
The Cosmos
Planets & Life
PHYS 214
Dr Rob Thacker
Dept of Physics (308A)
thacker@astro.queensu.ca
Please start all class related emails with "214:"

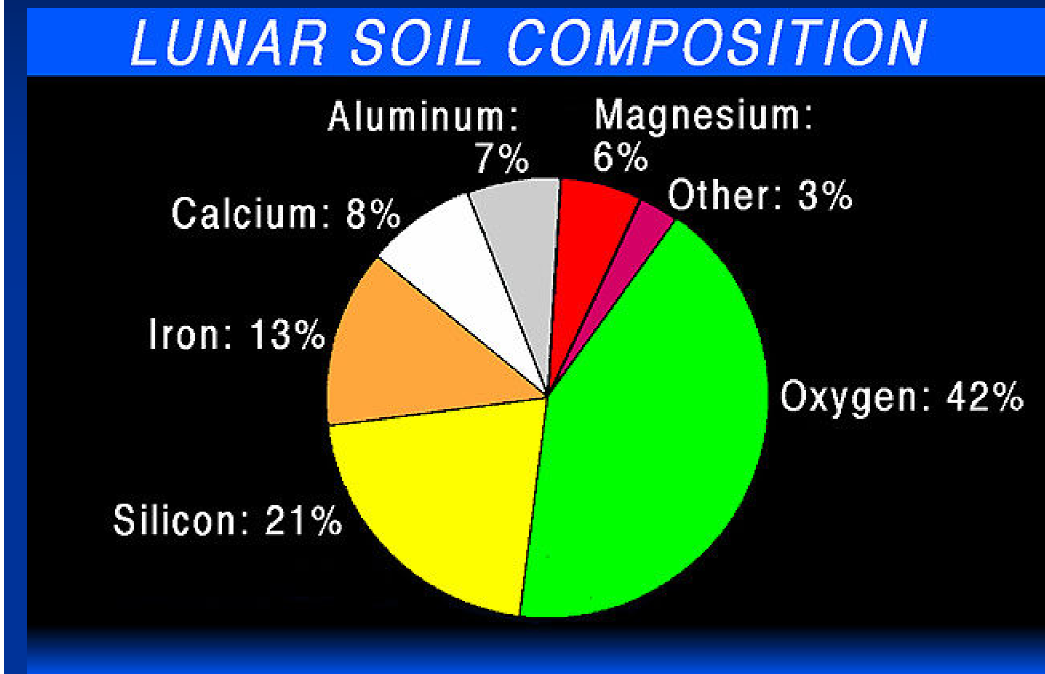
Today's Lecture

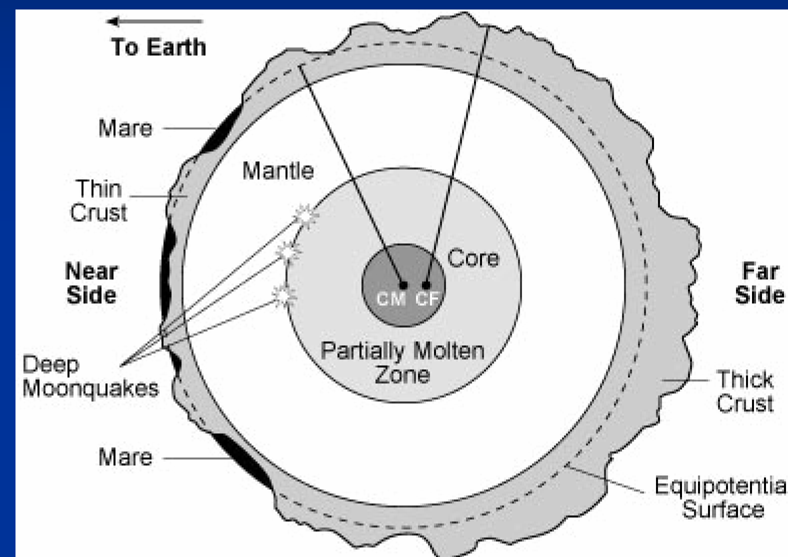
- Earth History
  - Formation of the Moon
  - Origin of the hydrosphere
  - Plate tectonics
  - Snowball Earth
- This lecture will actually draw together a few ideas we've seen in other contexts

Formation of the Moon

- Possible theories –
  - Earth broke-up "fissioned" to form Moon
    - Not dynamically possible
  - We talked about "disks within disks" for forming planetary systems - this suggests Moon should have similar composition to Earth
    - It doesn't – so Earth and Moon are unlikely to have formed together
  - Moon is a captured planetesimal
    - Without an impact event capture requires a 3rd body to remove (angular) momentum from the system – seems improbable

