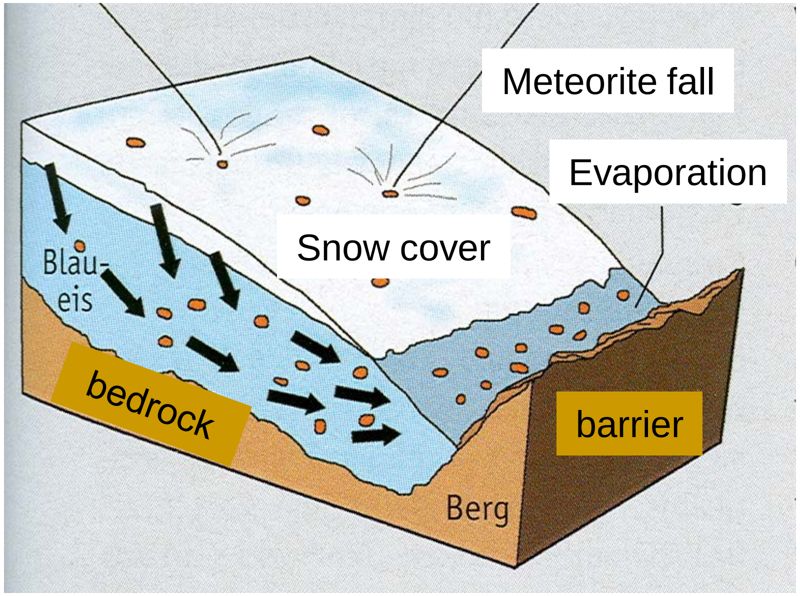
Meteorites – free samples from the solar system

It is easier to believe that Yankee professors would lie, than that stones would fall from heaven [Thomas Jefferson, 3rd president of the USA]

Collection of meteorites

A **meteoroid** is the optical (rarely also acoustical) phenomenon (shooting star) created by a body entering the Earth's atmosphere from space with high speed. Most meteoroids „burn up" above ~ 80 km height. Bodies larger than ~10 cm can be slowed down intact and fall to the ground. A **meteorite** is the body the causes the meteoroid and which can be collected on the ground if it survives.

Rarely, a meteorite is found after observing the fall. Sometimes, a meteorite can be easily distinguished from terrestrial material by its unusual properties (iron meteorites), its appearance, or because the location where it is found is otherwise devoid of stones (desert dunes, glaciers).



In the past 20 years, many meteorites have been found in Antarctica. Falling on the glaciers, they are incorporated into the ice.

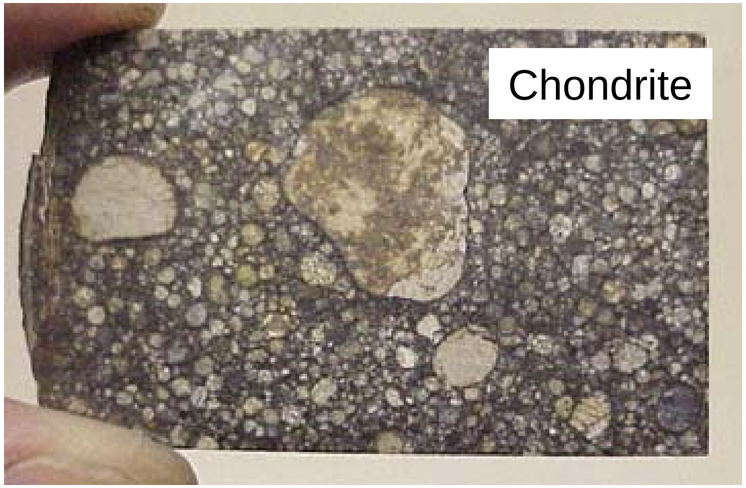
In some regions, the glacier looses mass by evaporation, setting the meteorites free. They can be found in such regions in large numbers.

