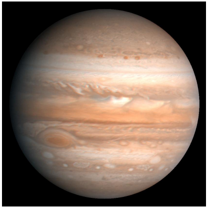
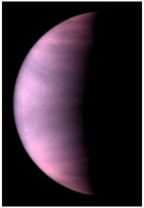
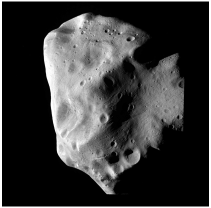
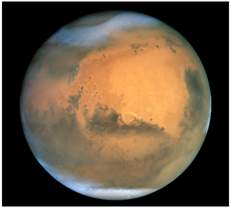
Lecture 1:
The Solar System

"Planet formation"

April 2016

Bertram Bitsch (Lund Observatory)

Structure of the lectures

1 The Solar System

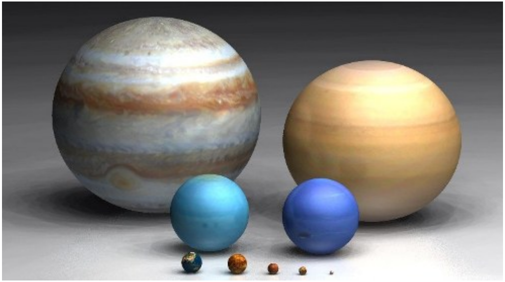
2 Protoplanetary discs

3 Growth of particles

4 Formation and migration of giant planets

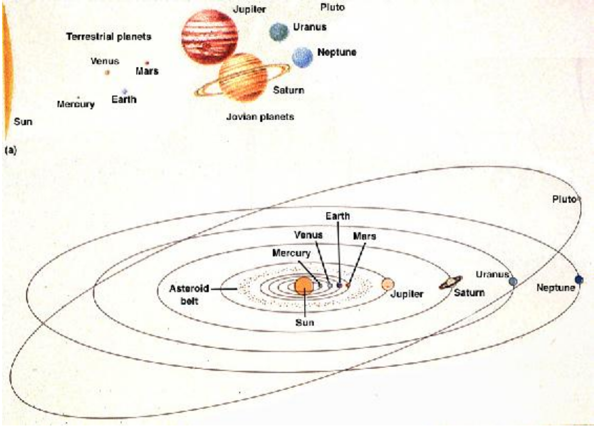
5 Multiple planet systems

Solar system



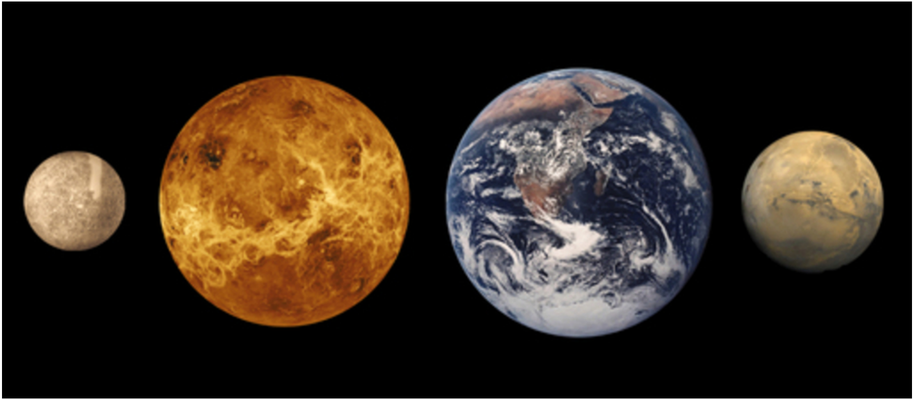
- *Terrestrial planets:* Mercury, Venus, Earth, Mars
- *Gas giants:* Jupiter, Saturn
- *Ice giants:* Neptune, Uranus

Structure of the solar system



Mercury	0.39 AU	Jupiter	5.20 AU
Venus	0.72 AU	Saturn	9.54 AU
Earth	1.00 AU	Uranus	19.2 AU
Mars	1.52 AU	Neptune	30.06 AU

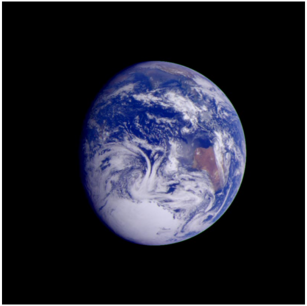
Terrestrial planets



- Innermost four planets in the solar system
- Consist primarily of silicate rocks
- Focus on topics most relevant for planet formation and exoplanets (internal structure, surfaces, atmospheres)

Earth

Earth



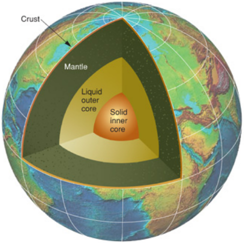
$$a = 1.0 \text{ AU}$$
$$M = 6.0 \times 10^{24} \text{ kg}$$
$$R = 6371 \text{ km}$$
$$T_{\rm surf} = 287 \text{ K}$$
$$\rho = 5.515 \text{ g/cm}^3$$

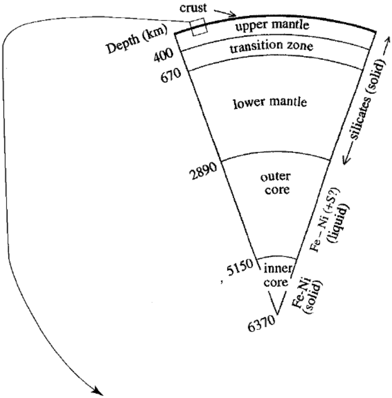
Water
Plate tectonics
Big moon
Life
Planet studied in most detail

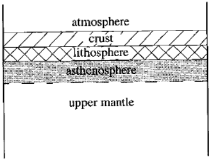
Internal structure of Earth

- Inner solid core of Fe-Ni
- Outer liquid core of Fe-Ni
- Si-rich solid mantle undergoing solid-state convection

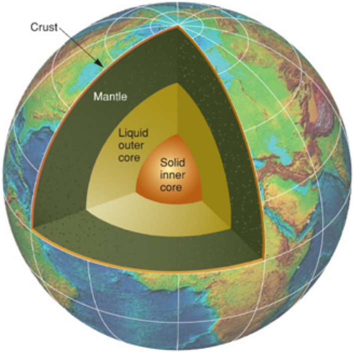
- Thin *elastic* lithosphere (< 1400 K) sits on top of *plastic* asthenosphere (> 1400 K)

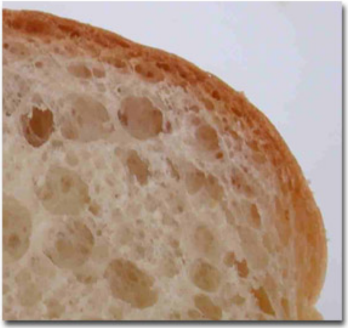






Plastic versus elastic

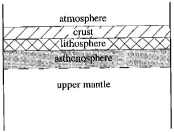


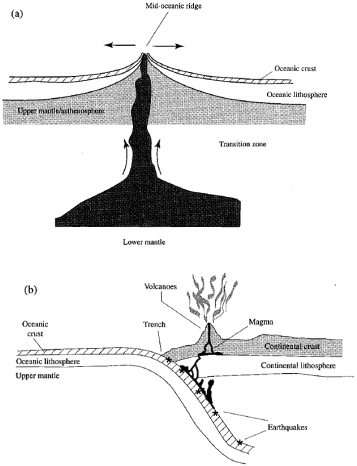


- Heat produced by radioactive decay of ^{235}U, ^{238}U, ^{232}Th and ^{40}K is transported to surface by convection
- Rock at temperature above 1400 K is deformable (plastic) and can sustain convection flows
- Earth lithosphere is cold and can not sustain convection flows (elastic)

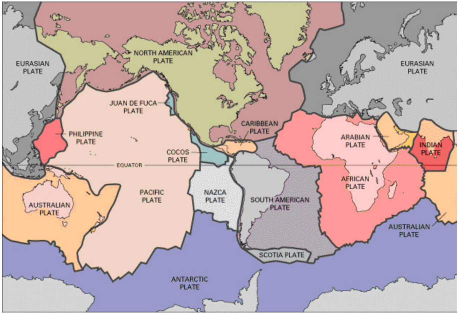
Plate tectonics

- Lithosphere is cold and elastic and does not support convection flows
- Mantle and asthenosphere are *plastic*, meaning that they are solid, but can undergo deformation (convection) over geological time-scales
- Mantle convection flows penetrate lithosphere at mid-ocean ridges
- Oceanic crust created from cooling magma quickly (basalt)





Plates and ridges



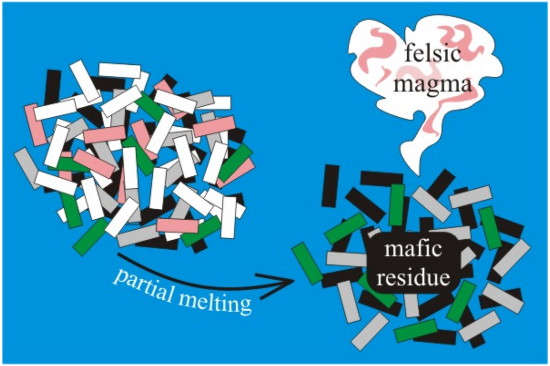
Basalt and granite

- In order to understand terrestrial planets we need to know some basics about *igneous* rocks

- Igneous rocks form through solidification of magma (molten rock)

- Two major types of rock:
  - *Basalt* forms as magma cools rapidly after entering planetary surface
  - *Granite* forms from partial melting of basalt

Partial melting



- Basalt can be separated into "mafic" and "felsic" components by heating and partial melting
- Molten "felsic" component separates from solid "mafic"

