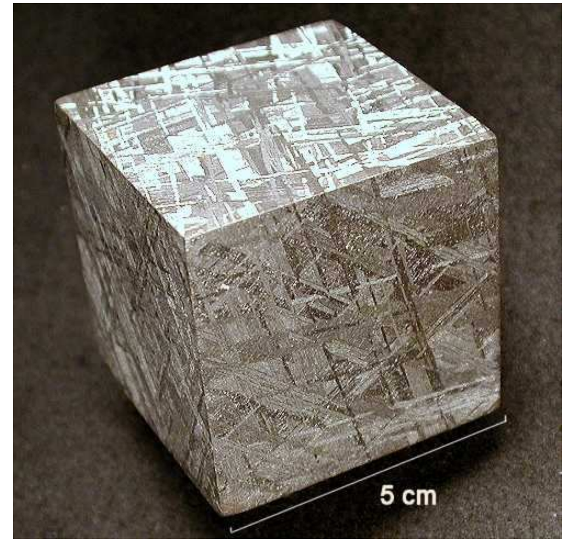
Pluto with satellite Charon
(imaged with adaptive optics)



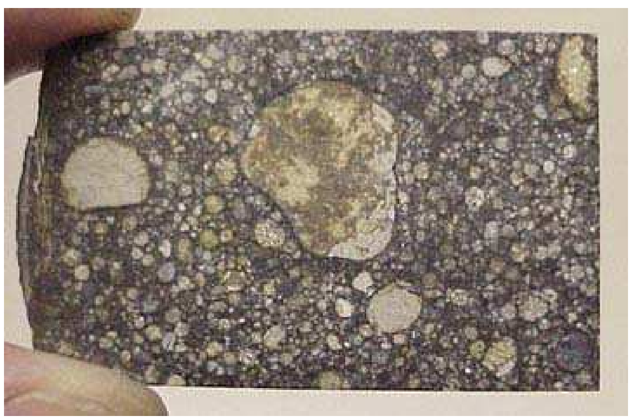
Kuiper belt objects (red dots)

