

Einführung in die Physik des Sonnensystems

**Ringvorlesung
Dozenten vom Max-Planck-Institut für
Sonnensystemforschung in Katlenburg-Lindau**

SS 2008

Seminarraum Astrophysik, Montags 10:15 - 12:00

**Folien in:
<http://www.solar-system-school.de/lectures.html>**

Themen und Dozenten

1. Überblick über das Sonnensystem	Christensen	14.04.
2. Oberflächen und innerer Aufbau der Planeten	Christensen	21.04.
3. Planetary Atmospheres	Titov	28.04.
4. Kleine Körper im Sonnensystem	Boehnhardt	05.05.
5. Bildung von Planetensystemen	Boehnhardt	19.05.
6. Extrasolare Planeten	Schmitt	26.05.
7. Internal structure of the sun / helioseismology	Gizon	02.06.
8. Konvektion und solares Magnetfeld	Schüssler	09.06.
9. Photosphäre und Chromosphäre	Solanki	16.06.
10. Übergangsregion und Korona	Marsch	23.06.
11. Sonnenwind, CMEs und Heliosphäre	Marsch	30.06.
12. Planetare Magnetosphären	Büchner	07.07.
13. Solar-terrestrische Beziehungen	Büchner	14.07.

Anrechnungspunkte (3 ECTS) im Bachelor/Masterstudiengang durch schriftlichen Test nach Abschluss der Vorlesung.

Überblick über das Sonnensystem

Ulrich Christensen

Die Sonne

Einfluss der Sonne auf die Erde und andere Körper

Die Planeten

Satelliten der großen Planeten

Kleine Körper (Asteroide, Kometen, Meteorite)

Suggested reading

Chapters 1 + 2

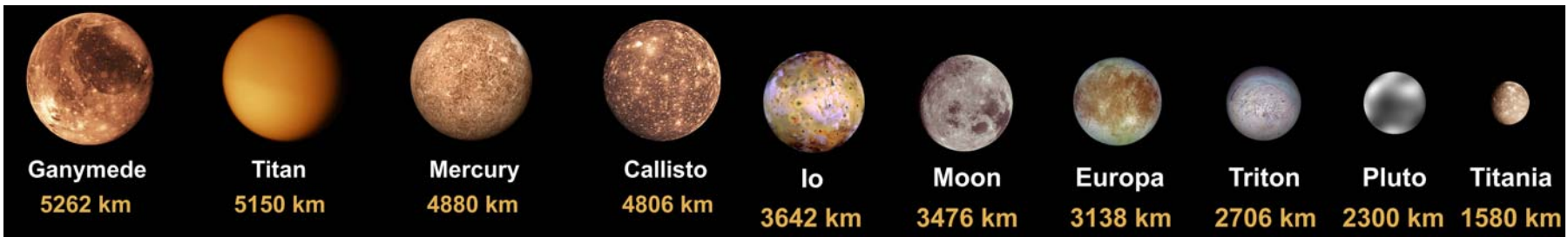
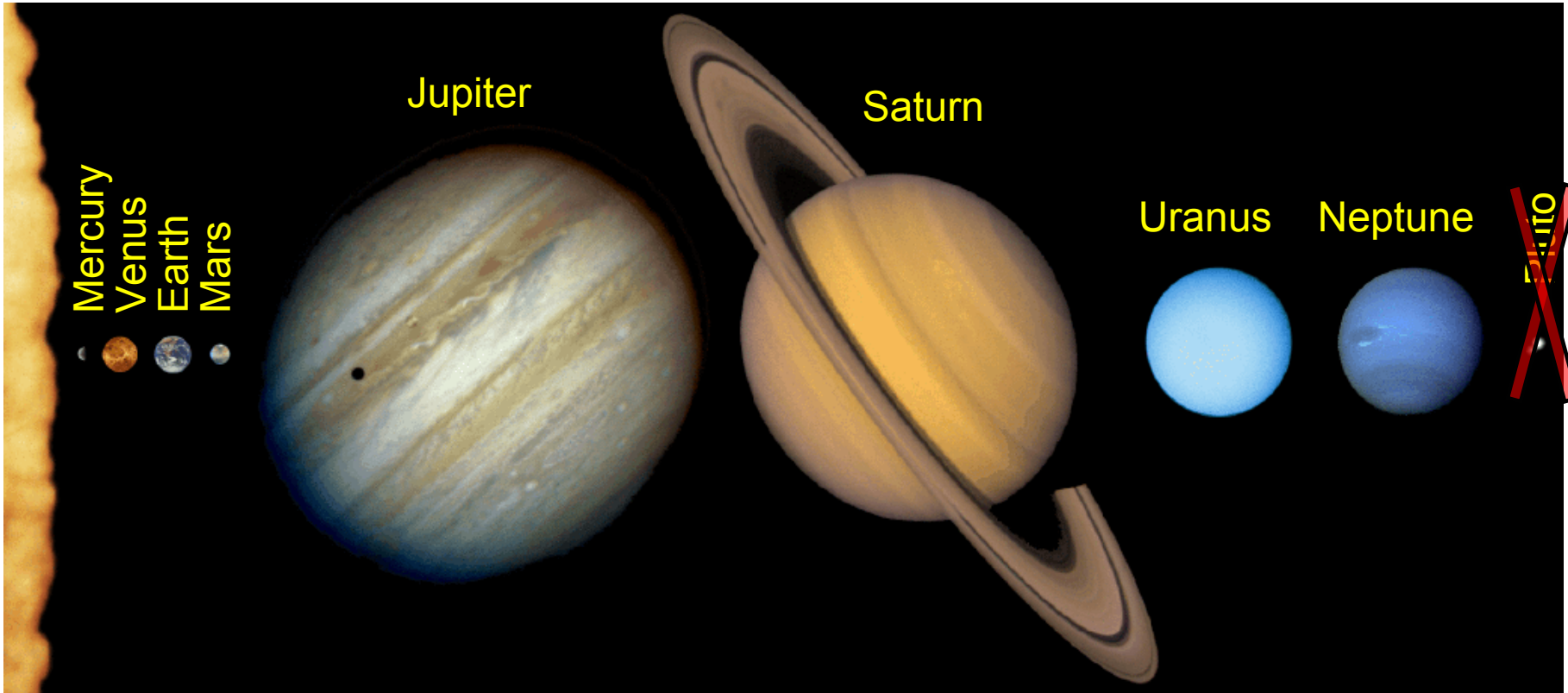
McBride, N., Gilmour, I. (Ed.), An introduction to the Solar System, Cambridge University Press, 2003. (*Overview on Planetary Sciences at an elementary level*).

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*)

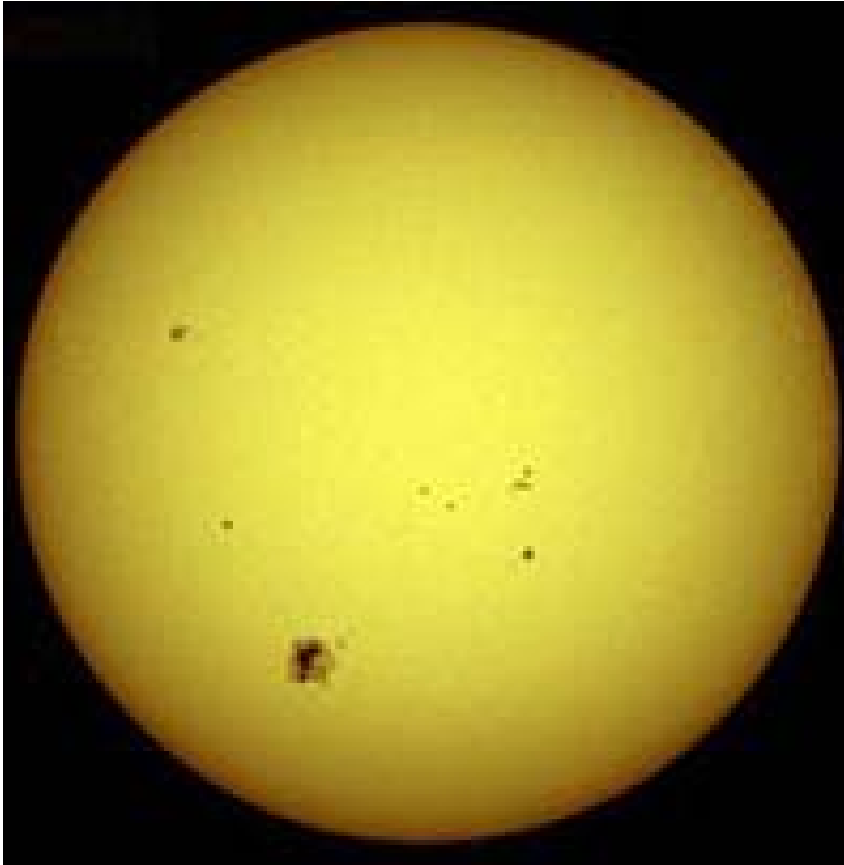
De Pater, I., Lissauer, J.J., Planetary Sciences, Cambridge University Press, 2001. (*Modern introduction to most aspects of planetology at intermediate to advanced level*).

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



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 wide)

Energy flux: 63 MW/m²

(at Earth distance 1370 W/m²)

Rotation period: 25.4 days (25-30)

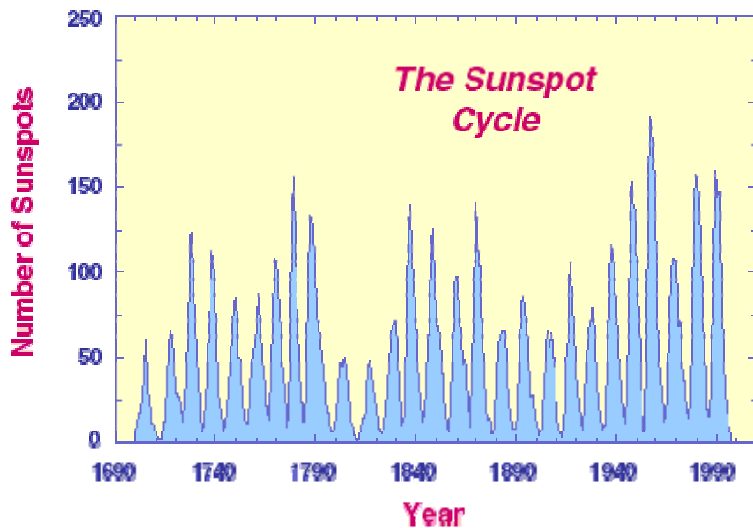
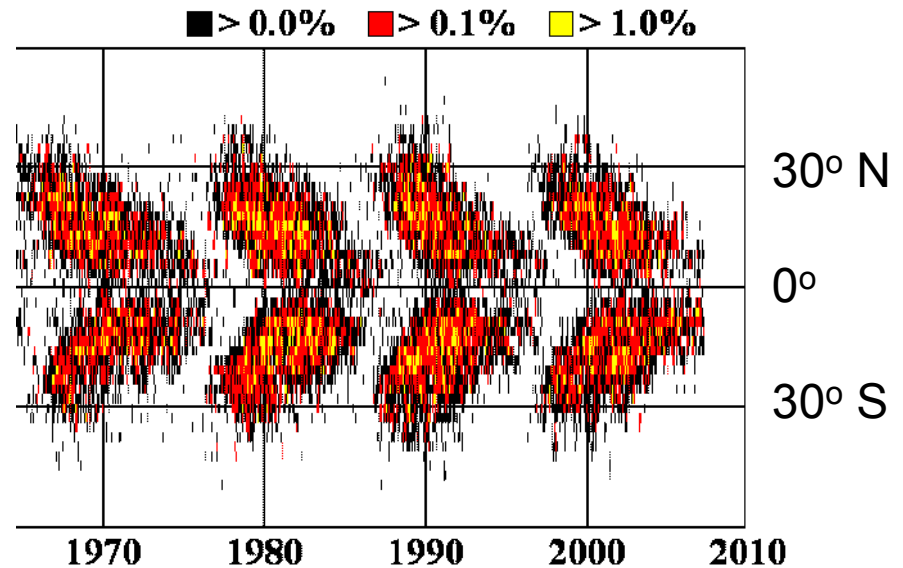
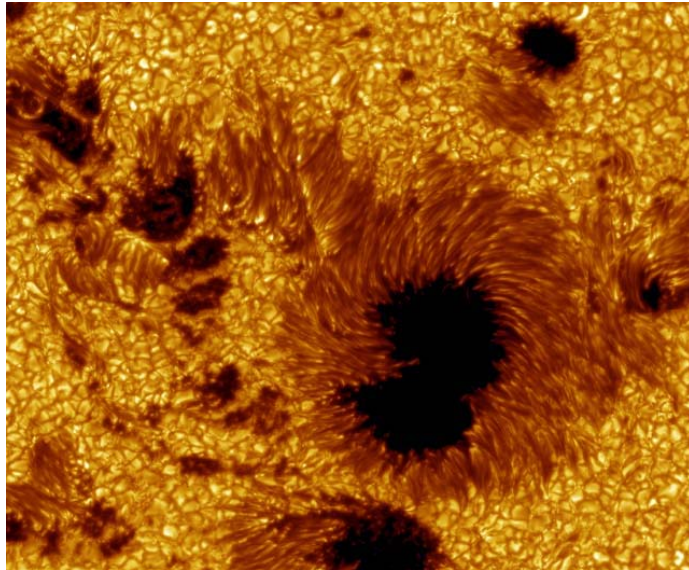
Composition near surface (spectroscopy):