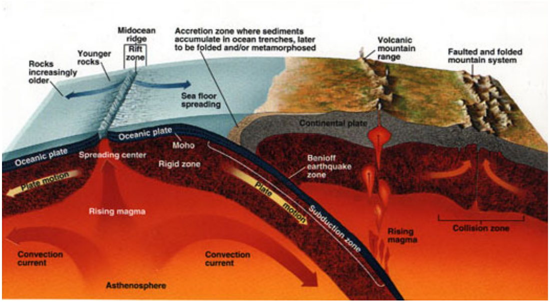
Basalt

- Dark colour
- Contains 40%–50% Si
- Rich in heavy elements like Ti, Al, Fe
- Found on Earth, the Moon, Venus, Mars, Mercury, asteroids

Granite

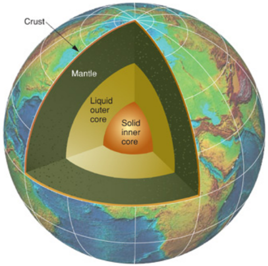
- Gray colour
- Contains 70% Si
- Formed by partial melting of basalt
- Makes up continental plates on Earth
- Not present on other planets

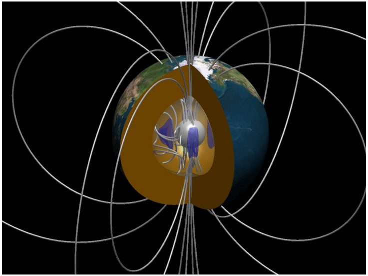
Subduction



- Heavy oceanic plates subduct under lighter continental crust where plates converge
- Plates pulled down by own weight and pushed away from mid-ocean ridge by convection flow in mantle
- Partial melting separates granitic magma
- Ocean crust converted to continental crust

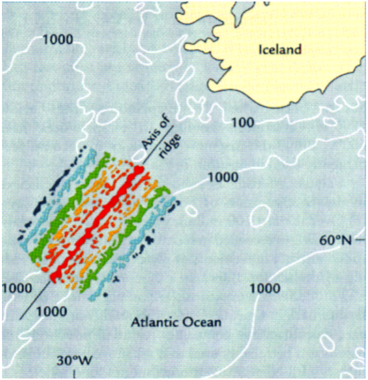
Magnetic field





- Earth too hot to be a permanent magnet (Curie point at 800 K)
- Magnetic field maintained by convective motion in the fluid outer core
- *Geodynamo* requires a conductive fluid, convection, and rotation
- Magnetic field amplified until $E_{\rm mag} = E_{\rm conv}$
- Magnetic field reversals approximately every 300,000 years

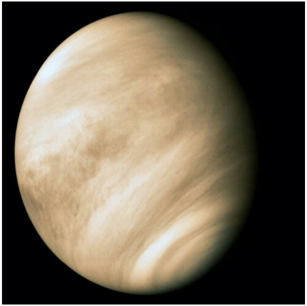
Magnetic field reversals



- Cooling below the Curie point leaves imprint of magnetic field
- Instantaneous magnetic field freezes into new oceanic crust
- Magnetic field reversals recorded in mid-ocean ridge basalt
- Similar features seen on Mars

Venus

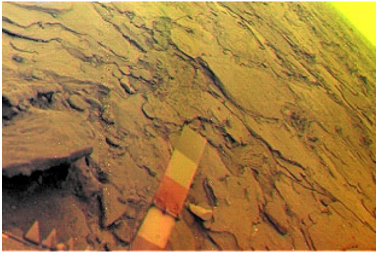
Venus

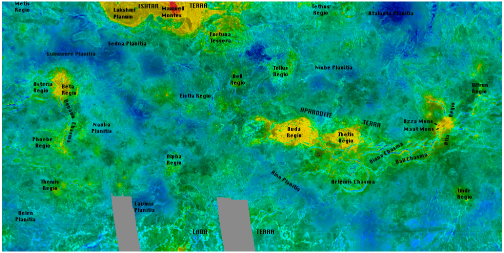


$$a = 0.7 \text{ AU}$$
$$M = 4.9 \times 10^{24} \text{ kg } (0.815\ M_\oplus)$$
$$R = 6052 \text{ km}$$
$$T_{\rm surf} = 735 \text{ K}$$
$$\rho = 5.204 \text{ g/cm}^3$$

Thick atmosphere
Slow rotation
Young surface
Similar mass and radius to Earth
Very different surface and atmosphere

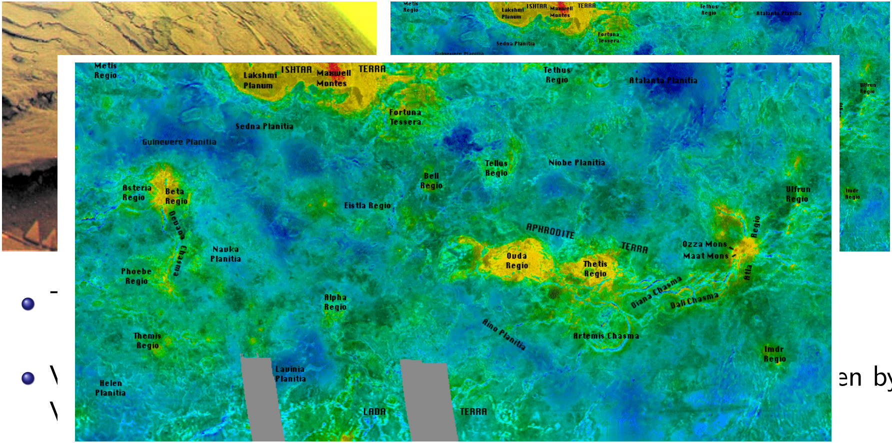
Surface of Venus





- Thick clouds block visible radiation from surface
- Venera probes took pictures of basaltic surface (above image taken by Venera 14 in 1982)
- Mapped with radar by Magellan orbiter with 0.2–1 km accuracy
- Highlands, lowlands, volcanoes

Surface of Venus



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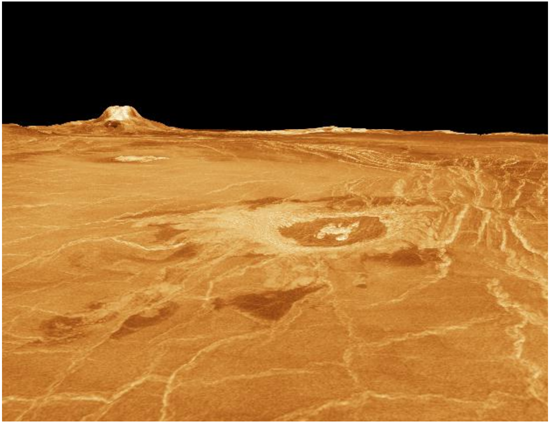
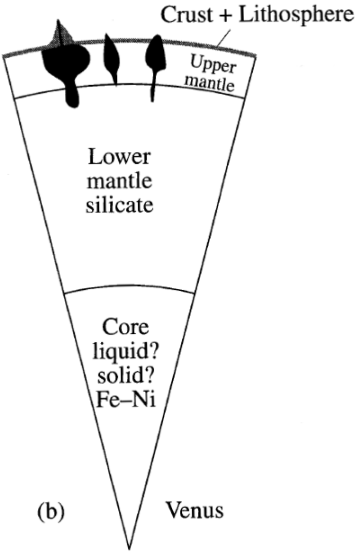
Surface of Venus



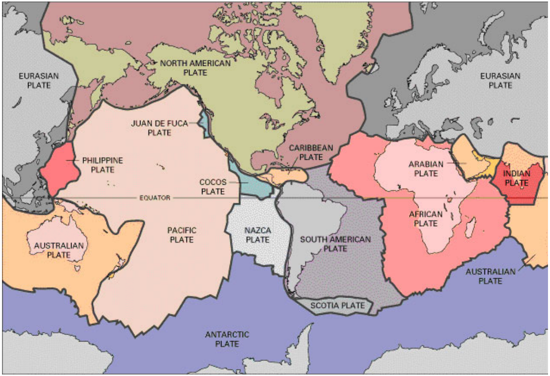
- Minimum impact crater size of 3 km
- Crater counts show surface age of 200 - 1000 Myr
- No signs of active plate tectonics
- Global resurfacing event 300 Myr ago?

Internal structure of Venus

- Very weak magnetic field caused by interaction between solar wind and ionosphere
- Must lack either convection or conducting fluid core
- Lack of plate tectonics causes build up of heat in mantle
- Convection not possible if temperature *decreases* with depth
- Periodic *global resurfacing* events when mantle temperature increases enough to weaken the lithosphere



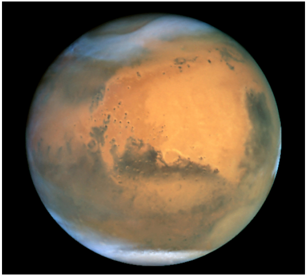
Water and plate tectonics



- Need water to weaken oceanic crust in contact with continental crust and allow subduction?
- Need water to weaken lithosphere?
- Water lowers melting point of subducting plates, allows separation of granite into continents

Mars

Mars



$$a = 1.5 \text{ AU}$$

$$M = 6.4 \times 10^{23} \text{ kg } (0.107\ M_\oplus)$$

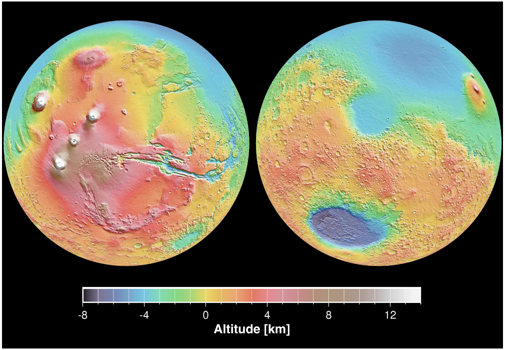
$$R = 3390 \text{ km}$$

$$T_{\rm surf} = 214 \text{ K}$$

$$\rho = 3.934 \text{ g/cm}^3$$

Thin atmosphere
Cold
Very distinct northern and southern hemisphere
Signs of water flow

Surface of Mars



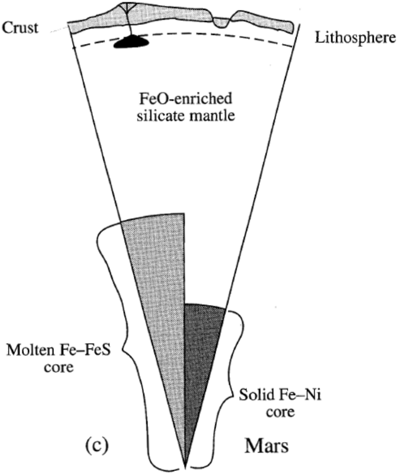
- Crustal dichotomy:
  - Low northern hemisphere with few impact craters
  - High southern hemisphere with many impact craters
- Tharsis region around equator seat of many shield volcanoes (including Olympus Mons)
- Vallis Marineris is 4000 km long, up to 7 km deep and 200 km wide

Internal structure of Mars

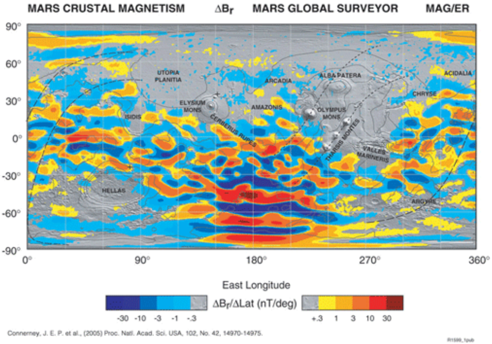
- Mars shows no dipole magnetic field

⇒ Inner solid core?