Meteorites





Iron meteorite

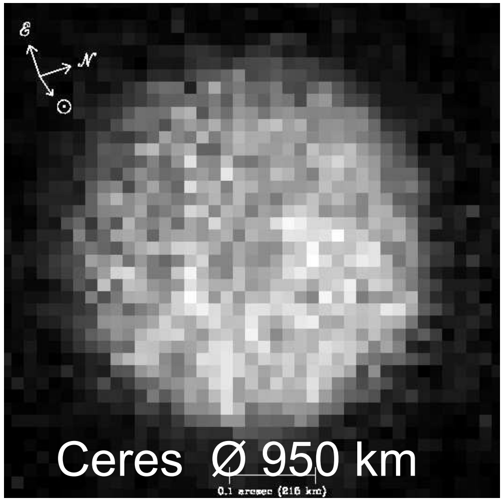


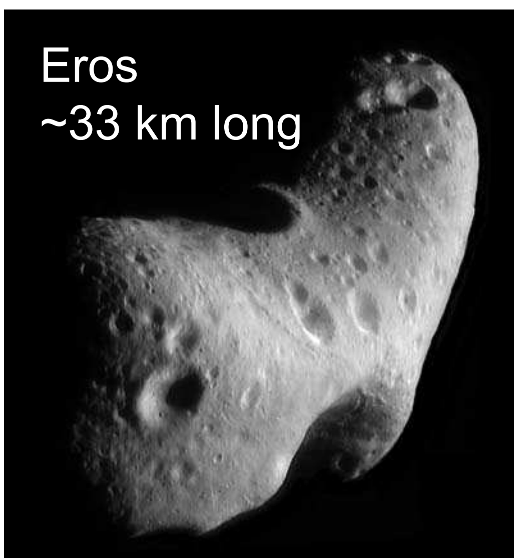
Chondrite

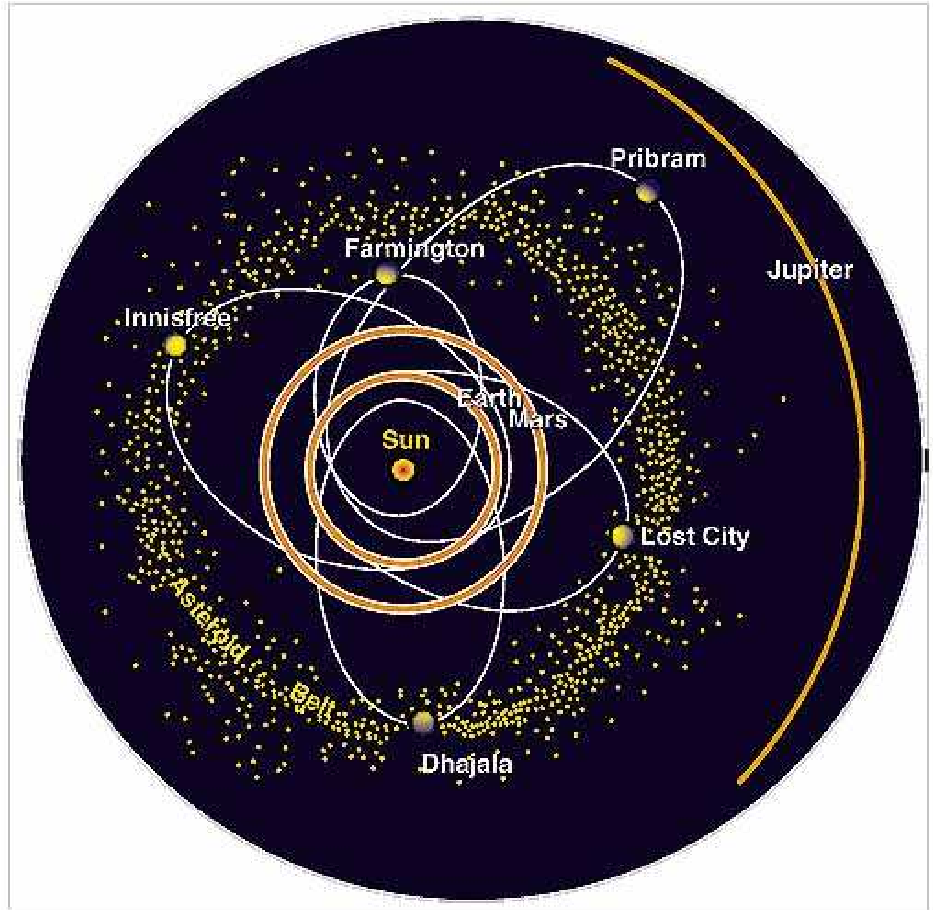
Achondrite (Basaltic)

Chondritic meteorites are most common. In chondrites the relative abundance of volatile is similar to that in the solar atmosphere. $\Rightarrow$ Chondrites represent primitive matter from the formation of the solar system.