Lunar composition



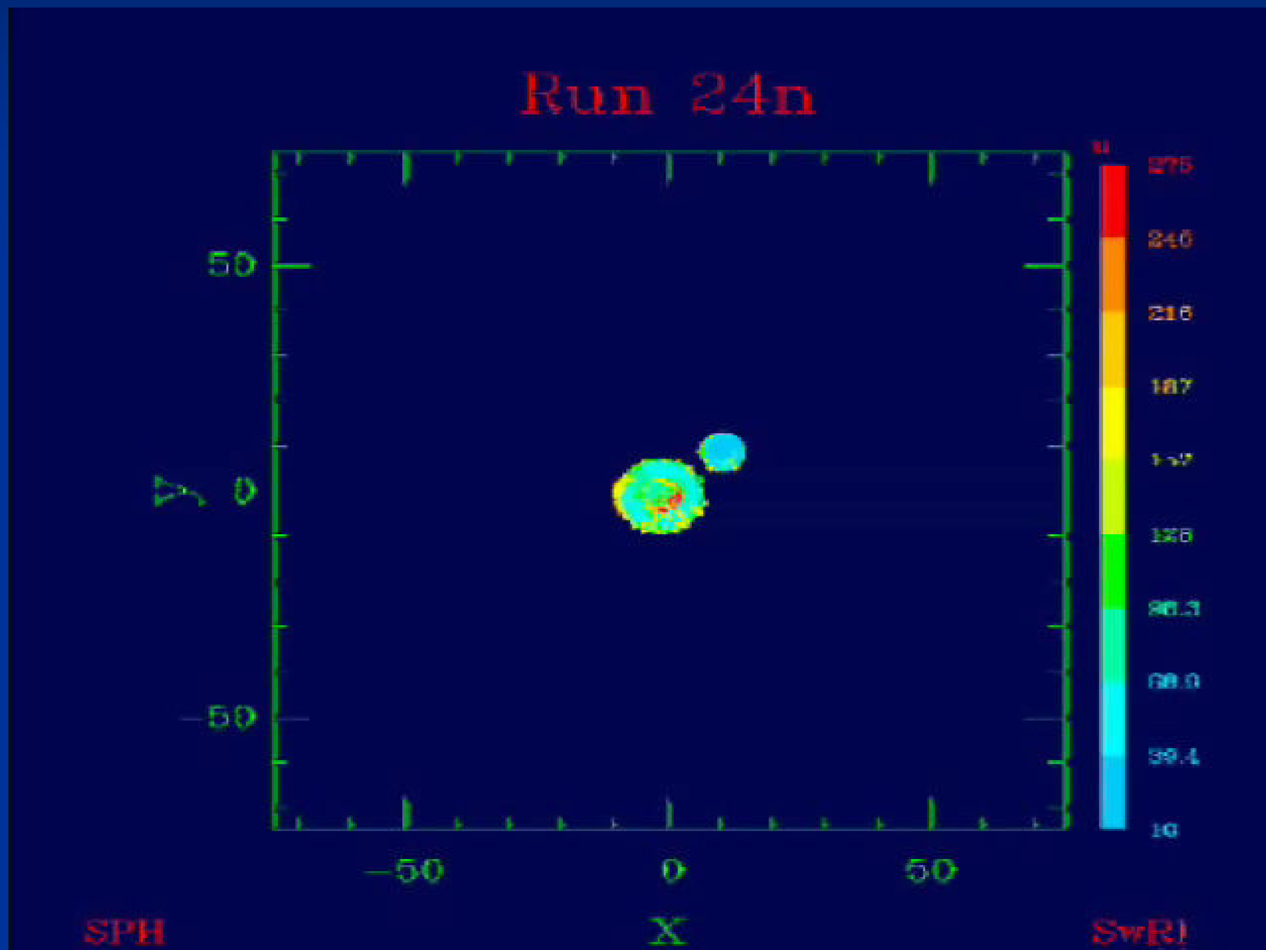


- Much less Fe than the Earth (Fe for Earth about 35%)

Impact event: the most probable theory

- An object close to the size of Mars impacts the proto-Earth around 4.5 Gyr ago
  - The resulting impact ejects large amounts of material into a ring or disk that orbits around the Earth
- This material quickly begins to collapse together under mutual gravitation and forms the Moon
  - The collapse of the ring could even be a short as a year
- The resulting Moon is still very hot, and has a mass of 1/80th that of the Earth
  - Cannot maintain an atmosphere
- Explains age, composition, lack of iron; and is very plausible given conditions in early solar system.

