Indian Institute of Technology, Kanpur
Department of Earth Sciences

ES0213: Fundamentals of Earth Sciences

Lecture 04. Solar System: origin and characteristics

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IITK Experimental Rock Deformation Laboratory

Aims of this lecture

- Origin and history of Solar System
- Chemistry and structure of young Earth

Origin of Solar System and Planets

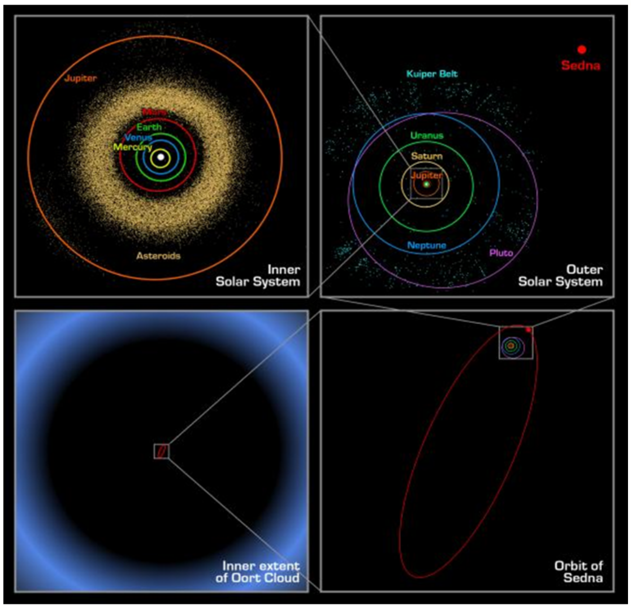
- How was the Solar System Formed?

  A viable theory for the formation of the solar system must be
  - based on physical principles (conservation of energy, momentum, the law of gravity, the law of motions, etc.),
  - able to explain all (at least most) the observable facts with reasonable accuracy, and
  - able to explain other planetary systems.

- How do we go about finding the answers?
  - **Observe:** looking for clues
  - **Guess:** come up with some explanations
  - **Test it:** see if our guess explains everything (or most of it)
  - **Try again:** if it doesn't quite work, go back to step 2.

Solar System from space

- Sun, a star, at the center…
- Inner Planets (Mercury, Venus, Earth, Mars) ~ 1 AU; They are all rocky planets…
- Asteroid Belt, ~ 3 AU
- Outer Planets (Jupiter, Saturn, Neptune, Uranus), ~ 5-40 AU; They are all gaseous planets..
- Pluto: Odd one, a comet… not a planet
- Kuiper Belt ~ 30 to 50 AU
- Oort Cloud ~ 50,000 AU; Where comets come from…



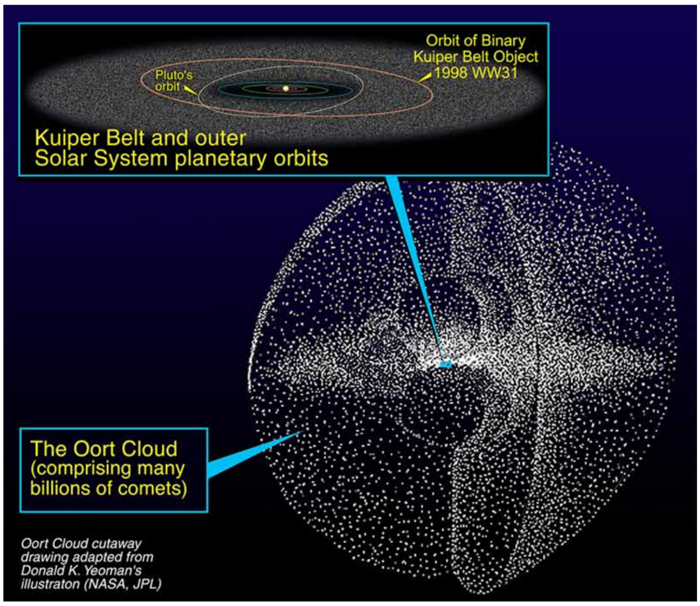
Source: NASA

The Kuiper Belt and the Oort Cloud

- **Kuiper Belt**
  A large body of small objects orbiting (the short period comets) the Sun in a radial zone extending outward from the orbit of Neptune (30 AU) to about 50 AU. Pluto maybe the biggest of the Kuiper Belt object.

