

## Satellites and minor bodies of the inner Solar System

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## The Moon

- Moon's mass  $\sim 0.012 M_{\text{Earth}}$  and radius  $\sim 0.27 R_{\text{Earth}}$
- Mean density:  $\rho_{\text{Moon}} = 3.341 \text{ g cm}^{-3} < \rho_{\text{Earth}} = 5.515 \text{ g cm}^{-3}$
- The size of the core is not known, but it is probably less than 4% in volume
- The Moon does not have a hydrosphere, nor a significant atmosphere
- Synchronous rotation (tidally locked to Earth)
- Very large surface temperature excursions



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## Satellites of rocky planets

- Mercury and Venus do not have satellites
- Mars has two satellites of very small size ( $\sim 10 - 20 \text{ km}$ )
- Only the Earth has a satellite with a relatively large size
  - this is a further specificity of Earth with respect to other rocky planets of the Solar System
  - in addition to: hydrosphere, continuous tectonic activity, etc.

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## The Moon's surface

- The Moon's surface material provides an example of processes of alteration in absence of atmosphere and magnetic field:
  - Solar wind
  - Cosmic rays
  - Micrometeorites
- The result of this surface processing is a surface layer of thin, porous material, called regolith
  - The regolith layer has a thickness of a few meters above the solid rock
  - The term "regolith" comes from studies of terrestrial geology, meaning a layer of loose, heterogeneous superficial material covering solid rock



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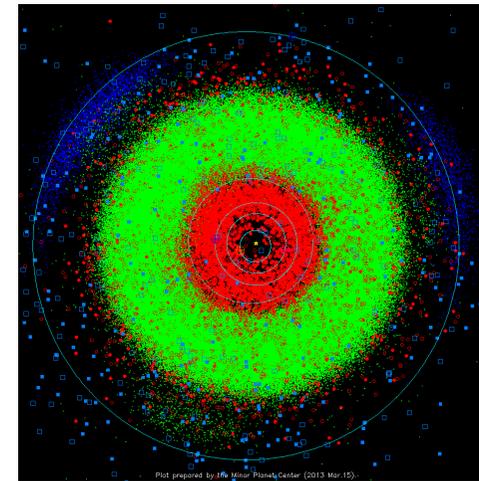


- As a result of its small size, the internal heat sources of the Moon, and the geological activity have decayed rapidly after its formation
- Due to the lack of an atmosphere and of geological activity, the Moon surface has preserved the characteristics acquired in the course of the history after its formation
  - The surface is very rich of impact craters
  - Moon's craters provide a record of the history of minor bodies collisions in the inner Solar System at the location of the Earth
  - Since Moon's craters can be dated accurately, we can reconstruct the history of impacts on Earth

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## Minor bodies in the inner Solar System: the asteroid belt

green:  
asteroid belt



Blue: Trojans  
in Jupiter's  
orbit

<http://www.minorplanetcenter.net>

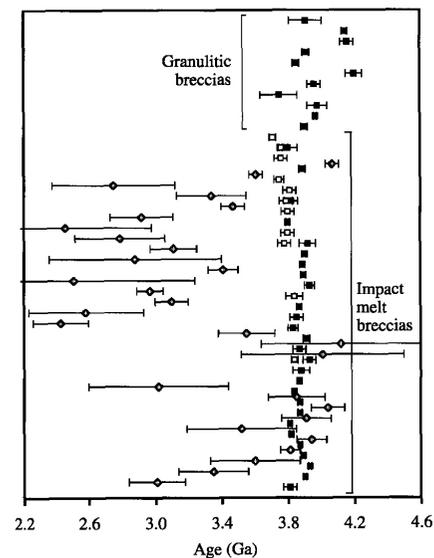
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### Ages of Moon's impact craters

A peak in the frequency of impacts is found around 3.8 Ga

This peak indicates the existence of an episode of dynamical instability in the Solar System at that epoch

Since this episode takes place quite late with respect to the epoch of formation of the Solar System (4.5 Ga), this event of intense collisions is called the "Late Heavy Bombardment"