Asteroids

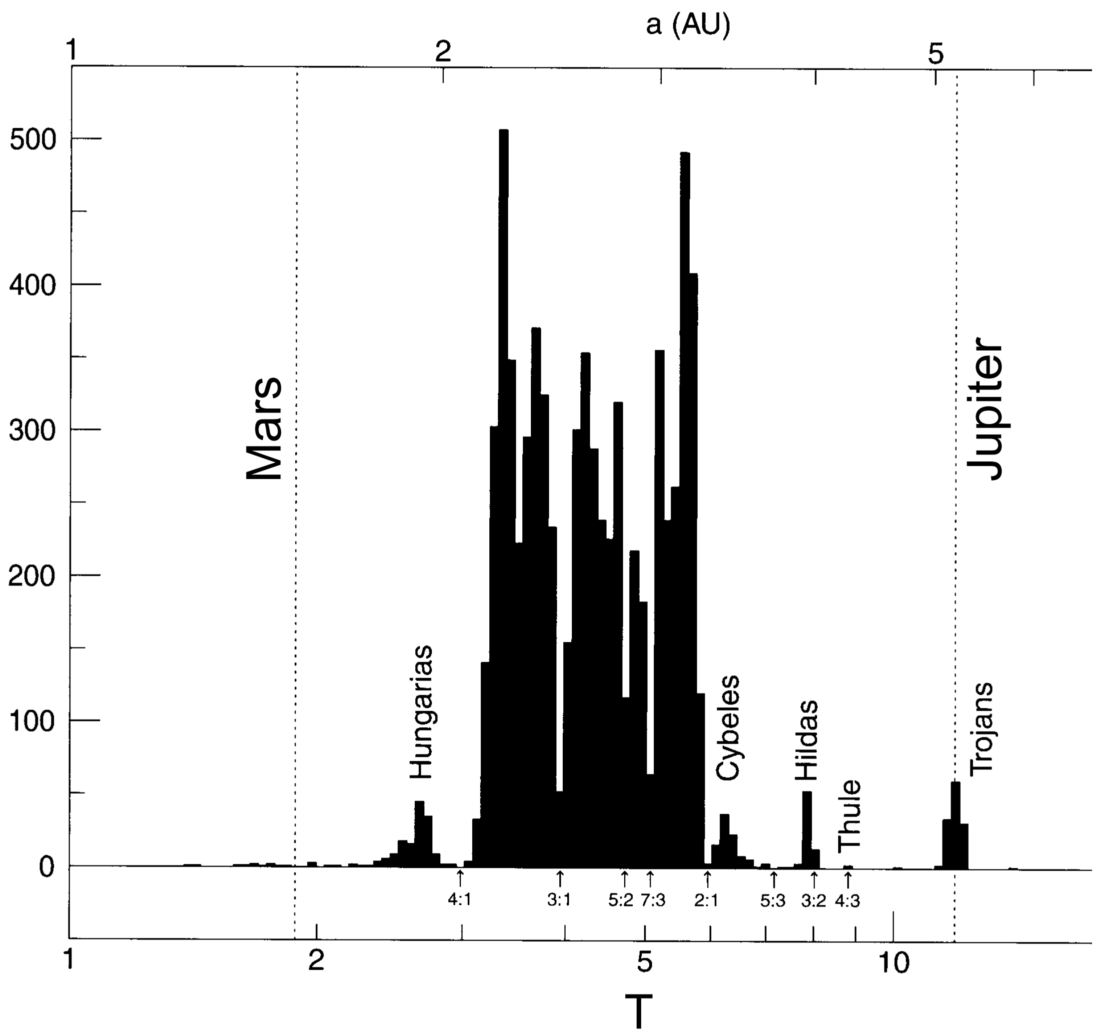






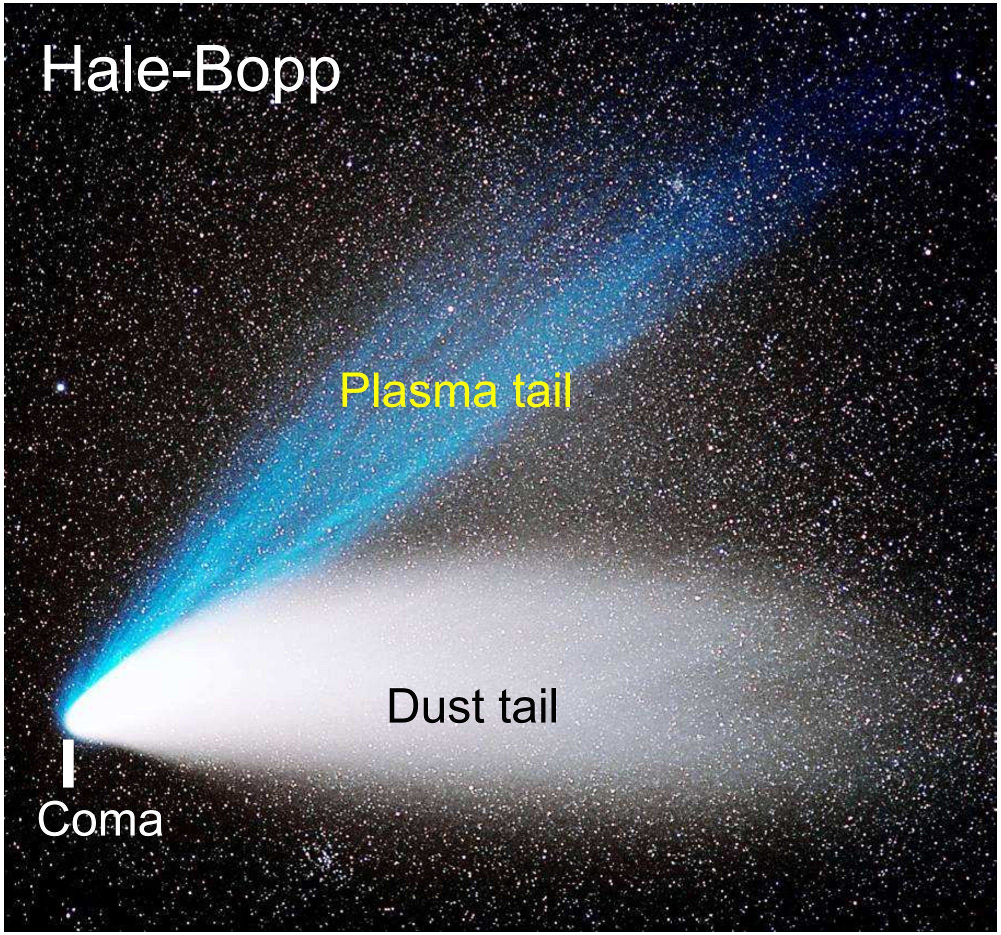
More than 10,000 bodies >1km (up to 1000 km) in size orbit between Mars and Jupiter. Most meteorites come from the asteroid belt.