- **Oort Cloud**
  Long Period Comets (period > 200 years) seems to come mostly from a spherical region at about 50,000 AU from the Sun.

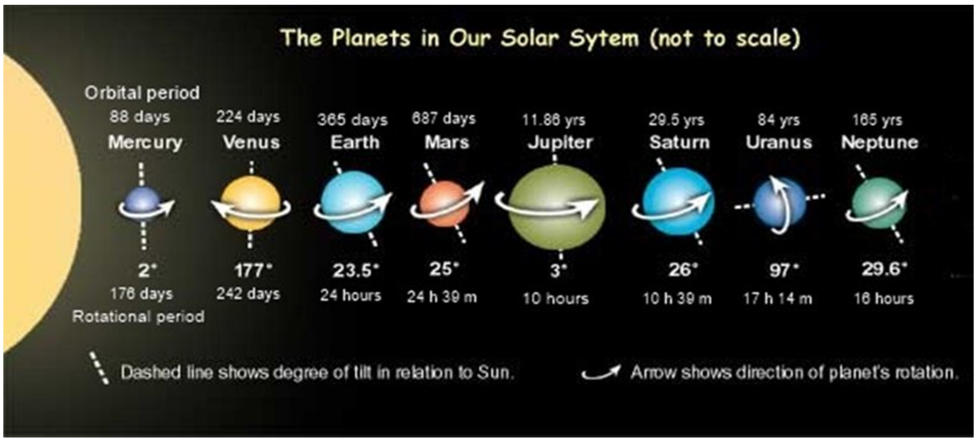
To know more on this:
http://www2.ess.ucla.edu/~jewitt/David_Jewitt.html



Source: NASA

Orbital path and spin

- All the planets orbit the Sun in the same direction
- The rotation axes of most of the planets and the Sun are roughly aligned with the rotation axes of their orbits.
- Orientation of Venus, Uranus, and Pluto's spin axes are not similar to that of the Sun and other planets.



Terrestrial and Jovian Planets

TERRESTRIAL PLANETS	JOVIAN PLANETS
Smaller size and mass	Larger size and mass
Higher density	Lower density
Made mostly of rock and metal	Made mostly H, He and other gasses
Solid Surfaces	No solid surface
Few moons and no rings	Rings and many moons
Closer to the sun and closer together with wormer surface	Further from the sun and further apart with cool temperatures

The planets

Planet	Relative Size	Dist. Frm. Sun (AU)	Avg. Equt. rads (Km)	Mass (Earth=1)	Avg. Density (g/cm³)	Orbital Period	Rotation Period	Axis Tilt	Avg. Surf. T (K)	Composition	Known Moons (2004)	Rings
Mercury		0.387	2.44	0.055	5.43	87.9 d.	58.6 d.	0.0°	700 K (D) 100K (N)	Rocks, Metals	0	No
Venus		0.723	6.051	0.82	5.24	225 d.	243 d.	177.3°	740 K	Rocks, Metals	0	No
Earth		1	6.378	1	5.52	1.00 yr.	29.93 h.	23.5°	290 K	Rocks, Metals	1	No
Mars		1.52	3.397	0.11	3.93	1.88 yr.	24.6 h.	25.5°	240 K	Rocks, Metals	2	No
Jupiter		5.2	71.492	318	1.33	11.9 yr.	9.93 h.	3.1°	125 K	H, He, Hydrogen compounds	79*	Yes
Saturn		9.54	60.268	95.2	0.7	29.4 yr.	10.6 h.	26.7°	95 K	H, He, Hydrogen compounds	31*	Yes
Uranus		19.2	25.559	14.5	1.32	83.8 yr.	17.2 h.	97.9°	60 K	H, He, Hydrogen compounds	27	Yes
Neptune		30.1	24.764	17.1	1.64	165 yr.	16.1 h.	29.6°	60 K	H, He, Hydrogen compounds	14	Yes

* Includes provisional moons

Origin of Solar System and Planets

Historically, two hypothesis were put forward to explain the formation of the solar system….

- **Gravitational Collapse of Planetary Nebula (Latin for "cloud")**

  Solar system formed form gravitational collapse of an interstellar cloud or gas.