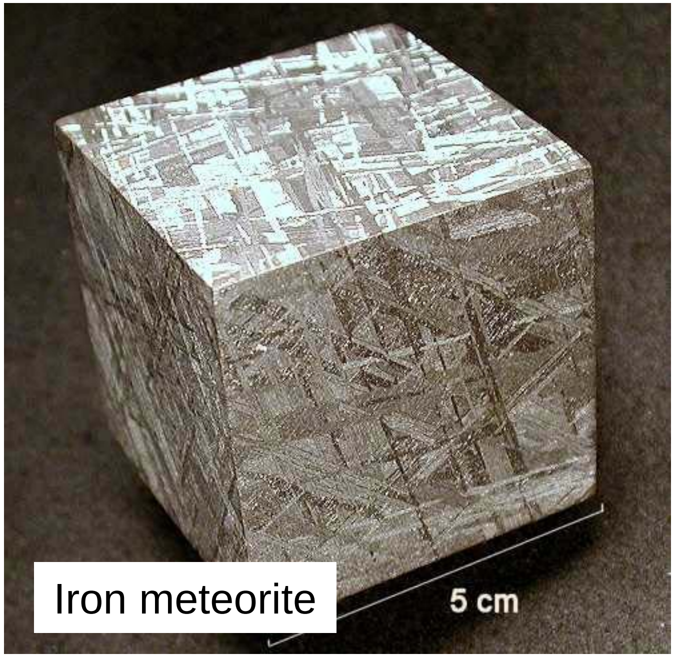
Classification of meteorites

1. Stony meteorites (94%)
   1.1 Chondrites (86%): „Primitive meteorites“
   Olivine, Pyroxene, Iron
   Have not been molten, except for inclusions called chondrules
   1.1.1 Carbonaceous chondrites (4%)
   Contain carbon and other compounds that evaporate at elevated temperature
   1.2 Achondrites (8%)
   Crystallized from a melt. Mostly of basaltic composition.
   Special classes:
   - Lunar meteorites
   - SNC-meteorites (probably from Mars)
   - HED-meteorites (probably from Vesta)