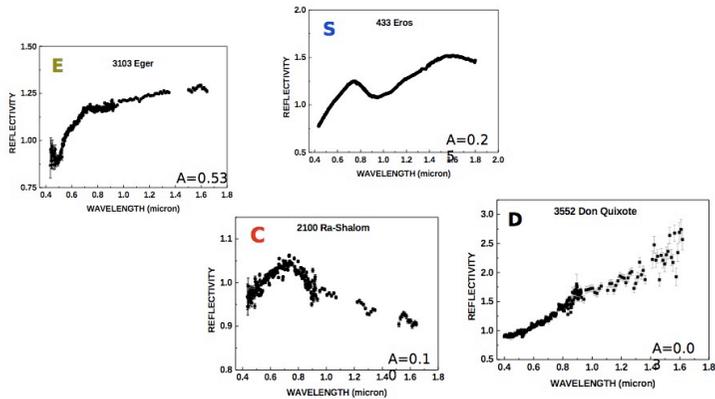
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## Classification of asteroids

- Asteroids are classified according to spectroscopic and/or dynamical measurements
- Spectroscopic/reflectivity observations provide a taxonomical classification related to the physical/mineralogical properties of the surfaces
  - Accurate spectroscopic/reflectivity data are available only for a fraction of asteroids
- Dynamical measurements provide a classification in the space of orbital parameters
  - A large database is available for performing a classification of asteroid families

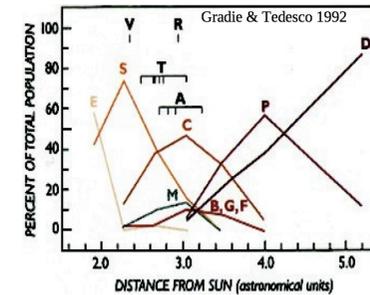
## Taxonomical classification of asteroids

- Based on the study of their reflectivity in different spectral bands
  - The spectral response is indicative of the mineralogy
  - Examples: type E: Enstatite, type S: Silicates, ...



## Radial distribution of asteroid types

- The radial distribution of the types varies with heliocentric distance
- The radial distribution probably reflects a temperature gradient in the Solar System
  - Bodies closest to the Sun are the most processed
  - The most distant bodies are believed to be more primitive

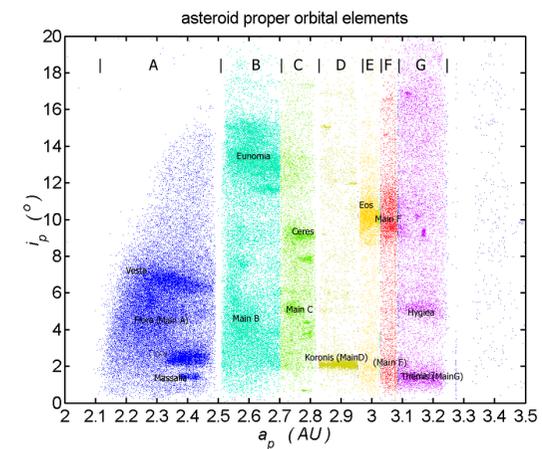


## Taxonomical types and mineralogy of asteroids

| Tax.Type | Minerals  |
|----------|---|
| A        | Olivine $\pm$ FeNi metal                                |
| V        | Pyroxene $\pm$ Feldspar                                 |
| E        | Enstatite<br>Mg-rich pyroxenes                          |
| M        | Metal $\pm$ Enstatite<br>Hydrates Silicates + Organics? |
| S        | Metal $\pm$ Olivine $\pm$ Pyroxene                      |
| O        | Olivine+Pyroxene  |
| Q        | Olivine+Pyroxene (+metal)                               |
| R        | Olivine+Orthopyroxene                                   |
| C        | Iron-bearing hydrated Silicates                         |
| P        | Anhydrous silicates + organics                          |
| D        | Organics+Anhydrous silicates                            |

## Dynamical classification: asteroid families

An asteroid family is a population of asteroids that share similar proper orbital elements, such as semimajor axis, eccentricity, and orbital inclination. The members of each family are thought to be fragments of one asteroid collision