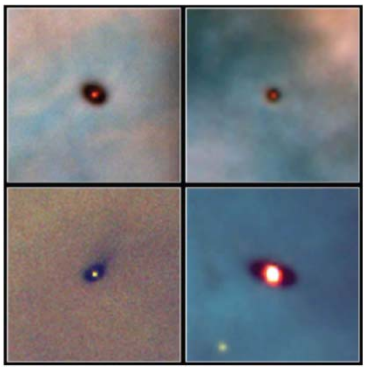
- **Close Encounter (of the Sun with another star)**

  Planets are formed from debris pulled out of the Sun during a close encounter with another star.

  But, it cannot account for the angular momentum distribution in the solar system, Probability for such encounter is small in our neighborhood…

Origin of Solar System and Planets

- Planet formation is a common outcome of star formation; but solar system is unique.
- The solar system may be unique, but to know the origin of Earth and other planets of the solar system observations of other planetary systems are necessary.
- Most developing stars, as viewed through telescopes, are approximately 99 percent gas and 1 percent dust; still they appear opaque at visible wavelengths.



Hubble images of 4 protoplanetary disks around young stars in the Orion nebula, located 1,500 light-years from the Sun. The red glow in the center of each disk is a newly formed star approximately 1 million years old.

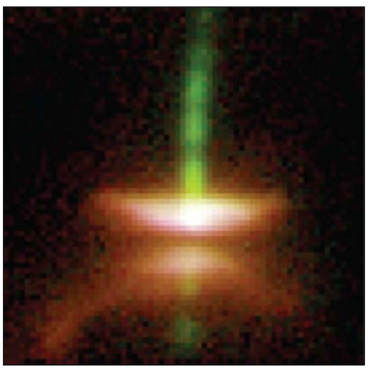


Image of Herbig-Haro 30, a prototype of a young (~1 my old) star surrounded by a thin, dark disk and emitting powerful bipolar jets of gas.. The gas jets, shown in green, are driven by accretion.

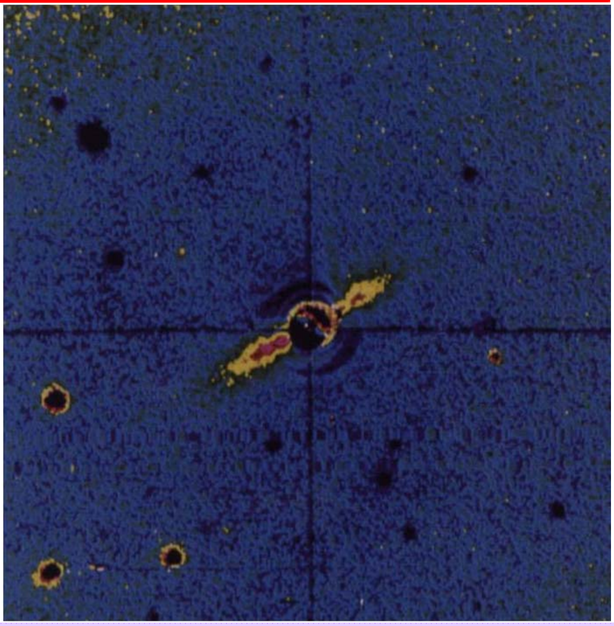
http://hubblesite.org/gallery/album/nebula_collection/

Origin of Solar System and Planets

IRAS telescope image of β Pictoris.

A solar system in the making?

Red = solid material.