2. Iron meteorites (5%)
   Fe, Ni (5-25%), FeS (variable)

3. Stony iron meteorites [Pallasites] (1%)
   mixture

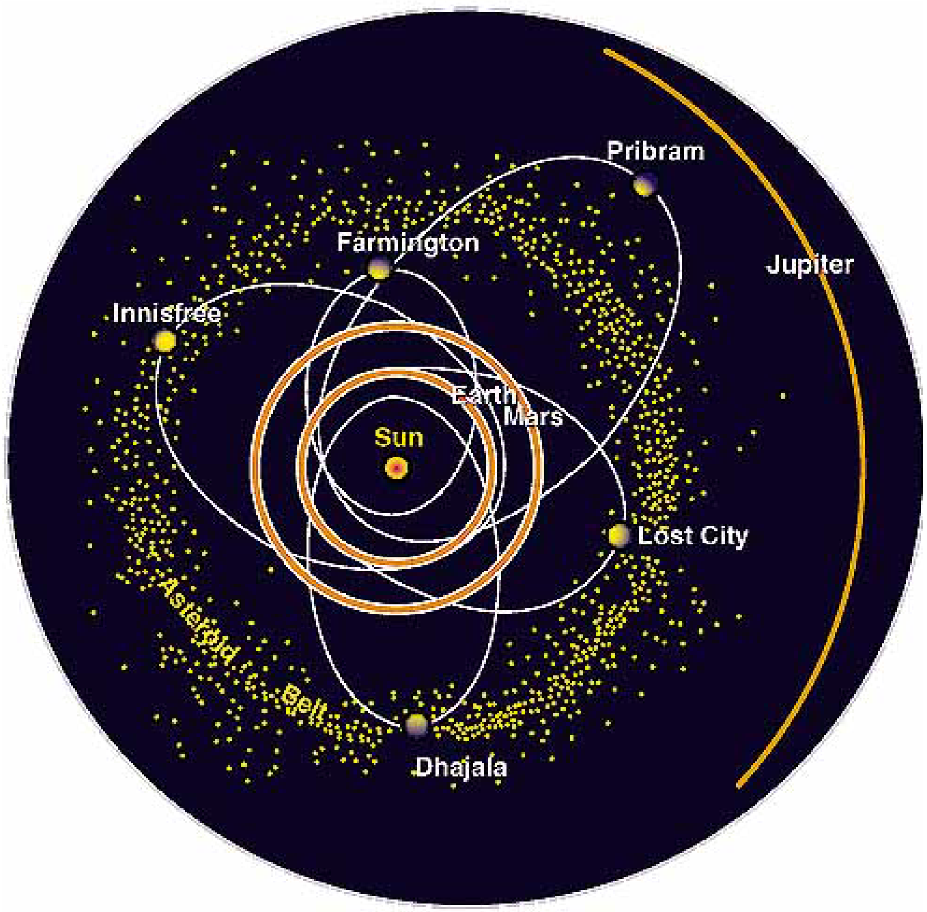




Origin of meteorites

In very few cases, the track of the falling meteorite in the (upper) atmosphere has been recorded simultaneously by several automatic cameras. This allows to reconstruct the pre-impact orbit in the solar system. In each case, it is fairly elliptical with the apohelion in the asteroid belt.

Collisions in the asteroid belt break up larger bodies and send the fragments onto different orbits. The orbits of some fragments are perturbed by large planets in such a way that the perihel migrates to less than 1 AU, opening the chance for collision with Earth.