- Thick lithosphere

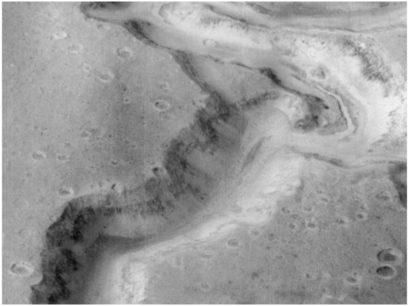


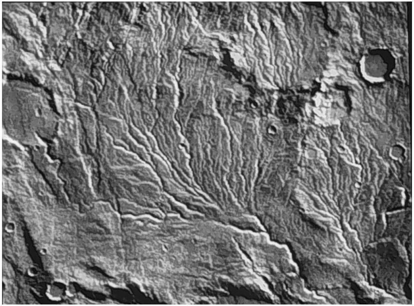
Evidence for past magnetism



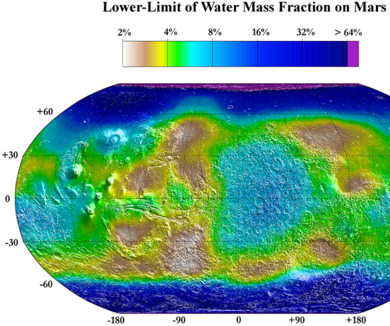
- Northern lowland and impact craters show little magnetic field
- Ancient southern highland shows stripy magnetic field features
- Similar to magnetic field frozen into oceanic crust on Earth
- Evidence of magnetic field and plate tectonics in the first few 100 Myr on Mars

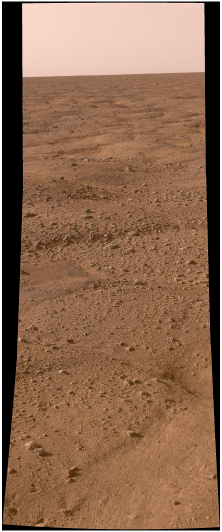
Mars rivers





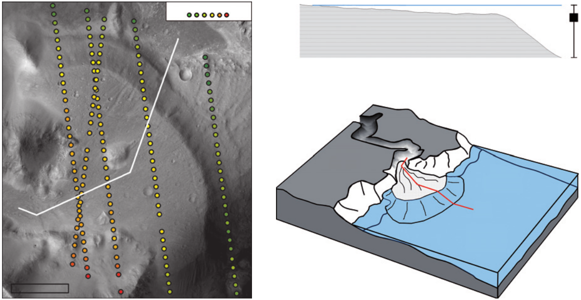
Permafrost





- Neutron detector on Mars Odyssey (arrived 2001) detected water ice in the top meter of the surface
- Phoenix lander (arrived 2008) saw hexagonal structures associated with freezing and thawing of permafrost

Water on Mars

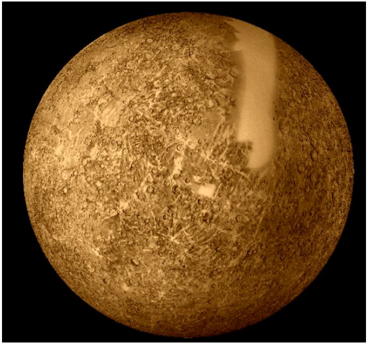


(Di Achille & Hynek 2010)

- Atmospheric pressure too low for liquid surface water
- Polar ice caps of CO_2 and H_2O ice partially sublimate in the summer and recondense in the winter
- Evidence for river deltas in the early Martian history

Mercury

Mercury

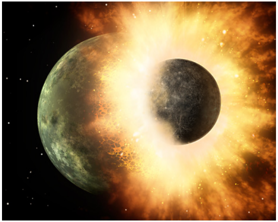


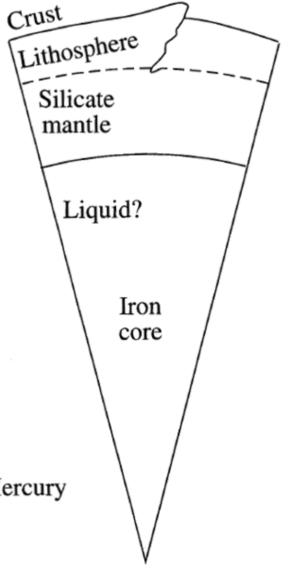
$$a = 0.39 \text{ AU}$$
$$M = 3.3 \times 10^{23} \text{ kg } (0.055\ M_\oplus)$$
$$R = 2440 \text{ km}$$
$$T_{\rm surf} = 443 \text{ K}$$
$$\rho = 5.427 \text{ g/cm}^3$$

No atmosphere
Magnetic field like Earth's
Rich in iron
Mass dominated by core

Internal structure of Mercury

- Mercury has dipole magnetic field like Earth
- High mean density implies 60% Fe
- Iron core extends to 60% of the planet's mass
- Thick 200 km lithosphere
- Mantle removed by giant impact?



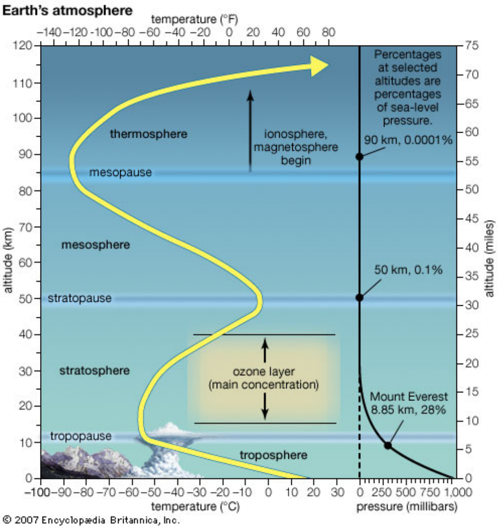


(a) Mercury

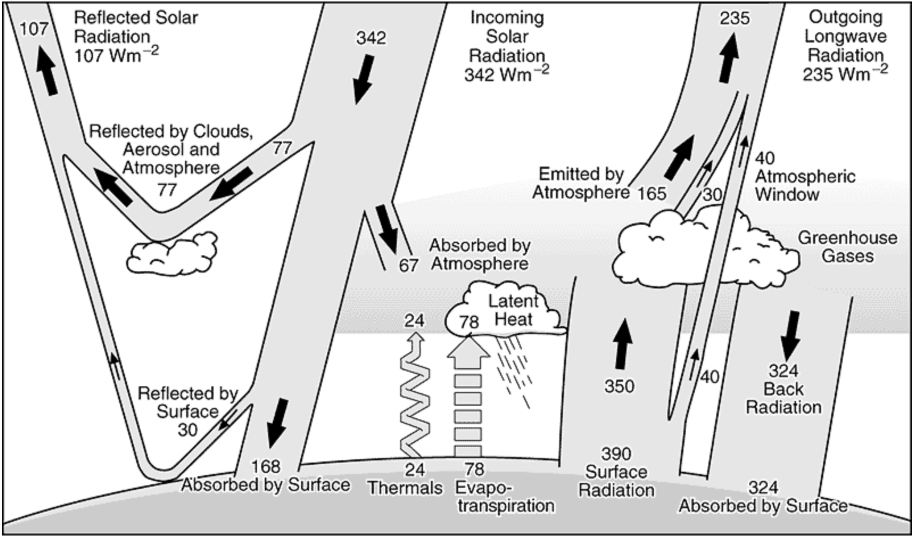
Thermal structure of planet atmospheres

- Effective temperature and thermal structure of planet atmospheres is an important area of study
- Implications for habitability and for observability of exoplanets
- Can also be used to understand the Earth's atmosphere and climate better

⇒ Need some basic knowledge of radiative transfer



IPCC



Intergovernmental Panel on Climate Change (IPCC)