## Largest bodies in the asteroid belt

| Name  | R [km] | M [kg]               | $\rho$ [g/cm <sup>3</sup> ] | a [AU] | e     | i [°] |
|-------|--------|----------------------|-----------------------------|--------|-------|-------|
| Ceres | 473    | $9.4 \times 10^{20}$ | 2.2                         | 2.77   | 0.076 | 10.6  |
| Vesta | 262    | $2.6 \times 10^{20}$ | 3.5                         | 2.36   | 0.099 | 6.4   |

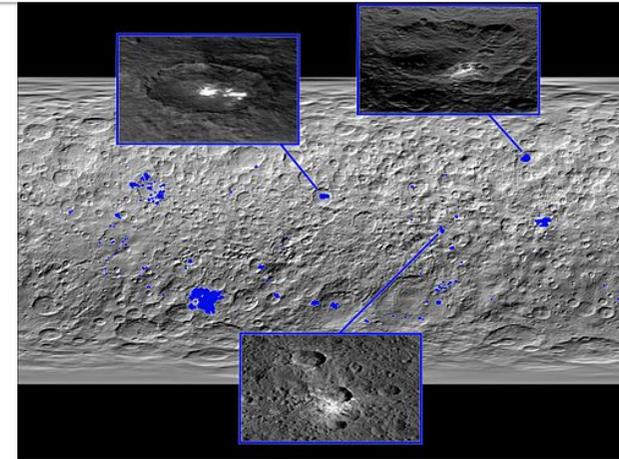
Ceres is a dwarf planet, the only one in the asteroid belt  
Vesta is the largest asteroid

Both have been recently observed with the *DAWN* NASA space mission

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## Bright spots on Ceres

The *DAWN* mission has revealed the presence of bright spots on Ceres' surface  
The bright spots are best explained as resulting from briny water erupted from Ceres' interior that subsequently sublimated, leaving behind only the salt deposits



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## Ceres

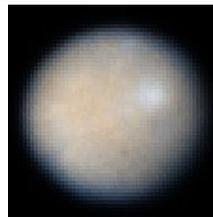
The dwarf planet in the asteroid belt

Ceres comprises 25 percent of the asteroid belt's total mass. Computer models show that nearly round objects such as Ceres have a differentiated interior. This sets Ceres apart from its asteroid neighbors, which are undifferentiated.

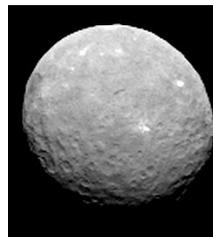
The Herschel Space Observatory found evidence for water vapor on Ceres. The vapor may be produced by *cryovolcanoes* or by ice sublimating near the surface. This suggests that Ceres contains *large amounts of water ice* beneath its surface.

Ceres' water would be in the form of ice and located in the mantle, which wraps around the dwarf planet's solid core.

Ceres from *HST*



Ceres from *DAWN*

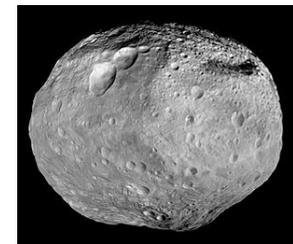


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Vesta from *HST*



Vesta from *DAWN*



## Vesta

Vesta is the second-most-massive body in the asteroid belt, though only 28% as massive as Ceres. The density ( $3.46 \text{ g/cm}^3$ ) is higher than that of most asteroids. It has a differentiated interior.

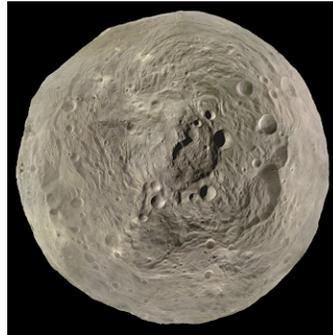
Vesta's shape is close to a gravitationally relaxed oblate spheroid. Analysis of Vesta's shape and gravity field using data gathered by the Dawn spacecraft has shown that Vesta is currently not in hydrostatic equilibrium

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The DAWN mission has revealed the presence of huge craters in the south pole of Vesta

### Vesta craters

The surface of Vesta displays many impact craters. The most prominent are the 500-km-wide Rheasilvia crater, centered near the south pole, and the 400 km-wide Veneneia crater.



