4.9 Billion Years AD

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1. Introduction

I am standing outside on Earth in 4.9 billion years AD on a summer's day. It is always summer here, for the Earth's rotation is tidally locked to the giant Sun which dominates almost a third of the sky[1], redder and brighter than ever before. It is warm, warm enough that the surface of this side of the planet is molten from the Sun's heat. There are no oceans or continents, nor is there any life left on the planet, unless you count me and I am not certain that those of times past would do so. How did the planet end up like this and what happened to the living beings who shared it with my ancestors? What is the future of life in the solar system?

2. Cycles of life

That life ever existed on Earth at all is a remarkable thing. Venus, of a similar size to Earth, but closer to the Sun, has an average surface temperature of 460˚C due to the powerful greenhouse effect of its dense carbon dioxide atmosphere. Mars, further out from the Sun than Earth, also has a carbon dioxide atmosphere, but at less than one percent of the atmospheric pressure on the surface of Earth. With an average temperature of -53˚C, it is far too cold and dry to sustain a complex ecosystem like that of Earth. Life, as we understand it, requires liquid water, something that Venus and Mars both lack.

Carbon dioxide, methane, water vapour and other trace atmospheric gases absorb and re-radiate infra-red wavelengths, trapping heat in the lower atmosphere in a process known as the greenhouse effect (GHWeb). Ward and Brownlee (2002) identified three cycles that moderate the greenhouse effect and allow the Earth's surface to remain at a temperature where water can remain liquid:

- Plate tectonics
- The carbon cycle
- The carbonate silicate cycle

2.1 Plate Tectonics

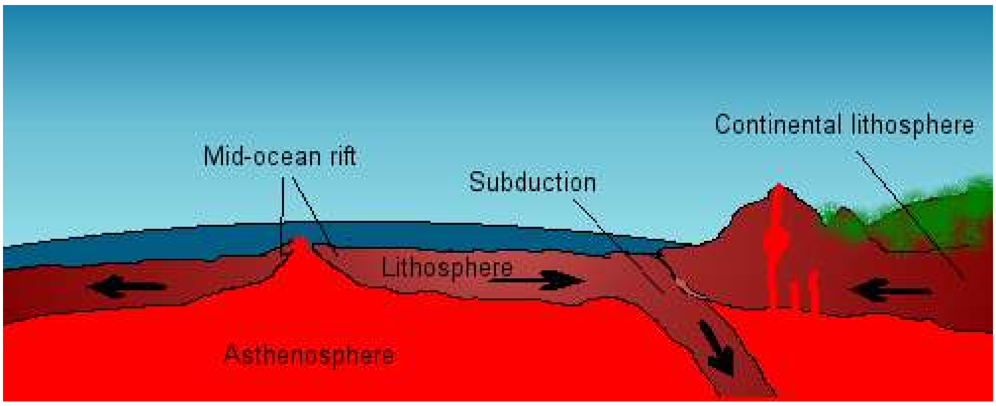

Figure 1Plate Tectonics

1 Own calculations

The Earth's crust, or lithosphere, is divided into sections, called plates, which float atop the asthenosphere,. The asthenosphere is made plastic by the radioactive decay heat from the Earth's interior. The slow drift of these plates is responsible for the motion of the continents and where the plates meet is the site of volcanoes and earthquakes. New crust is constantly being created in the mid-ocean ridges. The spreading ocean floor plates are subducted under the continental plates, the rock remelting.

The magma bubbling up from the mid-ocean ridges reacts with the ocean's water to form hydrated minerals, cooling to granite and andesite. These are lighter than the basic basalt that forms the majority of the plates. When the oceanic plate is subducted, the lighter silicates float upwards. Thus the continental plates cannot sink beneath the oceanic plates and the size of the continents is continually increasing (Ward & Brownlee 2002). Without water there would be no continental crust and no subduction. The plates would be locked together, eventually forming a continuous crust, as is seen on Venus and Mars.