Atmospheres of Venus – Earth – Mars

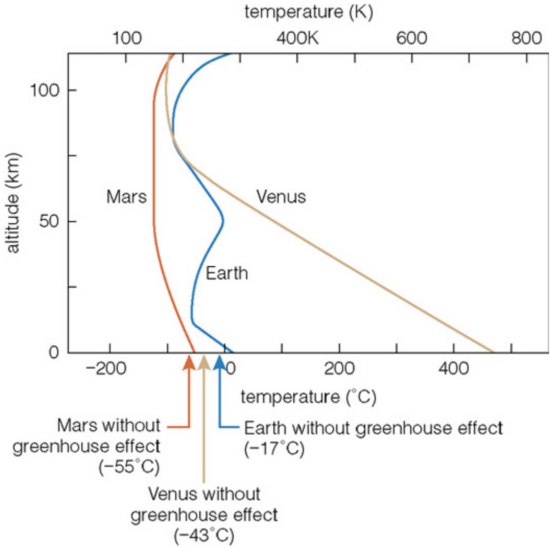
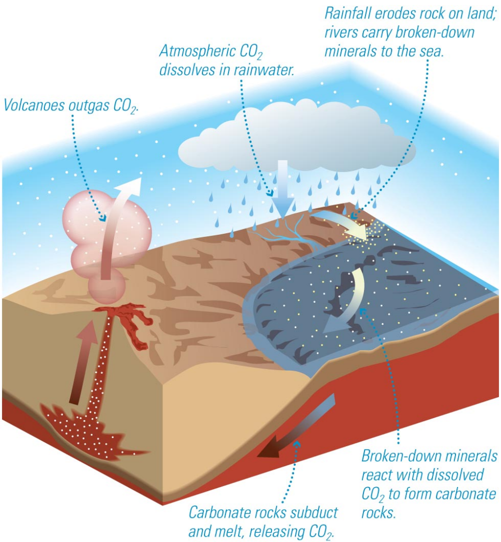


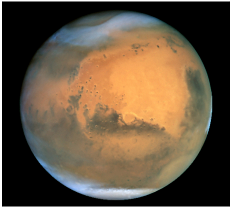
Image by F. Bagenal

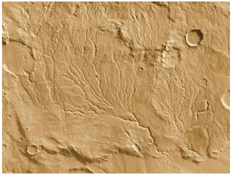
CO_2 cycle

- CO_2 reacts with silicate minerals in soil to form carbonate
- Carbonate sediments are carried into the Earth by plate tectonics
- CO_2 recycled by volcanoes



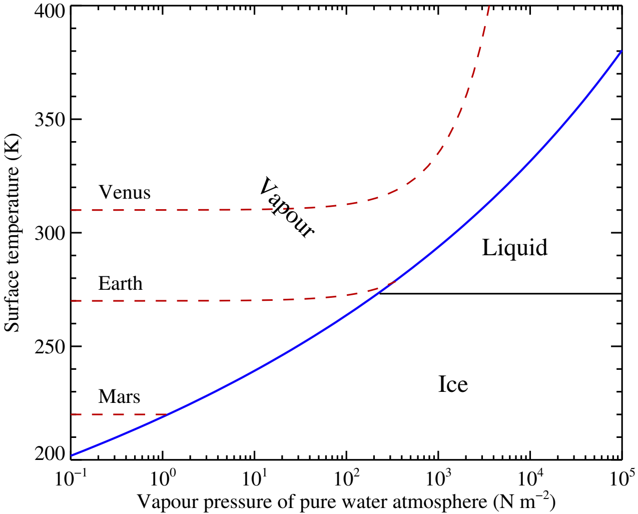
Climate evolution on Mars



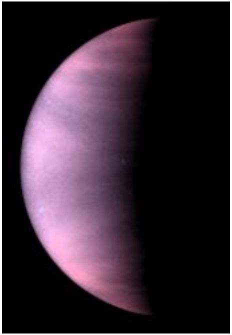


- Channels document wet past (until $\sim$ 3.8 Gyr)
- Primordial oceans absorbed CO_2, cooling down atmosphere
- Too small to sustain volcanism and plate tectonics
- No CO_2 recycling
- Water now present as ice below the surface and on poles

Run-away greenhouse effect

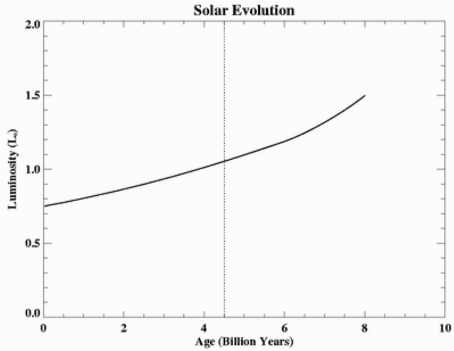


Climate evolution on Venus



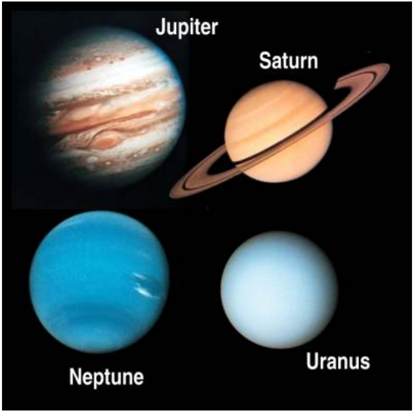
- Started out water rich like Earth?
- Closer vicinity to Sun caused run-away evaporation of oceans
- Water atmosphere destroyed by UV irradiation
- No CO_2 cycle without oceans and plate tectonics - CO_2 stays in atmosphere

Climate evolution on Earth



- Luminosity of young Sun was 30% lower than today – giving $T_{\text{eff}} = 233$ K (today $T_{\text{eff}} = 255$ K)
- Still no geological evidence of increased glacial activity on young Earth
- Continual decrease in greenhouse gases over time can counteract increase in solar luminosity
- Alternatively the young Earth had a lower albedo, because the total surface area of continents was smaller

Gas and ice giants



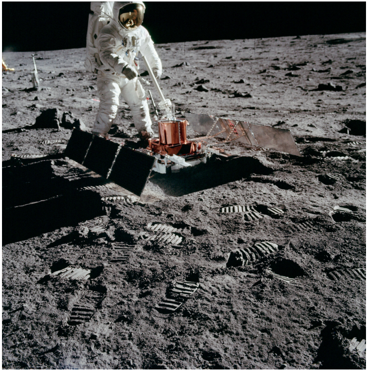
- Dominant mass of the solar system
- Jupiter and Saturn consist primarily of hydrogen and helium
- Uranus and Neptune consist primarily of ice
- Extensive moon systems

Equatorial and polar radii

	Jupiter	Saturn	Uranus	Neptune
$P_{\rm rot}$/hours	9.92	10.65	17.24	16.11
$\overline{\rho}/(\mathrm{g\ cm^{-3}})$	1.3275	0.6880	1.2704	1.6377
$R_{\rm eq}/(10^3\ \mathrm{km})$	71.492	60.268	25.559	24.766
$R_{\rm pol}/(10^3\ \mathrm{km})$	66.854	54.364	24.973	24.342

- Giant planets come in two flavours:
  - Gas giants consisting mainly of hydrogen and helium
  - Ice giants consisting mainly of ices
- Substantial difference between equatorial and polar radii due to fast rotation
- Distortion depends on internal structure

Seismometer



- No seismic data like for Earth and Moon

⇒ Must rely on models and measured gravitational moments to derive internal structure of giant planets

Gravitational moments

$$\Phi(r,\theta) = -\frac{GM}{r}\left[1 - \sum_{n=2}^{\infty}\left(\frac{R_{\rm eq}}{r}\right)^n J_n P_n(\cos\theta)\right]$$

- Departure from spherical symmetry expanded with Legendre polynomials in $x = \cos(\theta)$

$$\begin{aligned}
P_0(x) &= 1\\
P_1(x) &= x\\
P_2(x) &= \tfrac{1}{2}(3x^2 - 1)\\
P_3(x) &= \tfrac{1}{2}(5x^3 - 3x)\\
P_4(x) &= \tfrac{1}{8}(35x^4 - 30x^2 + 3)\\
P_5(x) &= \tfrac{1}{8}(63x^5 - 70x^3 + 15x)\\
P_6(x) &= \tfrac{1}{16}(231x^6 - 315x^4 + 105x^2 - 5)
\end{aligned}$$

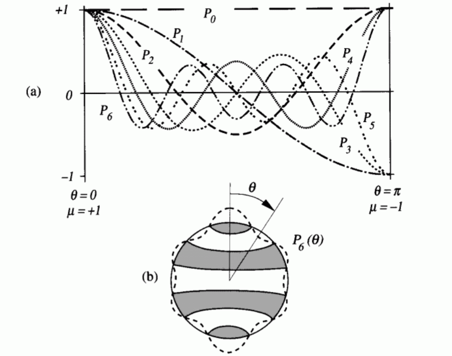
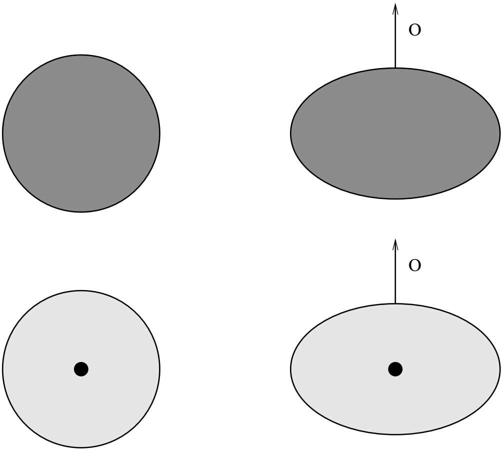


Fig. 6.3. A few low-degree Legendre functions. (a) Functions $P_0(\mu)$ through $P_6(\mu)$ are shown on the interval $-1 \le \mu \le 1$. (b) Function $P_6(\mu)$ is shown along the circumference of a circle; gray and white zones indicate areas where the function would be positive or negative, respectively, if wrapped around a sphere.