73% H

25% He

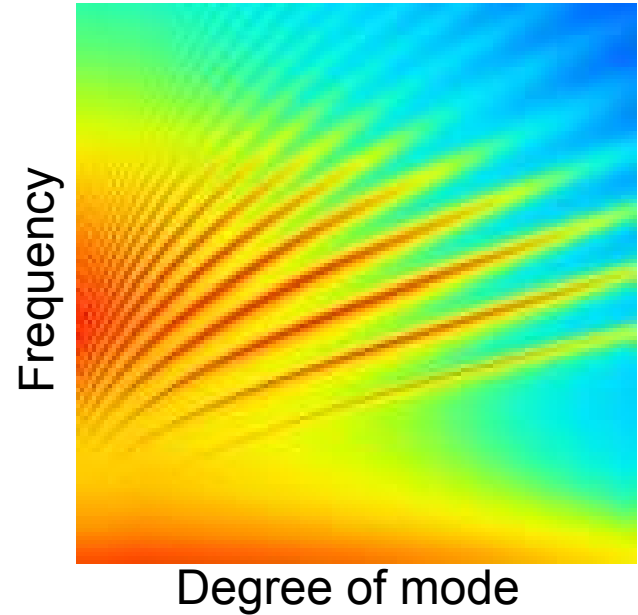
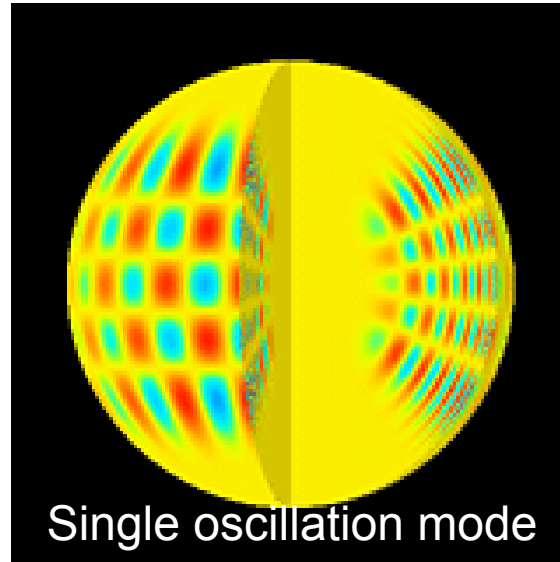
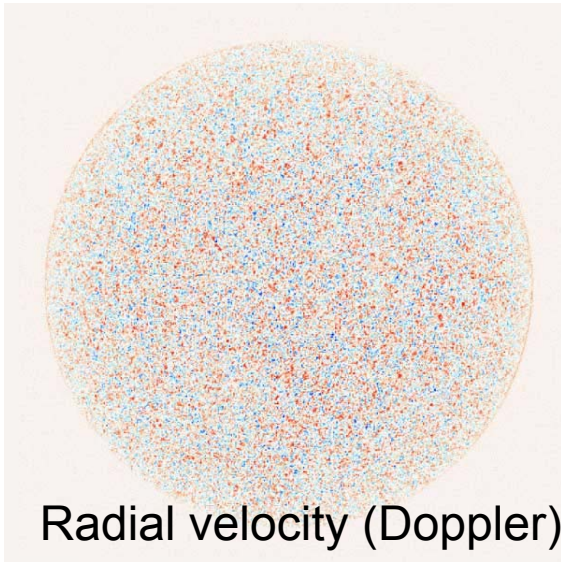
2% heavy elements (O, C, Fe,)

Sunspots



Sunspots in pairs or groups. Lifetime 1 – 50 d
Sunspot cycle of 11 years (22 years)
Sunspots between $\pm 35^\circ$ 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



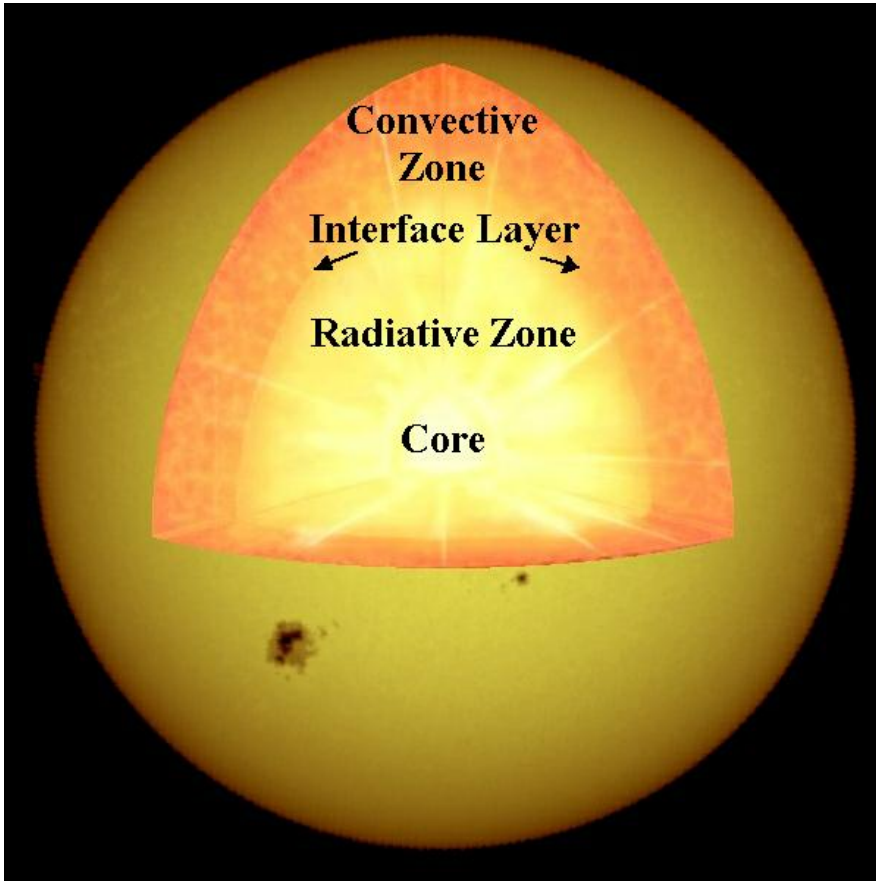
Models of the sun's interior based on theory and a data from helioseismology

Global helioseismology:

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

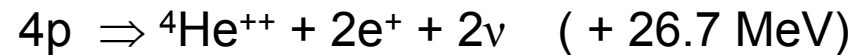
Each mode has a characteristic frequency that depends on the structure of the sun (and motions inside the sun)

Solar interior



In the **core** ($0-0.25 R_{\odot}$) temperature is up to 15 million K.

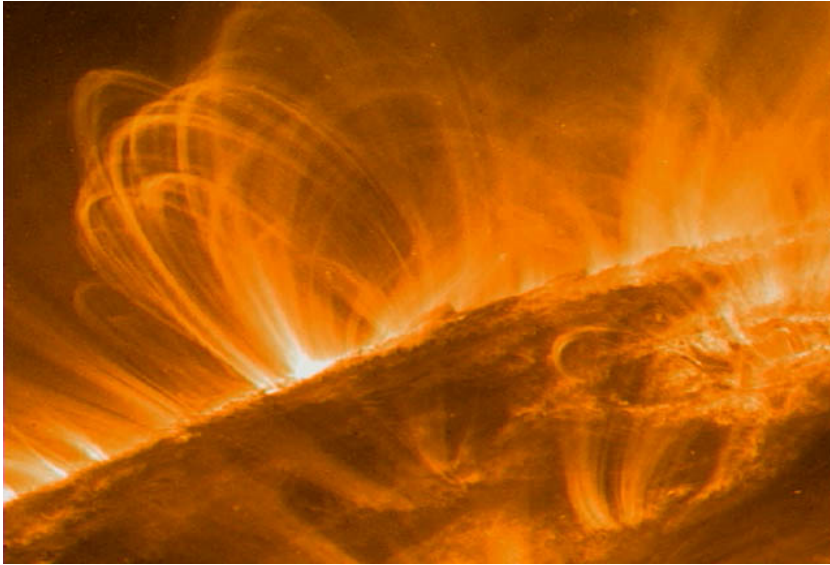
Thermonuclear fusion creates energy mainly through the „pp-chain“ :



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

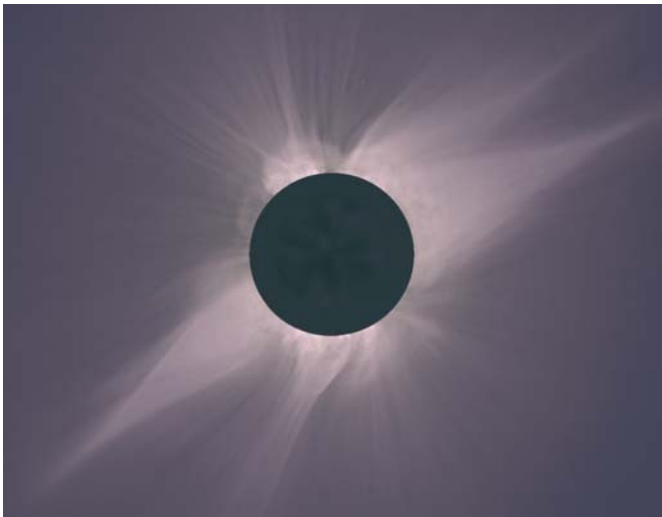
In the **convective zone** ($0.7 - 1.0 R_{\odot}$) the matter is too opaque for radiative transport. Convective motion of the conducting plasma generates magnetic field by a dynamo process in the convective zone and at the interface to the radiative zone (tachocline).

