Formation of the Solar System &
the Structure of Earth

OCEAN 355 Lecture Notes #2

Origin of Solar System from nebula

- Slowly rotating cloud of gas & dust
- Gravitational contraction
- High P=High T (PV=nRT)
- Rotation rate increases (conserve angular momentum)
- Rings of material condense to form planets (Accretion)

Stanley (1999)
Observational Clues to the Origin of the Planets

- Inner planets are small and dense
- Outer planets are large and have low density
- Satellites of the outer planets are made mostly of ices
- Cratered surfaces are everywhere in the Solar System
- Saturn has such a low density that it can't be solid anywhere

The Solar System

Stanley (1999)
Formation of the Earth by Accretion: 1

- Initial solar nebula consisted of cosmic dust & ice with least volatile material condensing closest to the Sun and most volatile material condensing in outer solar system.


distance from sun ~ ~ ~ ~

**Formation of the Earth by Accretion: 2**

- **Step 1:** accretion of cm sized particles
- **Step 2:** Physical Collision on km scale
- **Step 3:** Gravitational accretion on 10-100 km scale
- **Step 4:** Molten protoplanet from the heat of accretion

http://zebu.uoregon.edu/ph121/l7.html
Formation of the Earth by Accretion: 3

• Tremendous heat generated in the final accretion process resulted in initially molten objects.
• Any molten object of size greater than about 500 km has sufficient gravity to cause gravitational separation of light and heavy elements thus producing a differentiated body.
• The accretion process is inefficient, there is lots of leftover debris.
• In the inner part of the solar system, leftover rocky debris cratered the surfaces of the newly formed planets (*Heavy Bombardment*, 4.6-3.8 Ga).
• In the outer part of the solar system, the same 4 step process of accretion occurred but it was accretion of ices (cometisemals) instead of grains.

http://zebu.uoregon.edu/ph121/7.html

The Sun & Planets to Scale

NASA-JPL
More Planetary Eye Candy from Hubble

http://hubblesite.org/gallery/album/solar_system_collection/1

Jupiter, Saturn, Uranus, Mars

After much outcry, NASA plans a final space shuttle servicing mission to HST in Aug. '08 to extend capabilities through 2013

In 2004, NASA administrators canceled a final servicing mission to the telescope that had been scheduled for 2008. The officials based the decision on concerns for the safety of astronauts after the loss of the space shuttle Columbia in 2003. Scientists, politicians, and astronomy enthusiasts protested that the decision would bring an early end to the telescope's observations. NASA officials then agreed to study the possibility of sending a robotic craft to perform needed repairs.

HOUSTON - NASA managers officially are targeting August 7, 2008, for the launch of the fifth and final space shuttle servicing mission to the Hubble Space Telescope. During the 11-day flight, Atlantis' seven astronauts will repair and improve the observatory's capabilities through 2013.

Mission planners have been working since last fall, when the flight was announced, to determine the best time in the shuttle manifest to support the needs of Hubble while minimizing the impact to International Space Station assembly. NASA also will support a "launch on need" flight during the Hubble mission. In the unlikely event a rescue flight becomes necessary, shuttle Endeavour currently is planned to lift off from Launch Pad 39-B at NASA's Kennedy Space Center, Fla. However, managers constantly are evaluating the manifest to determine the best mission options.

Shuttle missions beyond the Hubble flight, designated STS-125, still are being assessed. Shuttle and station program officials will continue to consider options for the remainder of the shuttle flights to complete construction of the space station by 2010, when the fleet will be retired. Those target launch dates are subject to change.

Earth Accretion Rate Through Time

http://www.whoi.edu/science/MCG/pge/project4.html

- Hafnium-182 decays to Tungsten-182 with a half-life of 9 Myr
- ~60 Myr after the beginning of the Solar System all $^{182}$Hf would have decayed
- Hf is retained entirely in the mantle during core-mantle segregation while W is preferentially partitioned into the core.
- If core formation occurred during the lifetime of $^{182}$Hf, an excess of $^{182}$W should develop in the mantle as a consequence of its enhanced Hf/W ratio
- This excess of $^{182}$W has been measured & indicates that core formation on Earth occurred ~30 Myr after the beginning of the Solar System
- So inner planets formed very rapidly (<30 Myr) with smaller bodies forming faster
- Moon must have formed by another mechanism…

Terrestrial Planets Formed Rapidly

Kleine et al. (2002). Nature 418: 952-955
Yin et al. (2002). Nature 418: 949-952
Accretion continues…

