Formation of the Solar System

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Key Questions

• What is the Solar System made of?
• How and when did the planets form?
• How have they evolved subsequently?
• How typical is our Solar System?

• Suggested reading if you want more than is posted for class reading.
  April 2004 issue of Physics Today (especially the articles by Stevenson and Canup)

What does the Solar System consist of?

• The Sun: 99.85% of the mass (78% H, 20% He)
  (Jupiter and Saturn almost another 0.1%)  
• Nine Eight Planets
• Satellites
• A bunch of other junk (comets, asteroids, Kuiper Belt Objects etc.)
**Where is everything?**

Note logarithmic scales!

1 AU is the mean Sun-Earth distance = 150 million km

Nearest star (Proxima Centauri) is 4.2 LY=265,000 AU

**Where is it? (cont’d)**

Distances on this figure are in AU. Areas of the planets are scaled by their masses. Percentages are the total mass of the solar system (excluding the Sun) contained by each planet. Note that Jupiter completely dominates.

We conventionally divide the outer solar system bodies into gas giants, ice giants, and small bodies. This is a compositional distinction. How do we know the compositions?

<table>
<thead>
<tr>
<th>Basic data</th>
<th>Distance (AU)</th>
<th>$P_{\text{orb}}$ (yrs)</th>
<th>$P_{\text{rotation}}$ (days)</th>
<th>Mass ($10^{24}$ kg)</th>
<th>Radius (km)</th>
<th>$r$ ($g$ cm$^{-3}$)</th>
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<tbody>
<tr>
<td>Sun</td>
<td>-</td>
<td>-</td>
<td>24.7</td>
<td>2x10^9</td>
<td>695950</td>
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<tr>
<td>Mercury</td>
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<td>0.24</td>
<td>58.6</td>
<td>0.33</td>
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<td>0.62</td>
<td>243.0R</td>
<td>4.87</td>
<td>6052</td>
<td>5.24</td>
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<td>1.00</td>
<td>5.97</td>
<td>6371</td>
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<tr>
<td>Mars</td>
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<td>1.88</td>
<td>1.03</td>
<td>0.64</td>
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<td>3.93</td>
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<tr>
<td>Jupiter</td>
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<td>1899</td>
<td>71492</td>
<td>1.33</td>
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<tr>
<td>Saturn</td>
<td>9.57</td>
<td>29.60</td>
<td>0.44</td>
<td>568</td>
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<td>102.4</td>
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<tr>
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<td>248.6</td>
<td>6.39R</td>
<td>0.013</td>
<td>1152</td>
<td>2.05</td>
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</table>

See e.g. Lodders and Fegley, *Planetary Scientist’s Companion*
Solar System Formation

- The basic characteristics of this Solar System — composition, mass distribution, angular momentum distribution — are mainly determined by the manner in which the solar system originally formed
- To understand the subsequent evolution of the planets (and other objects), we need to understand how they formed
- We’ll look at composition first . . .

Solar System Is Chemically Zoned

- Silicates: \( \rho \approx 3.0 \text{ g/cm}^3 \)
- Iron alloys: \( \rho \approx 8.0 \text{ g/cm}^3 \)
- Ices (compressed \( \text{H}_2, \text{H}_2\text{O}, \text{NH}_3, \text{CH}_4 \)): \( \rho \approx 1.0 \text{ g/cm}^3 \)
- \( \rho_{\text{planet}} = \rho_{\text{Fe}} \text{VF}_{\text{Fe}} + \rho_{\text{Si}} \text{VF}_{\text{Si}} + \rho_{\text{ice}} \text{VF}_{\text{ice}} \)
- where VF is volume fraction

In the beginning . . .