Regions above the photosphere



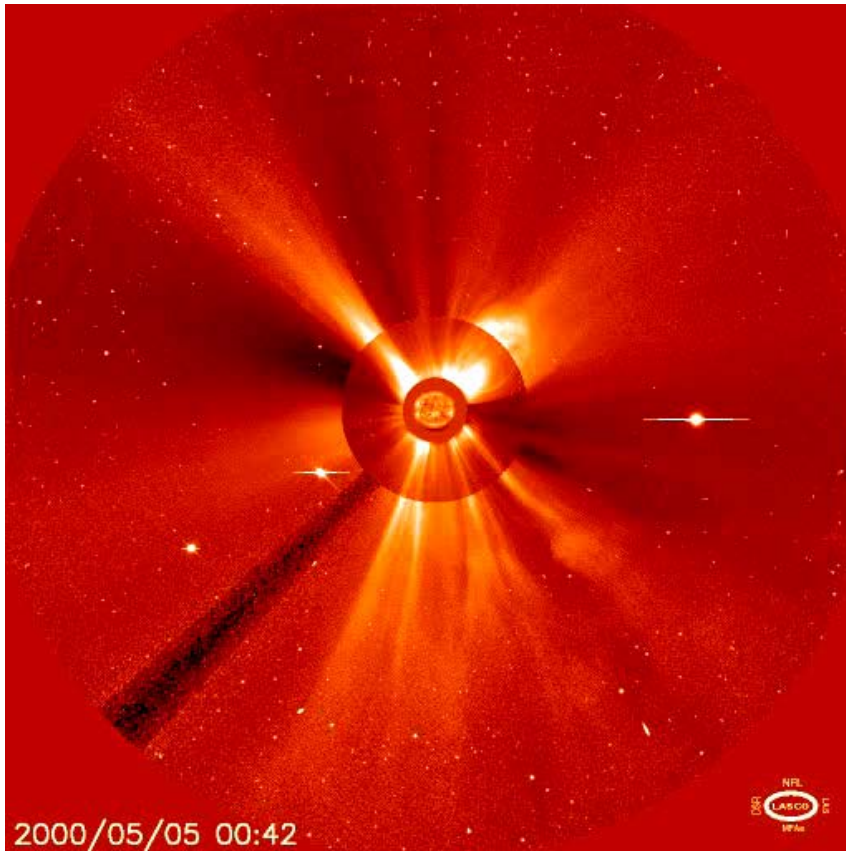
In the **chromosphere** (up to ~ 8000 km above the photosphere) the density drops by a factor 10^6 , but the temperature rises again near its top to $\sim 10^6$ K.

The **corona** is visible at a total eclipse (and in artificial eclipses). Thin hot plasma ($1- 2 \times 10^6$ 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

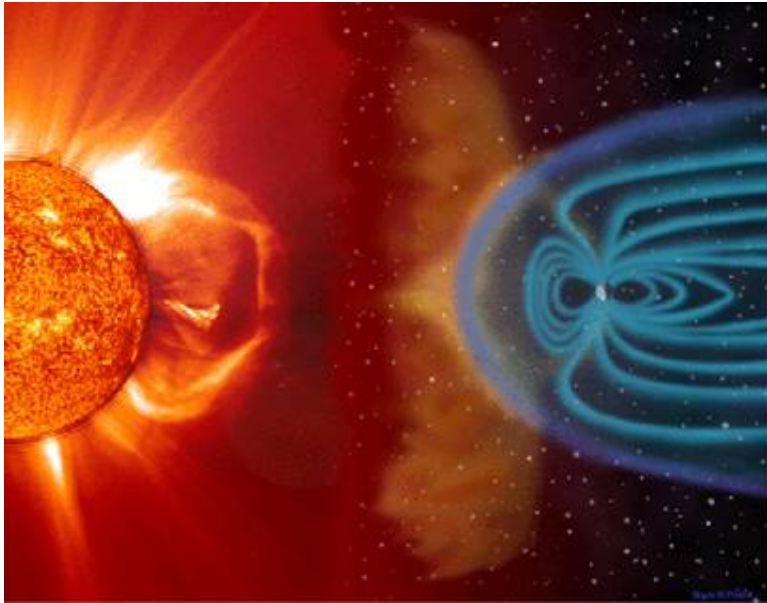


Images taken with the LASCO coronagraph on the SOHO spacecraft

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, generation 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

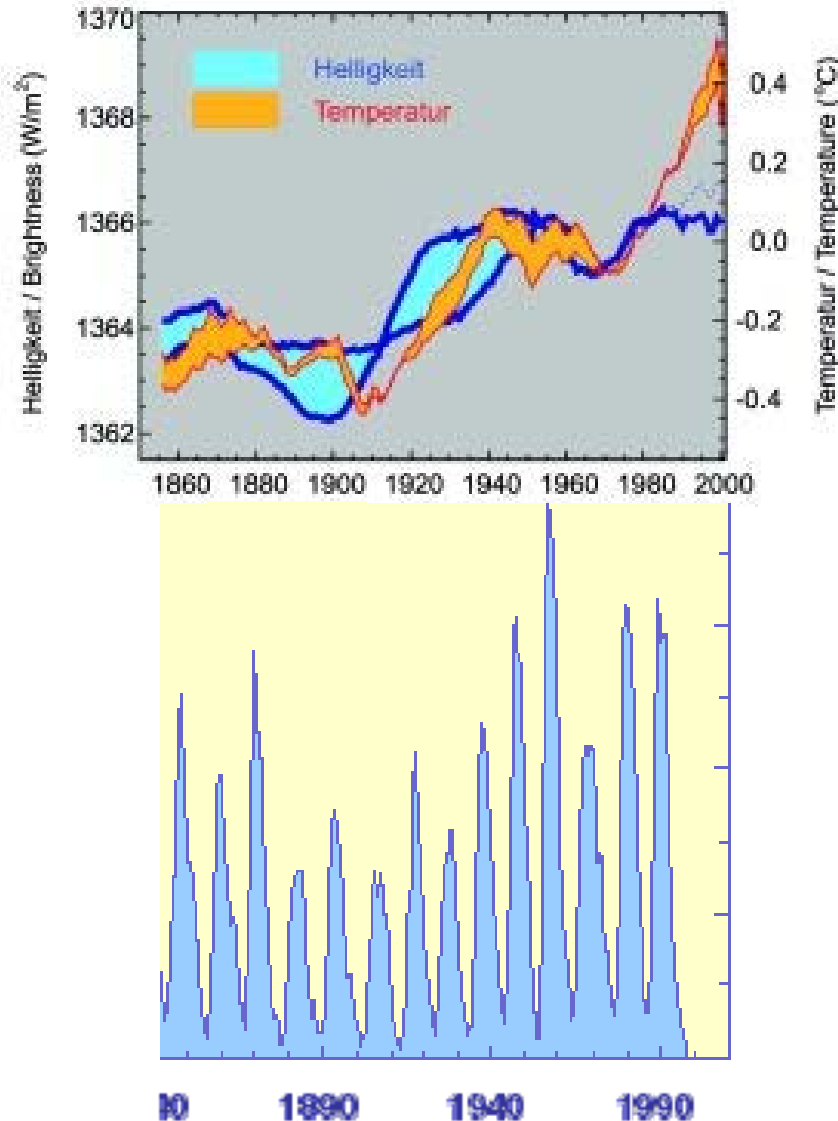


Intrinsic magnetic field of planet deflects stream of charged particles. Closed cavity is formed (**magnetosphere**). Planet's fieldlines confined by **magnetopause**. Solar wind velocity supersonic \Rightarrow **bow shock**. Solar wind flows around the magnetosphere. Earth: magnetopause is at $\sim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

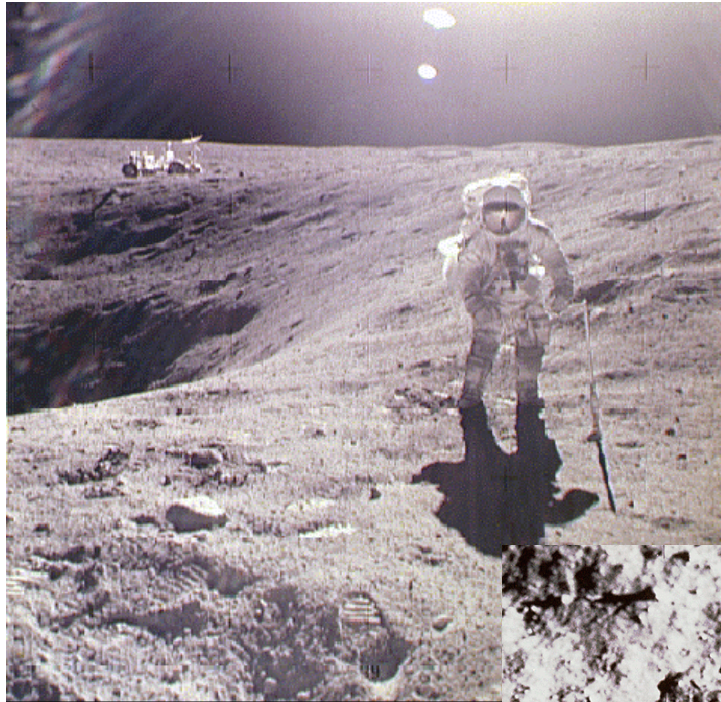
The Moon



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.

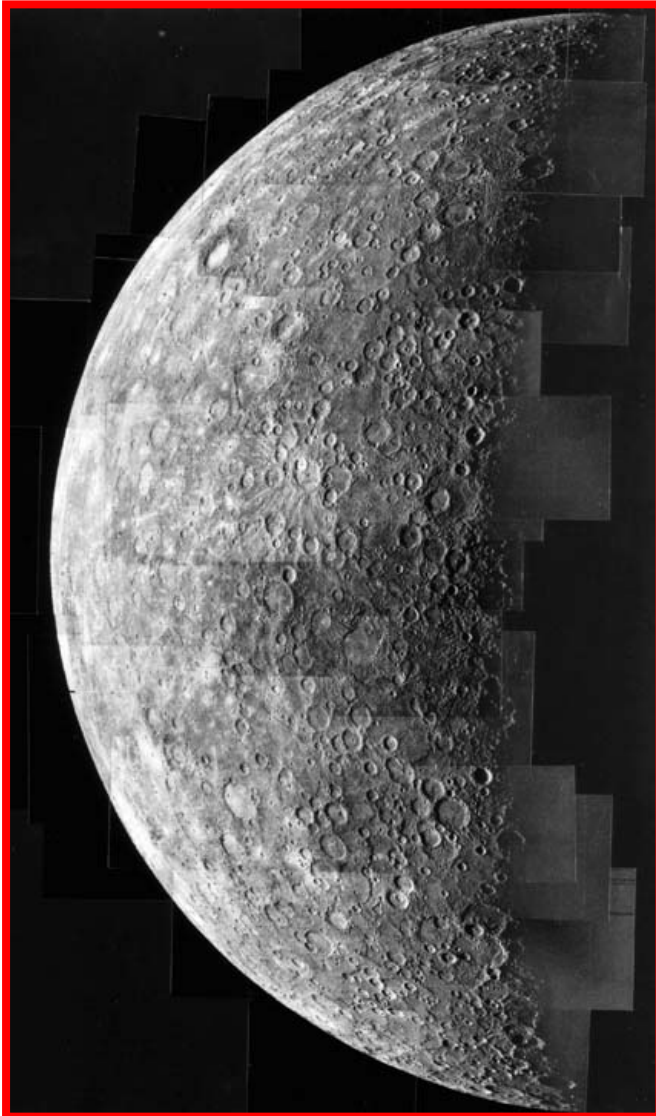
Crater density serves as measure for the age of the surface on planets from which we have no samples, with the moon taken for calibration.

