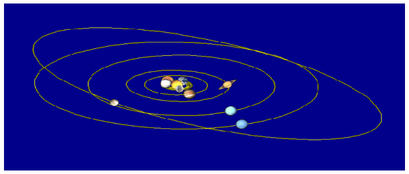
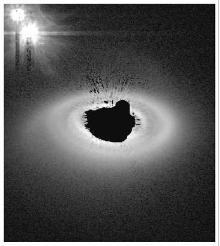
Planet Formation (in the Solar System)





dust disk of HD141569A

Planets in the solar system were formed in a disk
---proto-planetary nebula (or, solar nebula)---
~4.6 Gyr ago.

We have an incomplete theory on how this worked.
But improving as more extra-solar systems are discovered...

concepts: 1) Minimum-mass solar nebula.
2) Planetesimal hypothesis.
3) Frost line.

application: 4) Story about giant & terrestrial planet formation.
test: 5) Isotope dating results; possible problems.

Solar nebula: the **disk** surrounding the newly formed Sun
- High angular momentum, does not fall into the Sun directly
- Likely had the same elemental composition as the Sun
Sun: H 70% H, He 28%, C, N, O ~1.3%, Ne ~ 0.17%, Mg, Al, Si,S, Ca, Fe, Ni ~0.36%
--- also seen in meteorites
- A substantial nebula likely existed for a few Myr,
then, either accreted to the star or blown away by stellar winds & UV
+ a ***small*** fraction locked into planets

Minimum-mass solar nebula

Current mass sum: ~ 1.5 M_J ~ 0.0015 $M_\odot$, originally must be a lot more

Reconstruction of a minimum disk (lower limit):
Replenish all planets back to solar abundance, add them all up
*(Mercury: *350, Earth: *235, Jupiter: *5, Saturn:*8, Uranus:*15...)*
Yields a minimum mass for the solar nebula
$M_{MMSN} \sim 10\ M_J \sim 0.01\ M_\odot$

density decreases outward
at least 85% lost (preceding generations of planets?)
used as starting points in theoretical modeling
compatible with many other observed disks

Evolution of the nebula depends on its initial mass (stability, temperature...)

2) Can planets form in the solar nebula by direct gravitational collapse, just like how stars are thought to form?

No. At least not likely in the case of M_{MMSN} (too low by a factor of ~20)

Tidal gravity from the Sun far exceeds the self-gravity of a sphere of gas
(tidal bulge >~ size of sphere that wants to collapse)

3) The planetesimal hypothesis

Planets are formed step-by-step, starting from dust particles as small as a virus

1) Disk cools, rock/icy grains condense,
forming micron-sized dust grains (mass ~10^{-15} kg, micron)

2) Sticking together, these form pebbles (~1 g, cm)

3) Quick collidisions lead to planetesimals (~10^{12} kg, km) --> the asteroid belt?

4) A few planetesimals dominate -- planetary embryos (~ 10^{18} kg, 100 km)

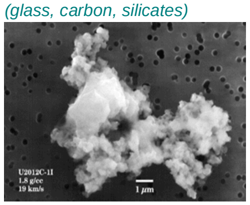
5) Embryos slowly collide, form planetary cores (~ 10^{21} kg, 1000 km, *proto-Earth*)

6) Cores accrete gas and become gaseous planets (~10^{22} kg, *proto-Jupiter*)

steps 2 & 3: dust *somehow* builds up to planetesimals *(stickiness? grav. influence?)*

Many of these planetesimals survive to today

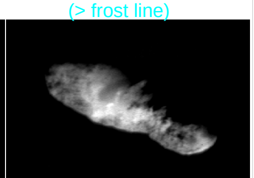
an interplanetary dust particle (glass, carbon, silicates)



rocky planetesimals
(< frost line)

Asteroid Eros (~35km)

icy planetesimals
(> frost line)