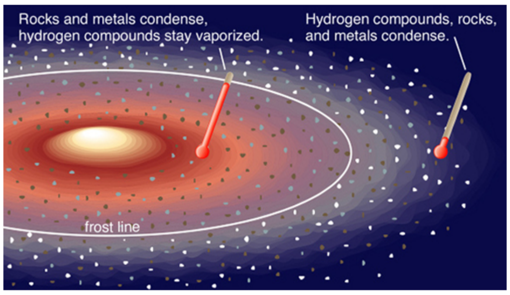


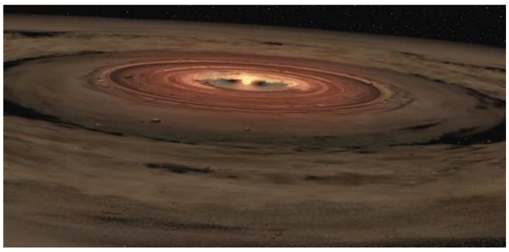
Gravitational Collapse – a scenario

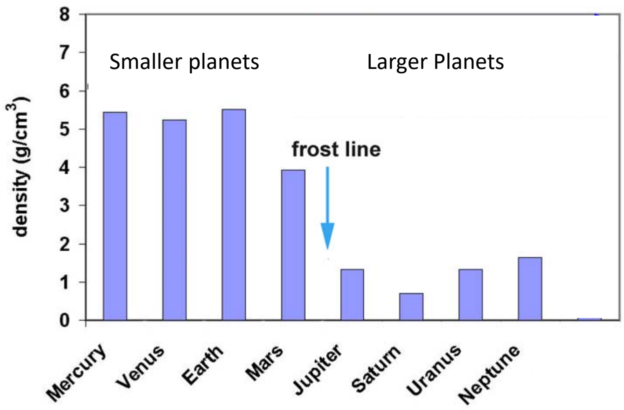
- The solar nebula was initially somewhat spherical and a few light years in diameter
  - very cold
  - rotating slightly
- It was given a "push" by some event
  - perhaps the shock wave from a nearby supernova
- As the nebula shrank, gravity increased, causing collapse
- As the nebula "falls" inward, gravitational potential energy is converted to heat.
  Conservation of Energy
- As the nebula's radius decreases, it rotates faster
  Conservation of Angular Momentum
- Finally it forms a disk like shape
  Orderly motion

Origin of Planets – Nebular Hypothesis

- In the solar system there are two major types of planets -







Origin of Planets – The model

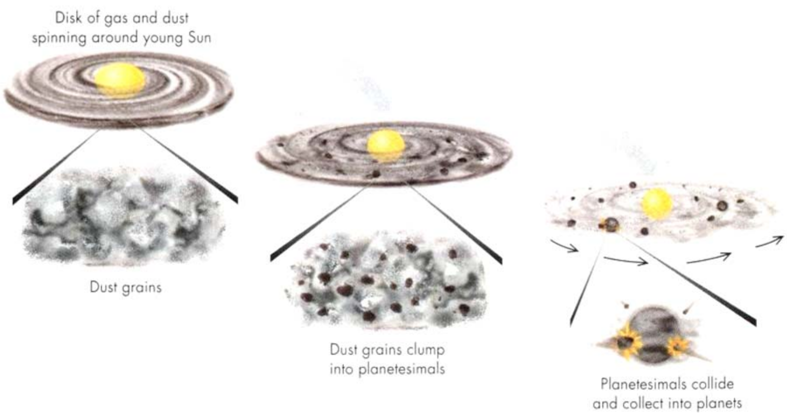
- The Nebular Hypothesis - Planeresimals

A 3rd, 4th or nth generation nebula forms 4.56 Ga.

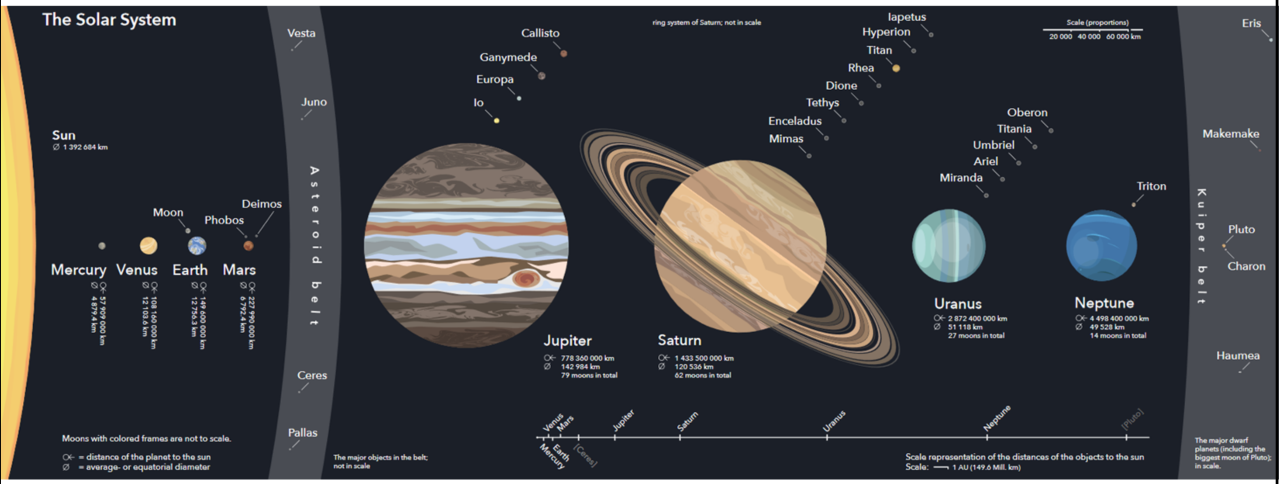
- H and He left over from the big bang.
- Heavier elements produced by stellar fusion and supernovae.