**Chicxulub Crater, Gulf of Mexico**
- 200 km crater
- 10-km impactor
- 65 Myr BP
- Extinction of 75% of all species!

**Meteor (Barringer) Crater, Arizona**
- 1 km diam. Crater
- 40-m diam Fe-meteorite
- 50 kyr BP
- 300,000 Mton
- 15 km/s

http://www.gi.alaska.edu/remsense/features/impactcrater/imageexplain.htm

Interplanetary Dust Accumulation

**40±20 x10^4 metric tons/ yr**
(40 x10^{10} g) interplanetary dust accretes every yr!

2090 kg / 2007 Sport Trac Explorer

http://www.whoi.edu/science/MCG/pge/project4.html
Size & Frequency of Impacts

- 100 m object impacts every 10 kyr
- 10 km object every 100 Myr
- 40±20 x 10^4 metric tons/yr interplanetary dust accretes every yr!

The Asteroid Belt

- A relic of the accretion process. A failed planet.
- Gravitational influence of Jupiter accelerates material in that location to high velocity.
- High-velocity collisions between chunks of rock shatter them.
- The sizes of the largest asteroids are decreasing with time.

<table>
<thead>
<tr>
<th>Total mass (Earth = 1)</th>
<th>0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of objects &gt; 1 km</td>
<td>~100,000</td>
</tr>
<tr>
<td>Number of objects &gt; 250 km</td>
<td>~12</td>
</tr>
<tr>
<td>Distance from Sun</td>
<td>2-4 AU</td>
</tr>
<tr>
<td>Width of asteroid belt (million km)</td>
<td>180</td>
</tr>
</tbody>
</table>
Asteroid 243 IDA

- Meteorite = asteroid that has landed on earth
- All chondrites (meteorites) date to ~4.5 B.y.
- Cratering indicates early origin

Differentiation of the Earth: 1

- VM Goldschmidt (1922) published landmark paper “Differentiation of the Earth”:
  1. Earth has a chondritic (meteoritic) elemental composition.
  2. Surface rocks are not chemically representative of solar abundances, therefore must be differentiated.
- Proto-planet differentiated early into a dense iron-rich core surrounded by a metal sulfide-rich shell above which floated a low-density silicate-rich magma ocean.
- Cooling of the magma caused segregation of dense silicate minerals (pyroxenes & olivines) from less dense minerals (feldspars & quartz) which floated to surface to form crust.
- In molten phase, elements segregate according to affinities for:
  Fe = siderophile, sulfide = chalcophile & silicate = lithophile.
Differentiation of Earth: 2

- Driven by density differences
- Occurred within ~100 Myr

Differentiation of the Earth: 3

**Differentiation of Earth**

Homogenous planetesimal

Earth heats up

Accretion and compression (T~1000°C)

Radioactive decay (T~2000°C)

Iron melts--migrates to center, forming core

Frictional heating as iron migrates

Light materials float--crust

Intermediate materials remain--mantle

**Differentiation of Continents, Oceans, and Atmosphere**

Continental crust forms from differentiation of primal crust

Oceans and atmosphere

*Two hypotheses*

*internal*: degassing of Earth’s interior (volcanic gases)

*external*: comet impacts add H₂O CO₂, and other gases

Early atmosphere rich in H₂, H₂O, N₂, CO₂; deficient in O₂

---

**Earth’s Crustal Evolution: 1.**

**3 Types of Planetary Crust**

1° = original crystalline material to solidify from magma oceans of newly accreted bodies. None of this survives on Earth, but the white highlands of the moon are a good example. Impact that created moon produced 1° crust.

2° = slow heating by radioactive decay melts small quantities of rock in planetary interiors. Results in eruption of basaltic lavas. E.g., Earth’s ocean floor, surfaces of Mars & Venus, lunar maria.

Taylor & McLennan (1996); NASA-JPL
Hypothesis for lunar origin - Moon forms from debris ejected as a result of the collision of a roughly Mars-sized impactor with early Earth

- Geophysical simulations use a method known as smooth particle hydrodynamics, or SPH and can achieve resolutions sufficient to study the production of orbit-bound debris necessary to yield the Moon.
- Off-center, low-velocity collisions yield material in bound orbit from which a satellite may then accumulate.
- Simulations must account for mass, angular momentum and compositions of the earth-Moon system.
- Must yield an Earth that retains an iron-rich core and a moon that is appropriately iron-depleted and the right density.