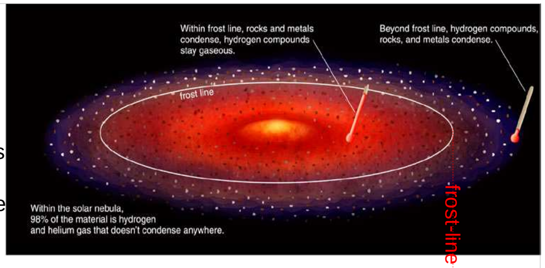
Comet Borelly (~ 8km)

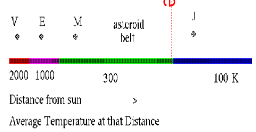
Not everthing is collected into planets---there is left-over junk
1) Some irregular moons – captured planetesimals
2) Kuiper belt -- primordial planetesimals formed at ~30 AU
3) Oort cloud -- planetesimals ejected outward by Jupiter & co.
4) Early bombardment stage (first ~700 Myr)

These pristine (un-differentiated, un-processed) materials provide a window to the early solar system.

frost line

Distance from Sun where temperature was low enough for hydrogen compounds (H_2O,...) to condense into ices, between the present-day orbits of Mars and Jupiter

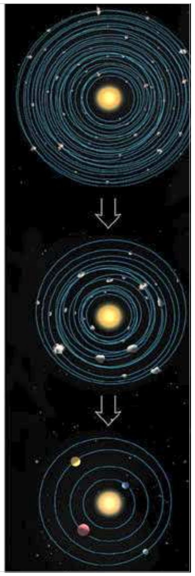




frost-line ~4AU

1) Rocky planetesimals inside frost-line
   T_{melt} < 1300 K, rocks & metals, refractory
   Asteroid belt, terrestrial planets, volatiles in gas phase
2) Icy planetesimals outside frost-line (H_2O: T_{melt} ~150 K @ near vacuum pressure)
   T_{melt} < 150 K (roughly), H_2O-ice, carbon-grains, volatile
   Cores of giant planets, Kuiper belt & Oort cloud (comets),
3) Higher mass-fraction in solids outside the frost-line (solid mass jumps by ~5)
   Carbon, oxygen ~ twice more abundant than heavier elements

Giant & terrestrial planet formation



5th step: planetesimals conglomerate into
10^3 km-sized cores

If core massive enough, H & He can be accreted
----> a giant planet
Jupiter, Saturn, Uranus & Neptune all have cores+gaseous env.

If core does not grow fast enough it cannot accrete gas
----> a terrestrial planet

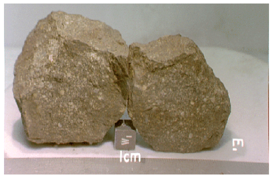
Explains

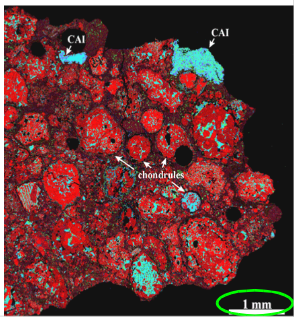
1) Giant planets gas rich, terrestrial no gas.
2) Giant planets formed outside frost line.
   Enriched in metals + icy-rocky core of 10-20 $M_\oplus$
   Outside: more solid (ice), smaller velocity, gas easier to accrete
3) Terrestrial planets formed inside frost line.
   Contain rocky, refractory material.
4) seems to explain our system, but correct?

When was the Solar system formed?
---- Isotope dating

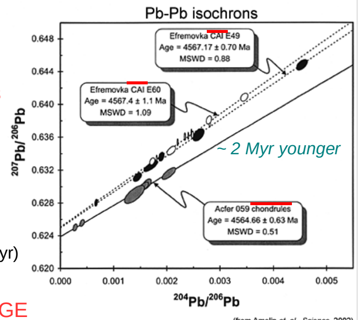
The pristine, leftover junk is useful: meteorites (asteroids, comets, Moon, Mars...)
(pristine: abundances of parent, daughter & non-radiogenic element un-altered)
not melted since condensation, no differential settling, trap some gas

85% of all meterorite finds are chrondrites *(meteoric stone containing chrondrules)*
--- Abundance pattern remarkably close to the Sun
    except for H & He, some volatiles, primordial
--- Chrondrules and CAI (calcium-aluminum-inclusion) appear to have been melted once: heating to ~1700 K + a rapid cooling (~10 min)
    Not melted since!





