General Introduction

The Earth as an evolving geologic body

Unique/important attributes of Planet Earth
1. Rocky planet w/ strong magnetic field
   Mercury has a weak field, Mars has a dead field
Unique/important attributes of Planet Earth

2. Bimodal Topography
   Continents (Tibet) plus ocean basins

3. Plate tectonics
Unique/important attributes of Planet Earth

4. Single, relatively large moon

![Image of Earth and Moon]

Figure 6-6. Properties of the Earth—Moon system: The Moon follows a nearly circular path about the Earth. This orbit is located 30 Earth diameters away from us. The pull on the Moon's mass (1.2 percent of that of the Earth) causes the Earth to wobble in its orbit about the Sun. It is the center of mass of the Earth—Moon system that follows a smooth course about the Sun.

5. Liquid water

![Image of liquid water]
Unique/important attributes of Planet Earth

6. Oxygenated atmosphere
   ~0.2 bars $O_2$, ~0.8 bars $N_2$

Unique/important attributes of Planet Earth

6. Life
A Tale of 2 Energy Sources

1. **Internal Heat** *(accretion, radioactivity, chemical)*
   - Tectonics/earthquakes/mountain building
   - Volcanism
   - Chemosynthetic Life

2. **External Heat** *(sun)*
   - Climate - Atmosphere and Ocean circulation
   - Erosion/Precipitation
   - Photosynthetic Life

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Cycles & Cycles!

- Tectonic (~600 m.y. or $2 \times 10^{16}$ seconds)
- Climatic/Orbital
- Seasonal
- Tidal
- Solar!

All effect sea-level!

How does Earth’s surface temperature vary with time?
Solar cycles?

Topics for Remainder of Lecture

1. Planetary structure
2. Modes of accretion
3. Formation of the Moon
4. Hadean atmospheres
**Planetary structure**

**Differentiated planet**
- FeNi core: $11 \text{ g/cm}^3$
- Silicate shell: $3-4 \text{ g/cm}^3$

**Earth**
- 67% silicate
- 33% FeNi

**Heterogeneous accretion**

Mirror condensation sequence. Fast $10^4$ to $10^6$ years.

Invert to get Fe below chondrules.
Homogeneous accretion

Core formation

Fig. 2. Iron migration at a later (nearly-linear) phase of core formation. Below the thermal boundary, free correlations into dislocations, which migrate down rapidly, ensuring incomplete chemical equilibration with the mantle environment.
Core formation consequences

Core Formation Timing

- $^{182}\text{Hf}$ decays to $^{182}\text{W}$, half-life 9 Myrs
- Hf is lithophile, W is siderophile, so we can use observations to time core formation
- Complication! Crustal formation can also lead to Hf/W fractionation

Early core formation – excess $^{182}\text{W}$ in mantle

Late core formation – no excess $^{182}\text{W}$
Core Formation Timing

- Core formation can happen very early (Vesta)
- Larger objects show later core formation
- Anomalous lunar data due to the way the Moon formed

Moon Facts

1. Moon and Earth formed simultaneously.
   Moon has a bimodal age distribution.
   Anorthositic Highlands: > 3.9 Byr
   Mare Basalts: 3.1 to 3.9 Byr
   Surface covered by igneous rock. Moon started molten.

Anorthosite: Plutonic, silicic
Light colored
>90 plagioclase feldspar
\((NaAlSi_3O_8 \text{ to } CaAl_2Si_2O_8)\)

Basalt: Volcanic, mafic
Dark colored
Olivine: \((Mg,Fe)SiO_4\)
Pyroxene: \((Ca,Mg,Fe)_2Si_2O_6\)
Ca feldspar
Moon Facts

2. Moon is large (1.2% of Earth mass).
High angular momentum relative to other planetary systems

\[
\text{Angular momentum} = \text{Moment of Inertia} \times \text{Angular velocity}
\]

![Diagram of Earth-Moon System](image)

Figure 6.6. Properties of the Earth-Moon system: The Moon follows a nearly circular path about the Earth. This orbit is located 30 Earth diameters away from us. The pull on the Moon’s mass (1.2 percent that of the Earth) causes the Earth to wobble in its orbit about the Sun. It is the center of mass of the Earth-Moon dumbbell that follows a smooth course about the Sun.

Moon Facts

3. Moon has progressively retreated from Earth through time. (2 mm/year).

To conserve angular momentum, as Earth’s rotation slows, distance to Moon increases and period of Moon decreases.

Kepler’s Law: \[ \text{Period} = g \left( \frac{(\text{Distance from host})^3}{\text{Mass of host}} \right)^{0.5} \]
Moon Facts

4. Moon is less dense than Earth (3.3 g/cm$^3$ vs. 5.5 g/cm$^3$).
5. Moon is depleted in volatiles relative to nebula. So is Earth’s mantle, but moon is even more depleted.
6. Moon started molten (anorthositic crust).

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Moon Origins

1. **Formed by Fission (George Darwin)**
   Pacific Basin is hole left behind.
   Requires very high spin rate (1 hr or less).
   Problem: Dynamical issues. How did it decelerate?