SPH results suggest:
- The object had 10-12% of Earth's mass (Mars-size!)
- Produces a satellite with <3% Fe by mass. Unable to be subsequently captured.
- Happened near end of Earth's accretional history.
- Resulted in melting of Earth crust.
Numerical Simulation of Moon-Formation Event

- Mars-size object (10% $M_E$) struck Earth
- Core merged with Earth
- Moon coalesced from ejected debris of impactor’s mantle
- Explains high rotation rate of Earth
- Heat of impact melted crust
- Magma ocean #2

The Moon

- Critical to life (stabilizes tilt)
- Rocks from crater rims are 4.0-4.6 Ba (heavy bombardment)
- Jupiter’s gravity shielded Earth and Moon from 1,000x more impacts!
Earth’s Crustal Evolution: 1.
3 Types of Planetary Crust

1° = original crystalline material to solidify from magma oceans of newly accreted bodies. None of this survives on Earth, but the white highlands of the moon are a good example. Impact that created moon produced 1° crust.

2° = slow heating by radioactive decay melts small quantities of rock in planetary interiors. Results in eruption of basaltic lavas. E.g., Earth’s ocean floor, surfaces of Mars & Venus, lunar maria.

Taylor & McLennan (1996); NASA-JPL

Earth’s Crustal Evolution: 2

3° Crust = Formed from slow, continuous distillation by volcanism on a geologically active planet (i.e., plate tectonics).
• Results in highly differentiated magma distinct from basalt. i.e., the low-density, light-colored granite we see in rocks on the continents.
• Earth may be the only planet where this type of crust exists.
• Unlike 1° & 2° crusts, which form in < 200 M.y., 3° crusts evolve over billions of years.

Taylor & McLennan (1996)
Igneous Rocks

Basalt
(2° Crust; Oceanic crust)

Granite
(3° Crust; Continental Crust)

The Crust
Ocean Crust
- 3-15 km thick
- Basaltic rock
- Young (<180 Ma)
  - Density ~ 3.0 g/cm³
Continental Crust
- 35 km average thickness
- Granitic rock
- Old (up to 3.8 Ga)
  - Density ~ 2.7 g/cm³
- Crust "floating" on "weak" mantle

The Mantle
- ~2900 km thick
- Comprises >82% of Earth’s volume
- Mg-Fe silicates (rock)
  - Two main subdivisions:
    - Upper mantle (upper 660 km)
    - Lower mantle (660 to ~2900 km; "Mesosphere")
Why is Continental Crust “Elevated Relative to Oceanic Crust?”

- High-density Basalt sinks into mantle more than low-density Granite.
- Volcanism continually produces highly differentiated continental crust on Earth.
- Venus surface appears to be all basalt.
- Plate tectonics & volcanism do not appear to be happening on Venus (or Mars, Moon).
- So Earth may be unique in Solar System. And plate tectonics & volcanism may be critical in determining habitability.

Lithosphere & Asthenosphere

Lithosphere/Asthenosphere: Outer 660 km divided into 2 layers based on mechanical properties. Includes the Mantle + Crust

- **Lithosphere**
  Rigid outer layer including crust & upper mantle
  Averages 100 km thick; thicker under continents

- **Asthenosphere**
  Weak, ductile layer under lithosphere
  Lower boundary ~660 km (entirely within mantle)

The Core

- **Outer Core**
  ~2300 km thick
  Liquid Fe with Ni, S, O, and/or Si
  Magnetic field is evidence of flow
  Density ~ 11 g/cm³

- **Inner Core**
  ~1200 km thick
  Solid Fe with Ni, S, O, and/or Si
  Density ~13.5 g/cm³

- **Earth’s Interior: How do we know its structure?**
  - Avg density of Earth (5.5 g/cm³)
  - Denser than crust & mantle
  - Composition of meteorites
  - Seismic wave velocities
  - Laboratory experiments
  - Chemical stability
  - Earth’s magnetic field

From Stanley (1999)
Basics of Geology

Lithospheric Plates

• 8 large plates (+ add’l. small ones)
• Average speed: 5 cm/yr
• 3 types of motion result in 3 types of boundaries: sliding toward (subduction zones), sliding away (ridge axes), sliding along (transform faults)
Convection Drives Plate Movements

Tectonic Activity in the South Atlantic

From Stanley (1999)
Rock Basics

Igneous + metamorphic = Crystalline Rocks

From Stanley (1999)

The Rock Cycle

From Stanley (1999)
### Igneous Rocks 101

#### Felsic
- Si-, Al-rich. Light-colored, low-density. Feldspar (pink) & quartz (SiO₂)-rich. Most continental crust. Granite most abundant.

