The first million years of the Solar system: from dust to planets

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Three different types of information to reconstruct the origin of the Earth

- Astrophysical observations of young stellar systems analogous to our early Solar system

- Cosmochemical studies of meteorites (fossils of the epoch of the disk before the formation of the Earth)

- Geological and geochemical studies of Hadean and archean rocks
Two kinds of samples: light from stars or solid samples from meteorites (including Mars), the Earth, and the Moon
Orion the Hunter

(Globe by Coronelli for the king of France Louis XIV in 1682)
The Orion constellation
The Orion nebula (M42)
Distance: 1344 ly
Size: 24 ly

Chandra Orion Ultradeep Project
Courtesy Eric Feigelson (COUP/NASA)
HST images, Taurus-Auriga molecular cloud (Padget et al., 1999)
From a cloud of interstellar gas and dust to the Solar system
Theoretical evolution of a forming star (Hertzsprung-Russel diagram)

Luminosity $L = \frac{dE}{dt}$

Effective temperature (black body temperature)
Observed evolution of a forming stars

Credit Preibisch et al. (2005), Siess et al. (2000)

Average duration of each class from Evans et al. 2009
HL Tauri in Taurus constellation
(d= 450 light year, age 100 000 years)

Credit ALMA
(ESO/NAOJ/NRAO)
More than 1 million asteroids >1km
≈ 200 asteroids > 100 km
Biggest one: Ceres 933 km

Mission JAXA Hayabusa
Asteroïd Itokawa = chondrite LL
(Yurimoto et al., 2011)
The chondrite Orgueil has the chemical composition of the Sun: it shows that presolar dust and gas transformed into planetesimals.
Chondrites are “sediments” formed in the accretion disk.

They are fragments of planetesimals (100 -1000 km size) that populated the Solar accretion disk a few Myrs after the start of the Solar system (much before the formation of the Earth but much after time zero).

Chondrites are made of:
- chondrules (10 µm-mm) and their fragments: silicate spherules melted at high temperature in the disk from pre-existing solids
- Ca-, Al-rich inclusions (CAIs) made in the disk from condensation products from the gas
- matrix made from a variety of minerals (low T phases, presolar phases, ...)
Dust (0.1–10 μm)

Gas condensation, inheritance from ISM

Dust agglomerate (<1 m)

Fractal agglomeration, compaction

Planetesimal (1–1,000 km)

Collisional growth, gravitational instability

Embryo (1,000–5,000 km)

Orderly, runaway, and oligarchic growths

Planet (10,000 km)

Chaotic growth

Dauphas & Chaussidon (2011)
We can date very precisely all these processes using natural radioactivity.

Meteorites are the oldest rocks we know: they have accumulated the products of the radioactive decay of several parent isotopes (e.g. isotopes of uranium decay to isotopes of lead).

High precision analyses of the concentration of the parent and daughter isotopes allow to reach a precision of ± 0.2 million years on an age of 4.5 billion years.
Dating condensation with refractory inclusions

Dating accretion with chondrules

Dating Mars with the formation of its core

Dating the accretion of the Earth with the formation of the Moon and the formation of the Earth core
The refractory inclusions are the oldest components of meteorites, the oldest minerals of the solar system.

Age = 4567.3 ± 0.2 million years (Connelly et al., 2012)
“Exceptional” example of a compound chondrule from Allende made of 16 individual chondrules accreted together (Bischoff et al., 2017)

Minimum age of chondrules = age of accretion of chondrites
≈ 4563 million years
Martian meteorite fell in 1815 in France in the village of Chassigny

Dating of martian meteorites tell that Mars has reached 50% of its size 1.8 Myr after the start of the solar system

Credit MNHN Paris

Dauphas & Pourmand 2011
Example of numerical simulations showing the accretion of the Earth from planetesimals and embryos

- Earth accreted 50 to 150 Myr after the start of the solar system
- Giant collision toward the end of accretion with a Mars size body to give the Moon

O’Brien, Morbidelli & Levison, 2006
The Earth covered with a magma ocean $\approx 4.5$ Gyrs ago
the Earth \approx 4.4 \text{ G yrs ago}
No rock from this early period (Hadean) has been preserved

Red = rocks older than 2.5 Gyr at the surface of the Earth
(yellow rocks older than 2.5 Gyr below the surface)
Zircons ($\text{ZrSiO}_4$) from archean rocks in western Australia
Wilde et al. 2001

Cavosie et al., 2006

Zircons as old as 4.37 Gyr show that a crust was existing at that time on Earth
Formation of the solar system

50% of Mars is accreted

Formation of the Earth (core, early crust, atmosphere, oceans)
Chandra observation (7 days long, 50 X-rays images)  
Courtesy Eric Feigelson (COUP/NASA)