The nebula condenses into an accretion disk.

- Gravity pulls objects inward into a disk
- Causing it to spin faster and heat up.



The solar system



Origin of Planets – the solar system

- The primary difference between the inner and outer planets (rock versus gas and ice) is thought to reflect the temperature gradient in the solar nebula.

- Near the Sun, mainly silicates and metal would have condensed from the gas (so-called refractory materials), whereas beyond the asteroid belt, temperatures were low enough for ices (i.e., water, methane, ammonia) containing more volatile elements to have condensed, as well as solid silicates.

- Was the process that as the nebula cooled and solids formed unidirectional? NO. The solids typically were re-melted, re-evaporated, and re-condensed repeatedly as materials were circulated through different temperature regimes and variously affected by nebular shock waves and collisions between solid objects.

Origin of the larger planets – The models

The formation of giant planets starts with condensation and coalescence of rocky and icy material to form objects several times as massive as Earth. These solid bodies then attract and accumulate gas from the circumstellar disk (Pollack et al., 1996).

- Jupiter and Saturn, the two largest outermost planets fit well with this model as they have H and He, almost equal to solar proportions; but they have heavier elements (residing in the core) in greater than solar proportions.
- Uranus and Neptune have much less abundance of H and He compared Jupiter and Saturn; also have atmospheres consisting of solar ice.

An alternative to the standard model is that the rock and ice balls are not needed to induce the formation of gas-giant planets; they can form directly from the gas and dust in the disk, which can collapse under its own gravity like mini versions of the Sun (Boss, 2002).

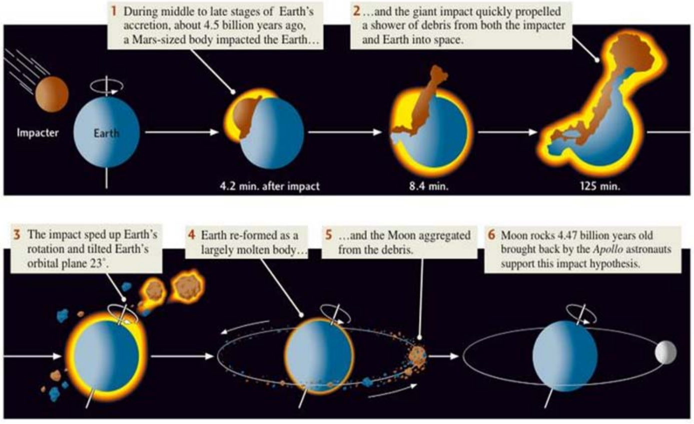
Origin of the inner planets – The models

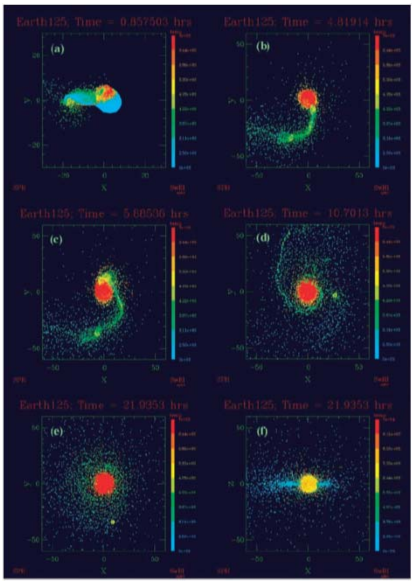
The model for the formation of inner planets is based on the information from meteorites and proposes two distinct stages of planer formation – early- and late-stage.

