The Cosmos

Planets & Life

PHYS 214

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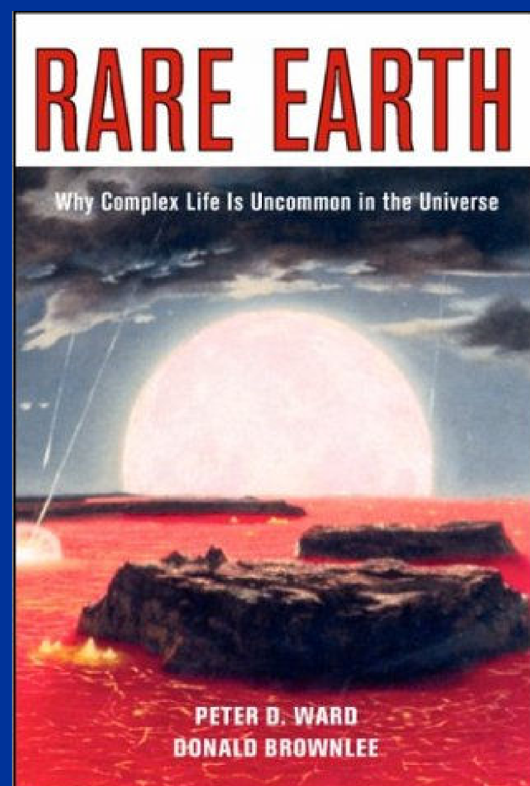
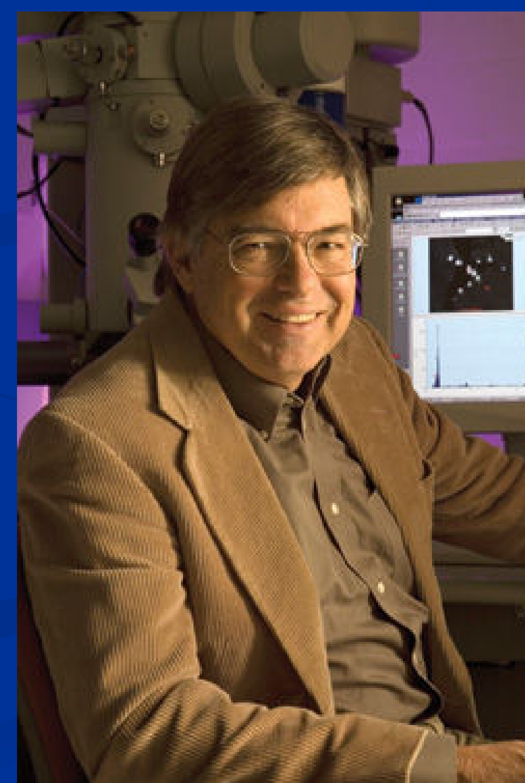
Please start all class related emails with "214:"

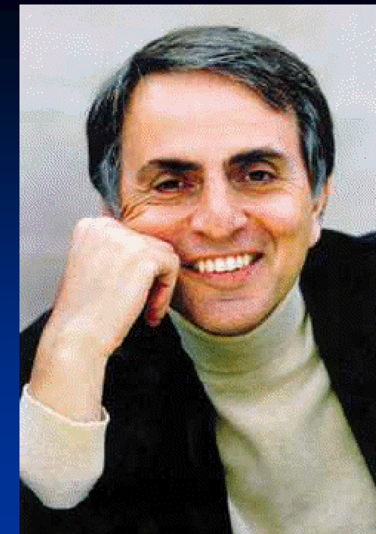
Today's Lecture

- Rare Earth Hypothesis (REH)
  - Peter Ward & Don Brownlee (Univ. of Washington)





Could the Earth be "special"?



- "Who are we? We find that we live on an insignificant planet of a humdrum star lost in a galaxy tucked away in some forgotten corner of a universe in which there are far more galaxies than people…." *Carl Sagan*

One of the underlying tenets of scientific investigation is that we do not occupy a special place in the Universe. Yet, the Earth definitely is "special" within the solar system as life only appears to have occurred here. Could it be that life is a coincidence of so many factors that, in reality, the Earth is actually special within the galaxy?