Isotope dating: results



(from Amelin *et. al.*, *Science*, 2002)

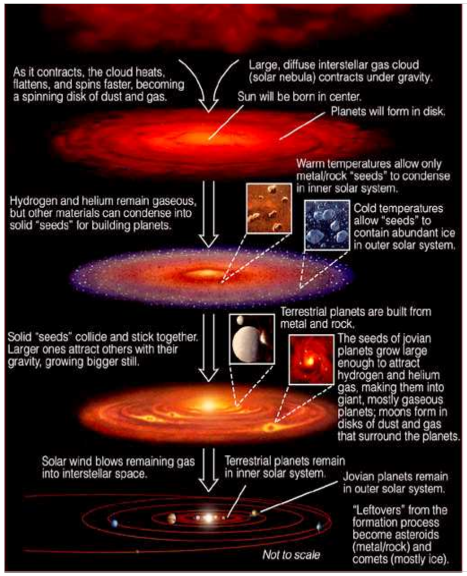
1. The AGE of the solar system (from chrondrites): 4567.2±0.6 Myrs

   Dated using long-lived radio-active nuclei (e.g., $^{238}U \rightarrow {}^{206}Pb$, $t_{1/2}$=4.47 Gyr)

2. There was a last supernova a few Myr before AGE
   Dating using short-lived radio-active nuclei
   (e.g. ^{60}Fe, $t_{1/2}$=1.5Myrs & ^{26}Al, $t_{1/2}$=0.7 Myr)
   SS formation triggered by a supernova?

3. Earth formed within ~10 Myr after AGE
   Relative age dating can be rather accurate using short-lived nuclei
   (e.g. $^{182}Hf \rightarrow {}^{182}W$, $t_{1/2}$=9 Myr, Yin et. al, Klein et. al, Nature 2002)
   TROUBLE FOR THEORISTS!

4. Moon formed within ~30 Myr after AGE
   Age of Moon (since last melt) ~4.5 Gyr, Apollo samples & lunar meteorites.
   Oldest rock on Earth ~4.28 Gyr (Nuvvuagittuq, Hudson Bay, QC)
   (rare, most old rock ~3.8 Gyr, after late heavy bombardment)
   Mars (since last melt) ~4.5 Gyr (Martian meteorites ALH84001 --life?)
   Age of oldest fossils ~ 3.5 Gyr (blue-green algae)

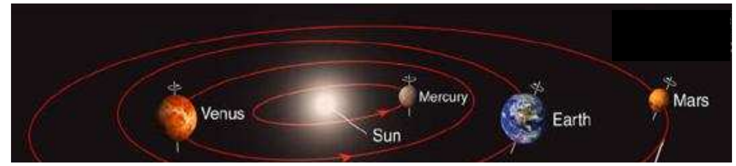


Open issues

have to form planets in ~ few Myrs

1) how did the gas disk disperse?
2) how are planetesimals made? Are dust grains sufficiently sticky?
3) what makes chrondrules?
4) How do planetesimals survive collisions?
5) What is Jupiter's role in the fate of other planets?
6) Do giant planets only form outside frost lines? If so, how to explain the extra-solar hot Jupiters?
7)....

Origin of the Moon



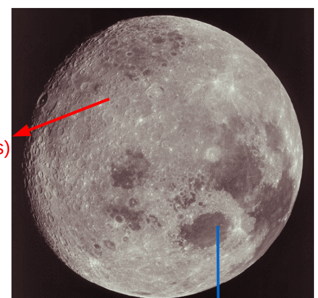
Earth is unique among terrestrial planets in having a large moon
radius ~ 1737 km, mass ~ 10^{23} kg ~ 1% Earth mass ~ Mercury

1) largest satellite/planet mass ratio (except. Pluto/Charon)
2) Moon raises tide, lunar cycles
3) Moon always faces us with the same side *(nodding -> see 59% of Moon)*
4) Moon stabilizes Earth's spin axis/climate