2.2 The Carbon Cycle

Carbon is a fundamental element in living tissue. Through the process of photosynthesis plants take in carbon dioxide and release oxygen, while respiration in animals reacts atmospheric oxygen with consumed carbon to release carbon dioxide back into the atmosphere. Should a life form become become buried, their carbon may be subducted by plant tectonics and removed from the cycle or replaced by carbon dioxide released through volcanic activity.

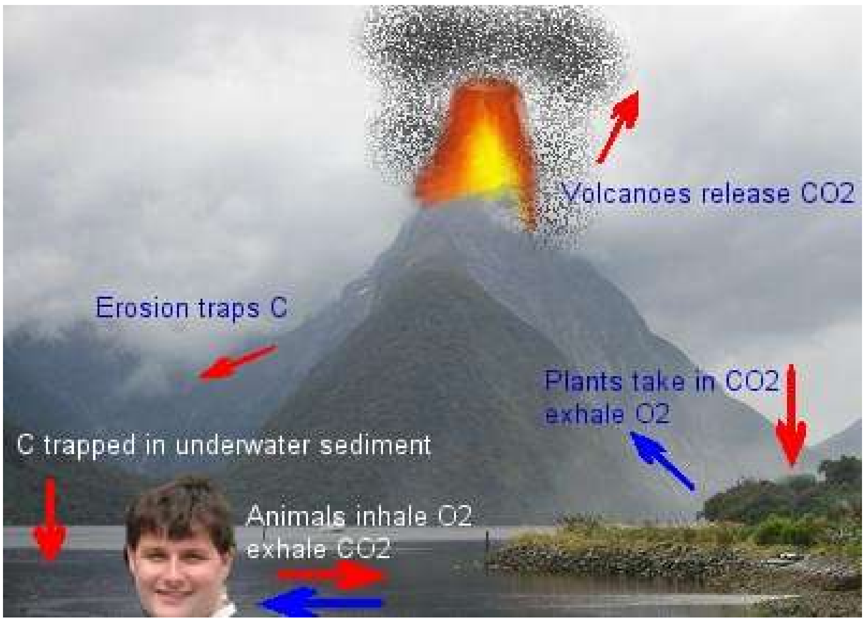

Figure 2The Carbon Cycle

2.3 The Carbonate-Silicate Cycle

As noted by Arrhenius in 1896, carbon dioxide can react with water to form carbonic acid. The carbonic acid, in the presence of water, can react with silicate minerals to form carbonates of calcium and magnesium, which then precipitate out. Phytoplankton and other organisms also produce shells of calcium carbonate, which drift to the sea floor to form limestone. If subducted, the limestone can melt and react with other compounds and may re-release the carbon dioxide into the atmosphere through volcanos (EOWeb).

3. The Cycles Break

The interaction between the biological, geological and erosion processes described in Section 2 have kept Earth's climate remarkably stable for billions of years. The planet has even rebounded from possible global freezings (Hoffman & Schrag 2000). However, like a living organism, the cycles that keep the planet alive cannot be continued for eternity.

3.1 The Greenhouse Effect and the Future of the Carbon Cycle

Humans are disrupting the natural flow of the carbon cycle by releasing geologically sequestered carbon in the form of fossil fuels (coal, oil, natural gas) back into the atmosphere. This activity is believed to be causing an increase in average global temperatures due to an enhanced greenhouse effect.

The availability of fossil fuels is, however, finite, so eventually the additional human contributions should cease. Since photosynthesis began two billion years ago, life has reduced the concentration of carbon dioxide in the air from up to 10% of the atmosphere (Kasting 1993) to current levels of less than 0.04%. The reduction of carbon dioxide is predicted to continue (Caldeira & Kasting 1992) until photosynthesis is no longer sustainable at some stage between 500 and 800 million years from the present (Franck et al 1999). The death of plant life will lead to an end to the production of oxygen, which will react with rocks and other atmospheric gases, reducing its atmospheric concentration. Eventually, oxygen levels will be low enough to mean the end of animal life as well.