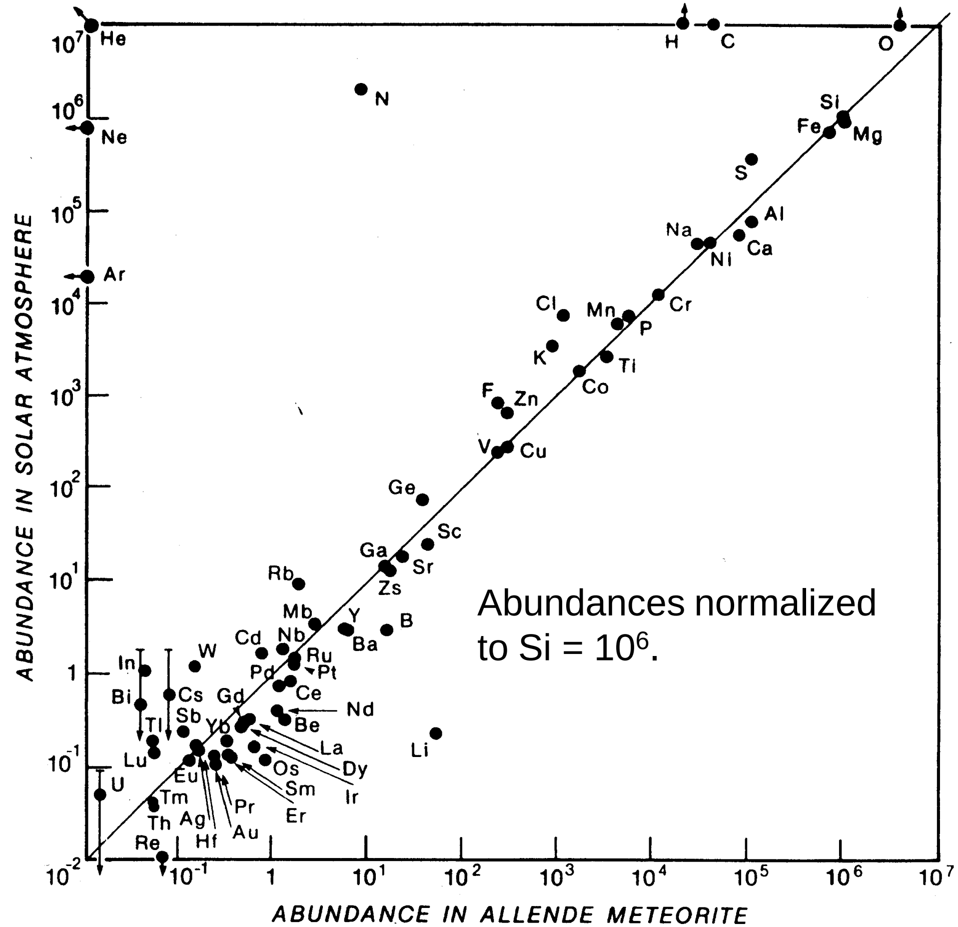


The asteroid belt is made up of material that condensed from the protoplanetary nebula at the beginning of the solar system, but failed to aggregate into a large planet (because of gravitational perturbations by Jupiter). It is believed to represent the original material from which terrestrial planets once formed.

Carbonaceous chondrites

Carbonaceous chondrites, in particular those of the subclass CI, have an unusually high abundance of volatile elements (C, H, N, ...). They represent the most primitive (i.e. least processed, least heated) meteorites available. Their inventory of chemical elements is representative of the composition of the protoplanetary nebula, excluding only the most volatile elements.

This is demonstrated by the good correlation of the element abundance in the meteorite with that in the solar atmosphere (determined by spectroscopy).