It is estimated that the impact responsible for such craters excavated about 1% of the volume of Vesta, and it is likely that *the Vesta family and V-type asteroids are the products of this collision*. It would also be the *site of origin of the HED meteorites*

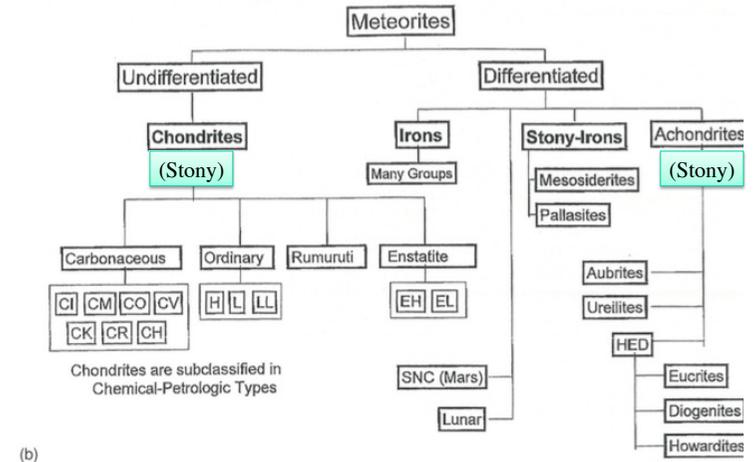
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## Classification of meteorites

Different types of classification exist

One traditional subdivision is between chondrites and non-chondrites

Alternatively, between stony and “irons”



## Meteorites

- **Most meteorites are fragments of asteroids**
  - A few are fragments of Mars or Moon’s surface
- **Meteorites provide a unique information on the first stages of the formation of the Solar System**
  - Dating, primordial chemical composition, material from which planets accreted, planetary formation mechanisms and time scales, chemical differentiation processes, ...
- **Meteorites are classified according to their chemical composition and structure**
  - Meteoritic classes are associated with asteroid types
  - The classification of meteorites is quite complex, featuring many subdivisions

## Chondrites

- Chondrites are believed to be the most pristine material of the Solar System, originated from undifferentiated bodies
- They are composed of a *matrix* that features a large number of *inclusions*
- The **matrix** consists of a fine-grained (micrometre-sized or smaller) dust  
It is an optically opaque mixture of mineral grains  
Represents the least processed material
- The main types of **inclusions** are:
  - Condrules  
Grain-shaped structures mostly composed of silicates  
Believed to be produced in very short and intense heating episodes
  - CAI  
Calcium-Aluminum inclusions, highly refractory, probably the oldest material found in the Solar System  
Metal FeNi, troilite (FeS), olivine compounds

## Examples of chondrites

- **Ordinary chondrite**
  - LL3

The matrix represents a small part of the structure of chondrites

The structure is dominated by the inclusions



- **Carbonaceous chondrite with CAI**
  - CV3

In carbonaceous chondrites the inclusions are less evident



## Non chondritic meteorites

- Characterized by material that has been processed
- They show evidence of melting and/or differentiation of primitive material, suggesting an origin in differentiated bodies
- They do not show inclusions: the inclusions have been probably metamorphosized
- Probably fragments of asteroids in advanced or final stages of formation
- In a very few cases, fragments of Mars and the Moon



Lodranite  
Non chondritic, primitive



Eucrite  
Non chondritic, differentiated aachondritic

## Carbonaceous chondrites CI

- Very rare meteorites
- Important because very pristine and rich of organic material
- Of astrobiological interest

The Allende meteorite is an example of carbonaceous chondrite



- They do not show inclusions
  - Inclusions are believed to have been deleted by aqueous alterations that took place in the asteroidal body
  - The lack of inclusions suggests that in the past, the parent asteroids must have experienced cometary-like activity

## Alteration and processing of meteorites

The different characteristics of meteorites (and asteroids) are believed to be due to the type of processing (alteration) experienced during the stages of formation or at later epochs

Two important types of alterations are aqueous and thermal processing

Such types of alterations cast light on the evolution of the meteorites and their parent bodies

## Evolutionary history of meteorites