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



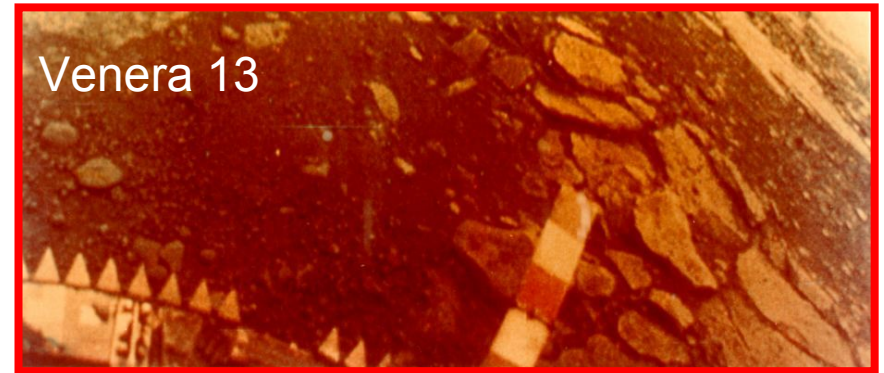
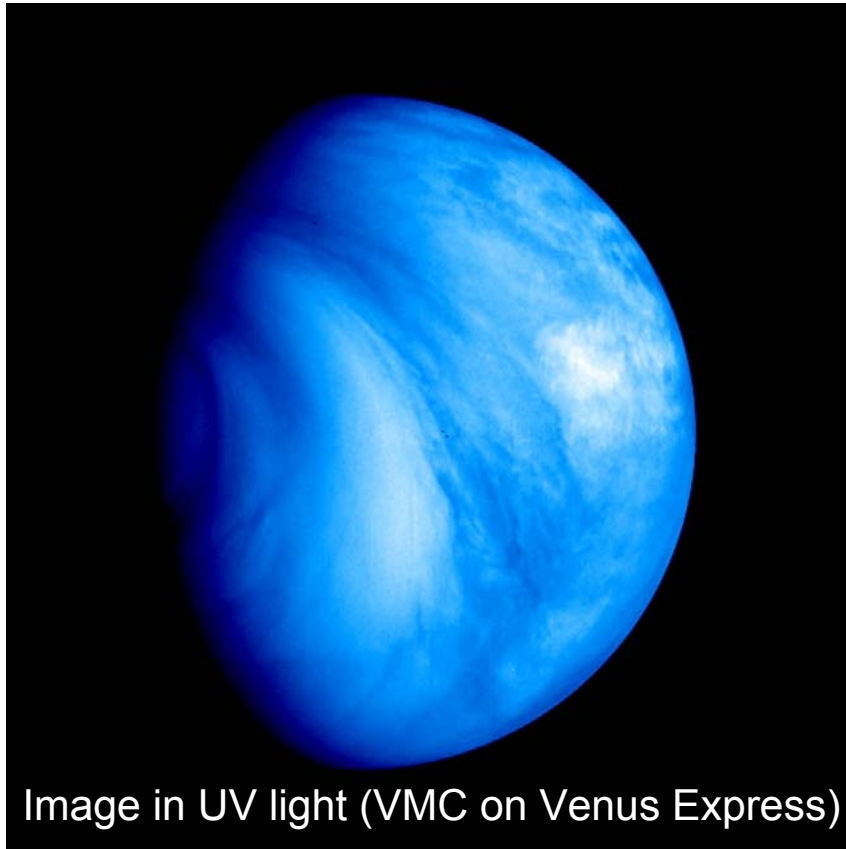
Radius = 2,400 km (38% Earth)
 $\rho_{\text{mean}} = 5440 \text{ kg m}^{-3}$ (98% Earth)
 $T_{\text{rot}} \approx 59 \text{ d} = 2/3 T_{\text{orbit}}$

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

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

Messenger mission (first flyby January, 14, 2008) and Bepi Colombo (launch 2013) will contribute strongly to enhance knowledge.

Venus



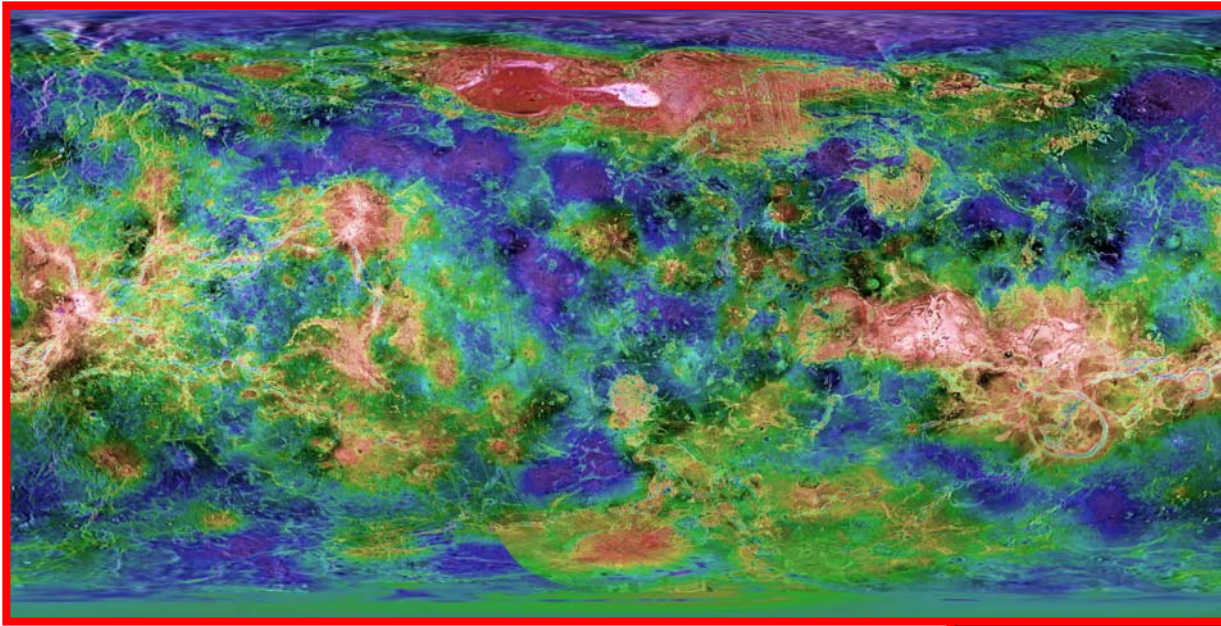
Radius: 6080 km (95% R_{Earth})
Slow rotation: $T = 225$ d, retrograde

Atmospheric pressure: 90 bar
Temperature: 450°C

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

Surface: Basaltic rocks

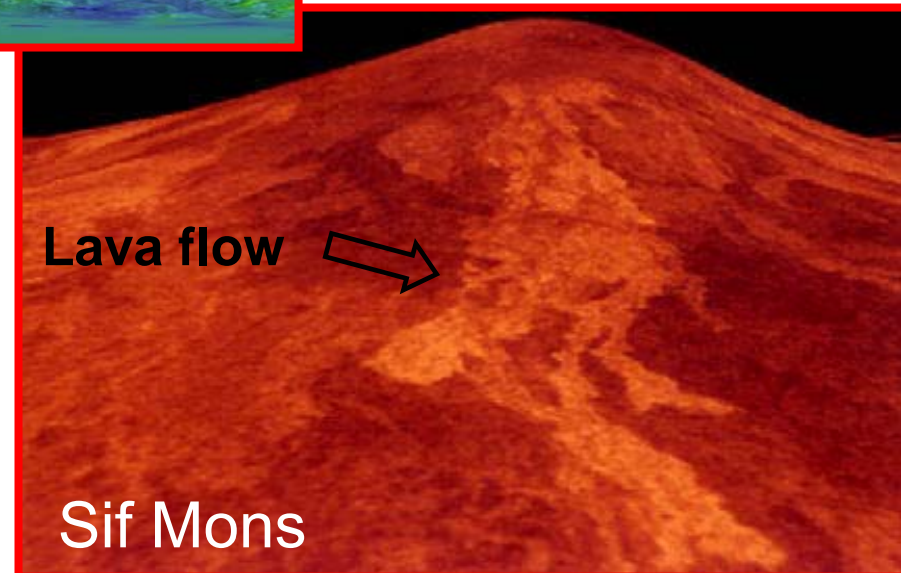
Venus: Topography & volcanism



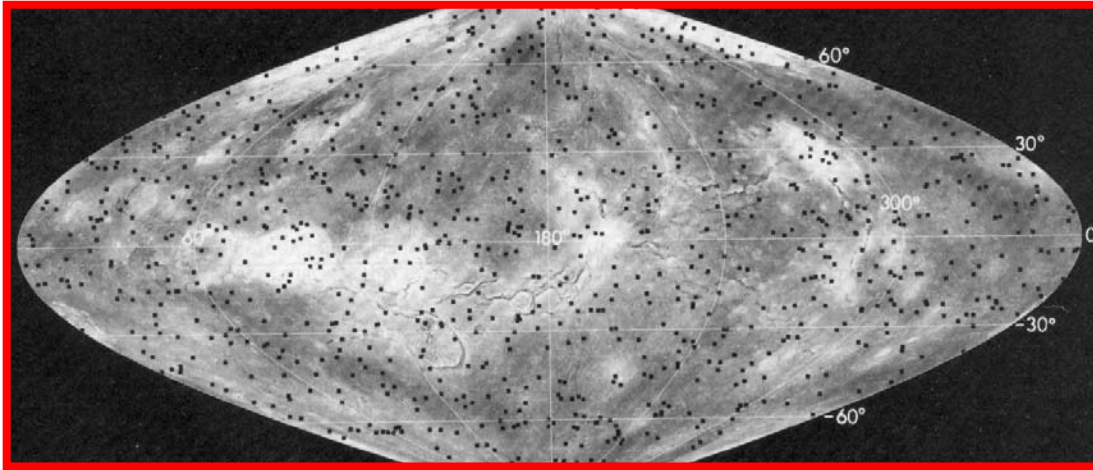
Many signs of volcanism.

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.



Venus: Cratering



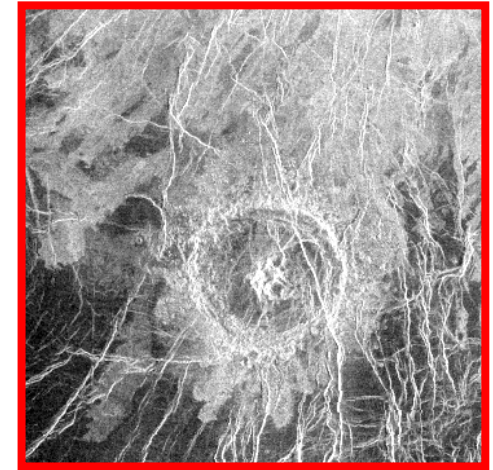
Global distribution of impact craters

Crater density statistically uniform \Rightarrow different surface units have similar age.

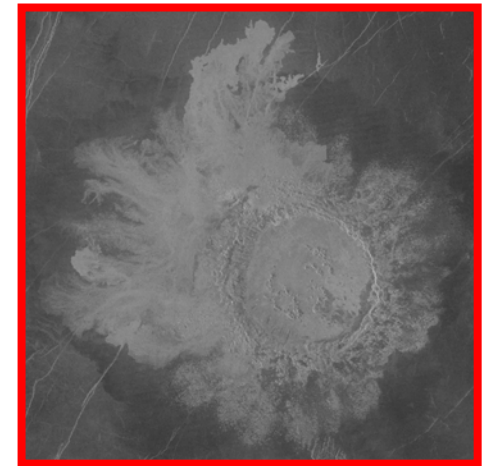
Crater density much lower than on Moon / Mercury \Rightarrow surface age \approx 500 Myr.

Few craters are tectonically overprinted or embayed by lava flows.