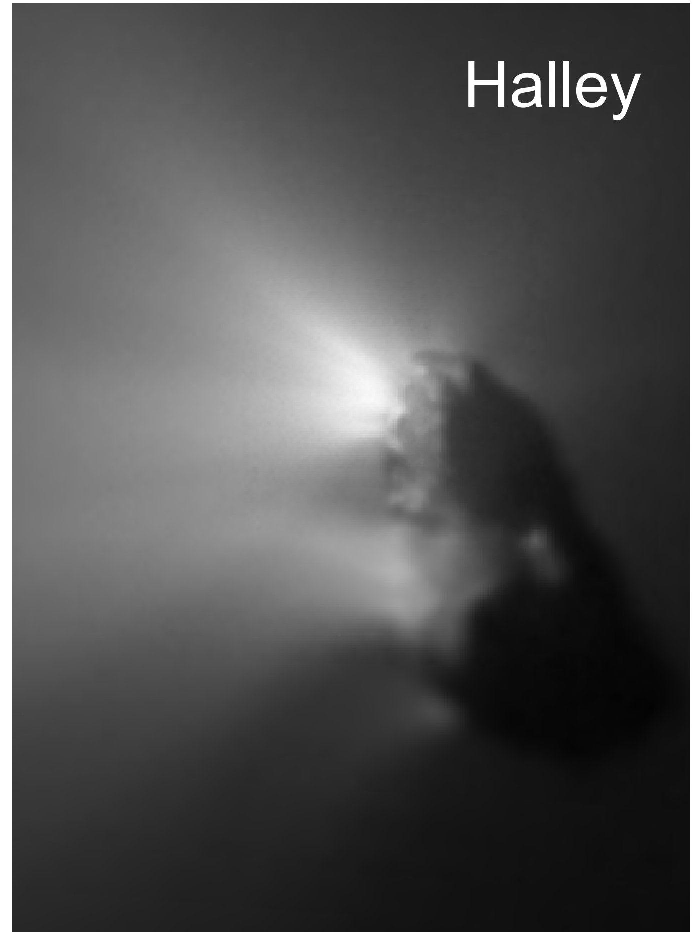
Resonances



When ratio of the orbital period of a small body and a large planet are is a rational number, the minor body may be expelled from the location by the planet‘s perturbation (unstable resonance) or may be trapped in this orbit (stable resonance).
In the asteroid belt both types of resonances are found in a plot of number of objects versus distance.

Comets





Comets have usually highly elliptical orbits. Close to perihelion they form coma and tail by ejecting gas and dust. The nucleus (size 1 – 50 km) consists of ice, frozen gas, dust and organic compounds („dirty snowball“). Comets come from the Kuiper belt and beyond (Oort cloud).