Simulation of the impact event



Accretion of the ring material

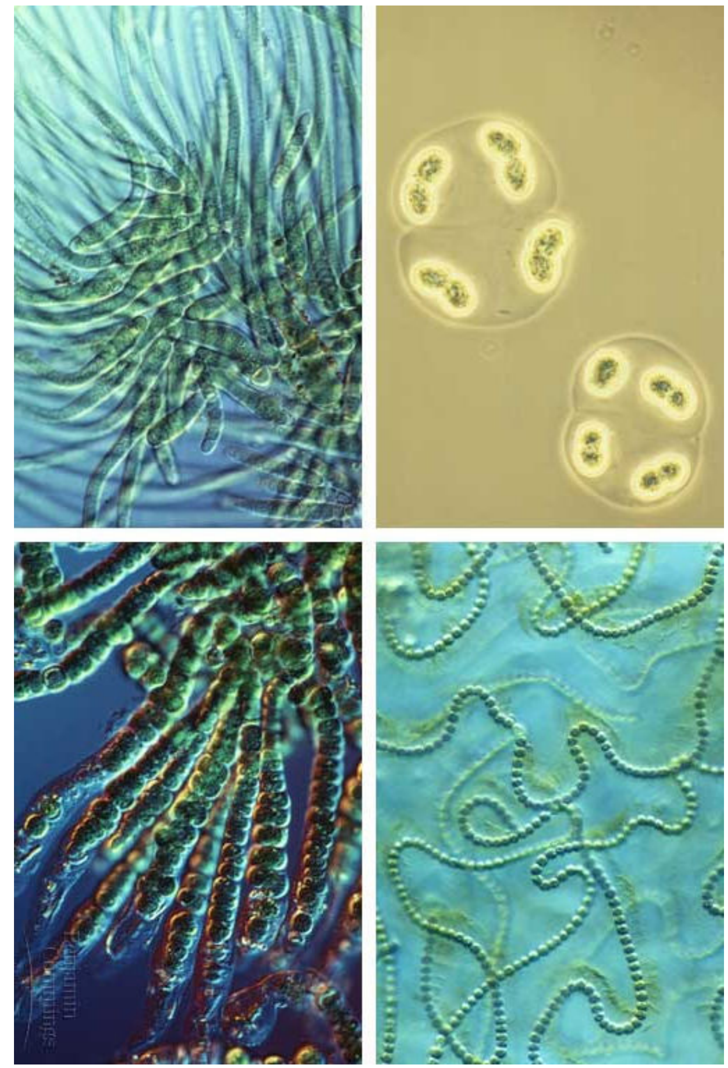
Movie

Early Earth atmosphere

- Any **first atmosphere** would have been swept away by strong solar wind from young Sun
- **Secondary atmosphere** began forming from:
  - deposition of volatiles (light elements: H, C, N, O) from ongoing **cometary & asteriod impacts**, continued for ~500 million years
  - **outgassing** from **volcanic activity**
- **Early atmosphere probably consisted of CO_2, N_2, CO, H_2O** (which went on to form **oceans**), and traces of H_2
  - this was a mildly **reducing** atmosphere (little oxidation)

Evolution of the atmosphere

- We already mentioned in lecture 20 the impact of cyanobacteria on the early atmosphere
- Photodissociation by UV under perfect circumstances can produce only 1-2% of current O_2
  - enough for **ozone** (O_3) to form, blocking UV and preventing further dissociation
- Once life was established and evolved to the point of cyanobacteria photosynthesis became possible
  - O_2 from **photosynthesis**:
  - $CO_2 + H_2O$ + sunlight = glucose + O_2



Presence of free oxygen

- The O_2 produced by cyanobacteria was being used to **oxidize** Fe and S either in solution or in rocks (recall the banded iron formations mentioned in lecture 20)
- Little **free oxygen** until ~2.4 Gyr ago
- Once the Fe and S were fully oxidized, **O_2 could remain** in atmosphere.
  - from 2.4 – 1.6 Gyr ago, atmospheric O_2 levels rose from ~0.001% to ~1%
  - Fairly steady rise since that point