Lunar Geology

no atmosphere, dominated by cratering

1) "land" is older & pock-marked
   early solar-system heavy-bombardment stage
2) "sea" is younger, smoother
   huge impacts, molten lava (dark)
   end of bombardment stage
3) little cratering after the heavy stage,
   no re-surfacing
   surface pulverized by micro-meteroites
   (Earth is constantly resurfaced; soil made by weathering & life)
4) clues to formation from comparison with Earth
   ~400 kg of lunar rocks returned in '70s
   lunar rock has little water and other volatiles (low boiling T material)
   iron-deficient (small iron core, < 200km)
   similar isotope pattern (e.g. Oxygen, different from meteorites)



Terrae (lands)
craters
~4 Gyr old

Maria (seas)
smooth
3.1-3.8 Gyr old

Various hypothesis for the origins of Planetary Satellites – and of our Moon

capture

Phoebe (@S), Deimos/Phobos(@M)
Moon: why oxygen isotopes?
small initial separation?
very massive?

fission

fast spinning planet
if above break-up speed
Moon: why volatiles gone?

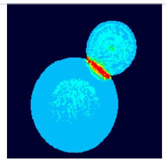
accretion disk

primordial accretion disk
Io, Europa... (@J)
Moon: why ecliptic plane?
why volatiles gone?

giant impact

molten ejecta recollect
also explain Pluto-Charon?
Moon: iron-poor, volatile poor
isotope ratios similar

Current Favourite --- impact



Canup et al.

I) How big was the impactor? (to melt a significant fraction of Earth)

$$\frac{1}{2} m v^2 \approx k_B T \frac{M_E}{\mu m_H}$$

$$v \sim 10\,\text{km/s}, \; T \sim 5000\,\text{K}, \; \mu \sim 10 \;\Rightarrow\; m \sim 0.05 M_E \sim M_{Mars}$$

some mass ejected by pressure gradient, formed a disk
In disk: volatiles: vaporized and lost; non-volatiles: molten and re-solidified quickly

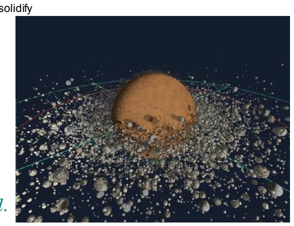
II) How fast does a 1 km-size piece of ejecta re-solidify?

$$k_B T \frac{4\pi}{3} R^3 \left(\frac{\rho}{\mu m_H}\right) \approx 4\pi R^2 \sigma T^4 \times t_{solidify}$$

takes mere hours...
(but need to check conduction is not the bottleneck; still should be fast)

III) How do the boulders re-collect?.
only one moon was formed in the disk
multiple moon-lets
accrete each other by mutual gravity

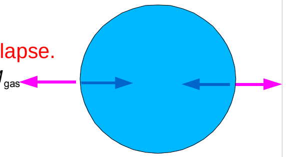
Kokubo et al.



Extra Notes: Can planets form in the solar nebula by gravitational collapse -- just like how stars form?

No. At least not likely in our case.
Tidal gravity of the Sun too strong, prevents collapse.

Consider forces on a ball of gas of size d and mass M_{gas} at a distance a from the Sun



Tidal force due the Sun: $f_{tide} \approx \frac{G M_s M_{gas}}{a^2} \left(\frac{d}{a}\right)$

Self-gravity of the gas ball: $f_{self} \approx \frac{G M_{gas}^2}{d^2} \approx \frac{G \rho d^3}{d^2} \approx G \rho d$

$$f_{self} > f_{tide} \;\to\; \boxed{\rho > \frac{M_s}{a^3}} \sim 2\times10^{-4}\ \text{kg/m}^3 \left(\frac{1\,AU}{a}\right)^3$$

-- *the Toomre criterion for structure formation in a disk*

For comparison: $\rho_{MMSN} \sim 10^{-5}\,\text{kg/m}^3 \left(\frac{1\,\text{AU}}{a}\right)^{5/2}$

MMSN contains a mass too low by a factor ~ 20.