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



Overprinted crater (rare)



Normal crater

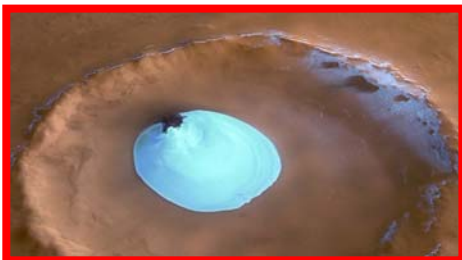
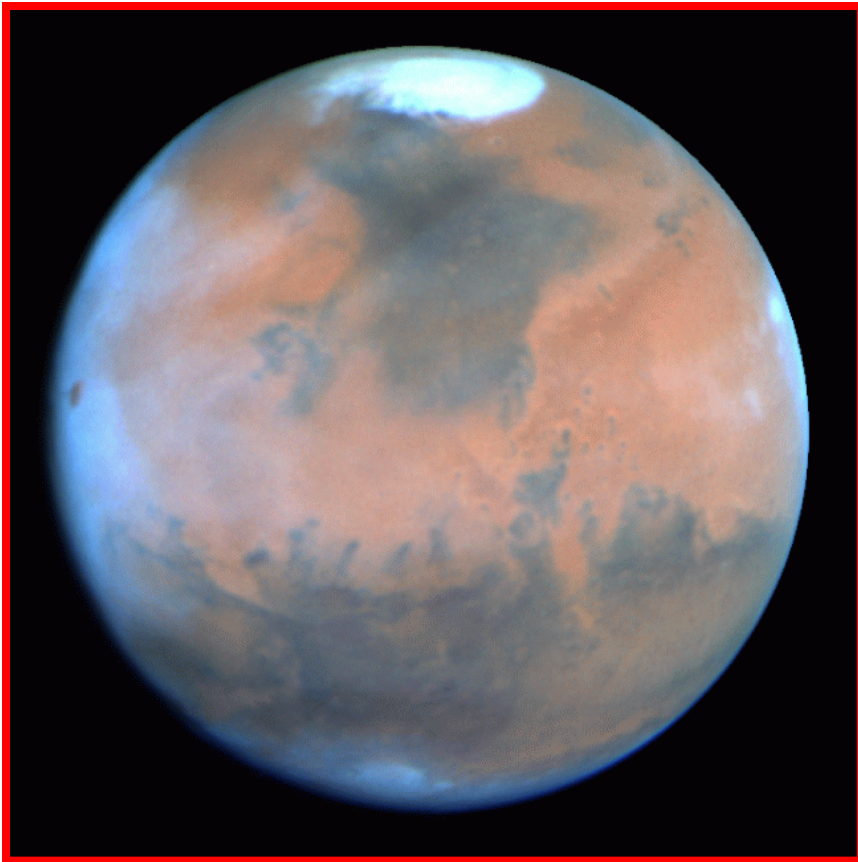
Mars

Radius: 3370 km (53% Earth)

Rotation period: 24 h 56 min

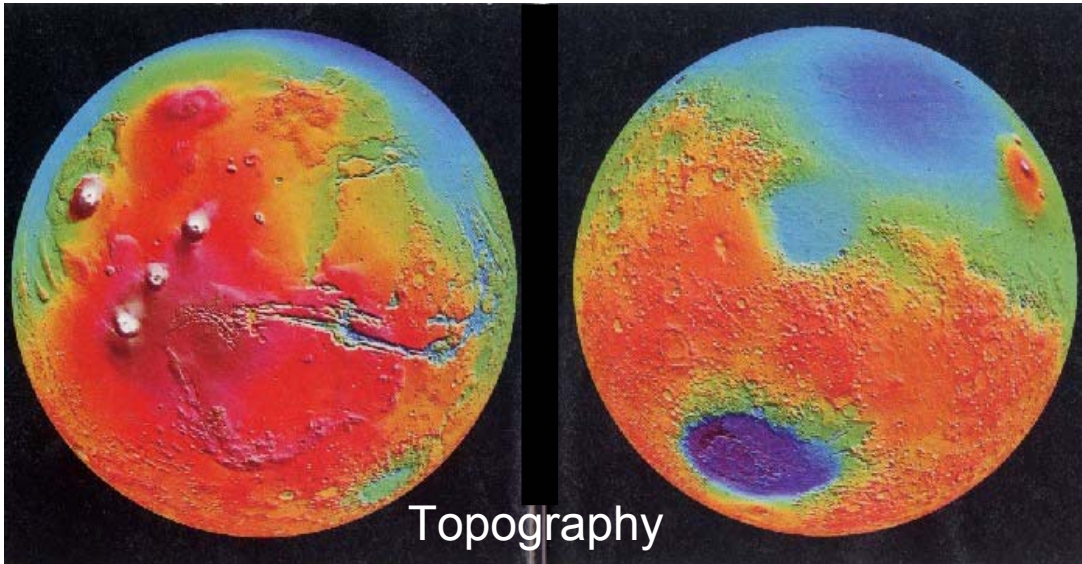
CO₂-atmosphere: 6 mbar, -40°C

Seasonal condensation of CO₂ in polar regions.



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

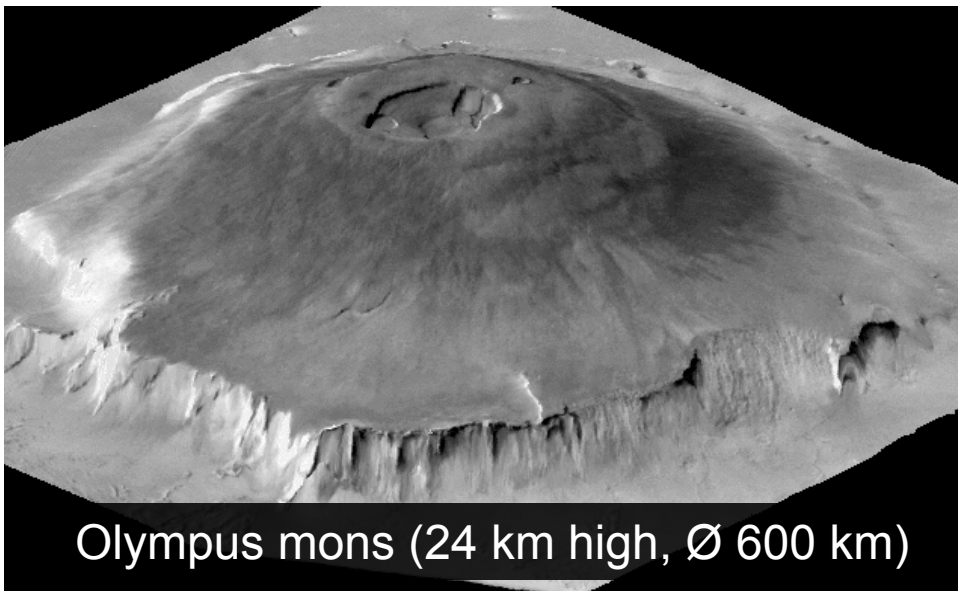
Mars: Topography & Volcanism



Southern highlands: heavily cratered: > 4 Gyr old

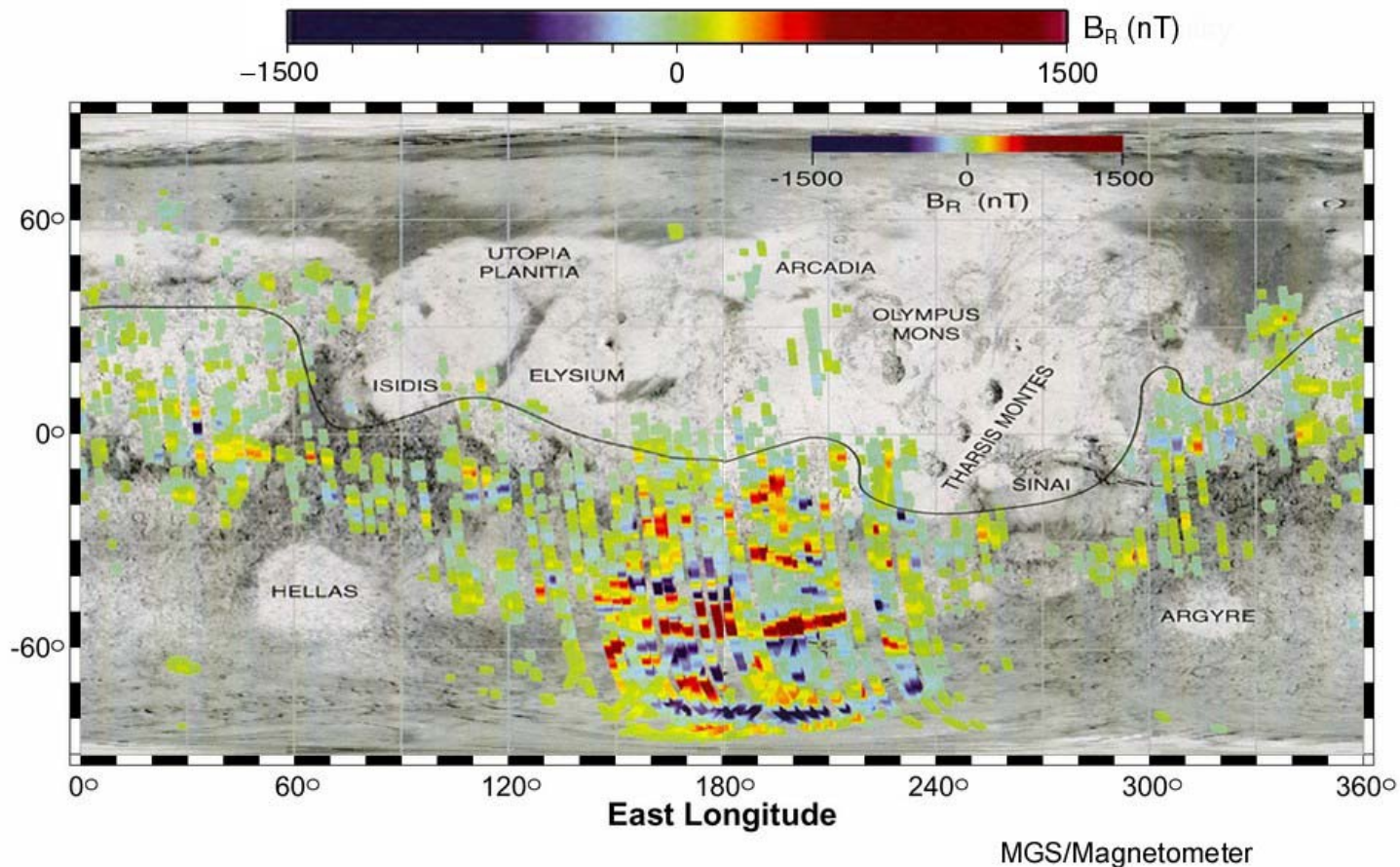
Northern lowlands: 2 – 4 Gyr (a few regions very young)

Tharsis bulge with giant volcanoes (2 – 4 Gyrs)



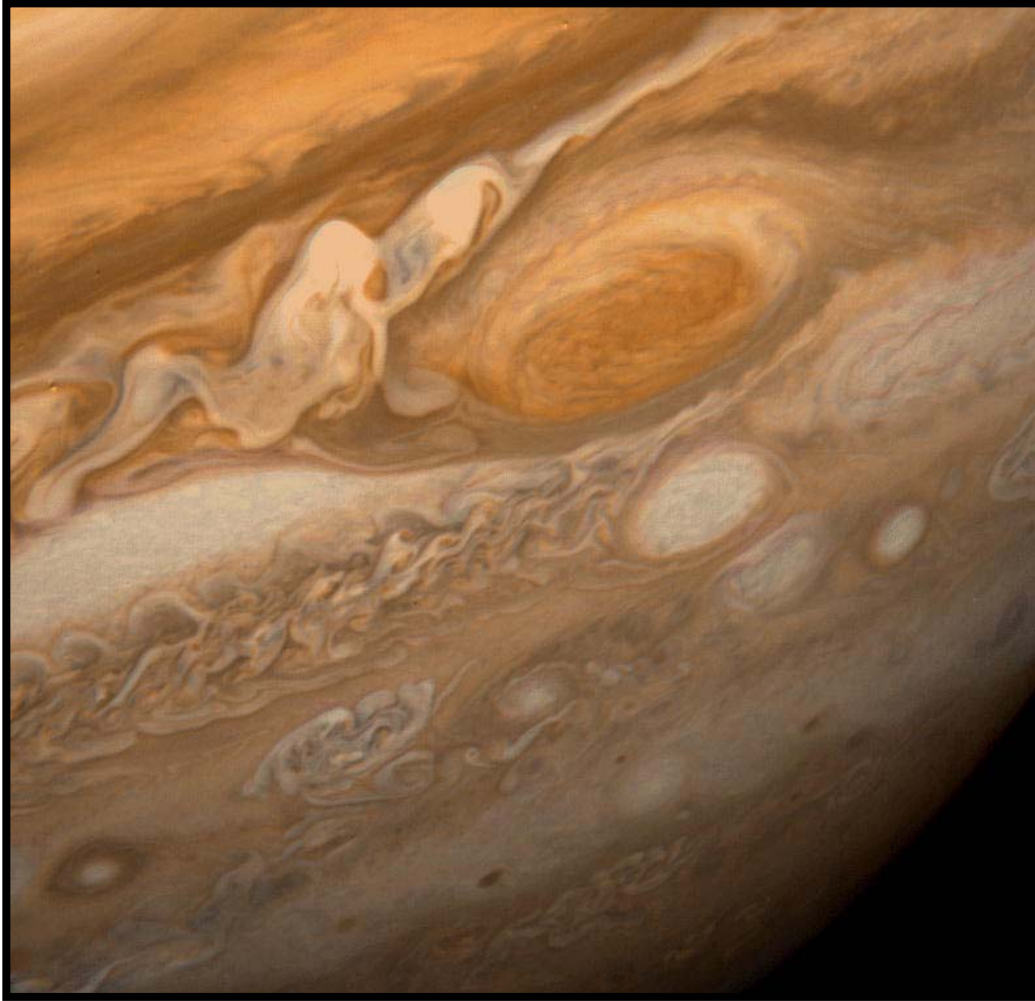
High resolution images allow to detect very small craters. Their scarcity in parts of the Olympus Mons Caldera suggest that volcanism is not extinct.