- The dust grains aggregated slowly at first, and growth accelerated along with object size as small objects were embedded into larger ones. The larger bodies are less affected by the presence of gas and their subsequent evolution is governed by mutual gravitational attractions. Gravitational interactions gave the largest planetesimals nearly circular and coplanar orbits—the most favorable conditions for sweeping up smaller objects.
- The later stages of planet formation took much longer, involved progressively fewer objects. The main phase of terrestrial planet formation probably took a few tens of millions of years. The final stages were marked by the occasional collision and merger of planetary embryos, which continued until the orbits of the resulting planets separated sufficiently to be protected from additional major collisions.

Formation of Moon - model

- Moon rocks provide one of the most persuasive pieces of evidence that Earth and the Moon have a common origin.

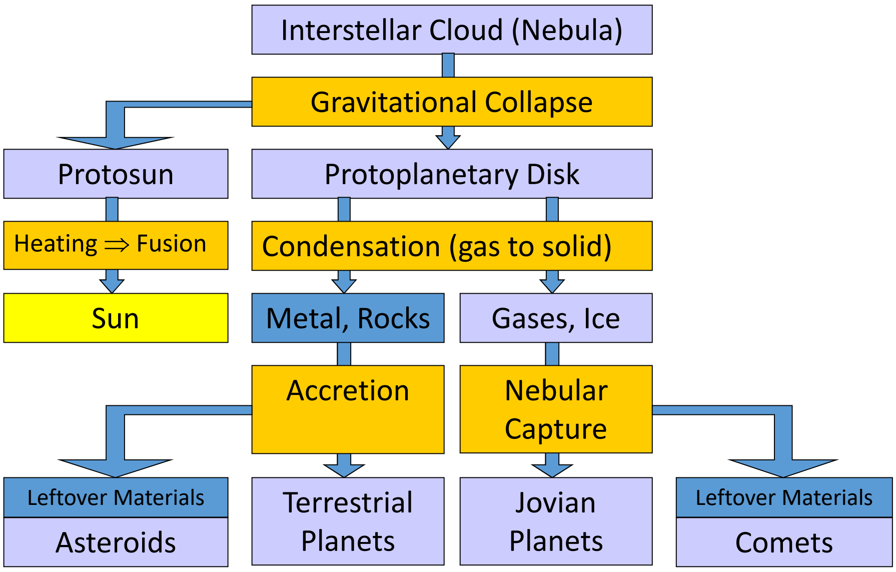




Origin of Solar System, Earth and Moon - steps

- The ball at the center grows dense and hot; fusion reactions begin – the SUN is born.
- More dust in the inner portion, more ice in the outer
  - Material accretes (clumps) into larger and larger planetesimals
  - Outer planets form ice / gas giants
  - Inner planets forms rocky, metallic planets
- Planetesimals accumulate into a larger mass
- An irregularly shaped proto-earth developed
  - Gravity shapes the earth into a sphere
  - The interior heats and becomes soft; differentiates into a Ni-Fe core and a rocky-silicate mantle and crust
- Moon formed
- The atmosphere develops from volcanic gases
- When the Earth becomes cool enough, moisture condenses and accumulates to form ocean [icy comet impact]

Origin of Solar System, Earth and Moon – Flow Diagram



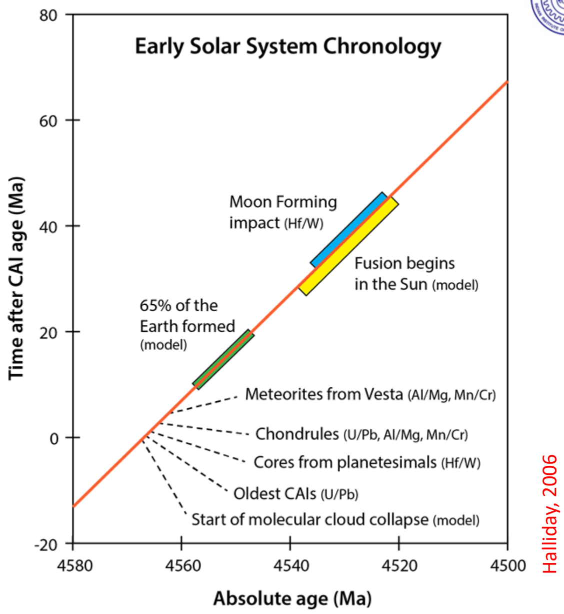
Information from meteorites

- Planets like Earth have undergone a significant geological modifications leaving hardly any evidences about the early development.
- Many meteorites, on the other hand, were not affected by the high-temperature processes that occurs in planetary interiors. Thus, they preserve significant clues about the state of the Solar System when the planets were forming.