2. **Co-accretion**
   Side-by-side from the same nebular pool.
   Problem: Problems with angular momentum, hard to explain density differences. Earth would suck up all the mass.
3. **Capture**
Gravitationally grab objects after a near miss. Certain for satellites of Mars.
Problem: Very very very unlikely to trap a lunar-sized object.
Simulations show the outcome is:
   a. Collision
   b. Escape

4. **Giant Impact**
A large, roughly Mars-sized object (10% mass of Earth) hits proto-Earth obliquely at relatively low velocity (5 km/s) during late accretion. Disrupts entire planet and sprays of a jet of material that condenses into the Moon.

**Explains a lot:**
   a. High angular momentum
   b. Chemical similarity between Earth and Moon
   c. Lack of volatiles
   d. Anorthositic highlands first crust formed from cooling magma ocean?

**Some issues:**
   a. Moon mainly is made up of impactor mantle (85%) 
   b. Core of proto-Earth had already segregated (little Fe in mantle to end up on Moon). Impactor had also differentiated and core fused with core of proto-Earth.
   c. Any early atmosphere is wiped out.
   d. Earth forms HOT, still losing some of that heat.
Moon Origins

1. The dominant rock type at Earth’s surface is basalt (formed by partial melting of upper mantle rock - more on this later). Basalt appears to be the major igneous surface rock on Venus and Mars. Formation appears to be ubiquitous characteristic of terrestrial planets.

2. Style of volcanism very different on these planets.
   a. Earth - continuous basalt formation at ridges.
   b. Venus - resurfaced catastrophically at 600 Myr.
   c. Mars - last basaltic volcanism ca. 1 Byr
Planetary Comparisons

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from sun (10^8 km)</td>
<td>1.50</td>
<td>1.08</td>
<td>2.28</td>
</tr>
<tr>
<td>$S$ (W/m²)</td>
<td>~1370</td>
<td>later</td>
<td>later</td>
</tr>
<tr>
<td>Equatorial radius (km)</td>
<td>6375</td>
<td>6050</td>
<td>3400</td>
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<tr>
<td>Albedo</td>
<td>0.3</td>
<td>0.8</td>
<td>0.2</td>
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<tr>
<td>Effective Radiating Temp. (K)</td>
<td>255</td>
<td>Hot</td>
<td>Cold</td>
</tr>
<tr>
<td>Mean Surface Temp. (K)</td>
<td>288</td>
<td>730</td>
<td>218</td>
</tr>
<tr>
<td>Atmospheric pressure (bars)</td>
<td>~1</td>
<td>~93</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>$N_2$ (%)</td>
<td>78.1</td>
<td>3.5</td>
<td>2.7</td>
</tr>
<tr>
<td>$O_2$ (%)</td>
<td>21</td>
<td>.0001</td>
<td>0.13</td>
</tr>
<tr>
<td>$CO_2$ (%)</td>
<td>0.038</td>
<td>96.5</td>
<td>95.3</td>
</tr>
<tr>
<td>$H_2O$ (%)</td>
<td>.00001 to 4</td>
<td>0.002</td>
<td>0.02</td>
</tr>
<tr>
<td>Argon</td>
<td>0.934</td>
<td>0.007</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Sources of Atmosphere

1. Degassing the planet

Fe + $H_2O \Rightarrow FeO + H_2$\

Degas before core formation

Degas after core formation

Overall, more C than Earth, and more reduced than all terrestrials.
Sources of Atmosphere

2. Comet and asteroid impacts. 
\(~10^6\) needed to generate one ocean mass

Too little Neon to directly sample nebula. 
\(Kr > Xe\) and \(Ar > >> Xe\) doesn’t fit chondrites.

![Graph showing abundances of noble gases in the atmospheres of the inner planets and in chondritic meteorites.](image)

**FIG. 1.** Abundances of noble gases in the atmospheres of the inner planets and in chondritic meteorites, given in cubic centimeters per gram of rock (after E. Anders). The dotted line connects points for solar system abundances that are used for comparison, normalized to hydrogen.

Loss of Atmosphere

1. Thermal Loss
   a. Jean’s Escape: molecule-by-molecule evaporation
   b. Hydrodynamic Escape: planetary wind

**One major cause of air loss is solar heating.**

**AIR EVAPORATES MOLECULE BY MOLECULE**

In an atmosphere's uppermost layer, or exosphere, nothing stops the fastest-moving atoms and molecules from flying off into space. This process, known as mass escape, accounts for much of the loss of hydrogen from our planet.

**HEATED AIR FLIES OUT IN A WIND**

As heated by sunlight, mass accelerates and attains escape velocity. This process, known as hydrodynamic escape, was particularly important on early Earth and Venus—in fact, it may be why Venus became what it is today.

![Diagram showing the exosphere](image)
Loss of Atmosphere
Evidence of Thermal Loss

Loss of Atmosphere
Evidence of Thermal Loss

Light gases such as hydrogen are more fragile than heavier ones such as oxygen. Their susceptibility to escape depends on the temperature at the top of a body’s atmosphere or, for airless bodies such as the moon, at its surface (vertical axis) and on the strength of its gravity (horizontal axis). If a body lies to the right of the line for a gas, it holds on to the gas; to the left, it loses the gas. For example, Mars loses hydrogen and helium, retains oxygen and carbon dioxide, and barely retains water.
Loss of Atmosphere

2. Non-thermal Loss
   a. Charge exchange
   b. Polar wind
   c. Photochemical
   d. Sputtering

3. Impact