The Greenhouse Effect And The Early Earth

A discussion of Earth's early climate is not central to the topic of stellar evolution, but it so important and touches on so many interesting problems – such as the search for inhabitable extraterrestrial planets, what it can tell us about current greenhouse warming, what it can tell us about early life on Earth – that I'm going to spend a couple of pages on it anyway.

The geological record clearly shows that the Earth was very warm when it was young. (This is not the place to discuss how carefully geologists look at the exact isotopic composition of cores drilled thousands of feet into rock, or the careful way they document the exact chemical make-up of rocky layers found all over the planet – they do it, and the evidence so gathered is indisputable: the early Earth was hot.) Indeed, there is no persuasive evidence that there was *any* permanent ice on the Earth for at least the first 2.2 billion years of its existence. Persistent and recurring ice ages are a signature of the aging Earth, not the young one.

This is exactly the opposite of what one would expect, based on the certain knowledge that the Sun (like all stars) has gotten brighter as it has aged. Based just on the Sun's luminosity, the Earth ought to be about 30 F$^{\circ}$ warmer now than it was in the beginning, but the geological record indicates exactly the opposite!

The only reasonable way to explain this is with a mighty greenhouse effect four billion years ago. This greenhouse effect would almost certainly have involved a high concentration of methane in the atmosphere, for two reasons: (1) methane is a much more efficient greenhouse gas than carbon dioxide, and (2) for the greenhouse effect to have been due solely or mostly to carbon dioxide would have required a level of CO_2 so high that it would have produced unusual rock chemistry that we simply do not see in the geological record.

Presumably, this methane would have come from bacteria. Bacteria that produce methane are as common as dirt – there are uncountable millions of them in your own intestines – but they cannot be as common now as they were billions of years ago. Free oxygen is poisonous to methanogenic bacteria, so they only places they can live now are places where oxygen gas cannot reach them, such as inside animal organs or under layers of thick river sludge. But oxygen gas is produced by plants and photosynthetic bacteria, and there is reasonable evidence that photosynthetic bacteria evolved *after* methanogenic bacteria, thus once upon a time leaving all of planet Earth open to colonization by methanogenic bacteria. This would surely have led to a lot of methane in the Earth's atmosphere.

Another good point: the rise of oxygen in Earth's atmosphere and the time of the first real ice age essentially coincide. This is *not* thought to be a coincidence. With the rise of oxygen-producing bacteria, and hence the filling of Earth's atmosphere with a gas poisonous to methanogens, the methane-producing bacteria would have been beaten into a slow retreat and the amount of methane in the atmosphere would have plummeted – thus drastically reducing the greenhouse effect and bringing on Earth's first ice age.

Since that time, roughly 2.3 billion years ago, the Earth has gyrated chaotically between prolonged ice ages and warmer intervals. One reason for this is positive feedback: as the climate becomes cooler, more of the Earth becomes covered with snow and ice, which strongly reflects sunlight back into space rather than absorbing it. This serves to make the Earth even colder, which causes heavier snowfall, which increases the reflection . . .

And going in the opposite direction, if an ice age starts to break then there is less ice and snow on the ground each year, which means the dark, exposed ground can absorb more sunlight and heat the Earth more generously, which helps bring it farther out of the ice age, and so there is even less snow on the ground . . .

In short, this feedback mechanism has a distinct tendency to make the Earth's climate "snap" back and forth between cold ice ages and fairly warm non-ice ages. A "middle ground" climate such as the one we have now, where there *is* permanent ice on the Earth but not *too* much if it, has not been the norm over the past several hundred million years. What we consider to be a "normal" climate is in fact a rather rare one, if you take a long enough view. (To give an analogy, the Earth's current climate is something like a 50 F° day in the middle of a Chicago January.)

The gradually increasing luminosity of the Sun has been balanced by, among other things, Earth's plants. Increased sunlight means increased photosynthesis, and that means less CO_2 in the atmosphere because plants consume CO_2 in the process of photosynthesis. Less CO_2 means less greenhouse effect, hence a cooling effect. There are many other factors that affect the Earth's climate, including slow cycles in the Earth's distance from the Sun, continental drift, outbreaks of volcanism, you name it. But there is no question that overall the Earth's climate has roughly compensated for the Sun's increasing brilliance over the past four billion years by roughly, in a lurching fashion, one way or another, decreasing its overall greenhouse effect. We may not know exactly the how or why of this, but we know it has happened.

Alas, the greenhouse effect cannot go any lower than zero. Even worse, there is no plausible *natural* way for a planet to refrigerate itself. (I emphasis natural, because the day may well come when a super-civilization descended from our own will decide that climate change is inconvenient, and – who knows? Perhaps they will place vast clouds of highly reflective metallic dust into orbit around the Earth to reflect away any excess sunlight. It is difficult even to guess at the limits and abilities of a super-civilization.) But neglecting intelligent intervention, the Earth only has about six hundred million years to go before the Sun will indeed become too bright for any possible greenhouse reduction to counter it, and then the Earth will be doomed. As the oceans begin to evaporate they will drastically *increase* the Earth's greenhouse effect through increased humidity. The extra humidity will only make the Earth hotter, which will simply make the oceans evaporate faster, and so it goes. The Earth will segue into a *wet greenhouse* mode and become a planet covered by heavy clouds of scalding steam. In time, over perhaps 500 million years or so, the ever-brightening Sun will break down the steam with ultraviolet light into hydrogen and oxygen. Then the hydrogen will escape (because the Earth's gravity is too light to hold onto hydrogen gas) and eventually all the water will be gone. Then the Earth will become a classic, dry, hot-house planet, no different in any important way from the 700 F° inferno that Venus is now.

And unless intelligent life intervenes or at least flees to someplace cooler and takes some of Earth's life with it in the equivalent of a latter-day Noah's Ark, that will be the end of life on Earth. After some five billion continuous years of harboring life, some of it very advanced indeed, the Blue Planet, the Living Planet, will have died.