- $J_n = 0$ for odd n due to hemispheric symmetry

Sketch of rotationally distorted planets



- A probe orbiting the constant density planet will clearly feel non-spherically symmetric gravity
- A probe orbiting the extremely centrally condensed planet will feel gravity from approximately a point source

Gravitational moments

- Gravitational moments determined by Pioneer/Voyager/Cassini:

	J_2	J_3	J_4	J_5	J_6
Jupiter	14736 ± 1	0	-587 ± 5	0	31 ± 20
Saturn	16298 ± 10	0	-915 ± 40	0	103 ± 50
Uranus	3343.4 ± 0.3	0	-28.9 ± 0.5		
Neptune	3411 ± 10	0	-35 ± 10		

- Rotation parameter

$$q_r = \frac{E_{\rm rot}}{E_{\rm grav}} = \frac{\omega_{\rm rot}^2 R^3}{GM}$$

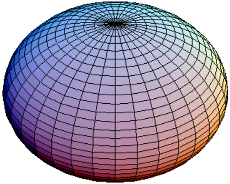
- Incompressible fluid of constant density has second harmonic

$$J_2 = \frac{1}{2} q_r$$

- Response coefficient

$$\Lambda_2 = \frac{J_2}{q_r}$$

Non uniform density



- Response coefficient

$$\Lambda_2 = \frac{J_2}{q_r}$$

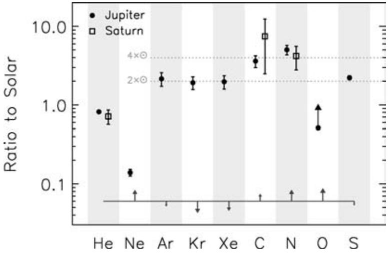
- $\Lambda_2 = 0.5$: constant density
- $\Lambda_2 < 0.5$: centrally concentrated

Planet	P	Λ_2
Mercury	59 d	60
Venus	243 d	73
Earth	23.9 h	0.314
Mars	24.6 h	0.429

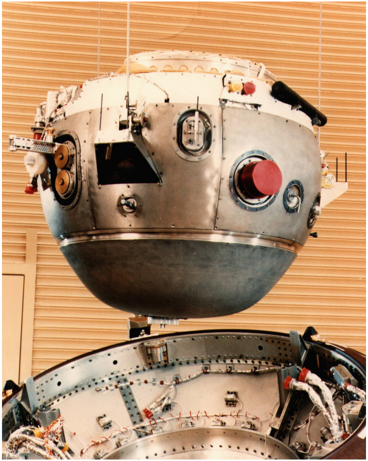
Planet	P	Λ_2
Jupiter	10 h	0.165
Saturn	10.5 h	0.105
Uranus	17.2 h	0.113
Neptune	16 h	0.131

Bulk composition

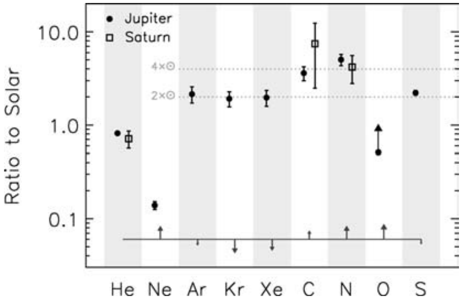
- *Galileo atmospheric probe* entered Jupiter's atmosphere in July 1995
- Measured pressure, temperature, composition down to 23 bar



(Owen et al. 1999, Guillot 2005)

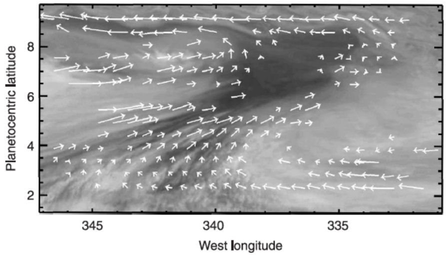


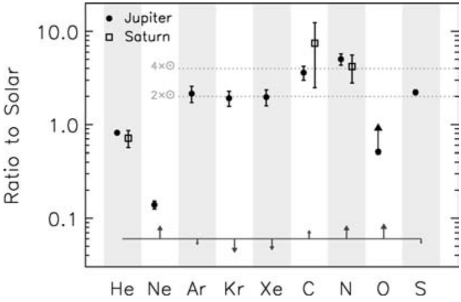
Helium separation



- Jupiter's troposphere is overabundant in C, N, S and in noble gases Ar, Kr, Xe compared to solar composition
- C, N, S brought to Jupiter in planetesimals of ice and rock
- Ar, Kr, Xe trapped in ice at low temperature and may have been delivered by planetesimals originating beyond 40 AU *(Owen et al. 1999)*
- Underabundant in He, Ne
- He droplets separate from H at high pressures
- Ne dissolved in droplets is also removed

Galileo and oxygen



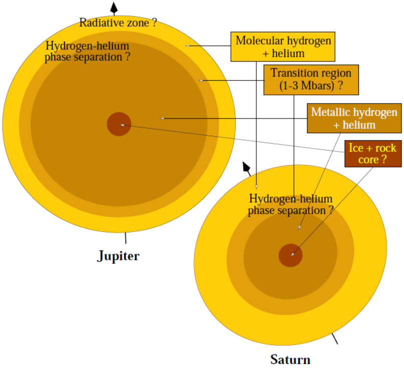


- Galileo probe landed in so-called hotspot in Jupiter's atmosphere
- Hot spots are dry and have no water clouds
- Radiation passes unhindered to space from deep layers

⇒ Oxygen abundance of Jupiter still unknown

- Juno mission will measure oxygen abundance from microwave spectroscopy
- Juno was launched in 2011 and will arrive at Jupiter in July 2016

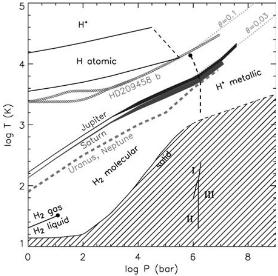
Three-layer structure

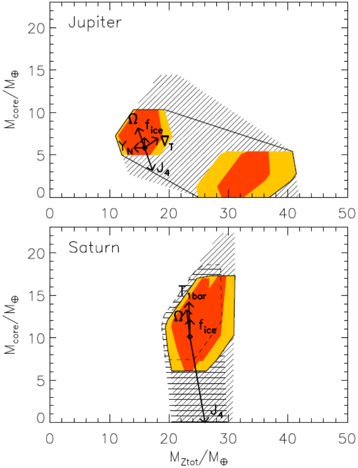


- Molecular hydrogen envelope depleted in He
- Metallic hydrogen envelope enriched in He
- Central core of rock and ice

Core mass of Jupiter and Saturn

- Uncertainty in core mass due to uncertainty in phase transition from molecular to liquid metallic hydrogen at high pressure
- Jupiter's density matched either by solid core or heavy elements mixed with gas

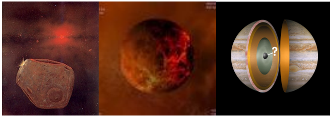




(Guillot 1999)

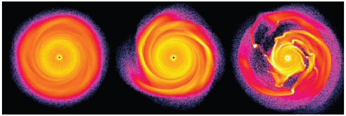
Two ways to form giant planets

Core accretion scenario:



- Dust grains stick to form km-sized planetesimals
- Planetesimal collide and build up 10-Earth-mass core of rock and ice
- Run-away accretion of gas onto core

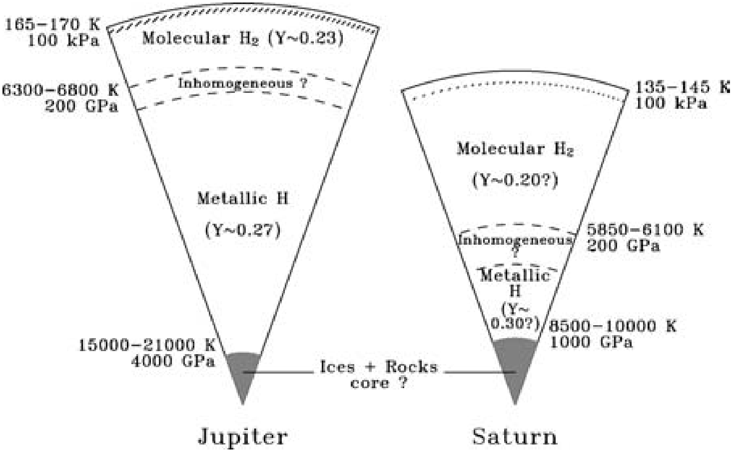
Disc instability scenario:



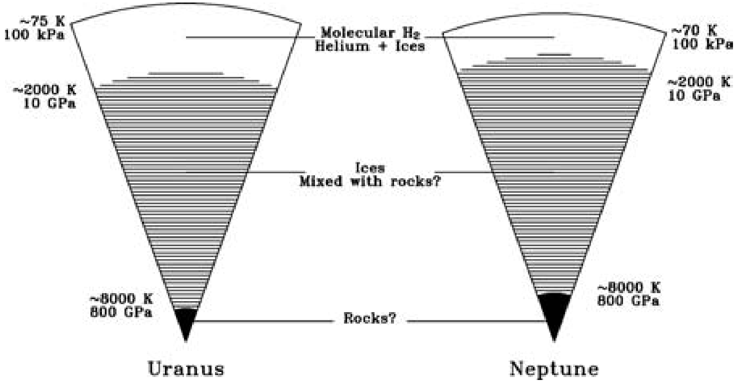
- Massive protoplanetary gas disc becomes gravitationally unstable
- Rapid formation of gas giants
- No need for a core

$\Rightarrow$ Lectures on planet formation

Interior structure of gas giants



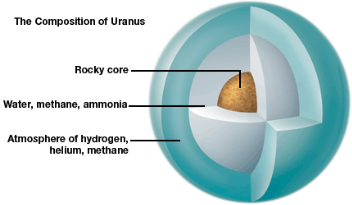
Interior structure of ice giants



Ice giants

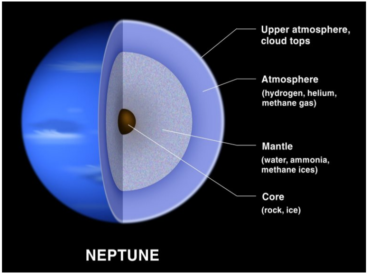
Structure of ice giants

1. Core of rock
2. Mantle of ice (water ice, ammonia ice, methane ice)
3. Thin gas atmosphere



- *Uranus*: 14.5 Earth masses, of which 13 Earth masses heavy elements
- *Neptune*: 17 Earth masses, of which 15 Earth masses heavy elements

