Early History and Composition of the Earth and Moon

Giant Impact Hypothesis

• Idea in a nutshell:
  – Body about 1/10 the mass of the Earth (Mars-sized) struck the Earth after it is half or more accreted, and after the Earth's core had at least partially formed.
  – Material, mainly from silicate mantle, is blasted into orbit around the Earth, eventually accreting to form the Moon.
Giant Impact Hypothesis
The Giant Impact theory is consistent with:

- Similar but different compositions:
  - Identical O isotopes
  - Lunar ‘depletion’ in Fe and volatiles
- Planetary accretion models
- Impact history of the Moon
  - Record of impacts by bodies up to 150 km.
  - Why not larger ones?
- high angular momentum of system and 23° tilt of Earth’s rotational axis.
- Mercury’s small mantle suggests it too suffered a late impact.

More Lessons from the Moon: “The Magma Ocean”

- Moon underwent extensive melting early in its history.
- Lunar crust consists of “anorthosite”.
  - May have formed as plagioclase crystallized and floated to the surface of this ‘ocean’ (or ‘swamp’?).
- If the Moon melted, did the Earth?
More Lessons from the Moon: The “late heavy bombardment”

- Many impact craters on Moon date to around 3.9Ga.
- If the Moon was bombarded, wouldn’t the Earth be as well?

Was the Late Heavy Bombardment Real, or an Artifact?

- Alternatively, some suggest it is an artifact of rapidly declining impact rate at this time (b) in the graph to the right.
  - In this view, impacts occurring around 3.9Ga are common enough to destroy evidence of earlier ones, giving the appearance of an increase in rate at 3.9 Ga.
- Most scientists, however, believe the Late Heavy Bombardment was real (view a to the right).
We’re Still being bombarded!

Impact! Manicouagan, Quebec 212 Ma
Impact! Chicxulub, Yucatan Peninsula 65 Ma

(Aside: How big was the Chicxulub bolide?)

- Rule of thumb from experiments
  - Crater is 10 to 15 times the diameter of the impacting body.
- Chicxulub is 200-300 km diameter
  - Impactor would have been 10-30 km in diameter.
Impact! Roter Kamm, Namibia 5 Ma

Impact! Barringer Meteor Crater, Arizona 49,000 yrs
The Impact of the Barringer Impact

A Major Impact 3.47 Ga ago?

- Paper in Science in Aug, 2002 reports evidence of the impact of a 20 km diameter body at 3.47 Ga
- Iridium (Ir) enrichment, Cr isotope anomalies, and spherules found in Barbarton (S. Africa) and Pilbara (Australia)
- Sedimentary environment appears to be low energy one disturbed by tsunami.
Formation of the Earth: Summary

- Accretion of dust to form planetesimals during or after gas loss from inner solar nebula.
- Planetesimals collide and accrete to form progressively larger bodies.
  - These may have already differentiated to form cores and mantles.
- Planetary differentiation (core formation) probably proceeds simultaneously with accretion.
- Last stages involve particularly violent collisions of large bodies.
  - One of these forms the Moon.
  - Conversion of this gravitation energy to heat results in extensive melting.
  - Loss of volatiles, along with any primitive atmosphere.
- Planetesimal bombardment continues until 3.9Ga.
  - Mass accreted <1%, but the surface is inhospitable.

Observation: the Earth has a layered structure

- **Atmosphere and Hydrosphere**
- **Low Density Crust** (6-35 km thick)
- **Intermediate Density Mantle** (~3000 km thick)
- **high density core** (~3000 km thick)
  - Liquid outer core
  - Solid inner core
Earth’s Layers

<table>
<thead>
<tr>
<th></th>
<th>Thickness (km)</th>
<th>Volume $10^{27}$ cm$^3$</th>
<th>Density g/cc</th>
<th>Mass $10^{27}$ kg</th>
<th>Mass Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>0.000005</td>
<td></td>
<td></td>
<td>0.00141</td>
<td>0.024</td>
</tr>
<tr>
<td>Hydrosphere</td>
<td>3.80</td>
<td>0.00137</td>
<td>1.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crust</td>
<td>17</td>
<td>0.008</td>
<td>2.8</td>
<td>0.024</td>
<td>0.4</td>
</tr>
<tr>
<td>Mantle</td>
<td>2883</td>
<td>0.899</td>
<td>4.5</td>
<td>4.016</td>
<td>67.2</td>
</tr>
<tr>
<td>Core</td>
<td>3471</td>
<td>0.175</td>
<td>11.0</td>
<td>1.936</td>
<td>32.4</td>
</tr>
<tr>
<td>All</td>
<td>6371</td>
<td>1.083</td>
<td>5.52</td>
<td>5.976</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Questions

• What is the composition of these layers?
• How did they form?
• When did the form?
  – Possible answers:
    • Immediately (i.e., formed at the same time the Earth did).
    • Formed subsequently.
Estimating the composition of Earth’s layers

- Atmosphere, ocean, and (to some degree) crust can be directly observed, and their compositions directly measured.
- Mantle and core cannot be.
  - Compositions can only be inferred.
  - Geophysical measurements (seismic velocity, moment of inertia, etc.) only constrain these compositions.
  - Other constraints:
    - Cosmochemical: Earth formed from a “chondritic” solar nebula.
    - Mantle must melt to produce basalt.