Mars: Magnetic field



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

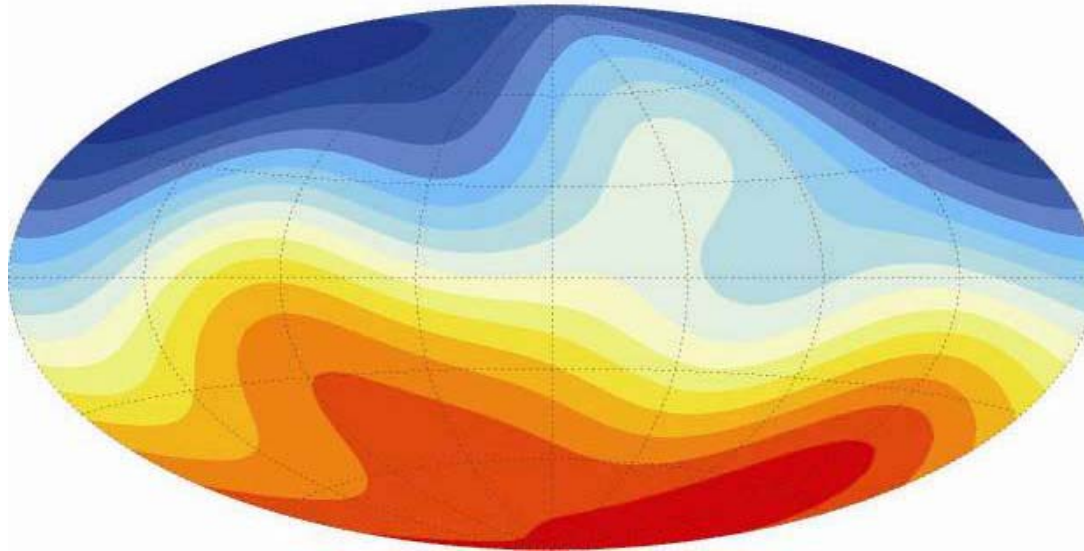
Rotation period: 10 h

Atmospheric composition:
85% H₂, 14% He, small
amounts of NH₃ and other
components forming clouds

Very dynamic atmosphere

Emitted energy 70% higher
than absorbed sunlight ⇒
5 W/m² internal heat flow

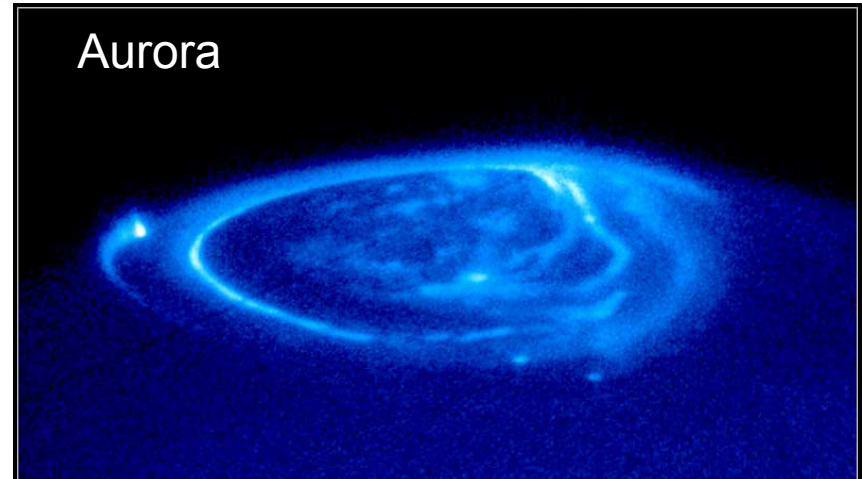
Jupiter: magnetic field



Radial field component
at Jupiter's surface

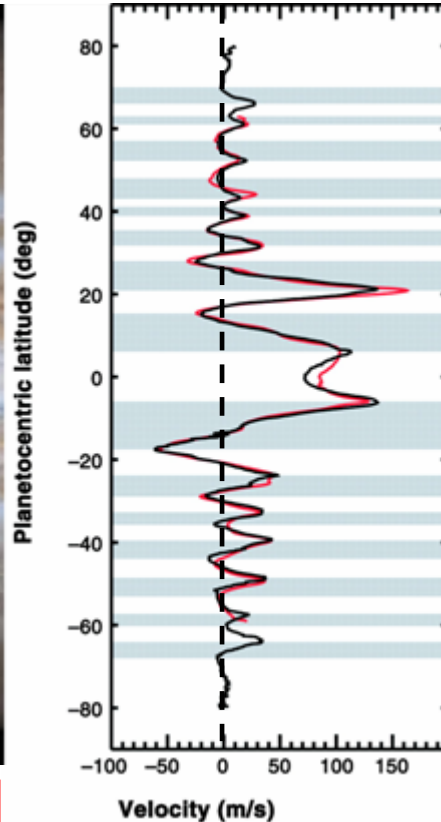
Dipole-dominated magnetic field
Field strength 10x Earth's field
Tilt of dipole $\approx 10^\circ$

⇒ Active dynamo in Jupiter



Aurora

Jupiter: zonal flow

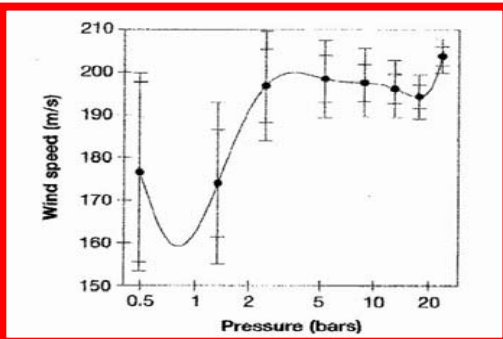


Strong zonal winds are associated with the latitudinal zones and bands, with velocities up to 150 m/sec, alternating in direction. The zonal velocity is larger than the velocity of the superimposed eddies. Wind speed and pattern has hardly changed in 25 yr.

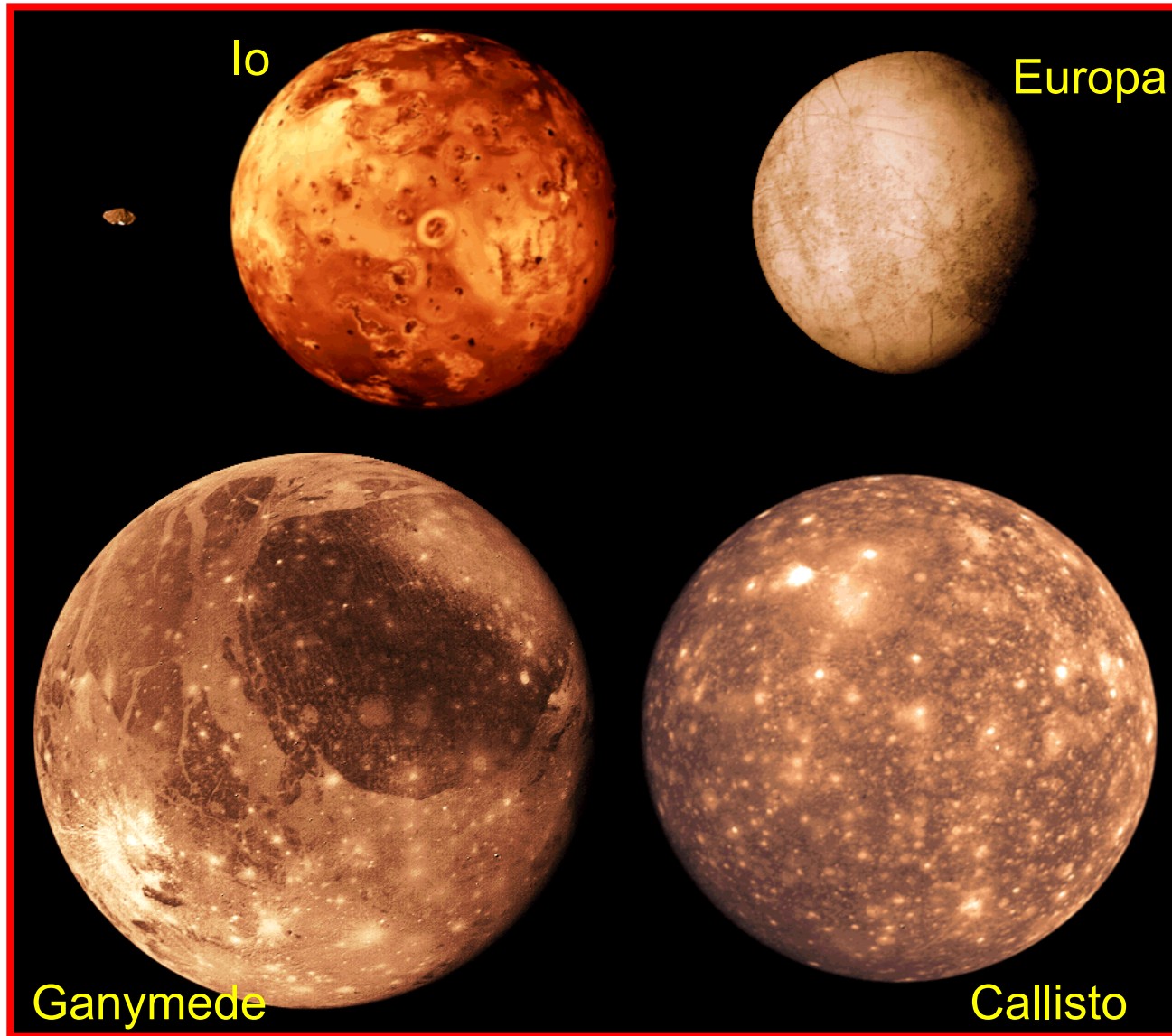
Two competing concepts for the origin of the zonal flow:

- (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.

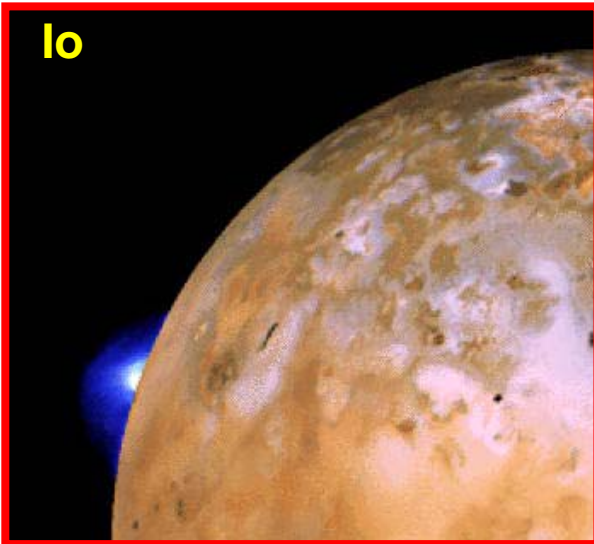
Observation by the Galileo probe that the wind speed does not decrease with depth below the cloud deck (up to the 20 bar pressure level) supports 2nd hypothesis.



