LIMITS TO CREATION OF OXYGEN-RICH ATMOSPHERES ON PLANETS IN THE OUTER REACHES OF THE CONVENTIONAL HABITABLE ZONE. K. J. Zahnle[1], [1]NASA Ames Research Center (Kevin.J.Zahnle@NASA.gov)

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. The astronomical mission to identify and characterize an inhabited planet remains focused on the quest to detect O2 (or its byproduct O3) because, apart from artificial molecules such as CF4, oxygen remains the leading indicator 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 caused by mantle evolution, probably consequent to secular cooling. (iii) It is caused by hydrogen escape, which irreversibly oxidizes the Earth. (iv) O2 is a Gaian response to the brightening Sun, suppressed until reduced greenhouse gases were no longer needed to maintain a clement climate. All but the first of these make implicit astronomical predictions that can be quantified and made explicit.

Here we will focus on the third hypothesis as the best posed, most readily quantified, and most testable. In this hypothesis hydrogen escape is like an hourglass: the oxygen left behind by the tiny but steady trickle of hydrogen into space inexorably oxidizes all the relevant reduced mineral buffers (they are titrated, as it were) before free abundant O2 first becomes possible.

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 hydrogen hourglass does make the clear prediction that O2 will not be present if hydrogen escape has been insufficient. We will therefore focus on this aspect of the hypothesis in this talk.

The fourth hypothesis—the Gaian response—makes two kinds of predictions. One is trivial almost to the point of tautology: if Gaian mechanisms are the norm, we should expect the temperatures of habitable planets to be under thermostatic control. Under Gaian governance, a habitable planet that receives less sunlight will compensate by emitting a more potent mix of greenhouse gases, and/or presenting an anomalously low albedo, and it will maintain liquid water at the surface despite the faintness of its sun. Some of the greenhouse gases will be best explained as biogenic. The second kind of prediction is implicit: the rate of biological evolution should be set by the rate of stellar luminosity evolution, because it is evolving 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 second hypothesis can make predictions is clear—to first approximation, the rate that planets cool must depend on the surface-to-volume ratio—but otherwise it is difficult to make much progress at present because, despite decades of work on the "mantle-first" hypothesis, there is no agreed-upon mechanism that directly links the thermal state of the mantle to the redox state of the surface and atmosphere.

Most studies of hydrogen escape from planets focus on determining how fast the hydrogen escapes. In general this requires solving hydrodynamic equations. But for planets from which hydrogen escape is modest or insignificant, the atmosphere can be approximated as hydrostatic, which is much simpler, and for which a relatively full-featured treatment of radiative cooling by embedded molecules, atoms, and ions such as CO2 and H3+ is straightforward. Previous work has overlooked the fact that the H2 molecule is extremely efficient at exciting non-LTE CO2 15 micron emission, and thus that radiative cooling can be markedly more efficient when H2 is abundant. We map out the region of phase space in which terrestrial planets keep hydrogen-rich atmospheres, which is what we actually want to know for habitability. Finally, we might briefly address the implications of diffusion-limited escape to the empirical observation that rocky planets with thin or negligible atmospheres are rarely or never bigger than ~1.6 Earth radii.