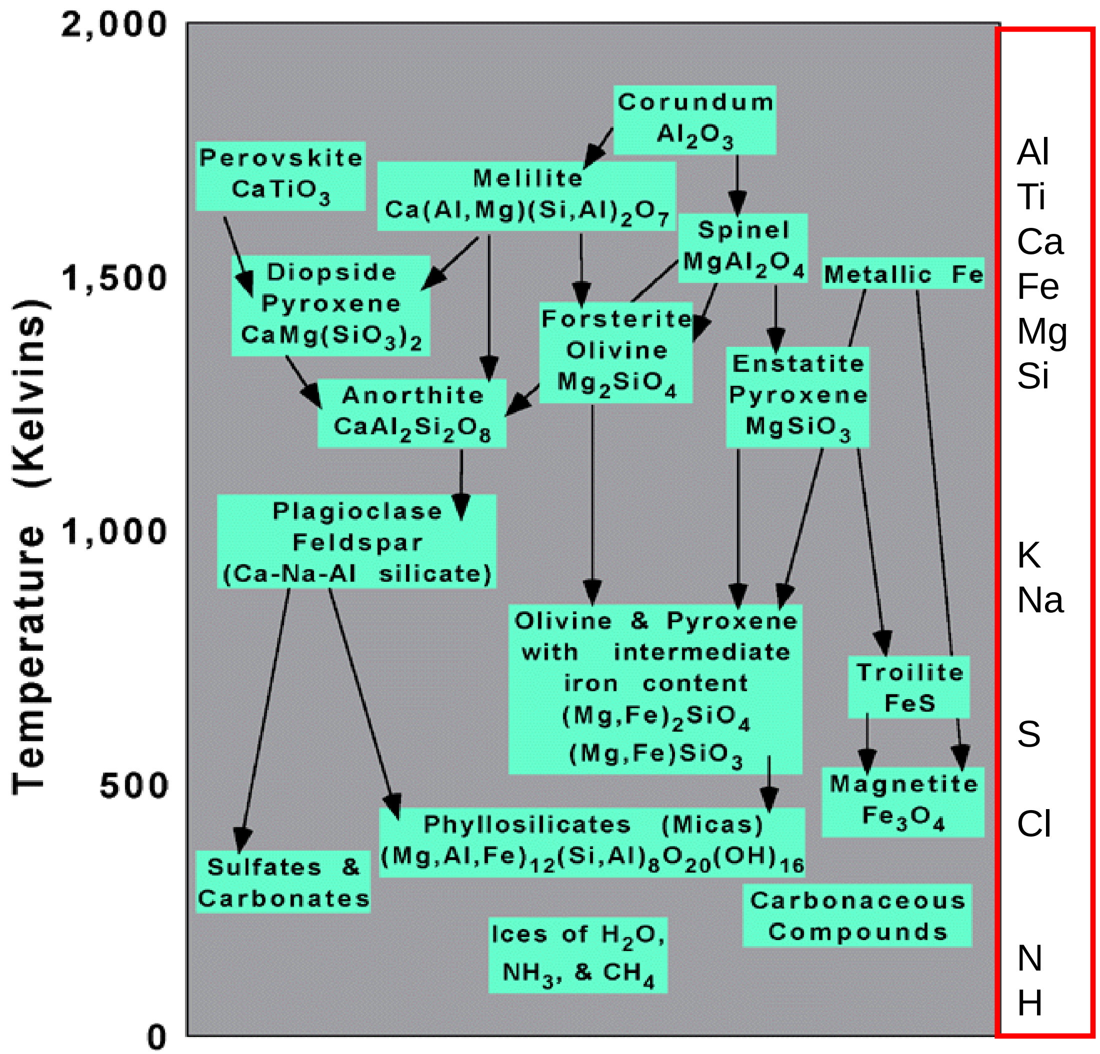


Christensen et al., Planetary Interiors and Surfaces, June 2011

Cosmochemical classification of elements

Classification according to condensation temperature T_c from solar nebula:
Refractory (T_c > 1200 K):
Mg, Si, Fe, Ca, Al, ..., U, ...
Moderately volatile (T_c≈1000 K):
Na, K, Zn, ...
Volatile (T_{cond} = 500 - 900 K):
S, Pb, Cl, ...
Highly volatile (T_{cond} < 500 K):
C, N, O ...

Classification according to partitioning between silicate phase and metal (Fe) phase in chemical equilibrium:
Lithophile elements concentrate in the silicate, e.g.
Mg, Al, Si, Na, U, ...
Siderophile elements concentrate in the metal, e.g.
Ni, S, P, Au, Pt, ...



Condensation sequence from solar nebula at p ≈ 10^{-4} bar

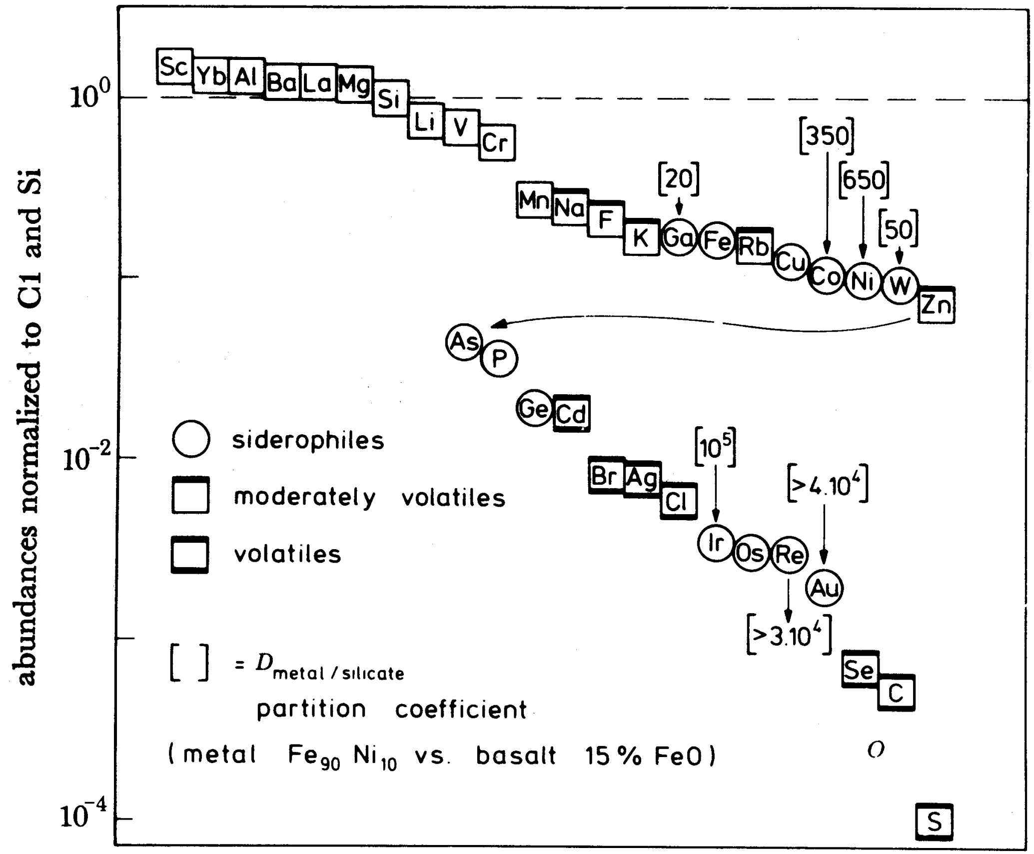
Earth‘s mantle composition compared to CI chondrites