Some Geochemistry

- Definitions:
  - Lithophile are those found in silicates and oxides in meteorites.
  - Siderophile elements are those found in metal phases (principally Fe-Ni alloy) in meteorites.
  - Volatile elements are those that have or form compounds having low boiling points. We divide the volatiles into 2 groups:
    - Highly volatile: gases at nearly any temperature. Compared to their abundances in the Sun, they are depleted in all classes of meteorites.
    - Moderately volatile: gases at moderate temperature, but eventually condense into the dust of the solar nebula. Same relative abundances in CI Carbonaceous Chondrites as Sun, but depleted in other classes of meteorites.
**Geochemical Periodic Table**

<table>
<thead>
<tr>
<th>GROUP</th>
<th>IA</th>
<th>Geochemical Classification of the Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H</td>
<td>H, He, Li, Be, B, C, N, O, F, Ne</td>
</tr>
<tr>
<td>2</td>
<td>Na</td>
<td>Mg, Al, Si, P, S, Cl, Ar</td>
</tr>
<tr>
<td>3</td>
<td>K</td>
<td>Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr</td>
</tr>
<tr>
<td>4</td>
<td>Rb</td>
<td>Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe</td>
</tr>
<tr>
<td>5</td>
<td>Cs</td>
<td>Ba, La, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At</td>
</tr>
<tr>
<td>6</td>
<td>Ra</td>
<td>La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu</td>
</tr>
</tbody>
</table>

- Refractory Lithophile
- Moderately Volatile
- Siderophile
- Highly Volatile

**Refractory Lithophile Elements**

<table>
<thead>
<tr>
<th>GROUP</th>
<th>IA</th>
<th>Geochemical Classification of the Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H</td>
<td>H, He, Li, Be, B, C, N, O, F, Ne</td>
</tr>
<tr>
<td>2</td>
<td>Na</td>
<td>Mg, Al, Si, P, S, Cl, Ar</td>
</tr>
<tr>
<td>3</td>
<td>K</td>
<td>Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr</td>
</tr>
<tr>
<td>4</td>
<td>Rb</td>
<td>Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe</td>
</tr>
<tr>
<td>5</td>
<td>Cs</td>
<td>Ba, La, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At</td>
</tr>
<tr>
<td>6</td>
<td>Ra</td>
<td>La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu</td>
</tr>
</tbody>
</table>

- Refractory Lithophile
Earth’s Layering Reflects a Chemical Differentiation

• Highly volatile elements form the atmosphere and oceans.
• Lithophile elements form the crust and mantle.
• Siderophile elements form the core.
  – But their distribution between core and mantle depends on availability of oxygen.

The “Chondritic” Model

• Chondritic meteorites (specifically CI) provide the best estimate of the composition of the raw material from which the Earth, and its sister planets, formed.
  – They therefore provide a starting point for estimating the composition of the Earth.
  – Earth need need not be “chondritic” but its composition must relate to that of chondrites in some rational way.
• Point of departure:
  – the relative abundances of refractory lithophile elements is constant in all chondrite classes.
  – Apparently, nebular processes did not change relative abundances of refractory lithophiles.
  – Therefore, these elements should be present in chondritic relative abundances in the silicate part of the Earth.
Given “chondritic” raw materials, what is the most likely composition of the mantle and core?

- “Silicate” mantle
  - Specifically, magnesium-rich silicate rock called peridotite.
  - Peridotite melts to form basalt.
  - Matches density and compressibility estimated from seismic waves.

- “Iron” core
  - More specifically Fe-Ni metal.
  - Fe-Ni in approximate “chondritic” proportions.
  - Few percent of a “light” element to match density.
  - Other “siderophile” elements as minor and trace constituents.
Estimating the composition of the Earth

- Assuming chondritic relative abundances of refractory lithophiles, concentrations of other elements in the Earth can be estimated by observing their relationship to refractory lithophile elements.

Composition of the Silicate Earth
Chondritic Abundances

Composition of the Silicate Earth

<table>
<thead>
<tr>
<th></th>
<th>CI Chondrites</th>
<th>CI Chondritic Mantle</th>
<th>LOSIMAG (Hart and Zindler)</th>
<th>Pyrolite (Ringwood)</th>
<th>Pyrolite (Sun and McDonough)</th>
<th>PRIMA (Allegre et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>22.77</td>
<td>49.52</td>
<td>45.96</td>
<td>44.76</td>
<td>45.0</td>
<td>46.12</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>1.64</td>
<td>3.56</td>
<td>4.06</td>
<td>4.46</td>
<td>4.45</td>
<td>4.09</td>
</tr>
<tr>
<td>FeO</td>
<td>24.49</td>
<td>7.14</td>
<td>7.54</td>
<td>8.43</td>
<td>8.05</td>
<td>7.49</td>
</tr>
<tr>
<td>MgO</td>
<td>16.41</td>
<td>35.68</td>
<td>37.78</td>
<td>37.23</td>
<td>37.8</td>
<td>37.77</td>
</tr>
<tr>
<td>CaO</td>
<td>1.30</td>
<td>2.82</td>
<td>3.21</td>
<td>3.60</td>
<td>3.55</td>
<td>3.23</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.67</td>
<td>1.457</td>
<td>0.332</td>
<td>0.61</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.067</td>
<td>0.146</td>
<td>0.032</td>
<td>0.029</td>
<td>0.029</td>
<td>0.034</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
<td>0.39</td>
<td>0.412</td>
<td>0.468</td>
<td>0.43</td>
<td>0.384</td>
<td>0.38</td>
</tr>
<tr>
<td>MnO</td>
<td>0.256</td>
<td>0.557</td>
<td>0.130</td>
<td>0.14</td>
<td>0.135</td>
<td>0.149</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.073</td>
<td>0.159</td>
<td>0.181</td>
<td>0.21</td>
<td>0.20</td>
<td>0.18</td>
</tr>
<tr>
<td>NiO</td>
<td>1.39</td>
<td>0.244</td>
<td>0.277</td>
<td>0.241</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>CoO</td>
<td>0.064</td>
<td>0.012</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>0.07</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.274</td>
<td>0.018</td>
<td>0.019</td>
<td>0.015</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>69.79</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>