From Albarede, *Geochemistry: An introduction*
Key Observations

- H and He most abundant
- Exponential decrease up to elements 40 to 50
- Abundance above 50 is low
- Zig-zag pattern: Even > odd (Oddo-Hacking Rule)
- Li, Be, B are anomalously low
- Fe is anomalously high

Nucleosynthesis

- Elements are generated by nucleosynthesis within stars.
- Elements are scattered during stellar explosions (supernovae) and form clouds of dust and gas (nebulae) ready to form the next generation of stars and planets.
- From star size and color, can estimate temperature at depth
  - $15 \times 10^6$ K at center of Sol
- Sol can burn H

Hydrogen burning:

\[ 4\text{H} \rightarrow 3\text{He} + \nu + \text{energy/light (gamma)} \]
(4 step process)
Up to $\sim 10^8$ K

10$^6$ K

He burning by $\alpha$ capture.

\[ 3\text{He} \rightarrow ^{12}\text{C} + \text{energy/light (gamma)} \]
Li, B, and Be are very unstable thermally, decay back to H.

\[ ^{12}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} \]
\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{24}\text{Mg} \]
$\alpha$ capture explains even over odd preference
Nucleosynthesis

$4 \times 10^9$ K

Star more than 10x more massive than Sol

$^{26}\text{Si} + ^{24}\text{Mg} \rightarrow ^{54}\text{Fe} + \text{energy}$

This is the last type of fusion reaction that releases energy

E.g., $^{56}\text{Fe} + ^{4}\text{He} \rightarrow ^{60}\text{Ni}$

This is why Fe is over abundant

Other Processes

Slow neutron capture

E.g., $^{98}\text{Mo} + \text{neutron} \rightarrow ^{99}\text{Mo} \rightarrow ^{99}\text{Tc} + \text{electron (e$^-$)}$

Fast neutron capture

E.g., $^{116}\text{Sn} + 5\text{neutrons} \rightarrow ^{121}\text{Sn} \rightarrow ^{121}\text{Sb} + \text{electron (e$^-$)}$

### Nucleosynthesis

- Fast neutron capture only occurs in supernovae (10x to 25x Sol mass).
- Presence of elements generated by these processes is evidence that our star is at least a second generation star, after a more energetic precursor.
- Elements are scattered during stellar explosions (supernovae) and form clouds of dust and gas (nebulae) ready to form the next generation of stars and planets

### Solar System Formation - Overview

- Some event (e.g. nearby supernova) triggers gravitational collapse of a cloud (nebula) of dust and gas
- As the nebula collapses, it forms a spinning disk (due to conservation of angular momentum)
- The collapse releases gravitational energy, which heats the centre; this central hot portion forms a star
- The outer, cooler particles suffer repeated collisions, building planet-sized bodies from dust grains (accretion)
- Young stellar activity (T-Tauri phase) blows off any remaining gas and leaves an embryonic solar system
- These argument suggest that the planets and the Sun should all have (more or less) the same composition
- Comets and meteorites are important because they are relatively pristine remnants of the original nebula
Timescale of events

1. Nebular disk formation
2. Initial coagulation (~10 km, ~10⁴ yrs)
3. Orderly growth (Moon size, ~10⁵ yrs)
4. Runaway growth (~10⁶ yrs), Jupiter forms, gas loss (?)
5. Late-stage collisions (~10⁷ yrs)

CAI (0 Ma)
Metal asteroids (~1 Ma)
HED's (~1-4 Ma)
Mars silicate diffn. (~40 Ma)
Moon-forming impact (~100 Ma)

An Artist’s Impression

Observations (1)

- Early stages of solar system formation can be imaged directly – dust disks have large surface area, radiate effectively in the infra-red
- Unfortunately, once planets form, the IR signal disappears, so until very recently we couldn’t detect planets (now we know of >300)
- Timescale of clearing of nebula (~1-10 Myr) is known because young stellar ages are easy to determine from mass/luminosity relationship.

This is a Hubble image of a young solar system. You can see the vertical green plasma jet which is guided by the star's magnetic field. The white zones are gas and dust, being illuminated from inside by the young star. The dark central zone is where the dust is so optically thick that the light is not being transmitted.
Observations (2)

- We can use the present-day observed planetary masses and compositions to reconstruct how much mass was there initially. I.e., the minimum mass solar nebula.
- This gives us a constraint on the initial nebula conditions e.g. how rapidly did its density fall off with distance?
- The picture gets more complicated if the planets have moved . . .
- The observed change in planetary compositions with distance gives us another clue – silicates and iron close to the Sun, volatile elements more common further out.