#### Mafic
- Mg-, Fe-rich. Dark-colored, high-density. Most oceanic crust. Ultramafic rock (more dense) forms mantle below crust.

#### Extrusive
- Cools rapidly; small crystals

#### Intrusive
- Cools slowly; large crystals

---

#### Plate Tectonics & the Rock Cycle

- Slab of lithosphere is subducted, melted & incorporated into asthenosphere
- Convection carries molten material upward where it emerges along a spreading zone as new lithosphere.

- Subducted sediment melts at a shallower depth where it contributes to magma emitted from an island arc volcano and a mountain chain volcano
- Erosion of volcanic rock provides sediment sediment to complete cycle

---

From Stanley (1999)
Sedimentary Rocks Represent Homogenous Mixture of Continental Crust


The Habitable Zone of the Solar System
Habitable Zone (Ecosphere)

- Region around a star where planet temperature allows liquid water to exist
- \(273 < T_p < 373\) K
- distance of the habitable zone from the star will vary depending on the type of star

480°C too hot no water

Venus atm.
- 90 bar
- 96% CO\(_2\)
- 3% N\(_2\)
Mars Atm.
95% CO$_2$
2.7% N$_2$
1.6% Ar

-60°C
too
cold.....

no atmosphere
.....and no life
Atm of 78% N\textsubscript{2}  
1% Ar, CO\textsubscript{2}  
and H\textsubscript{2}O  
15°C + oceans  
just right......

What Keeps the Earth Warm?

The power received from the Sun is balanced by heat emission from the Earth.
Must allow liquid water to exist!

Habitable Zone of Solar System

- The sun’s luminosity has increased 30% in last 4.6 Gyr!
- So the HZ has moved out
E.g., The Sun Habitable Zone of Solar System

- The Sun’s luminosity has increased 30% in last 4.6 Gyr!
- So the HZ has moved out

$t_{1}-t_{0}=4.6\text{ b.y.}$
Other Considerations Influencing HZ

*Caveat*: We are relegated to only considering life as we know it & to considering physical conditions similar to Earth

- **Greenhouse effect**: Increases surface $T$
  (e.g., Venus, at 0.72 AU, is within HZ, but $T_s \approx 745$ K!)

- **Lifetime of star**: larger mass = shorter lifetime
  (must be long enough for evolution)

- **UV radiation emission**: larger mass = more UV
  (deleterious to life… as we know it)

- **Habitable zone moves outward with time**
  (star luminosity increases with age)

Further Characteristics of the Habitable Zone

- **Liquid water**
- **Sources of carbon and energy**
  - $\text{CO}_2$, organic matter
  - energy from chemistry of rocks + water
  - energy from the sun
- **Mechanisms of renewal and recycling**
  - Nutrients limited
  - Space = habitat limited (continents…)
    - Mechanism = Tectonism. Is it that simple?
The Galactic Habitable Zone

“The Galactic habitable zone (GHZ), analogous to the concept of the circumstellar habitable zone, is an annular region lying in the plane of the Galactic disk possessing the heavy elements necessary to form terrestrial planets and a sufficiently clement environment over several billion years to allow the biological evolution of complex multicellular life.”


Habitable Zone of the Milky Way Galaxy

Requirements
- Metals (Fe)
- Protection from supernovae
- Time for evolution

1 Parsec = 3.26

Milky Way HZ

In the zone. A ring spreading within the Milky Way (green zone, bottom to top) embraces the galaxy’s life-friendly stars.


Early Earth History

- Sun and accretionary disk barred (4.57)
- Some differentiated asteroids (4.56)
- Mars accretion completed (4.04)
- The major formed during melting and reheating (4.5)
- Earth’s surface temperature (4.5)
- Loss of Earth’s early atmosphere (4.5)
- Earth’s accretion, core formation and degassing essentially complete (4.47)
- Earliest known zircon fragment (4.6)
- Upper age limit of most known zircon grains (4.3)
- Earliest surviving continental crust (4.0)
- End of intense bombardment (3.9)

Earliest granitic crust and liquid water. Possibility of continents and primitive life. Homestead of Earth could have repeatedly reprocessed surface rocks, induced destabilization, inflated and reorganized the hydrosphere. Life may have developed on more than one occasion.