Elements that are both refractory and lithophile are found in the Earth‘s mantle in the same relative concentration as in chondrites.

Moderately volatile elements are depleted by a factor 5-10, and volatiles by a factor of >50.
⇒ Earth did not form mainly from CI-chondrites, but from more refractory material.

Siderophile elements are depleted in the mantle by factors 10 – 300. Most of the Earth‘s inventory in these elements resides in the core.

Sulphur is both volatile and siderophile and is highly depleted in the mantle.

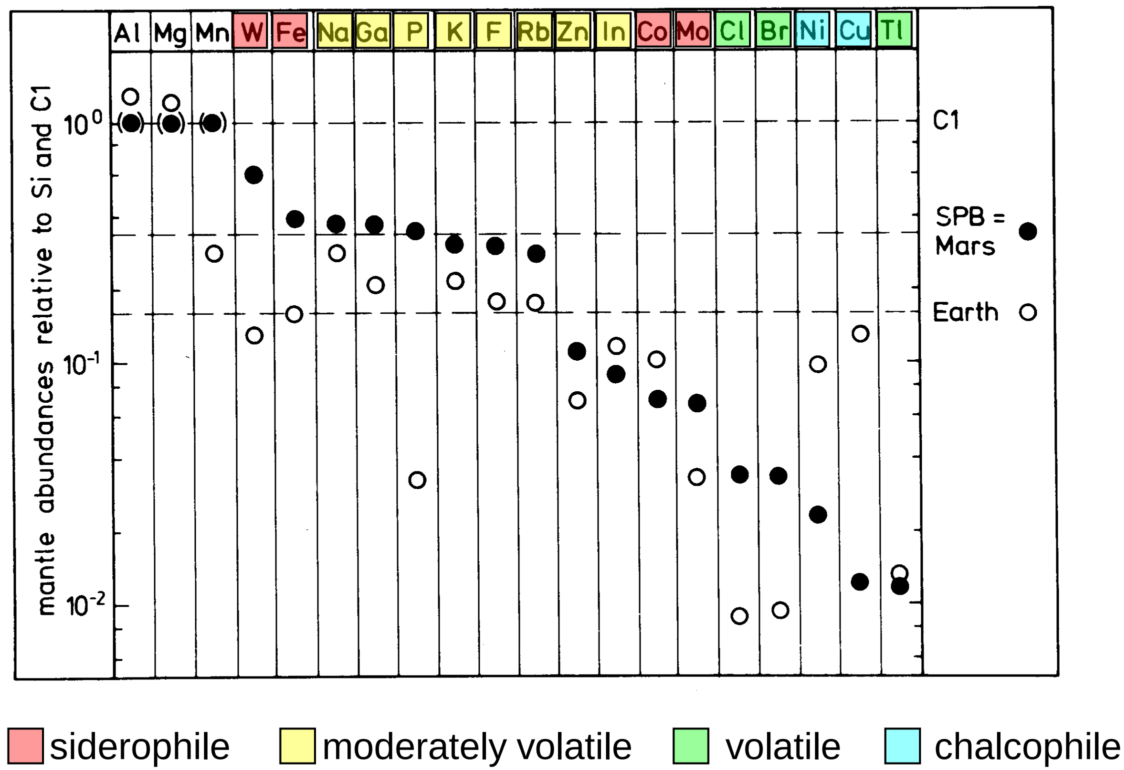


Concentration in upper mantle xenoliths relative to Si, divided by concentration in CI-chondrites relative to Si