Cartoon of Nebular Processes

- Nebular disk is flared
- Temperatures and pressures decrease radially – consequence of lower irradiation, and lower surface density and optical depth leading to more efficient cooling.

What is the nebular composition?

- Why do we care? It controls what the planets are made of?
- How do we know?
  - Composition of the Sun (photosphere)
  - Primitive meteorites (see below)
  - (Remote sensing of other solar systems - not yet very useful, though this is likely to change)
- An important result is that the solar photosphere and the primitive meteorites give very similar answers.
- This gives us confidence that our estimates of nebular composition are correct.
Solar photosphere

- Visible surface of the Sun
- Assumed to represent the bulk solar composition (is this a good assumption?)
- Compositions are obtained by spectroscopy
- Only source of information on the most volatile elements (which are depleted in meteorites): H, C, N, O

Primitive Meteorites

- Meteorites fall to Earth and can be analyzed
- Radiometric dating techniques suggest that they formed during solar system formation (4.56 Ga)

Three Basic Kinds
1. Ice-rich meteorites: <1% of falls, 0% of finds
2. Stony-Fe and Fe alloy meteorites: 10% of falls, 95% of finds
3. Stony meteorites: 90% of falls, 5% of finds

Primitive Meteorites

- Carbonaceous (CI) chondrites: a type of stony meteorite that contain chondrules (inclusions) and do not appear to have been significantly altered.
- They are also rich in volatile elements
- Compositions are very similar to Comet Halley (measured by Rosetta spacecraft) also assumed to be ancient, unaltered and volatile-rich
**Primitve Meteorites**

*Carbonaceous chondrites:*

Carbon-rich matrix with Hydrous Silicates

Serpentine - $X_2\text{Si}_2\text{O}_5\text{(OH)}_2\text{X = Mg, Fe}^{2+}, \text{Fe}^{3+}, \text{Ni, Al, Zn, or Mn.}$

Tremolite - $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}\text{(OH)}_2$

Some chondrules have odd composition:

CAI (calcium-aluminum inclusions):

- $\text{MgAl}_2\text{O}_4$ - spinel
- $\text{CaAlSi}_2\text{O}_7$ - gehlenite
- $\text{CaTiO}_3$ - perovskite

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**Meteorites vs. Photosphere**

- This plot shows the striking similarity between meteoritic and photospheric compositions.
- Note that volatiles (N,C,O) are enriched in photosphere relative to meteorites.
- We can use this information to obtain a best-guess nebular composition.

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**Nebular Composition**

- Based on solar photosphere and chondrite compositions, we can come up with a best-guess at the nebular composition (here relative to $10^6$ Si atoms):

<table>
<thead>
<tr>
<th>Element</th>
<th>H</th>
<th>He</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Ne</th>
<th>Mg</th>
<th>Si</th>
<th>S</th>
<th>Ne</th>
<th>Fe</th>
<th>Log (No. Atoms)</th>
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<tr>
<td>Log$_{10}$ (No. Atoms)</td>
<td>10.44</td>
<td>9.44</td>
<td>7.00</td>
<td>6.42</td>
<td>6.32</td>
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<td>6.0</td>
<td>5.76</td>
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<td>Condens. Temp (K)</td>
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<td>780</td>
<td>1340</td>
<td>1320</td>
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<td>1320</td>
<td>1320</td>
<td>1320</td>
<td>1333</td>
</tr>
</tbody>
</table>

- Blue are volatile, red are refractory.
- Most important refractory elements are Mg, Si, Fe, S (in the ratio 1:1:0.9:0.45).


This is for all elements with relative abundances $>10^5$ atoms.
Three kinds of planets . . .