Stable continents and oceans. Earliest records thought to imply early primitive life.
Formation of Earth’s Atmosphere and Ocean

Evidence from Zircons for Liquid Water 4.3 Ga

- Heavy oxygen isotope ratios (\(^{18}\text{O}/^{16}\text{O}\)) are produced by low-temperature interactions between rock & liquid water.
- 4.3 Ga zircons have high \(^{18}\text{O}/^{16}\text{O}\), implying the rocks that were melted to form the magma from which the zircons crystallized included material that had been at the surface in the presence of liquid water.

Wilde et al., Nature (2001)
Theories for Origin of Earth’s Volatile Components: Atmosphere & Oceans

• Arrived with the planetesimals, partly survived the accretion process and outgassed during volcanic activity (Hogbom 1894, Rubey 1951-5). Volcanic gases vary in composition; not primordial and may have been recycled many times. No record of the time and conclusive answers about this scenario (Turekian, 1972; Delsemme, 1997).
• Arrived with comets during the late bombardment - late veneer hypothesis (Delsemme, 1997)
• Arrived with one or more hydrated planetesimals from the outer asteroid belt (Morbidelli, 2001)
• Arrived with comets and mixed with accreted water

Formation of Atmosphere and Ocean

• Impact Degassing
  Planetesimals rich in volatiles (H₂O, N₂, CH₄, NH₃) bombard Earth
  Volatiles accumulate in atmosphere
  Energy of impact + Greenhouse effect = Hot surface
  (>450 km impactor would evaporate ocean)

• Steam Atmosphere?
  Or alternating condensed ocean / steam atmosphere

• Heavy Bombardment (4.6-3.8 Byr BP)
  1st 100 Myr main period of accretion
  Evidence from crater density and dated rocks on Moon, Mars and Mercury
Composition of Comet Halley
Volatiles (modeled)

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>78.5%</td>
</tr>
<tr>
<td>N₂</td>
<td>2.6%</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>1.5%</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.1%</td>
</tr>
<tr>
<td>H₂CO</td>
<td>4.0%</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.8%</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.5%</td>
</tr>
<tr>
<td>S₂</td>
<td>0.05%</td>
</tr>
<tr>
<td>HCO-OH</td>
<td>4.5%</td>
</tr>
<tr>
<td>HCN</td>
<td>1.0%</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>0.2%</td>
</tr>
<tr>
<td>CS₂</td>
<td>0.05%</td>
</tr>
<tr>
<td>CO</td>
<td>1.5%</td>
</tr>
<tr>
<td>N₂H₄</td>
<td>0.8%</td>
</tr>
<tr>
<td>C₄H₄N₂</td>
<td>0.4%</td>
</tr>
<tr>
<td>H₂O</td>
<td>92%</td>
</tr>
<tr>
<td>H₂</td>
<td>5.6%</td>
</tr>
<tr>
<td>H/C</td>
<td>2.6%</td>
</tr>
<tr>
<td>S</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

D/H Evidence for Origin of Earth’s Water from Meteorites

- Planets formed from collisional accretion of many primitive planets (10-1000 km diam) with unstable orbits around Sun.
- Addition of water-rich bodies during accretion contributed small fraction of water but most added by a few late giant impactors.
- Late impactors had D/H ratios similar to carbonaceous meteorites because they originated from the same cold region of the asteroid belt.

Composition of Earth’s Early Atmosphere

Atmospheric composition, shown by the relative concentration of various gases, has been greatly influenced by life on the Earth. The early atmosphere had fairly high concentrations of water and carbon dioxide and, some experts believe, methane, ammonia, and nitrogen. After the emergence of living organisms, the oxygen that is so vital to our survival became more plentiful. Today carbon dioxide, methane, and water exist only in trace amounts in the atmosphere.

Allegre & Schneider (1994)

Earth’s Early Atmosphere

Evidence for High Surface T on early Earth


- Oxygen isotope ratios in cherts & phosphates indicate surface temperatures may have exceeded 60°C for most of the period 4-1 Gyr ago

Water Elsewhere in Solar System: Water Ice on Mars


- South Pole water ice thickness: The total volume is estimated to be 1.6 x 10⁶ cubic kilometers, which is equivalent to a global water layer approximately 11 meters thick.
Evidence of Recent Water flow on Mars

- Martian gullies proposed to have formed by seepage & runoff of liquid water in recent martian times

Water on Europa

- One of Jupiter’s 4 large (Galilean) satellites
- 25% of Earth’s radius

- Crust composed of water & ice

- Fragmented chunks of water ice on Europa’s surface