Limits to Creation of Oxygen-rich Atmospheres on Planets in the Outer Conventional Habitable Zone

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Introduction: Why Earth has an oxygen-rich atmosphere is not a solved problem, although the crucial importance of O2 to life on Earth, and its generation by life on Earth, are unquestioned. The factors that promote or frustrate the generation of free oxygen are central to what we mean by habitability, because it is O2 that makes a world fit for creatures like us attending conferences like these. The astronomical mission to identify and characterize an inhabited planet remains justifiably focused on the quest to detect O2 (or its byproduct O3) because free oxygen remains the bronze standard of habitation as we know it. We can expect that eventually, perhaps within 100 years, we will have accumulated a database of such exoplanets and we will begin to be able to evaluate basic hypotheses regarding the origin of oxygen (if not the origin of life).

To the best of our knowledge, a general discussion of which habitable planets are conducive to oxygen has not taken place. Theories for the rise of oxygen fall into 4 categories: (i) It is governed by the intrinsic rate of biological innovation, independent of environmental factors. (ii) It is a biologically-mediated Gaian response to the brightening Sun, held in check until reduced greenhouse gases were no longer needed to maintain a clement climate. (iii) It is caused by mantle evolution, either consequent to secular cooling, or consequent to high pressure mineral physics that disproportionate FeO in perovskite and send iron to the core (Frost and McCammon 2008). (iv) It is caused by hydrogen escape, which irreversibly oxidizes the Earth (Catling et al 2001). All but the first of these make implicit astronomical predictions that can be quantified and made explicit.

The first hypothesis may be untestable.

The second hypothesis --- the Gaian response --- makes two kinds of predictions. The first kind is trivial to the point of tautology: if Gaian mechanisms are the norm, we should expect that the surface temperatures of habitable planets to be under thermostatic control. Under Gaian government, a habitable planet that receives too little sunlight will compensate by having a more potent mix of greenhouse gases, and/or an anomalously low albedo; whilst a planet too near its sun will compensate by raising its albedo. Some of the greenhouse gases or cloud condensation nuclei will be best explained as biogenic.

The other Gaian prediction is implicit: the rate of biological evolution should be set by the rate of stellar luminosity evolution, because it is Gaia's ingenuity that keeps pace with the star. To first approximation, this has been the case for Earth for most of its history. This prediction would imply that the emergence of O2 rich atmospheres is a function of spectral type.

That the third hypothesis makes predictions is clear. In mantle rule, planetary oxidation takes place from the bottom up. If the control is exerted through secular cooling (broadly, the mechanism must work by changing the rate and nature of traffic between the mantle and the surface; *cf.*, Holland 2009), we can presume that smaller-less massive planets will evolve faster because they cool faster. But otherwise it is difficult to make much progress at present because there is as yet no agreed-upon mechanism that directly links the thermal state of the mantle to the redox state of the surface and atmosphere. By contrast, perovskite disproportionation implies a step-function: the planet must be big enough for perovskite to disproportionate if O2 to be favored.

The fourth hypothesis --- hydrogen escape --- is probably the best posed, most readily quantified, and most testable. In this hypothesis hydrogen escape works something like an hourglass: all relevant reduced mineral buffers must be oxidized by the oxygen left behind by hydrogen escape (titrated, as it were) before O2 first becomes possible (Zahnle et al 2013). Hydrogen escape oxidizes the planet from the top down, beginning with the atmosphere, then the hydrosphere and surface, then the crust, and last the mantle. Hydrogen escape is also the hypothesis that most clearly sets a bias on the drift of biological toward a future oxygen economy.

Of course there is no guarantee that planetary oxidation causes the emergence of oxygenic photosynthesis, nor for that matter is there any guarantee that life is even present on the planet. It is easy to imagine planets where the table is set for O2 yet oxygenic photosynthesis fails to arise (e.g., Mars). But the fourth hypothesis does make the clear prediction that O2 will not be possible if hydrogen escape has been insufficient. We will therefore focus on this aspect of the hypothesis in this paper.

References:

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