Comparison of Earth and Mars mantle composition

The composition of the basaltic SNC-meteorites is taken to represent the volcanic crust of Mars (SPB = Shergotty parent body). A petrological model is used to calculate the relative abundance of elements in the mantle from which this basalt formed by partial melting.

Volatile elements are slightly less depleted in Mars than in Earth ⇒ Mars formed from more volatile-rich material. Plausible, because further away from sun.

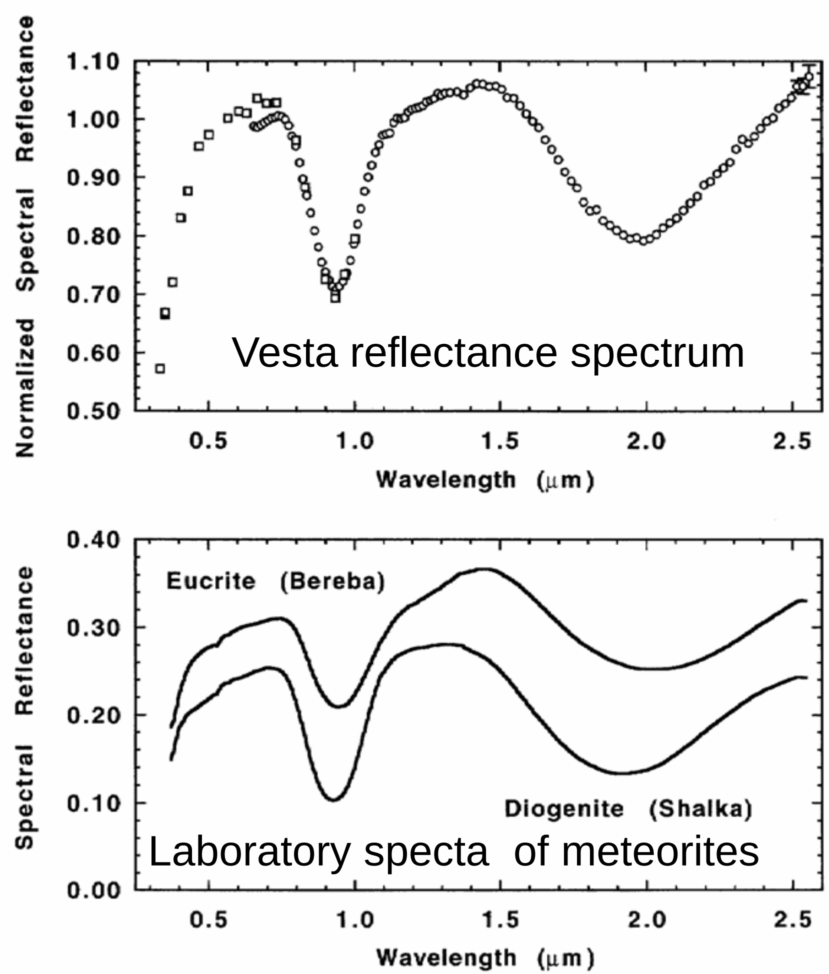


Siderophile elements are depleted in Mars‘ mantle ⇒ Mars has formed a metal core

Elements that are chalcophile (partition into a sulphide phase if present) in addition to being siderophile, like Ni and Cu, are more strongly depleted in Mars‘ mantle than in Earth‘s mantle ⇒ Mars‘ core may contain a significantly higher proportion of FeS than Earth‘s core

HED – meteorites from Vesta ?