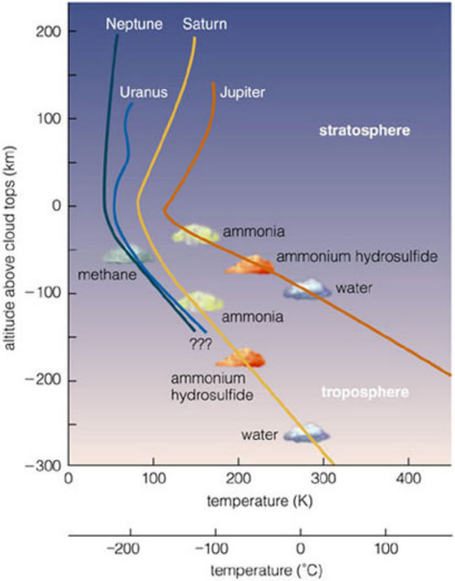
⇒ *Uranus and Neptune actually contain very little gas*



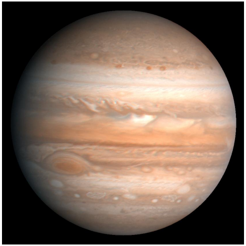
Condensable species in giant planets

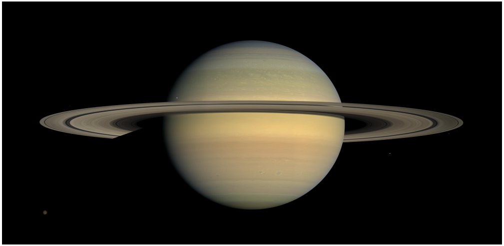
1. Aqueous solution clouds (liquid water mixed with NH_3 and H_2S) condense deep in the atmospheres at 300-400 K
2. Water clouds condense higher up at $T = 273$ K
3. Ammonia condenses at $T = 230$ K through the reaction $NH_3 + H_2S \rightarrow NH_4SH$ (ammonium hydrosulfide)
4. Ammonia and hydrogen sulfide condense at $T = 140$ K – whatever component has not been depleted in layer (3)
5. Methane condenses at $T \sim 80$ K

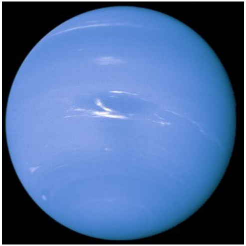
Atmospheric temperatures



Ammonia and methane clouds



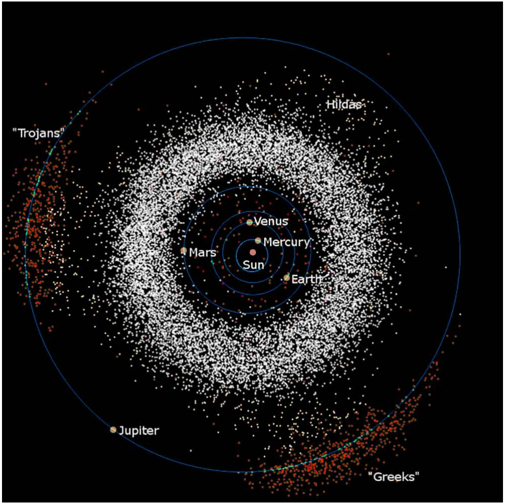




- Jupiter and Saturn show mainly ammonia clouds
- Uranus and Neptune cold enough for methane clouds

Overview of asteroids

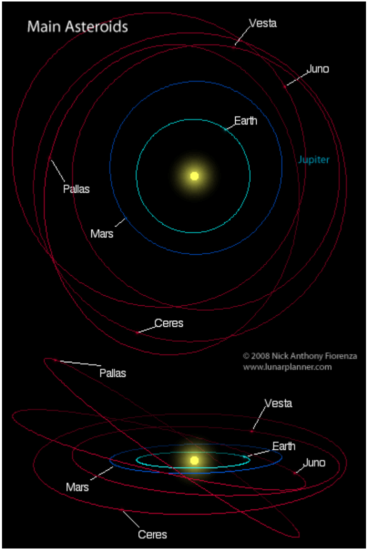
- First asteroid (Ceres) discovered in 1801 by Guiseppe Piazzi and Carl Friedrich Gauss
- Originally considered a new planet
- 1 – 2 million asteroids larger than 1 km in main belt between Mars and Jupiter
- Total mass in asteroid belt 0.0005 M_{Earth}
- Numbered by order of discovery, with additional name (e.g. 2 Pallas, 3615 Safronov)



Orbits and rotation

- Asteroid orbits have significant eccentricities and inclinations compared to terrestrial planets
- The dwarf planet Ceres contributes with 32% of the mass of the asteroid belt
- Most asteroids rotate relatively fast

Name	Diameter km	a AU	e	i $^\circ$	$P_{\rm rot}$ hours
Ceres	933	2.769	0.0780	10.61	9.075
Pallas	525	2.770	0.2347	34.81	7.811
Juno	267	2.668	0.0258	13.00	7.210
Vesta	510	2.361	0.0906	7.14	5.342

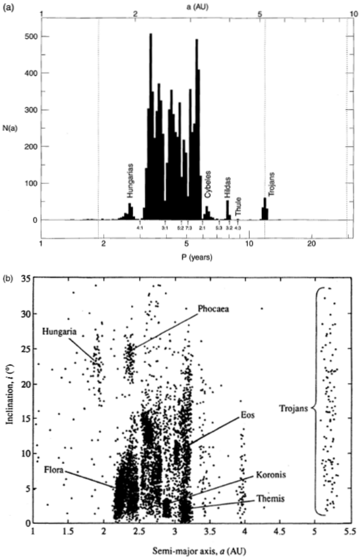


Distribution in semi-major axis

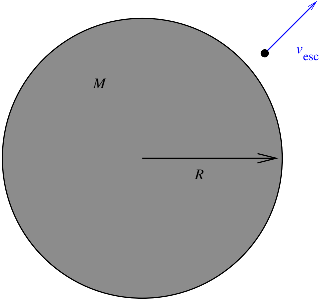
- Semi-major axis distribution shows distinct gaps at resonances with Jupiter

- Jupiter excites eccentricities in asteroid orbits, causing them to cross

⇒ The asteroid belt is slowly grinding down



Escape speed



- Escape speed:

$$v_{\rm esc} = \sqrt{\frac{2GM}{R}}$$

- Use mass $M = (4/3)\pi\rho_\bullet R^3$ for constant density sphere:

$$v_{\rm esc} = 0.1\,\frac{\rm km}{\rm s}\left(\frac{R}{100\,\rm km}\right)\left(\frac{\rho_\bullet}{2\,{\rm g\,cm^{-3}}}\right)^{1/2}$$

- Typical circular speed at $r = 3\,\mathrm{AU}$: $v_{\rm Kep} \approx 17\,\mathrm{km/s}$
- Gives radial speed $v_r = e \times v_{\rm Kep} \approx 2$–$4$ km/s
- Asteroids collide at speeds much higher than escape speed

$\Rightarrow$ The asteroid belt is grinding down

Collisional grinding

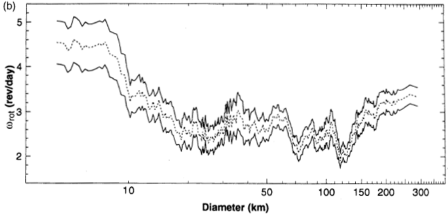
- Asteroid collision speeds far supersede the escape speed
- As small fragments collide with terrestrial planets or are expelled, the mass goes down and collision time-scale increases with time
- The few very large bodies left (Ceres, Vesta, etc.) were the lucky ones that never had catastrophic collisions with similarly large bodies

⇒ Catastrophic collisions lead to random rotation at near break up speed

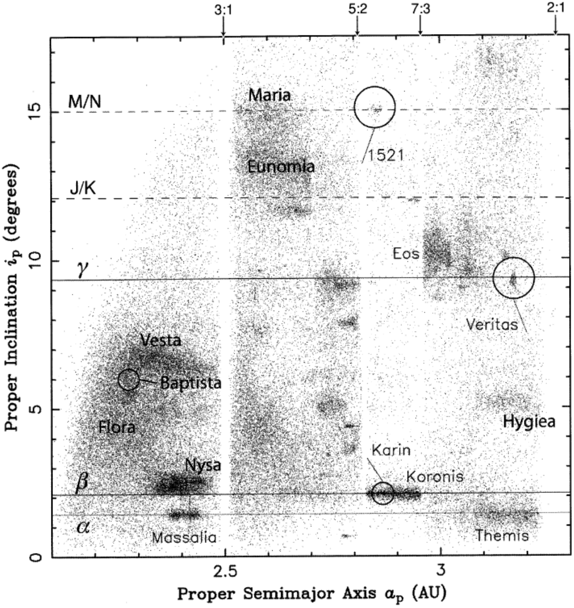
⇒ Asteroid belt used to be much more massive

$$\omega_{\max}^2 R = \frac{GM}{R^2} \quad \Rightarrow$$

$$\omega_{\max} = \sqrt{\frac{GM}{R^3}} \approx 10\,\mathrm{rev\,day}^{-1}\left(\frac{\rho_\bullet}{2\,\mathrm{g\,cm}^{-3}}\right)^{1/2}$$



Asteroid families



Physical properties

- Mass of asteroids determined either from presence of moon or perturbations on other asteroids
- Radius, shape and albedo from reflected sun light and emitted infrared radiation or radar
- Measure F_{ref} and F_{IR}:

$$\begin{aligned} F_{\mathrm{in}} &= f_{\odot}\sigma_{\mathrm{proj}} \\ F_{\mathrm{ref}} &= A_{\mathrm{b}} F_{\mathrm{in}} \\ F_{\mathrm{IR}} &= (1 - A_{\mathrm{b}}) F_{\mathrm{in}} \\ F_{\mathrm{in}} &= F_{\mathrm{ref}} + F_{\mathrm{IR}} \end{aligned}$$

- Isolate projected surface and albedo:

$$\begin{aligned} \sigma_{\mathrm{proj}} &= \frac{F_{\mathrm{ref}} + F_{\mathrm{IR}}}{f_{\odot}} \\ A_{\mathrm{b}} &= \frac{F_{\mathrm{ref}}}{F_{\mathrm{ref}} + F_{\mathrm{IR}}} \end{aligned}$$