- Nebular material can be divided into "gas" (mainly H/He), "ice" (CH$_4$, H$_2$O, NH$_3$ etc.) and "rock" (including metals)
- Planets tend to be dominated by one of these three end-members (see Stevenson article)
- Proportions of gas/ice/rock are roughly 100/1/0.1

- The compounds which actually condense will depend on the local nebular conditions (temperature)
- E.g. volatile species will only be stable beyond a "snow line". This is why the inner planets are rock-rich and the outer planets gas- and ice-rich

Terrestrial (silicate) planets

- Consist mainly of silicates ((Fe,Mg)SiO$_4$) and iron (plus FeS)
- Mercury is iron-rich, perhaps because it lost its mantle during a giant impact
- Volatile elements (H$_2$O, CO$_2$, etc.) uncommon in the inner solar system because of the initially hot nebular conditions
- Some volatiles may have been supplied later by comets
- Satellites like Ganymede have similar structures but have an ice layer on top (volatiles are more common in the outer nebula)
Gas and Ice Giants

- Jupiter and Saturn consist mainly of He/H with a rock-ice core of ~10 Earth masses
- Their cores grew fast enough that they captured the nebular gas before it was blown off
- Uranus and Neptune are primarily ices (CH$_4$,H$_2$O,NH$_3$ etc.) covered with a thin He/H atmosphere
- Their cores grew more slowly and captured less gas

Figure from Guillot, *Physics Today*, (2004). Sizes are to scale. Yellow is molecular hydrogen, red is metallic hydrogen, ices are blue, rock is grey. Note that ices are not just water ice, but also frozen methane, ammonia etc.

Samples

- In some cases we can check our theoretical predictions of planetary compositions by looking at samples
- Generally restricted to near-surface
- For the Earth, we have samples of both crust and (uniquely) the mantle (peridotite xenoliths)
- We have 382 kg of lunar rocks ($29,000 per pound) from 6 sites (7 counting 0.13 kg returned by Soviet missions)
- Eucrite meteorites are thought to come from asteroid 4 Vesta (they have similar spectral reflectances)
- The Viking, Pathfinder, Spirit/Opportunity and Phoenix landers on Mars carried out in situ measurements of rock and soil compositions
- We also have meteorites which came from Mars

How old is the solar system?

- We date the solar system using the decay of long-lived radioactive nuclides e.g. $^{238}$U-$^{206}$Pb (4.47 Gyr), $^{235}$U-$^{207}$Pb (0.70 Gyr)
- These nuclides were formed during the supernova which supplied the elements making up the original nebula
- The oldest objects within meteorites (calcium-aluminium inclusions, or CAI’s), have an age of around 4560 Myr B.P
- Some meteorites once contained live $^{26}$Al, which has a half-life of only 0.7 Myr. So these meteorites must have formed within a few Myr of $^{26}$Al production (in the supernova).
- Current best estimate of solar system age is 4568 Myr

Meteorite isochron (from Albarede, *Geochemistry: An Introduction*)
Accretion Timescales

• Theoretical calculations suggest that the rate of growth (accretion) decreases as surface density $\Sigma$ and orbital mean motion $n$ decrease. Both these parameters decrease with distance from the Sun (as $a^{-1.5}$ [Kepler's law] and $a^{-1}$ to $a^{-2}$, respectively).
• So rate of growth is a strong function ($\sim a^{-2}$) of distance
• So the inner planets probably formed earliest; Jupiter and Saturn grew fast enough to capture a lot of nebular gas, while Uranus and Neptune grew too slowly to do so
• Early stages of accretion are rapid (runaway growth) – in the inner solar system growth to Mars-size planetary embryos takes ~1 Myr

Late-Stage Accretion

• Once each planet has swept up debris out of the area where its gravity dominates that of the Sun (its Hill sphere), runaway growth ends and accretion slows down drastically
• Size of planets (the “isolation mass”) depends on radius of the Hill sphere and local nebular density, ~ Mars-size at 1 AU
• Collisions now only occur because of mutual perturbations between planets, timescale $\sim 10^{7-8}$ yrs, but can be important (e.g. Moon-forming impact)

High-resolution accretion

Raymond et al. 2006, run 2a, N=1054
Complications

1. Timing of gas loss
   a. Presence of gas tends to cause planets to spiral inwards, hence timing of gas loss is important
   b. Since outer planets can accrete gas if they get large enough, the relative timescale of planetary growth and gas loss is also important

2. Jupiter formation
   a. Jupiter is so massive that it significantly perturbs the nearby area e.g. it scattered so much material from the asteroid belt that a planet never formed there
   b. Jupiter scattering is the major source of the most distant bodies in the solar system (Oort cloud)
   c. It must have formed early, while the nebular gas was still present. How?