Allende Meteorite, a carbonaceous chondrite with Ca, Al rich inclusions (CAI – irregular shaped light colour objects) and chondrules (round light colour objects).

Information from meteorites

- The most primitive chondritic meteorites contain inclusions made up of minerals that condense at high temperature from a gas of solar nebula composition. These objects, called calcium-aluminum-rich inclusions (CAI), have been precisely dated using the decay of uranium to lead, where time is measured by the accumulation of the lead decay products formed at 4,567 (±1) Ma. This age is now generally accepted as "time zero" for the Solar System.

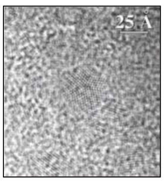


Recent geochronological data and models for the sequence and timing of events in the early Solar System.

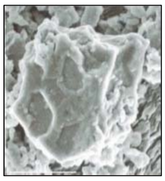
The primitive particles – Presolar Grains

- "Presolar grains" are stardusts manufactured by individual stars before the birth of our Solar System that are preserved in primitive meteorites.
- Each of these grains contains chemical elements that were made or reprocessed by an individual star and keeps information about the initial composition and chemical evolution.

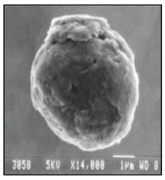
Type	Size	Concentration in Meteorites	Sources
Diamond (C)	1-5 nanometers	1000 parts per million	Supernovae
Silicon carbide (SiC)	0.1-10 micrometers	10 parts per million	Carbon-rich giant stars, or supernovae
Graphite (C)	1-10 micrometers	2 parts per million	Supernovae and carbon-rich giant stars
Aluminum oxide (Al_2O_3)	1-5 micrometers	0.1 parts per million	oxygen-rich giant stars
Spinel ($MgAl_2O_4$)	1 micrometer	2 parts per billion	oxygen-rich giant stars
Silicon nitride (Si_3N_4)	1 micrometer	2 parts per billion	Supernovae



Nano-diamond



SiC



Graphite

Composition of primitive Earth

- At the pre-accretion stage, a very strong differentiation affected by the solar wind, light pressure, short-lived temperature rise, and magnetic separation – GAS COMPONENTS MOSTLY REMOVED.
- The young Earth was a relatively cold celestial body. Nowhere within it had temperature exceeded the melting point of the Earth matter.
- The primordial Earth had a relatively uniform composition. Therefore, there was no Earth core at that time, and there was no chemical stratification into the mantle and crust.
- The source matter was hydro-silicates, carbonates, and sulfur as well as bases and some other easily fusible elements.

Composition of primitive Earth

Oxides	Comp. of conti. Crust [a]	Comp. of Mantle [b]	Comp. of Core	Comp. of Primordial matter (calculated)	Avg. Comp. of chondrites [c]	Avg. Comp. of coaly chondrites [d]
SiO_2	59.3	45.400	–	30.710	38.040	33.000
TiO_2	0.7	0.600	–	0.410	0.110	0.110
Al_2O_3	15.0	3.700	–	2.540	2.500	2.530
Fe_2O_3	2.4	1.970	–	–	–	–
FeO	5.6	6.550	49.340	22.760	12.450	22.000
MnO	0.1	0.130	–	0.090	0.250	0.240
MgO	1.9	38.400	–	25.810	23.840	23.000
CaO	7.2	2.300	–	1.570	1.950	2.320
Na_2O	2.5	0.430	–	0.300	0.950	0.720
K_2O	2.1	0.012	–	0.016	0.170	–
Cr_2O_3	–	0.410	–	0.280	0.360	0.490
P_2O_5	0.2	–	–	–	–	0.380
NiO	–	0.100	–	0.070	–	–
FeS	–	–	6.690	2.170	5.760	13.600
Fe	–	–	43.410	13.100	11.760	–
NiO	–	–	0.560	0.180	1.340	–
Total	100.0	100.000	100.000	100.000	99.480	98.390

[a] Ronov and Yaroshevsky (1978).

[b] Dmitriyev (1973) and Ringwood (1966).

[c] Urey and Craig (1953).