Taxonomic groups

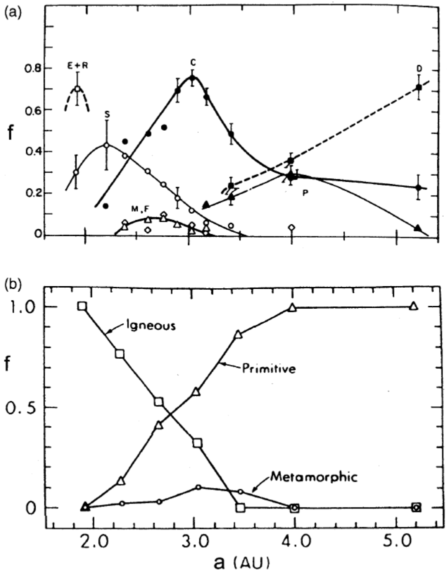
- Carbonaceous (C)
  40% of all asteroids
  Low density ($\rho \approx 1.2 - 2$ g/cm^3)
  Low albedo ($A_0 \approx 0.04 - 0.06$)
  Surface like "primitive" undifferentiated bodies

- Stony (S)
  30–35% of all asteroids
  Moderate albedo ($A_0 \approx 0.14 - 0.17$)
  Igneous bodies (crystallised from melt)

- Iron and stony-iron asteroids (M)
  Rare
  High density
  Cores of differentiated bodies

Spatial distribution of groups

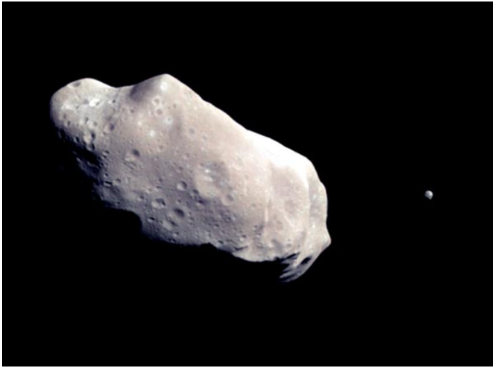
- Moderate albedo igneous (i.e. stony) bodies primarily in inner asteroid belt
- Low albedo primitive bodies primarily in outer belt
- Surfaces of high albedo bodies may be an effect of *space weathering*
- 1 Ceres has C-type surface, but known to be differentiated



951 Gaspra

- S type asteroid
- Dimensions 18.2 $\times$ 10.5 $\times$ 8.9 km
- Density $\rho \approx 2.7\,\mathrm{g\,cm^{-3}}$
- Too small for mass estimation as it did not perturb Galileo enough
- Surface dotted with small craters

243 Ida



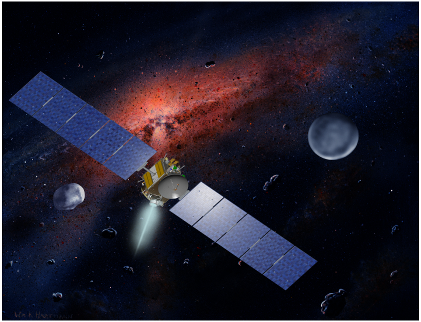
- S type asteroid
- Dimensions 53.6 $\times$ 24.0 $\times$ 15.2 km
- Density $\rho \approx 2.27 - 3.1\,\mathrm{g\,cm^{-3}}$
- Moon Dactyl first asteroid moon discovered (1.5 km diameter)
- Both probably formed by disruption of Koronis parent body about 2 Gyr ago

253 Mathilde

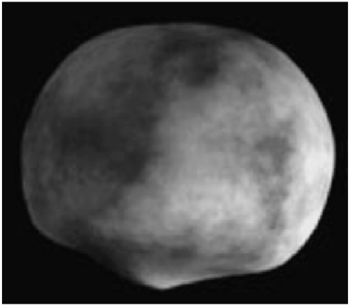
- C type asteroid
- Dimensions 66 × 48 × 46 km
- Density $\rho \approx 1.3\,\mathrm{g\,cm^{-3}}$
- Low density indicates loosely packed rubble pile

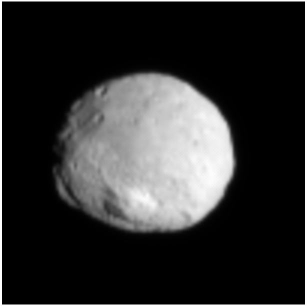
Dawn

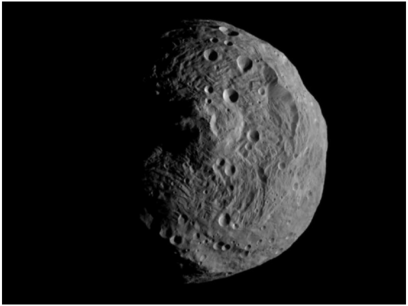
- Launched in 2007 with aim to study 1 Ceres and 4 Vesta
- Left Vesta in September 2012 (arrived at Ceres in 2015)
- Interior structure of Vesta and Ceres will become known
- Much more astrophysically interesting to study large pristine asteroids than smaller break up products

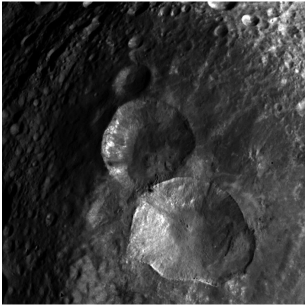


4 Vesta with Hubble and Dawn

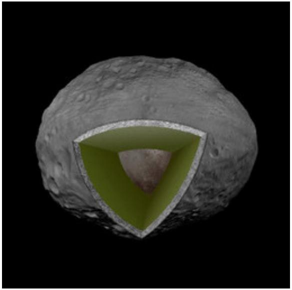


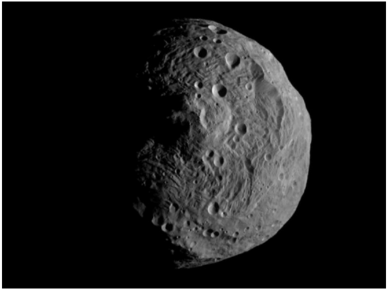






Surface of Vesta





- Giant crater near south pole (*Rheasilvia*)
- Surface basaltic, but more metallic in crater
- Gravitational moment consistent with fully differentiated body with iron core, silicate mantle and basalt crust
- Like a terrestrial planet

Rocks from the sky

- Meteor witnessed in October 1992 at east coast of USA
- Broke up into several pieces

Peekskill meteorite

- Meteorite hit parked car in Peekskill, New York
- 12.4 kg

Why are meteorites interesting?

- Rocks mostly from the asteroid belt
- Some are more exotic (parts of Moon/Mars)
- Nomenclature: meteoroid (in space), meteor (in the air), meteorite (on the ground)
- An estimated 10^7–10^8 kg of material hits Earth every year (mostly dust)
- Estimated 10^4–10^5 meteors make it to the ground as meteorites each year

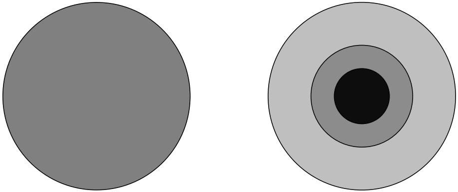
⇒ Meteorite ages are used to set the age of the solar system

⇒ Properties of meteorites give important clues to how the solar system formed

⇒ Elemental abundances in meteorites used for standard solar abundance

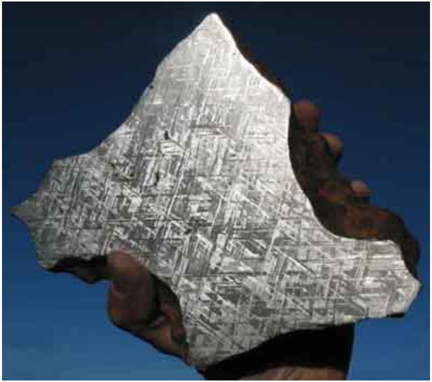
Types of meteorites

- Iron meteorites
- Stony-iron meteorites
- Stony meteorites
  - Chondrites – primitive
  - Achondrites – basaltic



- All meteorites are parts of larger parent bodies broken up in collisions
- Differentiated parent bodies give rise to iron meteorites (core), stony-iron meteorites (between core and mantle) and basaltic achondrites (mantle)
- Chondrite parent bodies were never molten and thus did not differentiate

Iron meteorites

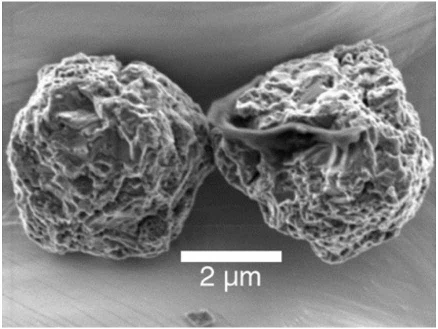


- Around 5.7% of falls
- Fe, Ni, Co make up 95% of the mass
- Giant Ni-Fe crystals (Widmanstätten) evidence for extremely slow cooling

Stony-irons and stony (achondrites)

- Stony-irons have comparable amounts of metal and rock
- Achondrites are similar to basalt on Earth

Chondrites



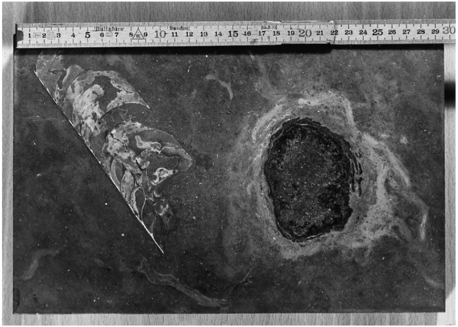
- Chondrites are "primitive" meteorites
- Parent bodies never melted
- Contain variable amounts of 0.1 – 1.0 mm *chondrules* and cm *CAI* (Calcium-Aluminium rich inclusions)
- Fine-grained matrix between chondrules
- Presolar grains