Timescale Summary

- Dust grains (~Moon-size, planetesimal) → Orderly growth → ~0.1 Myr
- Gas grains (~Mars-size, embryos) → Runaway growth → ~1 Myr
- Gas grains (~Earth-size, planet) → Late-stage accretion (Giant impacts, Gas loss?) → ~10-100 Myr

Consequences of Accretion

- Large amounts of energy delivered for bodies greater than ~ Mars-size
- Magma oceans develop, leading to further differentiation (e.g. lunar plagioclase crust)
- Initially homogeneous body separates into core plus mantle – molten iron percolates easily even through solid mantle

\[ ^{182}\text{Hf}^{182}\text{W} \text{ decay gives timescale of core formation (few to few tens of Myr for silicate bodies)} \]
Summary: Building a generic planet

• Planets accrete from the solar nebula, which has a roughly constant composition (except volatiles)
• Nebular gas may cause the planets to spiral inwards
• The quantity of volatiles accreted depends on the position and growth rate of the accreting body, and the timing of gas blowoff
• The process of accretion leads to conversion of grav. energy to heat – larger bodies are heated more
• If enough heating happens, a silicate body will differentiate, leading to a core-mantle structure
• Late-stage impacts can have dramatic effects (e.g. forming the Moon, tilting Uranus)

Two afterthoughts

• Orbital evolution and the Kuiper Belt
  – The outer planets may have moved (a lot!)
• Extra-solar planets
  – Our solar system is not typical (?)

Kuiper Belt

• ~800 objects known so far, occupying space between Neptune (30 AU) and ~50 AU
• Largest objects are Pluto, Charon, Quaoar (1250 km diameter), 2004 DW – probably even larger (Earth-size?) objects not yet discovered
• Two populations – low eccentricity, low inclination (“cold”) and high eccentricity, high inclination (“hot”)
• The Kuiper belt is the source of short period comets
• Difficult to form bodies >1000 km when so little total mass present (~0.1 Earth mass), and so far from the Sun (accretion is slow)
• See Mike Brown’s article in Physics Today Apr. 2004 and Alessandro Morbidelli’s review in Science Dec. 2004
Kuiper Belt Formation

What does the “Nice model” explain?

- Two populations (“hot” and “cold”)
  - Transported by different mechanisms (scattering vs. resonance with Neptune)
  - “Cold” objects are red and (?) smaller; “hot” objects are grey and (?) larger
  - Hot population formed (or migrated) closer to Sun
- Formation and (current) position of Neptune
  - Easier to form it closer in; current position determined by edge of initial planetesimal swarm (why should it have an edge?)
- Small present-day total mass of Kuiper Belt for the size of objects seen there
  - It was initially empty – planetesimals were transported outwards

Extra-Solar Planets

- A very fast-moving topic
- What are they like?
- Is our Solar System typical? No!
What are they like?

- Big, close, and often highly eccentric – “hot Jupiters”
- What are the observational biases?

Note the absence of high eccentricities at close distances – what is causing this effect?

Two populations?

A (schematic) explanation?

Two populations because of two pileup locations, at snow line and at inner edge of gas disk
Summary

- **What is the Solar System made of?**
  The same stuff as the photosphere and carbonaceous chondrites – rock/metal, ices and gas (H/He)

- **How and when did the planets form?**
  By accreting from dust grains to planetesimals (0.1 Myr) to embryos (1 Myr) to planets (10-100 Myr)

- **How have they evolved subsequently?**
  In lots of ways! Giant impacts have had important effects; so have the migration of Uranus and Neptune due to scattering of planetesimals by Jupiter

- **How typical is our Solar System?**
  Not very, judging by the hot Jupiters observed in many other solar systems