Don't *be drawn in by anthropocentric quotes:*

"If we are alone in the Universe, it sure seems like an awful waste of space."

Underlying basis of the REH

- The development of intelligent life has required many unlikely coincidences that are highly improbable of occurring elsewhere
  - Note, this doesn't mean the Earth is *unique* – just *rare*

Could we actually be alone?

Components of the REH

(1) Galactic Habitable zone
(2) Appropriate stellar type
(3) Suitable planetary system
(4) Suitable size of planet
(5) Presence of a large moon
(6) Requirement of a magnetic field
(7) Plate tectonics
(8) Appropriate atmospheric chemistry
(9) Evolutionary selection processes (e.g. glaciations, impact events)

Galactic Habitable Zone

- In addition to the issues we discussed, it is also possible that passage through a spiral arm is negative precondition on life
  - Spiral arms in galaxies actually represent a pattern that rotates at different speeds to the actual material
    - Very active star formation – lots of material & new stars that could perturb the orbits of the planets
  - It is not clear how significant an issue this is, the Sun *may* well have passed through spiral arms several times
- Nonetheless, on the basis of the GHZ argument it is expected that 5-10% of the stars in the MW fall in the GHZ

Appropriate stellar type for life

- Aside from the age issue we discussed, Wien's Law tells us the peak emission for massive stars (such as O stars) is in the ultraviolet
  - This would have a strong ionizing effect on any atmosphere in the habitable zone (lots of photodissociation)
- The most massive stars are rare, so in terms of life around these systems we don't care too much
- Similarly we discussed briefly at the low mass end (K and M stars) the planets are probably tidally locked, but also need to extremely close to the star
  - If the planet is very close it is much more strongly impact by stellar activity (flares, winds etc) – could atmosphere survive?
- We aren't sure about the effect on the low mass end – very important, over 90% of stars are in the K & M classes
- Perhaps only 5% of stars are appropriate for life?

Suitable Planetary System

- We believe that terrestrial type planets are necessary to form life, however, in the REH gas giants are hypothesized to also play an important role in the formation of life
  - Protect inner regions of the solar system by scattering or colliding a large fraction of incoming material from the outer solar system
- Systems with too many gas giants tend to become unstable and may end up strongly disturbing the dynamics (could spiral into the Sun for example)
- Similar argument for a single gas giant that is too large
- Remember we’ve found quite a few systems with gas giants on highly elliptical orbits inside 2 AU – just how common is this?
- Is this too much of a stretch?

Suitable size of planet

- On the basis of the escape velocity argument (given in lecture 22) planets cannot be too small
  - With the loss of the atmosphere water might freeze, evaporate away or photodissociate due to the increased UV field
- A planet that is too large will tend to have many more impact events
  - Will also make it harder for mountain systems to form and then will likely be a "water world"
  - In this case the carbonate-silicate cycle cannot act

Presence of a large moon

- The ratio of the mass of the Moon to Earth is 1/80th – this is a surprisingly large number
  - Only Pluto and Charon come close in the rest of the solar system
- The pairwise nature of the Earth-Moon systems means that incoming asteriods are much less likely to hit Earth than if it were one system
- Also the Moon stabilizes the tilt of the Earth, if the tilt were to change quickly then dramatic changes in climate could occur (possibly very quickly)
  - Tilt of 90° would lead to poles facing the Sun for ½ year
- Would *complex* life be unable to adapt or to form in the presence of sudden changes in climate?