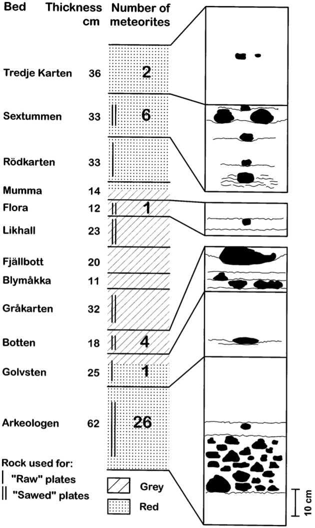
Ordinary chondrites

- 80% of all falls
- Depleted in Ca, Al, Ti
- Heated to above 500°C inside parent body
- Subclassification of ordinary chondrites:
  - H: high total Fe/high metallic Fe (42% of ordinary chondrites)
  - L: low total Fe (46% of ordinary chondrites)
  - LL: low total Fe, low metallic Fe (10% of ordinary chondrites)

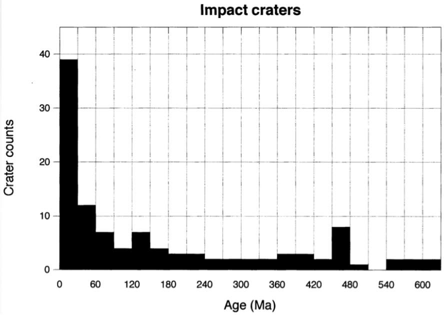
Fossil meteorites

- Fossil meteorites from Sweden and China show peak at approximately 480 Myr ago
- Work by Birger Schmitz from Lund University





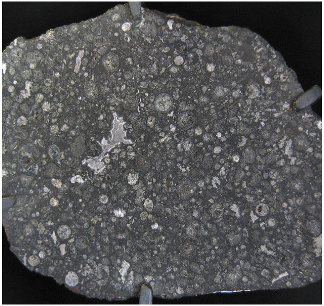
Asteroid collision



- *Gas retention age* of L chondrites around 500 Myr
- Peak in terrestrial craters around 480 Myr year ago
- Peak in fossil meteorites

⇒ Major asteroid collision 480 Myr years ago

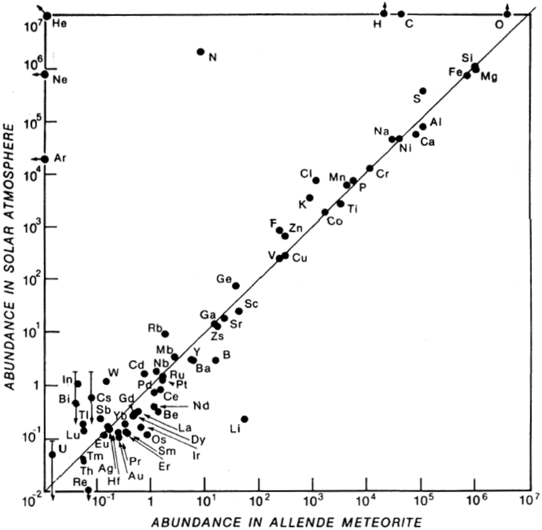
Carbonaceous chondrites

- 5% of all falls
- Rich in carbon
- Parent bodies only moderately heated
- Contain organic compounds such as aminoacids
- Subclassification: CI, CO, CK, CM, CV, CR
  (Ivuna, Ornans, Karoonda, Michei, Vigarano, Renazzo)
- *Most pristine bodies in the solar system*

Abundances in meteorites

- Elemental abundances of CI carbonaceous chondrites are very similar to the Sun's photosphere
- N, H, C, O too low in CI meteorites – volatiles
- Li too low in the Sun – destroyed as part of H fusion



⇒ *The planets and the Sun formed from the same material*

⇒ *Planet material was not expelled from the Sun*

Dating meteorites

Long-lived radionuclides

Parent	Daughter	Half-life
^{40}K	^{40}Ar, ^{40}Ca	1.25 Gyr
^{87}Rb	^{87}Sr	48.8 Gyr
^{147}Sm	^{143}Nd, ^{4}He	106 Gyr
^{187}Re	^{187}Os	46 Gyr
^{232}Th	^{208}Pb, ^{4}He	14 Gyr
^{235}U	^{207}Pb, ^{4}He	0.704 Gyr
^{238}U	^{206}Pb, ^{4}He	4.47 Gyr

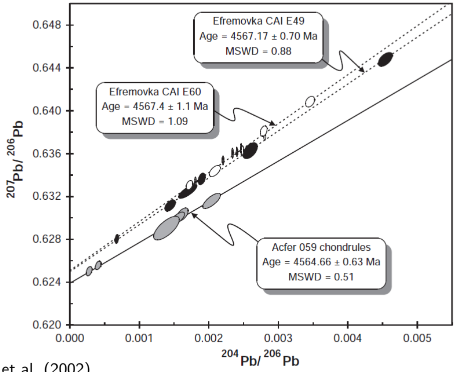
Extinct radionuclides

Parent	Daughter	Half-life
^{26}Al	^{26}Mg	0.72 Myr
^{41}Ca	^{41}K	0.1 Myr
^{53}Mn	^{53}Cr	3.6 Myr
^{60}Fe	^{60}Ni	1.5 Myr
^{107}Pd	^{107}Ag	6.5 Myr
^{129}I	^{129}Xe	17 Myr
^{182}Hf	^{182}W	9 Myr
^{244}Pu	$^{131-136}$Xe	82 Myr

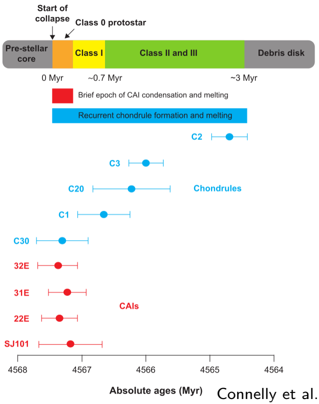
⇒ Long-lived radionuclides used for *absolute dating* of meteorites

⇒ Short-lived (extinct) radionuclides used for preciser *relative dating*

Age of chondrules and CAI by lead-lead dating



Amelin et al. (2002)



Connelly et al. (2012)

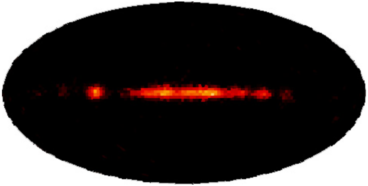
- Both CAIs and chondrules are really old – older than any rock on Earth
- CAIs are 2-3 million years older than chondrules
- The error in Pb-Pb dating is 0.5-1.5 Myr
- *CAIs are used as $t = 0$ of the solar system*

The importance of ^{26}Al

Decay of ^{26}Al:

$$^{26}\mathrm{Al} \quad \rightarrow \quad ^{26}\mathrm{Mg} \qquad (\tau_{1/2} = 0.72\ \mathrm{Myr})$$

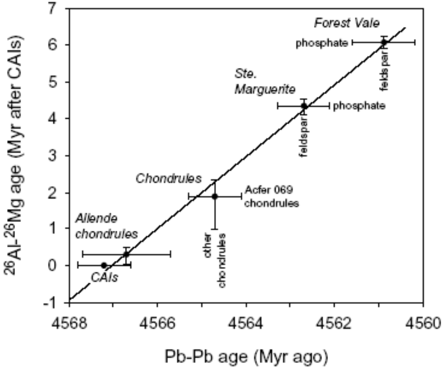
- ^{26}Al decays by electron capture or positron emission and releases 1.8086 MeV gamma ray photon
- ^{26}Al created inside massive stars and injected in the solar nebula by supernovae and winds
- Life-time comparable to planet formation time-scale makes ^{26}Al excellent for relative ages
- Radioactive decay of ^{26}Al heated meteorite parent bodies to differentiation



Knödlseder et al. 2001

Ages of chondrite components

- Long-lived radioisotopes give absolute age (but not very precise)
- Short-lived radioisotopes give relative age (very precise)



Sanders & Taylor 2005

Chronology of meteorite parent bodies

- Need ^{26}Al to heat meteorite parent bodies
- Half-life of ^{26}Al is only 0.72 Myr

$\Rightarrow$ *Melting of meteorite parent bodies (planetesimals) by radioactive decay of ^{26}Al puts meteorite parent bodies in close connection with star formation*

-4.567 Gyr: CAIs

- First condensations in the *solar nebula*

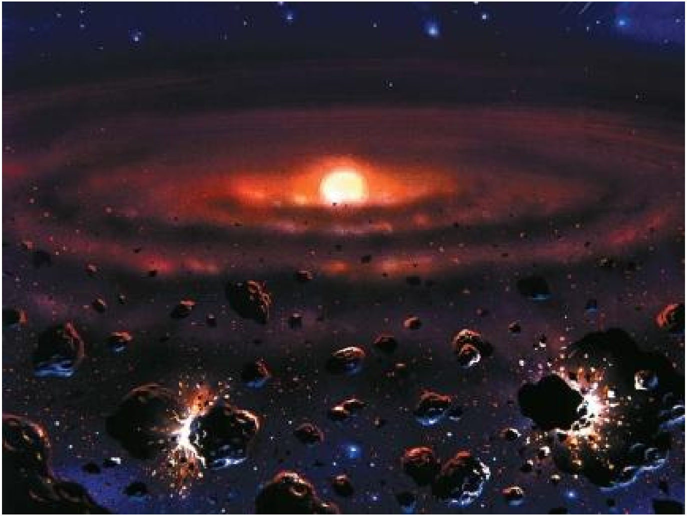
-4.566 Gyr: Differentiated parent bodies

- First $>$ 30 km asteroids (or planetesimals) to form
- Melted and differentiated by decay of ^{26}Al

-4.565 Gyr: Chondrules

- Chondrite parent bodies formed when ^{26}Al no longer abundant enough for melting?
- Chondrules could form by shock heating or lightning, or from molten asteroids colliding in liquid rock splashes
- Droplets solidify into chondrules that are accreted on differentiated parent bodies

Solar nebula



⇒ **Meteorites trace the first stages of planet formation**