Atmosphere retention

- The strength of the gravitational field of a body determines the ability of it to retain an atmosphere
- The key feature is the escape velocity, v_{esc}, the velocity required to escape the planets gravitational field.
- Kinetic energy must equal the amount of potential energy lost coming from infinity (where the PE is initially zero)

$$\frac{1}{2}mv_{esc}^2 = \frac{GMm}{R} \Rightarrow v_{esc} = \sqrt{\frac{2GM}{R}}$$

M=mass of Body
R=*radius*

- We can compare this value to the average velocity of the molecules in the atmosphere…

Average molecule speeds

- From the kinetic theory of gases, the root mean square (*i.e.* average) velocity of a gas molecule is

$$v = \sqrt{\frac{3kT}{m}}$$

k=Boltzmann's constant
T=gas temp in Kelvin
m=molecule mass

- The dependence on $1/\sqrt{m}$ means that lighter molecules have a higher velocity and are thus more likely to escape
- To maintain an atmosphere for the lifetime of the solar system the rms velocity of the gas should be less than $1/6^{th}$ of the escape speed
  - Why $1/6^{th}$? It comes from a statistical argument about the distribution of speeds of the molecules (many will have speeds higher than the rms value)
- For H at 300 K the speed is about 1920 m s^{-1}, while the Earth's escape velocity is about 11 300 m s^{-1} – so H will not stay in the Earth's atmosphere over long periods

Source of Earth's water

- Still the subject of open research – a number of possibilities have been suggested:
  - Water bearing ("wet") asteroids being involved in both the formation and later bombardment of the Earth
  - Earth formed 'dry' and comets depositing large volumes of water
  - Icy particles from the outer regions migrating inwards (unlikely)
  - Ice planets migrating (unlikely)
  - Merger with a single very wet planetesimal
- We know that material from the inner solar system is largely devoid of water now, so we suspect the source of water must have been the outer regions

Issues to explain

- A successful theory of water delivery to the Earth must explain:
  - The abundance of water (2.8×10^{-4} M_E on the surface and in the crust, and 0.8 - 8×10^{-4} M_E in the mantle, *quite uncertain!*)
  - The ratio of deuterium (^2H) to hydrogen (^1H) isotopes in seawater (1.5×10^{-4})

Arguments against the comet hypothesis

- There is no doubt that some comets have hit Earth and supplied water – the key issue is just how many and how big were they?
  - Typical comets in today's solar system – water mass about 10^9 tons
  - Mass of water in Earth's oceans: 10^{18} tons
  - Unlikely that 10^9 comets have impacted the Earth
  - *There are larger icy bodies out in the Kupier belt though*
- Given we know the isotopic ratio D/H of water on Earth (1.5×10^{-4}) how does this compare to that for comets?
  - Comet 1P/Halley: 3.16×10^{-4}
  - Comet Hyakatuke: 2.82×10^{-4}
  - So these comets contain about twice as much deuterium as Earth water
  - *However these comets didn't come from the Kuiper belt – is their D/H ratio representative of earlier impacts from those objects?*