3.2 The End of Plate Tectonics – a New Landscape

The face of the Earth has changed many times in its history and the continents are still in motion today. In around 250 million years from now a new supercontinent may form as the final configuration of the continents (PalWeb). This will have great consequences for the climate, animal and plant life as well as erosional process that trap carbon dioxide (Ward & Brownlee 2002).

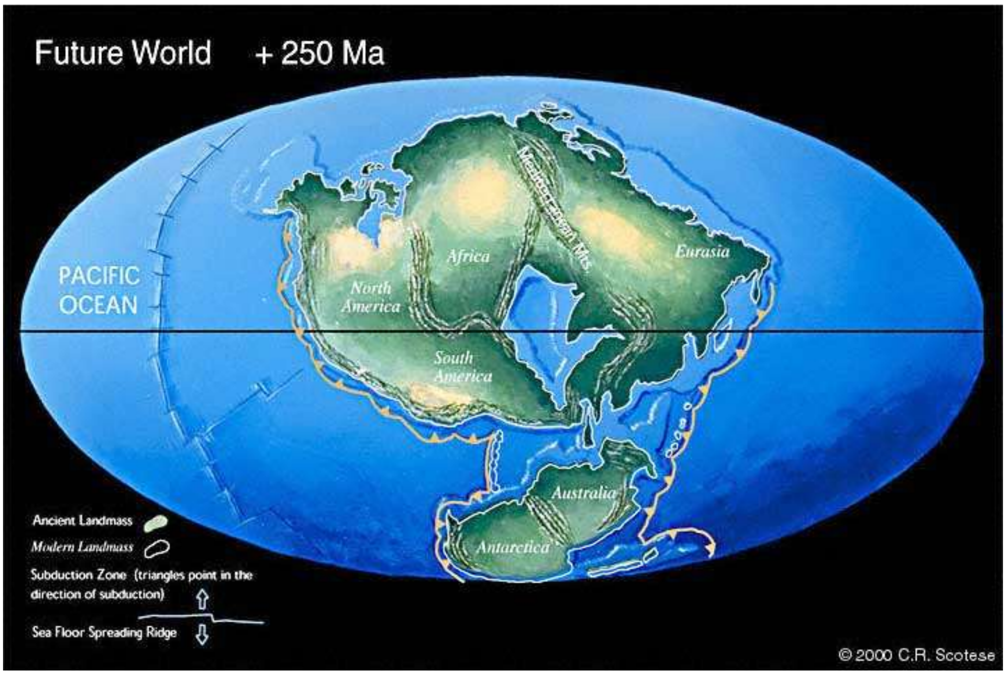

Figure 3The New Pangea (C. R. Scotese)

Ward and Brownlee (2002) report on research by Kevin Zahnle which suggests that the heat generated by radioactive decay in the Earth's interior may decline enough to stop plate tectonics sometime between 500 and 800 million years in the future. It is possible that individual hot spots will remain to form volcanoes, but the geological cycling of carbon would largely stop. Even if the decline is not enough to stop tectonic activity, the loss of Earth's oceans will ensure that the movement of the plates will end.

3.3 The Oceans Evaporate – Return of the Greenhouse Effect

Kasting et al (1984) predict increased evaporation of the oceans due to the rising luminosity of the Sun. Water vapour is a powerful greenhouse gas and this will further increase the surface temperature of the Earth and the evaporation rate. The increased flux from the Sun will also increase the rate of photodissociation of hydrogen from oxygen, allowing the former element to escape from the planet. Over a period of 2.5 billion years from now the Earth will lose its oceans and may experience a runaway greenhouse effect similar to that of Venus (Kasting 1986).

4. The Future of the Sun

The Sun, like the Earth, will evolve and change over the next 4.9 billion years. The conversion of hydrogen to helium by fusion in the Sun's core decreases the number of particles in the core, compressing it further and increasing the core's temperature. This allows the out layers of the Sun to expand, increasing its luminosity. The Sun is already 40% brighter than at its birth (Freedman & Kauffman, 2002) and is expected to increase it's luminosity by a similar amount over the next few billion years (Kasting 1986), doubling in size (Kippenhahn 1983). This is the process that will ensure that the Earth's oceans are baked from the surface.

