A GENERALIZED APPROACH TO ROCKY PLANET OXIDATION VIA GRAVITATIONAL DIFFERENTIATION: IMPLICATIONS FOR EXOPLANETS AND THE SOLAR SYSTEM

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Introduction: The oxidation of rocky planet surfaces and atmospheres is of key importance to understanding habitability in the Solar System, and to exoplanet biosignature detection. Previously, many different effects that can influence surface oxidation have been considered, including hydrogen loss [1], water or methane photolysis [2,3], mantle redox disproportionation [4] and Fe-O-Si interactions during accretion and core formation [5]. Here, we describe our progress towards a generalized description that can incorporate all of these processes within a single framework. Our key objectives are to understand the redox evolution of Solar System rocky planets and make testable predictions for low-mass exoplanets that will be characterizable in the near future by new space- and ground-based facilities.

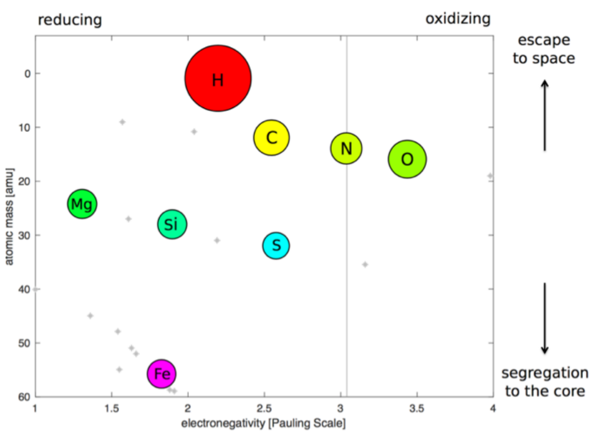

Figure 1: Plot of atomic mass vs. electronegativity for the major elements in the solar system, with the size of the circle corresponding to elemental abundance [10]. The abundance, high electronegativity and moderate atomic mass of oxygen (O) means there is always a tendency for rocky planet atmospheres and surfaces to oxidize in situations where gravitational differentiation is effective.

Methods: We define a general redox variable *N* as the number of accessible electrons in the system given a limited set of the most important redox-active species (Figs. 1-2). We treat the volatile layer, mantle and core as separate reservoirs that can exchange oxidising power at rates depending on their composition and thermodynamics. We model the escape of both hydrogen and heavier species (currently focusing on oxygen). H-O photochemistry is simulated using a 1D model with 100 levels and a small number of reactions (typically 30-40), with both eddy and molecular diffusion taken into account. The effect of star type and age is used to determine the input UV and XUV spectrum (Fig. 3). We have studied the relative effects of diffusion, XUV energy and Lyman-alpha radiation on hydrogen escape efficiency. For the moment, cooling by oxygen atoms is neglected. The climate effects of the atmosphere are taken into account using HITEMP line-by-line radiative transfer and a moist adiabat incorporating specific heat capacity dependence on temperature and the NBS/NRC steam tables for H_2O thermodynamics.

Our interior model is focused on a planet's magma ocean phase, because this period is critical to understanding the planet's later evolution. Magma ocean thermodynamics is handled following [6] and [7], with modifications to account for varying mantle density and thermal expansivity with depth. Tropospheric cold trap effects are assessed via dimensional analysis [8] and abiotic oxidation due to photolysis of species other than H_2O is also considered.

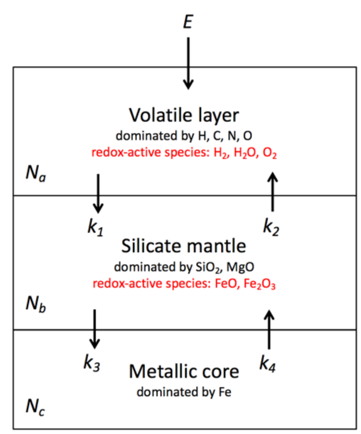

Figure 2: Summary of the key planetary reservoirs and redox-active species in our model. Differential escape preferentially removes hydrogen and hence represents a positive flux of net oxidizing power.

Results: We find photochemical inhibition of hydrogen loss via O_2 buildup scales roughly linearly with the atmospheric O_2 concentration, as long as the stratosphere remains H_2O-rich. For many terrestrial planets, we find that abiotic atmospheric O_2 buildup during any early runaway greenhouse phase [9] is short-lived, because the molten surface absorbs most oxygen liberated from H_2O photolysis (Fig. 4). However, loss of a planet's atmospheric cold trap remains a significant route to abiotic O_2 after the host star arrives on the main sequence. This is particularly true for exoplanets orbiting M-class stars, which has significant implications for O_2 'false biosignature' production [8]. In all cases, exoplanets that receive lower stellar fluxes and/or have higher mass, such as LHS1140b and TRAPPIST-1g, have the lowest probability of abiotic O_2 buildup (Fig. 5). Our results highlight the importance of obtaining observational constraints on the atmospheres of hot, sterile exoplanets such as GJ1132b and TRAPPIST-1b and –c. This will allow an independent test of our models before they are applied to potentially habitable exoplanets, where O_2 is a potential biosignature [10].

