PALAEOCLIMATE

Warming the early Earth

From about 4.5 to 2.5 billion years ago, the Sun was far fainter than today. Estimates for surface temperatures 3.5 billion years ago, however, range from a temperate 22 to 40 °C up to a sweltering 85 °C. Yet, today's greenhouse gas abundances would not even be sufficient to prevent the oceans from freezing over, much less maintain temperate climes under such a weak Sun. This problem of why the Earth was not heavily glaciated despite weak solar radiation has become known as the 'faint early Sun paradox'. For close to forty years, several solutions have been proposed, each being met with a considered rebuttal.

For example, small concentrations of the greenhouse gas ammonia could have warmed the early Earth. But the gas readily breaks down into the greenhouse-neutral gas N_2 under the influence of UV radiation, and would need to be shielded to heat the Earth. However, the stratospheric ozone layer that protects the Earth from UV radiation today developed at least another billion years later. Alternatively, a layer of organic haze could have offered the requisite UV protection. But it was later shown that such a haze would block not only the UV spectrum, but a great deal of visible light as well, actually countering ammonia's greenhouse warming.

So the paradox remained. Eric Wolf and Brian Toon have now revisited the organic haze idea from a new angle (*Science* **328,** 1266–1268; 2010): they suggest that the particles that make up the haze can be thought of as fractal aggregates with a complex shape, instead of the spherical blobs assumed in previous modelling attempts. Support for this idea comes from the organic haze that currently blankets Saturn's moon, Titan; the observed optical scattering of Titan's atmosphere is best simulated by particles that take the shape of fluffy aggregates. Although such fractal particles readily absorb UV radiation, they are mostly transparent to visible light and near-infrared radiation, at least relative to spherical particles of comparable mass.

An organic haze composed of fractal particles has the added benefit of UV protection for any early forms of life. But reopening the door to organic haze and ammonia doesn't necessarily mean shutting the door on other mechanisms of warming. Both methane and N_2 are key components of the proposed organic haze, and methane is a potent greenhouse gas.

A climate boost, from high methane concentrations in conjunction with the low planetary albedo of a planet characterized by small continents and duller clouds, has been proposed to explain the paradox (*Nature* **464,** 744–747; 2010). Furthermore, N_2 may not be as climate-inert as originally thought; it has been suggested that 2.5 billion years ago, atmospheric concentrations of N_2 were almost twice as high as present-day levels. The resulting increase in atmospheric pressure could have raised the absorption efficiency of existing greenhouse gases (*Nature Geosci.* **2,** 891–896; 2009).

These and other mechanisms for early warmth are not necessarily mutually exclusive, but there isn't particularly strong evidence to suggest they were working together, either. Challenges for each hypothesis remain, and are likely to remain for some time. The faint early Sun paradox persists, but not for lack of research efforts. But our best proxies for deep-time atmospheric conditions are just based on the fossil remains of organisms that did not evolve until hundreds of millions of years later. Elegant mineralogical analyses and state-of-the-art modelling are one way to approach this problem. Wolf and Toon, however, have shown that the evidence may not lie on the Earth's surface, but instead in the mists of a distant Saturnian moon.

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