Eucrites: Fe-rich basalts and gabbros
Diogenites: Mg-rich orthopyroxene cumulates
Howardites: Breccias, fragments of Eucr+Diog



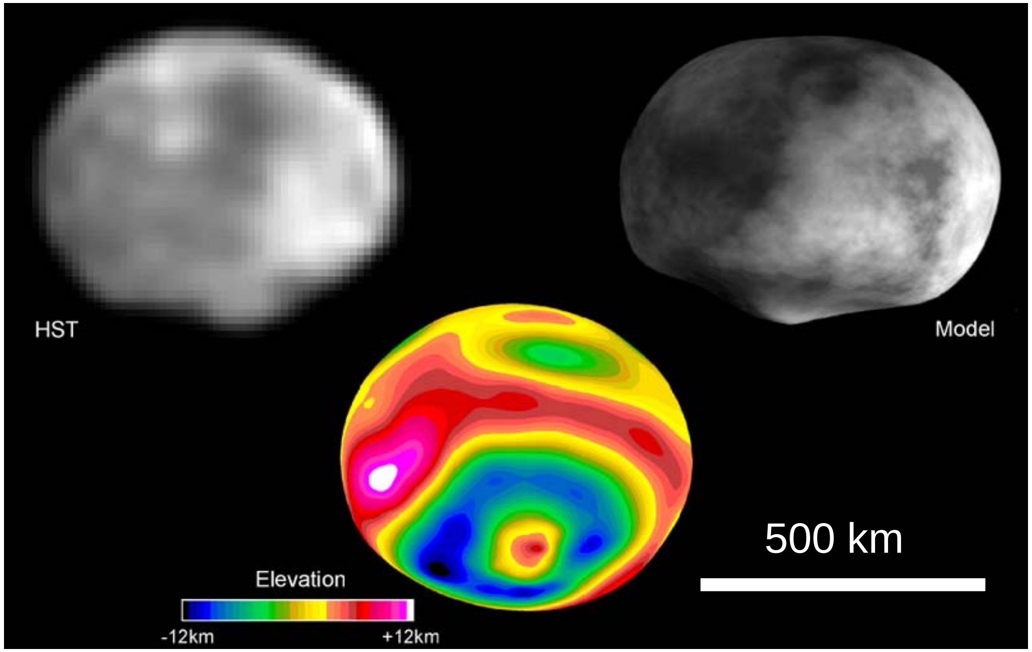
Laboratory reflectance spectra in the visible and infrared agree very well with the observed spectrum of Vesta (and a few minor asteroids called Vestoids), but not with that of other asteroids

Vesta and HED meteorites

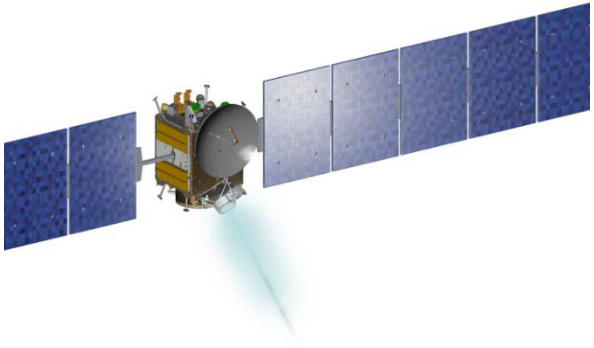
Vesta is the 3rd-largest asteroid. Images taken by the Hubble space telescope revealed a huge impact crater at the south pole.

Even though Vesta is a small body, it must have been hot enough once to partially melt and form basalts.

The mean density of Vesta is ~3700 kg m^{-3}, higher than Earth's mantle rock $\Rightarrow$ Vesta must contain significant iron. The HED meteorites are depleted in siderophile elements $\Rightarrow$ Vesta must have formed a metallic core.



HST-image and shape model derived from several images



NASA's Dawn mission (to be launched in 7/2007), will go into orbit and study Vesta in 2011, before it continues to Ceres. MPS has provided cameras for this mission.