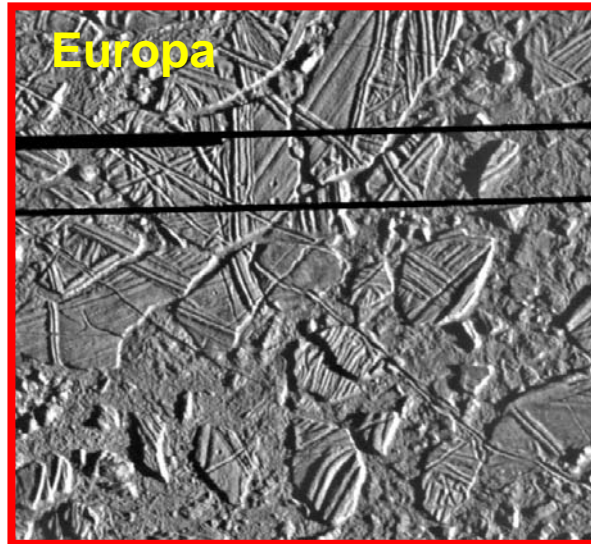
Galilean Satellites



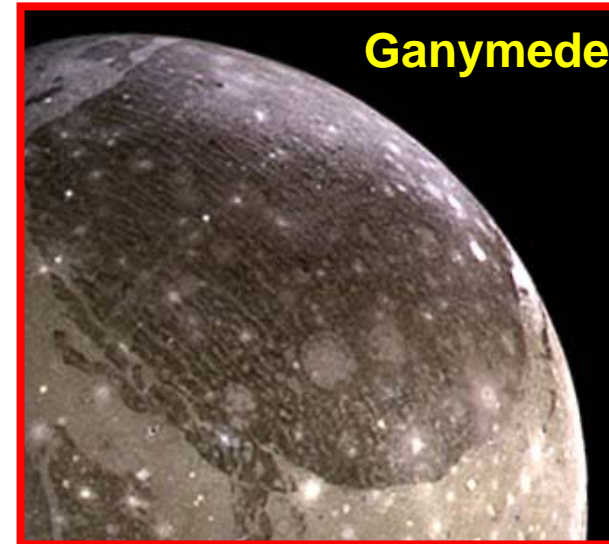
Galilean satellites: surfaces



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.



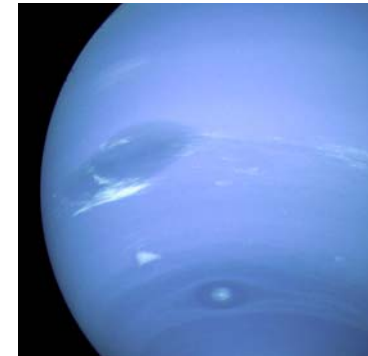
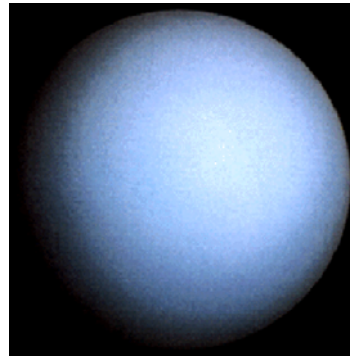
Europa - Very few impact craters. In some places fractured surface looking like pack-ice rafts that drifted on fluid substratum. Active interior, surface 50 Myr old (?)



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

Saturn, Uranus, Neptune

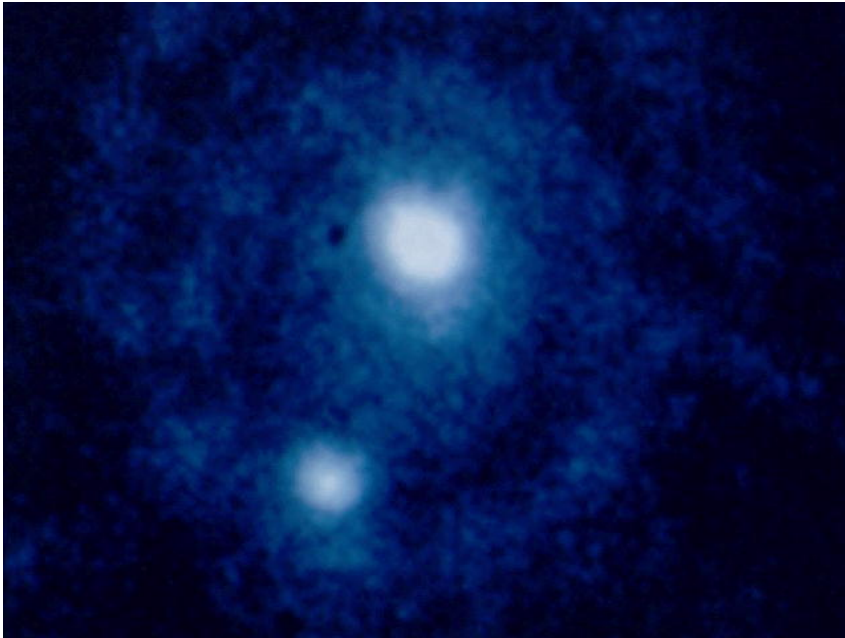
	Saturn	Uranus	Neptune
ρ [kg m ⁻³]	704	1290	1650
R [km]	60,200	25,900	24,800



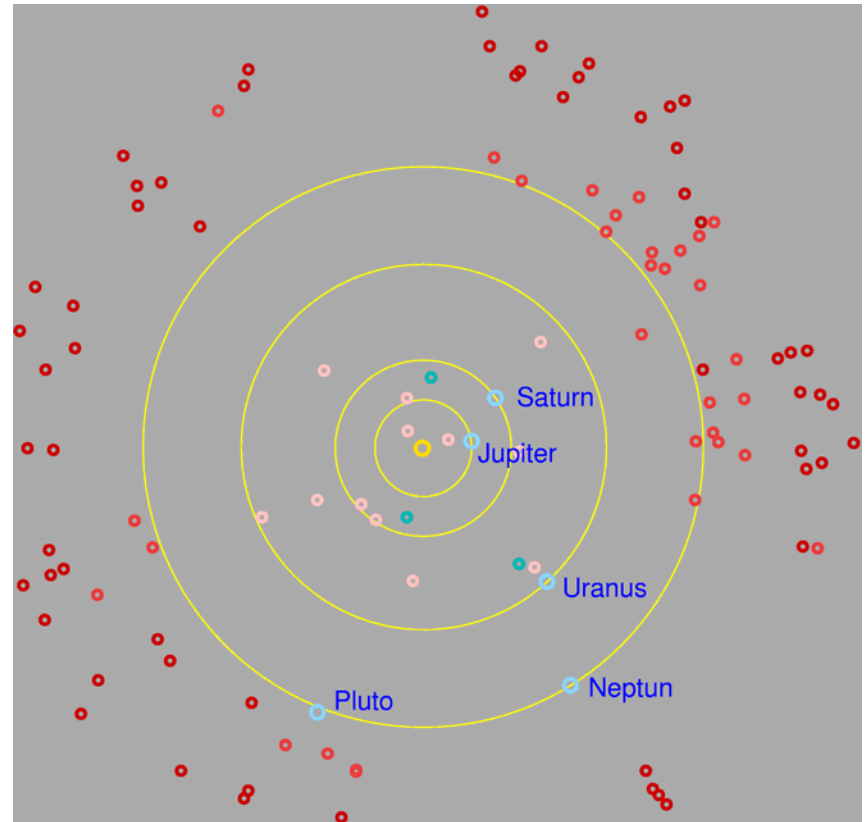
Saturn is the little brother of Jupiter: Mainly composed of H+He; strong alternating zonal jet flow at the surface; magnetic field very axisymmetric.

Uranus and **Neptune** are different: Surface CH₄ 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

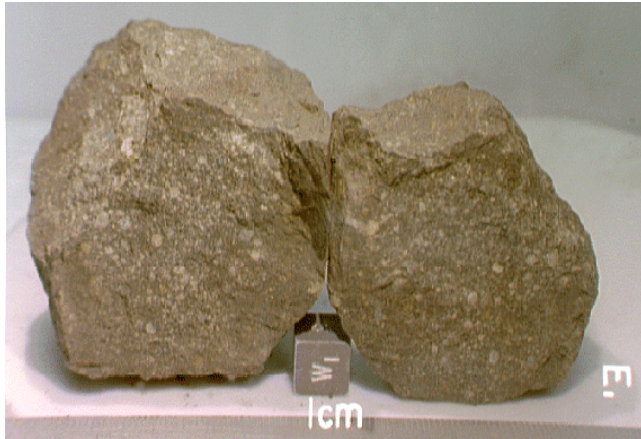


Pluto with satellite Charon
(imaged with adaptive optics)

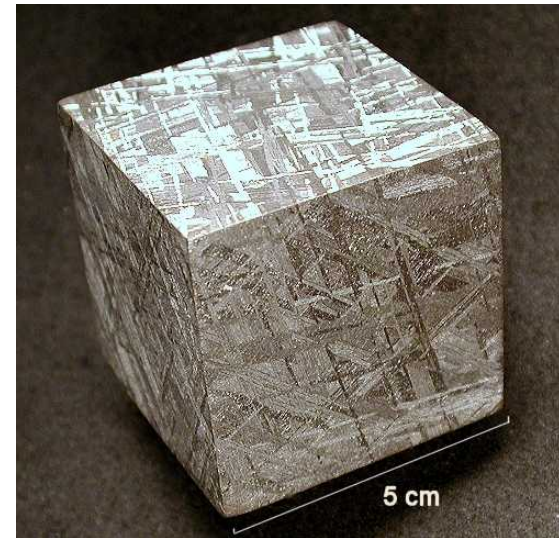
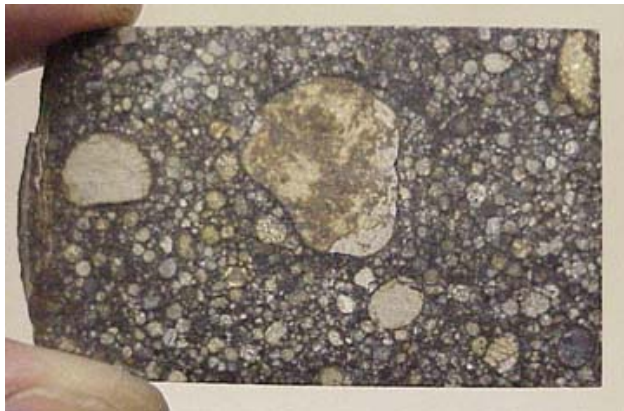


Kuiper belt objects (red dots)