Magnetic Field

- Cosmic rays and the solar wind contain high energy charged particles that unless deflected would lead to excessive radiation exposure for life
- The Earth's magnetic field is generated by the liquid Fe core by a dynamo effect
  - The core is kept liquid by continued decay of radioactive isotopes
  - Any planet with a long term magnetic field must thus have these isotopes (uranium 238, thorium 232, and potassium 40 for example)
  - The isotopes necessary for this decay become produced in fewer and fewer amounts with successive generations of supernovae!
    - Intriguingly this might put an upper limit on the age of the Universe capable of supporting LAWKI

Plate tectonics

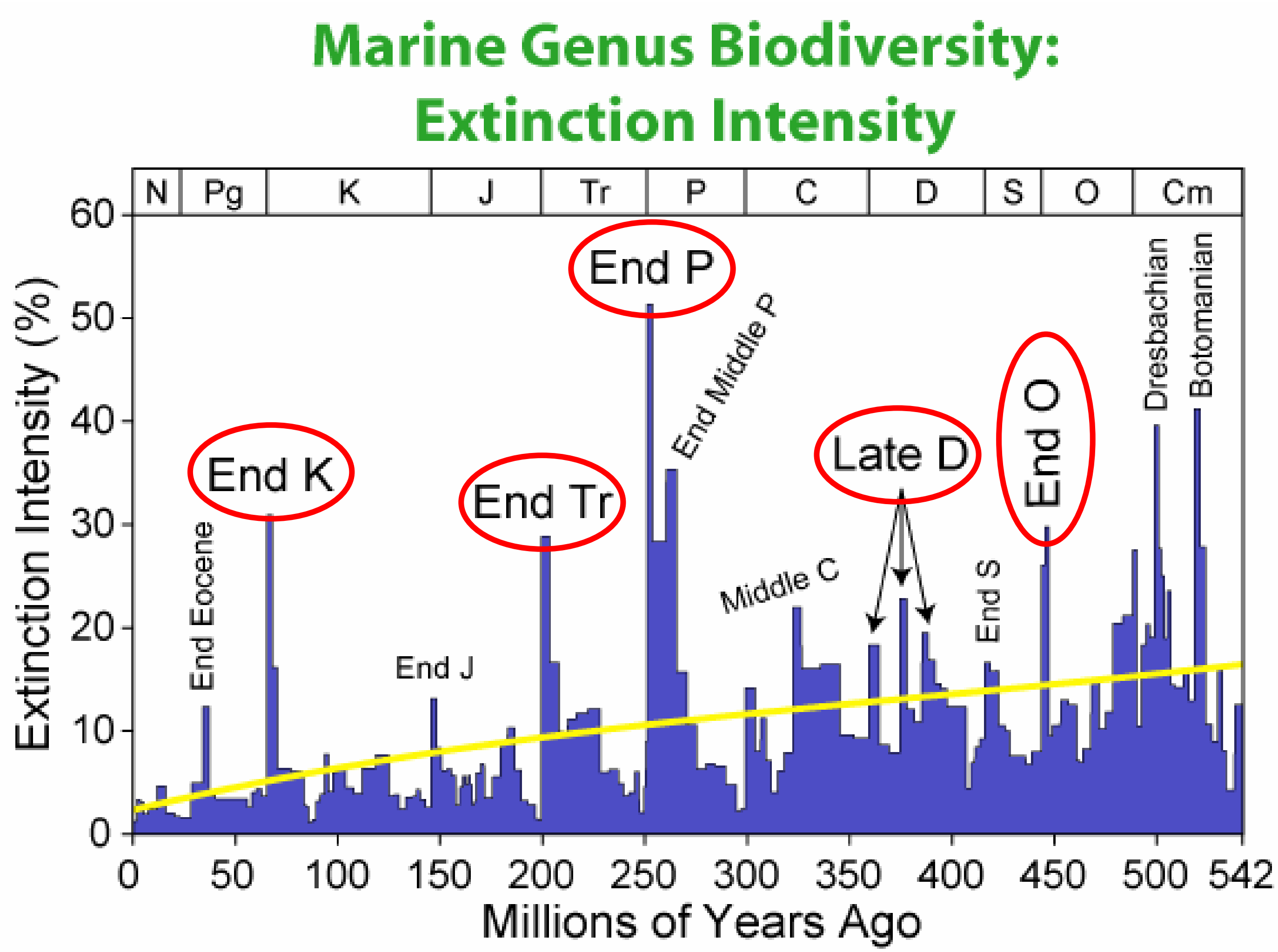
- We have already mentioned the importance of the carbonate-silicate cycle – plate tectonics is certainly necessary on Earth to create land masses capable of weathering
- Plate tectonics also leads to the development of different environments which may promote biodiversity
- Note a large satellite increases the probability of plate tectonics due to the tidal forces on the planet
  - In the Earth-Moon system it is also possible that the initial collision may have initiated plate tectonics
- Around 2.5 Gyr ago there is evidence of tectonic activity forming major land masses, perhaps creating favourable environments for photosynthesizing bacteria (recall the oxygen bloom between 2.7 Gyr and 1.6 Gyr ago)
  - This is then given as a precursor to the development of the eukaryotic cell