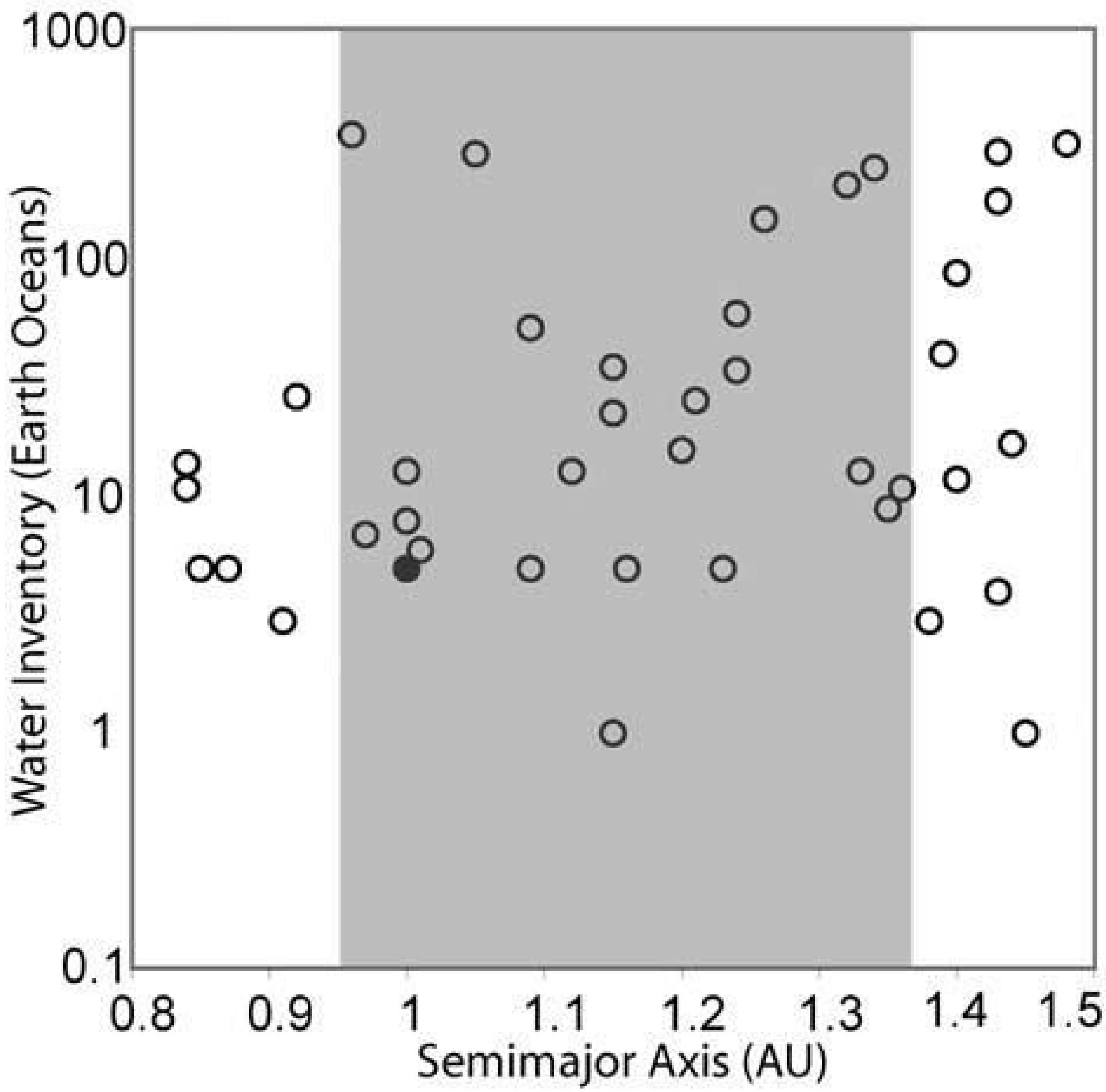
Hydrates

- These have been mentioned in relation to a number of issues in the course
- Useful to provide a definition:
  - Hydrate: A solid compound containing water molecules combined in a definite ratio as an integral part of the crystal.
- Hydrates don’t have to be appear to be “wet”
- Gas hydrates (*e.g.* CO_2 hydrate) can be solid under either very high pressures or very low temperatures
- Can also embed water in silicate structures – this leads to water bearing rocks

The "wet" planetesimal idea

- In this scenario hydrated minerals are involved in the formation of Earth
- As differentiation occurs the water is separated from the crystal structure and rises to the surface
- In this scenario wet planetesimals must arrive later so as not to lose all the water due photodissociation to oxygen and hydrogen
  - If all the water arrives early it will escape quickly and then be subject to the strong UV field
- Once a dense enough atmosphere is formed it and the temperature lowers then the water can begin to condense out of the atmosphere to form oceans

Simulating water delivery



- Raymond, Quinn & Lunine (2004) modelled the delivery of water to terrestrial planets in an HZ using a variety of different assumptions about the distributions of comets & water bearing minerals.
- Orbital properties of the gas giants in the system were also varied and importantly only objects more than 2.5 AU distant were allowed to be water bearing.
- Of the 45 terrestrial planets formed in the HZ, 35 received as much or more water than the Earth (solid dot).