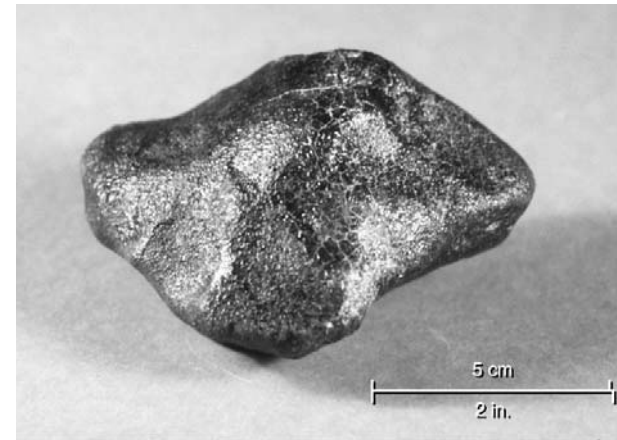
Meteorites



Chondrite



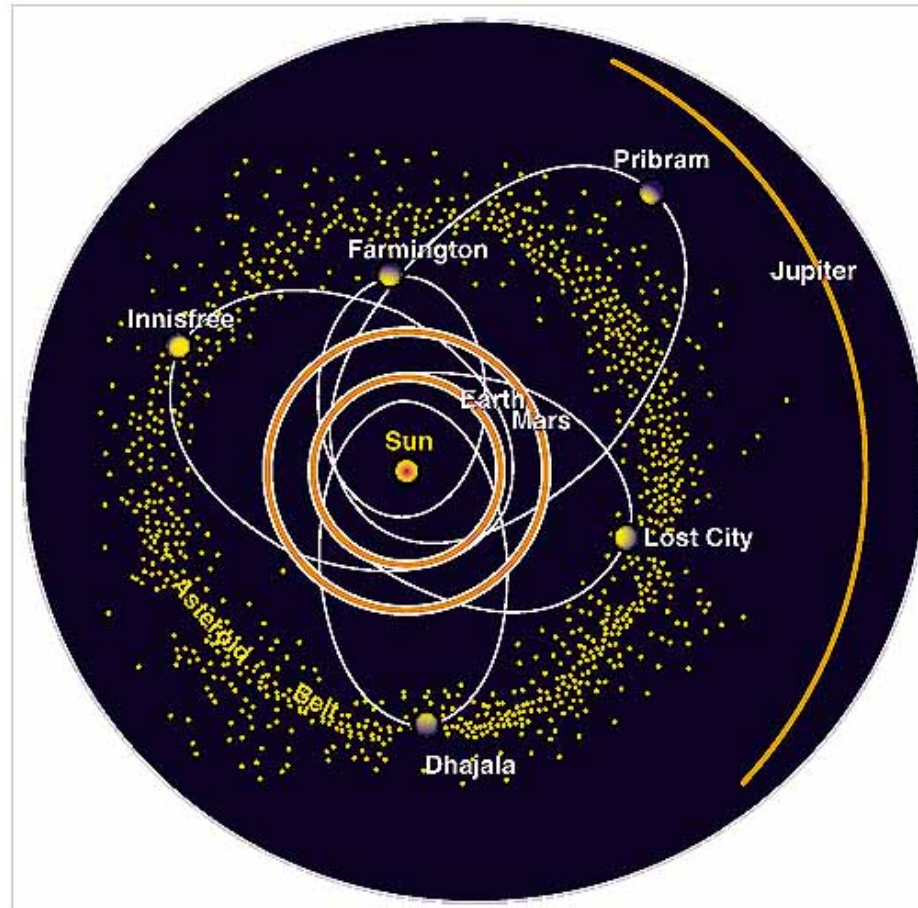
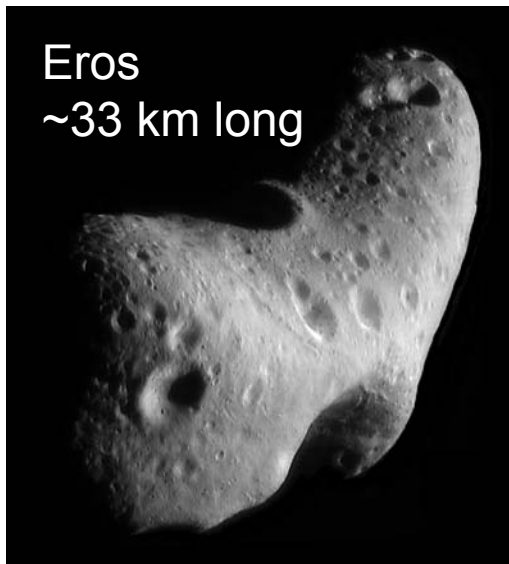
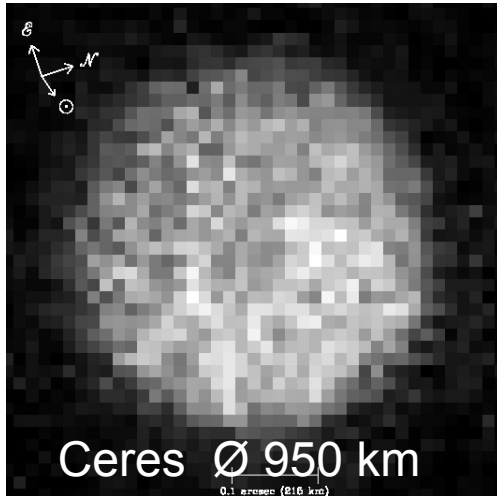
Iron meteorite



Achondrite (Basaltic)

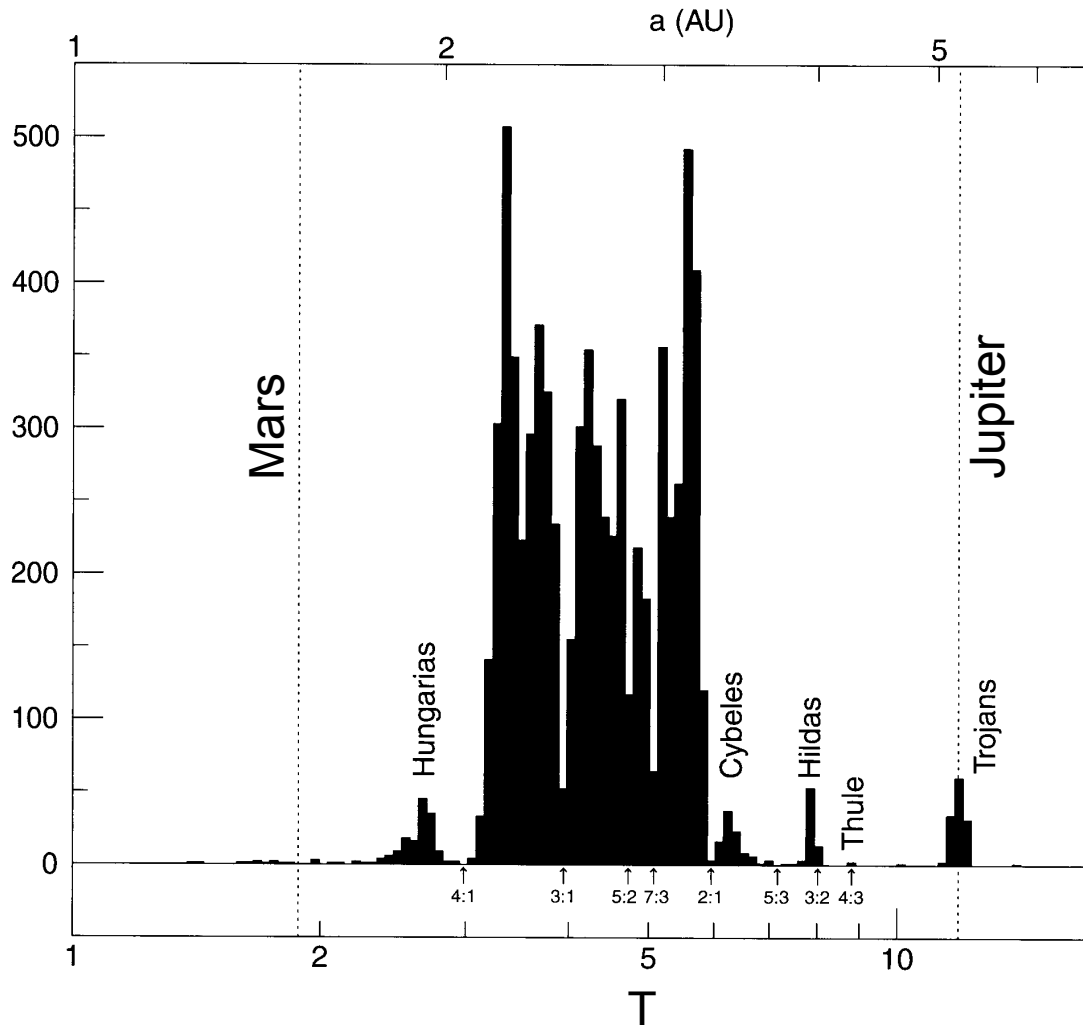
Chondritic meteorites are most common. In chondrites the relative abundance of volatile is similar to that in the solar atmosphere. \Rightarrow Chondrites represent primitive matter from the formation of the solar system.

Asteroids



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

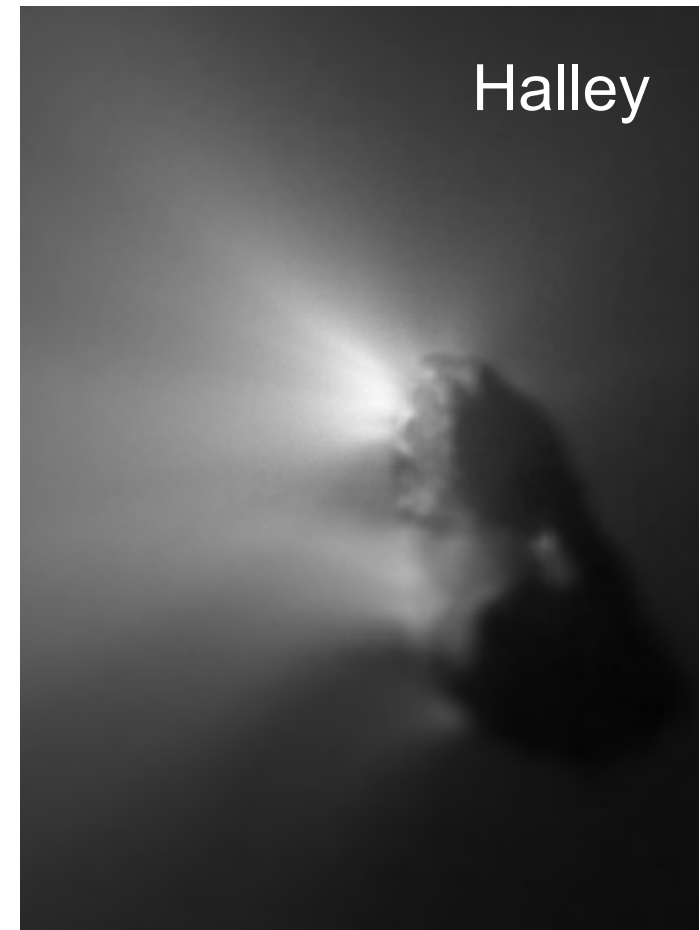
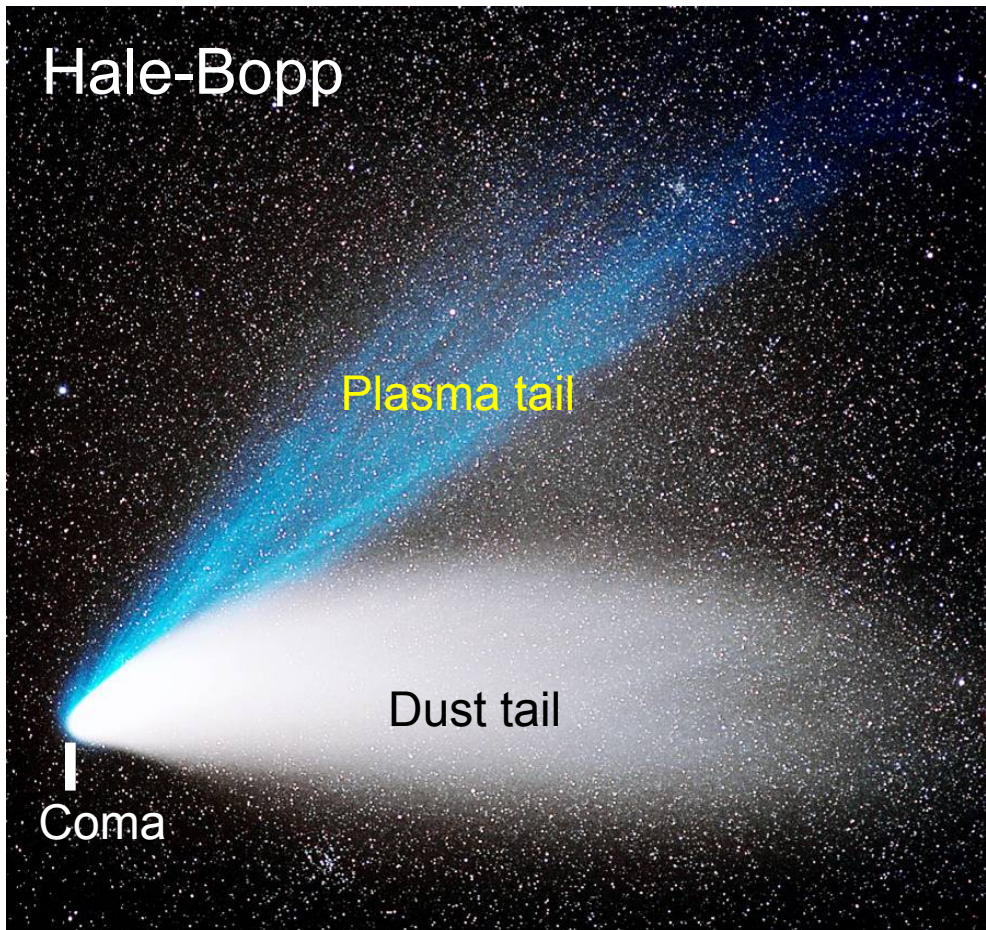
Resonances



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).