Atmospheric Chemistry

- We've seen the effect of a run-away greenhouse on Venus – yet it is only 0.3 AU closer to the Sun
  - To much CO_2 is clearly a problem if photosynthesis becomes unable to start
  - Is this too Earth-centric?
- Also perhaps need some O_3 to shield against UV radiation that is harmful to complex life evolved on land?

Evolutionary selection processes

- Mass extinction events have played an enormous role in the evolution of life on Earth
- Each event can serve as an "evolutionary pump" by creating many empty ecological niches
  - Systems in which all the niches are filled will see evolution occur more slowly
  - The time to fill empty niches seems to be short however (geologically speaking)
  - Of course, such events can select against complex life



5 main extinctions
are circled:
Ordovician
Late Devonian
End Permian
End Triassic
End Cretaceous
(dinosaur extinction)

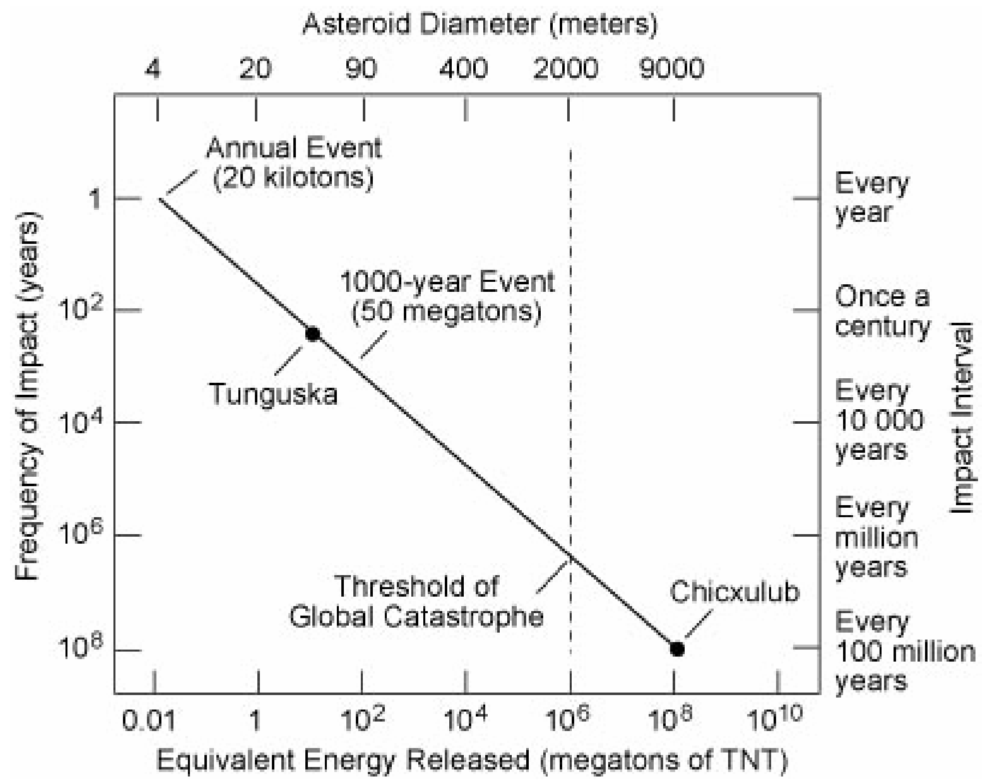
This graph should be viewed as incomplete though
As we only have records for biota that are easily fossilized.