Discussion: Rocky planet redox evolution is of key importance to habitability, prebiotic chemistry and exoplanet biosignature detection. By concentrating on the development of a general framework for this problem, we have been able to make specific predictions for potentially observable exoplanets. This approach has also allowed us to test the sensitivity of abiotic O_2 buildup to uncertain parameters, such as the initial H_2O delivery and redox state of the mantle.

We are currently testing the application of our model to questions in Solar System planet evolution, including volatile redistribution on Venus during a putative early magma ocean phase [11]. In particular, we are testing the prediction of [12] that mantle oxygen fugacity changes during a steam atmosphere magma ocean phase can explain the atmospheric nitrogen inventory of Venus vs. Earth. Results on this modeling will be presented at the conference.

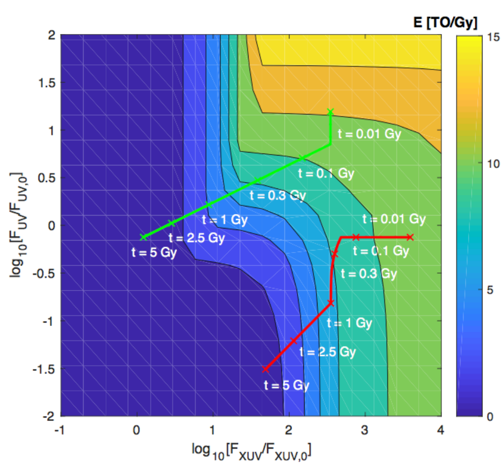

Figure 3: Tracks showing modelled stellar XUV and UV evolution vs. time. The green line shows the Sun, while the red line shows a model for Proxima Centauri. The Proxima data is scaled to represent a planet receiving a bolometric flux of 1366 W/m^2 at 5 Gy. For context, a contour plot of H escape rate as a function of stellar XUV and UV is shown in the background.

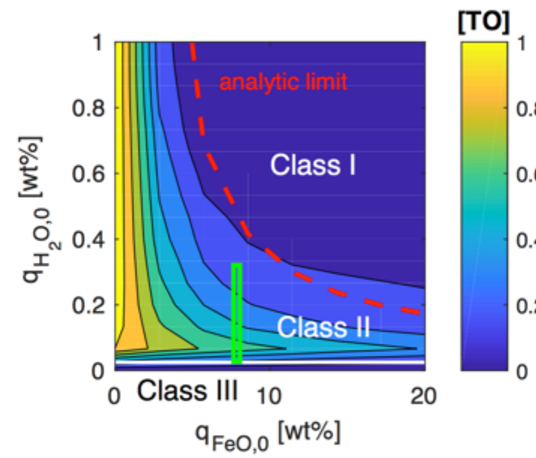

Figure 4: Contour plot of atmospheric O_2 immediately following the pre-main sequence runaway greenhouse phase of a planet orbiting an M-dwarf. The x-axis is initial specific concentration (weight fraction) of FeO in the mantle, while the y-axis is the initial volatile layer H_2O inventory, expressed as a specific concentration relative to the entire planet mass. See [10] for further details.

Planet	Abiotic O_2 buildup potential	Remarks
Prox Cen b	MEDIUM	Low received stellar flux, Earth-like mass.
GJ1132b	HIGH	High stellar flux: planet is likely sterile.
LHS1140b	LOW	Low stellar flux, high planet mass.
TRAPPIST-1b	HIGH	High stellar flux: planet is likely sterile.
TRAPPIST-1c	HIGH	High stellar flux.
TRAPPIST-1d	MEDIUM	Moderate stellar flux.
TRAPPIST-1e	MEDIUM	Moderate stellar flux.
TRAPPIST-1f	LOW	Low stellar flux.
TRAPPIST-1g	LOW	Low stellar flux.

Figure 5: Qualitative summary of the implications of our results for a range of nearby low mass exoplanets.

References:

[1] Watson, A. J., et al. (1981), *Icarus*, 48, 150-166. [2] Kasting, J. F. and Pollack J. B. (1983), *Icarus*, 53, 479–508. [3] Catling, C. J., et al. (2001), *Science*, 293, 839–843. [4] Fischer, R. A. et al. (2017), *EPSL*, 458, 252–262. [5] Frost, D. J. and McCammon, C. A. (2008) *AREPS*, 36, 389–420. [6] Schaefer, L., et al. (2016), *ApJ*, 829, 63. [7] Lebrun, T., et al. (2013) *JGR*, 118, 1155–1176. [8] Wordsworth, R. and Pierrehumbert, R. (2014) *ApJL*, 785, L20. [9] Luger, R., and Barnes, R. (2015) *Astrobiology*, 15, 119-143. [10] Wordsworth, R., et al. under revision at ApJ, arXiv:1710.00345. [11] Gillmann, C. et al. (2009), EPSL, 286, 503–513. [12] Wordsworth, R. (2016), *EPSL*, 447, 103-111.