OCN 201: Origin of the Earth and Oceans

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Is Earth like the rest of the Universe?

• Based on what we know… no…
• But it formed within our universe so the same building blocks led to formation of our solar system, then to Earth…
• So what makes our planet so different?
• The chemical composition of Earth and its location are key, as you will see…
With only a few exceptions, each of the reservoirs (sun, earth, oceans, atmosphere, life) is made up of a different set of elements.

This implies **CHEMICAL DIFFERENTIATION**
CHEMICAL DIFFERENTIATION:

--large-scale separation of chemical elements on the basis of their physical and chemical properties, by a variety of processes

**Solar System:**  
Sun  
Inner rocky planets  
(Mercury, Venus, Earth, Mars, asteroid belt)  
Outer gas-giant planets  
(Jupiter, Saturn)  
Outer ice-giant planets  
(Uranus, Neptune)

**Earth:**  
*Core of iron  
*Mantle and crust of rock  
Oceans  
Atmosphere  

(*How do we know? Meteorites, bulk density, seismic waves, sampling)
Our Solar System: sizes are to scale; distances are not!

Inner *rocky* planets: Mercury, Venus, Earth, Mars, asteroid belt

Outer *gas-giants*: Jupiter, Saturn

Outer *ice-giants*: Uranus, Neptune

(Pluto is rocky and about the size of Earth’s Moon. It was probably captured from outside the Solar System.)
Our Solar System, to scale.
The inner rocky planets lie close to the Sun.
Note the irregular orbit of Pluto
Bulk Composition of Earth

- Fe 36.0 wt%  
- O 28.7  
- Si 14.8  
- Mg 13.6  

93.1

Eight most abundant elements account for 98-99% of total Earth mass

*Note the Sun has 75% H and 23% He*
Formation of the solar system from the solar nebula: I

- Nebula: cloud of interstellar gas and dust aggregated to form stars, gravity compressed them and T rose to \( \sim 10M \)!
- Medium-sized star such as our Sun can only make elements up to C \((z=6)\) and O \((z=8)\) by fusion
- Our Sun will end its life as a Red Giant
- 5-6 Gy from now our Sun will expand so that Earth will lie within the Red Giant (I have recently seen a different idea…)
- More massive stars can make elements up to \( z = 26 \) (Fe)
- All other elements come from SUPERNOVA
<table>
<thead>
<tr>
<th>Name of Process</th>
<th>Fuel</th>
<th>Products</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen-Burning</td>
<td>H</td>
<td>He</td>
<td>$60 \times 10^6 , ^\circ K$</td>
</tr>
<tr>
<td>Helium-Burning</td>
<td>He</td>
<td>C, O</td>
<td>$200 \times 10^6 , ^\circ K$</td>
</tr>
<tr>
<td>Carbon-Burning</td>
<td>C</td>
<td>O, Ne, Na, Mg</td>
<td>$800 \times 10^6 , ^\circ K$</td>
</tr>
<tr>
<td>Neon-Burning</td>
<td>Ne</td>
<td>O, Mg</td>
<td>$1500 \times 10^6 , ^\circ K$</td>
</tr>
<tr>
<td>Oxygen-Burning</td>
<td>O</td>
<td>Mg to S</td>
<td>$2000 \times 10^6 , ^\circ K$</td>
</tr>
<tr>
<td>Silicon-Burning</td>
<td>Mg to S</td>
<td>Elements near Fe</td>
<td>$3000 \times 10^6 , ^\circ K$</td>
</tr>
</tbody>
</table>
For a **larger star**: As hydrogen runs out, starts to collapse, temperature goes up and then star explodes.

Supernova explosion lasts ~10 seconds.

All elements heavier than iron are formed in this way!
Left: Crab Nebula, remains of supernova first observed by Chinese in 1054

Right: First image of a possible planet outside our solar system (at bottom left of image at end of filament from star)

Left: Supernova 1987 A as viewed by the Hubble Space Telescope in 1994

Right: Red Giant or end of a solar system? The glowing gas of this nebula once formed the outer layers of a star of a size similar to our sun
Formation of the solar system from the solar nebula: II

- Composition of our solar system includes heavy elements
- Suggests our solar nebula was struck by expanding shock wave of a supernova
- Disturbance probably caused nebula to spin and splashed matter into space to become planets

$10^5$ light year
Formation of the solar system from the solar nebula: III

- Planets share common orbital plane because of spin.
- Disturbance from supernova could also have hastened gravitational condensation of nebula into Sun and planets.
A nebula (a large, diffuse gas cloud of gas and dust) contracts under gravity. As it contracts, the nebula heats, flattens, and spins faster, becoming a spinning disk of dust and gas.

Star will be born in center. Planets will form in disk.
Next stages...

Hydrogen and helium remain gaseous but other materials can condense into solid “seeds” for building planets.

Warm temperatures allow only metal/rock “seeds” to condense in the inner solar system.

Cold temperatures allow “seeds” to contain abundant ice in outer solar system.