Water must be retained by a planet

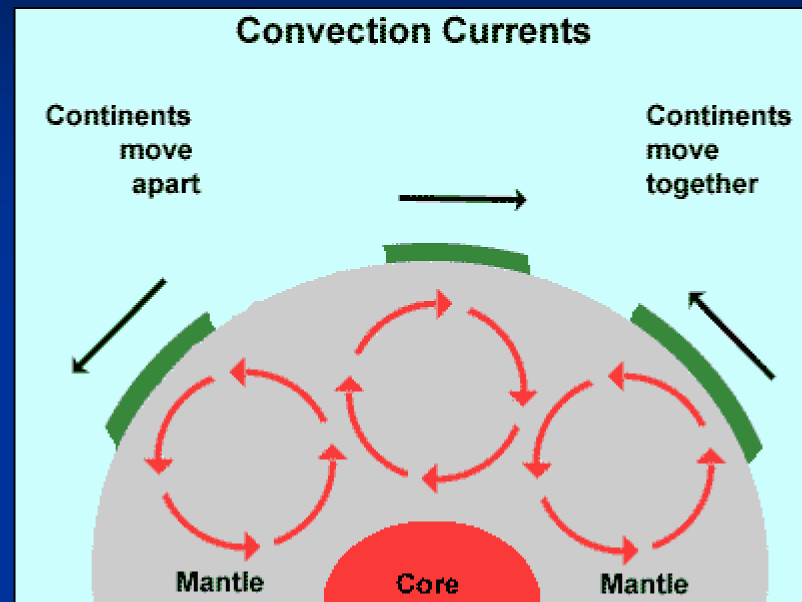
- Long term habitability requires that a planet retains its water
  - Water can be both lost to space by a combination of evaporation and also photodissociation
  - Water can also be lost into the planets interior during continental plate subduction – water-bearing minerals are formed and then buried into the mantle of the Earth
- On Earth, the increasing temperature of the Sun will boil away the oceans in about 2.5 Gyr
- It is also estimated that in 1 Gyr, ¼ of the Earth's current water will have been sequestered into the mantle!

Plate tectonics & life

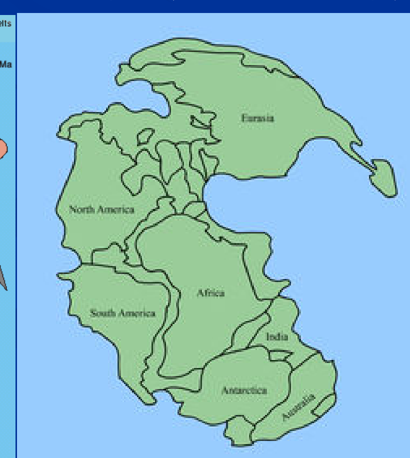
- We met plate tectonics briefly before in relation to the carbonate-silicate cycle (lecture 11)
  - Calcium carbonate is subducted into the Earth's mantle, part of the CO_2 storage before being released via vulcanism
- The mechanism behind plate tectonics is the continual flow of heat from the core of the planet to surface from two main sources
  - Ongoing radioactive decay of unstable isotopes
  - Continued release of heat stored in the Earth during its formation
    - For smaller bodies this heat can be released more quickly

Rifts & subduction zones

- Energy is transported by conduction, convection and advection (horizontal movement of material)
- The lithosphere is the outermost - rocky - part of the planet
- The athenosphere is the weaker hotter region underlaying the lithosphere
  - Rifts form where flows are moving plates apart (rift volcanoes associated)
  - Subduction occurs where the flows come together (needs water to lubricate it)
- The chemical composition of the planet must be such that lighter (granitic) rocks float on the denser (basaltic) rocks



Rodinia (1.1 Gyr ago)



Pangea (0.25 Gyr ago)

Snowball Earth

- The geological record suggests that dramatic changes occurred in the climate between 0.75 and 0.58 Gyr ago
  - Strong evidence for glaciations – glacial till deposited on all continents
- The snowball Earth theory is that these glaciations were global, with ice perhaps being 2 kilometers thick
  - Life could still survive under the icesheet
- Although it is unclear how the snowball starts, we can escape the snowball Earth state as the carbonate-silicate cycle must stop (no more weathering of rocks)
  - CO_2 slowly builds up in the atmosphere and begins a strong greenhouse effect
- Some researchers argue there may have been a series of snowball events
  - Each cooling followed by an excessively hot period due to the greenhouse effect

Snowball Earth-Cambrian Explosion link?

- The coincidence of the timescale for the snowball Earth period and the Cambrian explosion has led researchers to speculate on cause and effect
- Could a small region of water around the equator have enforced rapid evolutionary adaptation to the environment?
- Alternatively, perhaps the glaciations served to kill a certain form of life allowing others to thrive
- Much debate!

Summary of lecture 22

- The Moon was most likely formed by a major impact event of the Earth with a Mars-sized planetesimal
  - Recondensation of the ejected into a satellite probably happened very quickly
- The origin of Earth's hydrosphere is not that well understood
  - Believed to be a result of water bearing minerals from "wet" planetesimals, but comets did make some contribution
- Plate tectonics via the carbonate-silicate cycle plays a significant role in the evolution of life
- Snowball Earth events may well have had a profound influence on the development of life on Earth

Next lecture

- Ideas behind the Rare Earth Hypothesis