4.1 A Red Giant

The Sun will undergo a further expansion once it has converted all the hydrogen in its core into helium. At this point the core will contract inwards, releasing heat and igniting hydrogen fusion in a shell around the core. The pressure from the core burning will cause the Sun's outer layers to expand to 100 times their present size. While the surface temperature of the Sun will drop from 5800K to 3500K with a peak output in the red spectrum, its huge size will lead to a luminosity thousands of times greater than the present Sun (Jorgensen 1991). Thus 4.9 billion years from now we have a huge red, incredibly bright Sun dominating the burnt out husk of Earth.

4.2 Death of the Sun

The Sun may have less that 2 – 3 billion years as a red giant before the next stage in its evolution takes place, the step to helium burning in the core (Jorgensen 1991). For a star the mass of the Sun, this happens suddenly in a point called the helium flash. This core burning lasts only 100 million years, followed by shell helium burning and a second red giant phase. As fuel is used up, the interior undergoes periodic contractions which compress more hydrogen and helium, allowing fusion processes to begin again. The burst of energy associated with ignitions blows off the weakly held outer layers of the Sun, forming a planetary nebular and scouring whatever remains to the planets. Eventually, all fusion processes will stop, the core will compress to degenerate electron matter (AlWeb) and the Sun will die as a slowly cooling white dwarf, fading to black.

5. The Fate of the Earth

Rybicki and Denis (2001) undertook a detailed study of the final fate of the Earth as the Sun swells into a red giant. Their conclusions were dependant on the models used to simulate the future state of the Sun, the drag exerted on the planets by the enlarged solar envelope and tidal effects. Most models predicted that both Mercury and Venus would eventually be engulfed by the giant Sun. The fate of the Earth was uncertain, but they provided the following scenarios:

- Mass loss from the Sun may increase the orbital distance of the Earth from the Sun
- The Earth may be slowed by drag from the outer levels of the solar atmosphere, thus decreasing the orbital distance
- The enlarged diameter of the Sun may lead to greater tidal interaction with the Earth, again decreasing the orbital distance.

Even if the Earth is not engulfed by a red giant Sun, conditions would be inhospitable for life as we know it. However, as the Sun heats up it Earth will lose its now Venus-like atmosphere to reveal the sky once more.

6. The Sky at Night

We cross to the dark side of 4.9 billion years AD Earth to view the night sky. The constellations would look unrecognizable to ancient Earthly eyes, as the motion of the stars and our solar system through the galaxy has changed their positions relative to us and each other. Other stars have disappeared, ending their lives in a supernovae or just fading away. Our own galaxy may have changed through collision with the M31, or Andromeda, galaxy (Ward & Brownlee 2002). Even our Moon looks different, orbiting much further away from the Earth and in the process slowing the planet's rotation. In the future, drag through the outer layers of the solar atmosphere could send it spiraling back into Earth, returning to the site of its birth, causing more devastation to an already wrecked planet.

7. Options for Humanity

Korycansky et al (2001) suggest using flybys of massive comets to gravitationally extend Earth's orbit outwards as the Sun's luminosity increases. However, as we have seen, other changes through time will probably render Earth's surface uninhabitable for present lifeforms. We may use spaceflight to escape to other planets in the solar system, although it is unlikely the gas giants or their moons can be terraformed to our needs. Rather, we may need to adapt our own bodies to new environments or even into electronic entities living in a simulated universe. It is a sobering thought that life on Earth which has existed for almost 4 billion years, could end in less than 500 million.

8. Conclusion

As I stand on the Earth under a red giant Sun I reflect on the scoured landscape around me, devoid of plants, animals, ocean and air. There is no carbon cycle of respiration of life, no tectonic cycle to build mountains, nor rivers to wash sediment into the long evaporated oceans. In another couple of billion years from now even the land beneath me may have boiled away, the Earth swallowed by an even larger Sun. Yet that lies in the future, and for now I may spread my magnetic fields, drink in the solar wind and lets my electronic mind dream of days long ago.

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