Solid “seeds” collide and stick together. Larger ones attract others with their gravity, growing bigger still.

Terrestrial planets are built from metal and rock.

The seeds of gas giant planets grow large enough to attract hydrogen and helium gas, making them into giant, mostly gaseous planets; moons form in disks of dust and gas that surround the planets.
The Final Product…
Our Solar System

Terrestrial planets remain in inner solar system.
Gas giant planets remain in outer solar system.

“Leftovers” from the formation process become asteroids (metal/rock) and comets (mostly ice).

Not to scale
Summary of our Solar System

• By the time solar system spun and produced the current planetary arrangement, its composition was nearly final:
  ➔ 75% Hydrogen
  ➔ 23% Helium
  ➔ 2% everything else…

• Central part of nebula, mostly H and He became our Sun

• Material condensed on the periphery accreted gravitationally… but heat of sun affected its distribution

• Rocky planets (refractories) formed closest to sun

• Gas planets (volatiles) condensed furthest out

• Asteroid belt (between Mars and Jupiter) is a failed planet
Volatile and Refractories: I

- Volatiles... Have low boiling points, condense at VERY LOW temperature

- Light elements, i.e., H, He and others that are gases at room T (O, N, He, Ne, Ar, Kr, Xe, Rn) and simple compounds like CO$_2$, H$_2$O, NH$_3$, CH$_4$

- Formed the gas-giant planets: Jupiter, Saturn, Uranus, Neptune
Volatile and Refractories: II

- Refractories...Have high boiling points and are solids at even VERY HIGH temperatures
- Heavier elements: Ca, Al, Ti (1300-1500°C), Fe, Ni, Co, Mg, Si (1000-1300°C),
- Formed rocky planets: Mercury, Venus, Earth, Mars, and the Asteroid belt
- Pluto (about size of Earth’s moon) is thought to have been captured by solar system
Origin of the Sun and Earth:
The Solar Nebula and Planetisimals
As a result of collisions, planetesimals accrete.

This process ultimately forms Earth and the other rocky planets.
Formation of the Earth: I

- Earth formed by accretion of smaller bodies
- These “planetesimals” had formed earlier
- Composition of Earth suggests the planetesimals were already “cold” prior to accretion as Earth
- Earth is relatively depleted in noble gases… …but is enriched in elements that form volatiles
- Latter would have been lost from “hot” system
Formation of the Earth: II

• Accretion was relatively rapid (~150 My)
• Accretion would have heated “protoearth” which would result in loss of volatiles from a small body
• Therefore Earth must have had accumulated a large mass to retain volatiles by time it heated up
• Current mass of Earth allows retention of all volatiles except H and He… these are continuously lost to space
Steps in Formation of the Earth
### Bulk Composition of Earth

- Fe 36.0 wt%
- O 28.7
- Si 14.8
- Mg 13.6
- Ni 2.0 wt%
- Ca 1.7
- Al 1.3
- Rest 1.9

Seven most abundant elements account for 98.1% of total Earth mass.
Hypotheses for the Formation of the Moon

1. Capture of another celestial body by gravity
2. Fission as a result of rapid Earth rotation
3. Formation simultaneously with Earth by same process of accretion
4. Formation as result of Earth being struck by a large planetesimal (about size of Mars)
Formation of the Moon

- Moon has no metallic core (it stuck to Earth)
- Moon is dry (heat caused loss of volatiles)
- Enriched in refractories
- Off center impact (explains angular momentum of E-M system)
- Increased spin velocity of Earth
- Note: Uranus has large tilt of similar origin, Venus only rotates once a year ➔ one day equals one year on Venus
Age of the Earth: I

- Meteorites: most are $4.5 \pm 0.1$ Ga (two types, Stony and Iron)
- Moon:
  1) Highland crust (formed from magma ocean) is $\sim 4.4$ Ga
  2) Major bolide (comet or asteroid) impacts are $\sim 4.5-3.9$ Ga
  3) Melting of interior and eruption of Mare basalts $\sim 4.3-2.0$ Ga
• Earth:

1) Age of Earth indistinguishable from Moon and Meteorites... ~4.54 Ga

2) Accretion likely complete by 4.45-4.40 Ga

3) Oldest minerals (zircons) from much younger sedimentary rocks in W. Australia ~4.2 Ga

4) Oldest rocks: Acasta gneiss (NW Canada) ~3.96 Ga. Other rocks from Greenland, W. Aust, Antarctica, China, and Wyoming are 3.80~3.96 Ga)
ACASTA GNEISS, a group of metamorphic rocks in northern Canada, is the oldest known intact piece of the earth’s surface. Radioactive dating indicates that the Acasta gneiss is nearly four billion years old, proving that some continental material existed only a few hundred million years after the earth’s formation.

3.96 billion-year-old

Acasta Gneiss, NW Canada: oldest known intact piece of Earth’s surface
Age of the Earth: III

- Oldest life from N.W. Australia (bacteria like) is ~3.5+ Ga
- Oldest rocks from the seafloor are only ~170 Ma

WHY?
Aloha, see you next time...