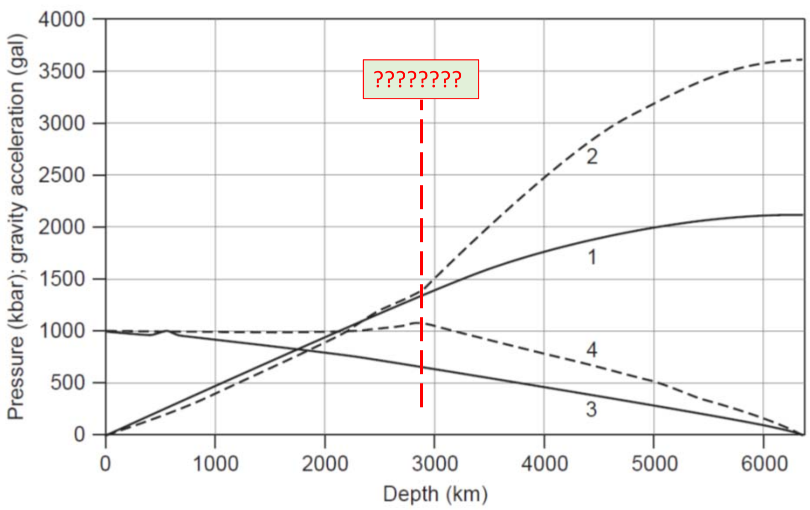
[d] *"Outlines of comparative planetology."* Nauka (1981)

Structure of primitive Earth

Depth (km)	Density (g/cm³)	Temperatu re (K)	Pressure (kbar)	g (cm/s²)
0	3.92	260	0	985
200	4.15	1147	82	980
400	4.38	1385	168	973
400	4.5	1385	168	973
600	4.76	1457	261	986
670	4.85	1294	285	955
670	5.02	1294	285	955
800	5.16	1433	358	941
1000	5.36	1411	456	921
1200	5.53	1400	556	898
1400	5.68	1393	656	874
1600	5.81	1387	754	848
1800	5.93	1384	852	821
2000	6.04	1381	1381	793

Depth (km)	Density (g/cm³)	Temperature (K)	Pressure (kbar)	g (cm/s²)
2200	6.15	1379	1042	764
2400	6.25	1378	1133	734
2600	6.35	1377	1223	703
2800	6.44	1376	1309	670
3000	6.52	1375	1393	638
3400	6.66	1373	1548	569
3800	6.78	1371	1688	498
4200	6.9	1369	1810	425
2600	6.99	1367	1912	350
5000	7.07	1365	1995	273
5400	7.11	1363	2057	196
5800	7.15	1361	2097	119
6200	7.18	1359	2116	52
6360	7.18	1358	2116	0

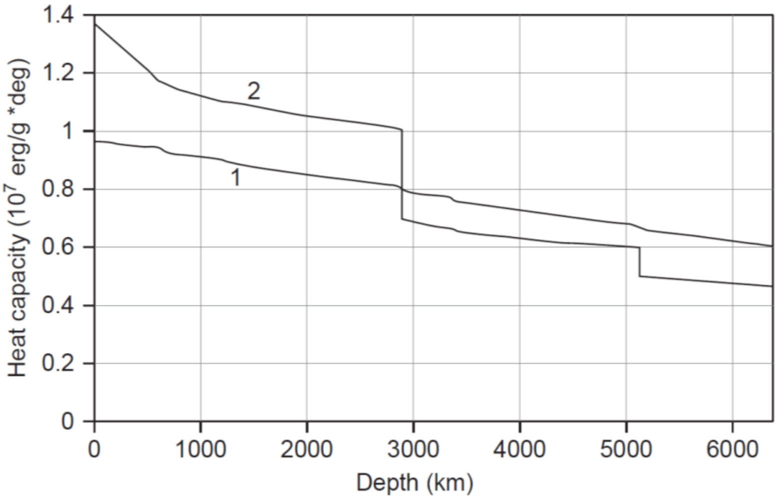
Pressure and Gravity Distribution



Pressure distribution
1: young Earth;
2: present-day Earth;

Gravity acceleration
3: young Earth;
4: present-day Earth.

Heat Capacity Distribution



Hear Capacity
1: young Earth;
2: present-day Earth;

Suggested Reading

- The origin and Evolution of the Solar System – MM Woolfson 2000, IoP

Next Lecture

We shall talk about the Earth as a System and learn some of its basic principles