Snowball Earth events

- Ward & Brownlee *suggest* that two key events were caused, or strongly tied to, snowball Earth events
  - the sudden increase in oxygen in the atmosphere around 2.5 Gyr ago and the appearance of the eukaryotic cell
    - Perhaps the first oxygen leaking into the atmosphere reacted with methane ($CH_4+2O_2 \rightarrow 2H_2O+CO_2$) triggering a reduction in the greenhouse effect and the onset of a snowball which selected the photosynthesizing bacteria
  - The Cambrian explosion seems to coincide with the end of evidence for global glaciation
    - The second period of glaciation was perhaps driven by plate tectonics and the break up of Rodinia increasing the amount of material that can weather, thus sequestering more CO_2
- Both these events actually predate the “big five” extinctions, although Kasting believes the second Snowball Earth events may have precipitated the biggest relative extinction ever

Impact events

- The most famous impact event is the Cretacious-Tertiary event that ended the era of dinosaurs
  - 50% of all species became extinct
  - Gave mammals new ecological niches that they evolved to fill
- However, only the Cretacious-Tertiary event is *clearly* related to impacts
  - Others may possibly be related, but the evidence is much weaker
  - Note that the Manicouagan crater in Quebec was formed 214 Myr ago, very close to the end-Triassic extinction



Bacterial life might well be common

- The geological record shows a large difference in time between life appearing and complex life evolving
  - Microbial life forms appear a mere 700 million years after the formation of the Earth
  - Complex life seems to take 3 Gyr
- Perhaps then single-cell life is quite common given the appropriate conditions
  - Indeed, given the presence of life in extreme environments this almost seems probable
    - Although again, we do not understand enough about the evolution/adaptation issue

Event	Time in the past event occurred / Myr	Time taken / Myr	Estimated minimum possible time / Myr
Origin of Life	3800-3500	<500	10
Oxygen photosynthesis	<3500	<500	Very small?
Oxygen in the environment	2500	1000	100
Tissue multicellularity	550	2000	?
Development of animals	510	5	5
Land ecosystems	400	100	5
Animal intelligence	250	150	5
Human intelligence	3	3	3

The Ward & Brownlee riposte to the Drake Equation

- $N=N^* f_g f_p n_E f_{pm} f_i f_c f_l f_m f_j f_{me}$

  N^*=number of stars in Milky Way
  f_g = fraction of stars in GHZ
  f_p= fraction of stars with planets
  f_{pm} = fraction of planets that are rocky
  n_E= number of planets in HZ
  f_i = fraction of habitable planets where microbial life arises
  f_l = fraction of planet's life span in which complex life is present
  f_m = fraction of habitable planets with a large moon
  f_j = fraction of planets with appropriate Jovian planets
  f_{me} = fraction of planets with a small enough number of extinction events

If any one of the f factors is very close to zero, then so will N!

Counter arguments

- Rare Earth hypothesis assumes that animal life will be somehow Earth-like in that it has some form of DNA
- How representative is Earth-life of all life? Does the hypothesis ultimately lack imagination?
  - We've seen how extremophiles can adapt on Earth, perhaps there are instances where more complex life evolved out of apparently bleak environments
- We can also question assumptions about the availability of free oxygen being the impetus in the development of the eukaryote cell
  - Unfortunately evolutionary biologists have stayed away from addressing this question
- Most importantly: one could expect unusual things about every planet where intelligent life forms – have Ward and Brownlee demonstrated that any of the factors they mention are ultimately *necessary?*

Summary of lecture 23

- The Rare Earth Hypothesis states that the challenging part of the creation of intelligent life is the evolution from simple to multicelled animals
  - Microbial life on the other hand may well be common throughout the galaxy
  - This evolution has been influenced by many environmental factors and we could be one really lucky event
- Remember though the argument does not suggest that Earth-type evolution is unique – just *rare*
  - There are at least 100 billion galaxies out there…
- The hypothesis is extremely interesting and challenges (optimistic) mainstream SETI thinking…

Next lecture

- Looking at Mars in more detail – our best hope for finding traces of life