CHALLENGES TO PREDICTING PLANETARY DIVERSITY

*Steven J Desch[1], Hilairy Ellen Hartnett[1], Cayman T Unterborn[1]

1. Arizona State University/CSPO

Current strategies for detecting life on exoplanets rely on finding (e.g., by transmission spectroscopy) atmospheric oxygen and/or CH_4 in abundances that demand production rates that cannot be explained by purely abiotic processes. To predict their abundances on a lifeless planet requires several inputs from many fields. Host star elemental abundances constrain the starting composition of the protoplanetary disk, especially H (H_2O), C, and S. Subsequent disk processes like snow lines can fractionate these, leading to planetary materials with different H:C:S ratios. Disk processes also are important for setting the redox state of planetary materials; e.g., by modifying the FeO/Fe^0 ratio by reaction of Fe metal with H_2O vapor in the disk. Within a planet, elements are further fractionated by sequestration in the core. Although H, C, and S do not dominate the density deficit of Earth's core, most of the H, C, and S on Earth nonetheless may reside in the core. This process depends on the mantle redox during core formation. Core formation in turn can affect the mantle redox state, e.g., through reactions like 3 Fe + SiO_2 àFeSi + 2 FeO, which can oxidize the mantle. Oxygen is produced abiotically by photolysis of H_2O vapor, but consumed by reduced gases (H_2S, CO) and minerals (Fe_2S) brought up from the planet interior. Translating O_2 abundance into a production rate requires fixing the speciation of S (H_2S vs. SO_2), and C (CH_4 vs. CO vs. CO_2), i.e., constraining the redox state of the near-surface interior. Likewise, CH_4 is destroyed by photolysis, but its production rate depends on the speciation of C. Predicting production rates of O_2 and CH_4, or just identifying the most important determinants, means combining results from stellar astronomy, astrophysical modeling of planet formation, geophysical modeling of core formation, and mineral and aqueous geochemistry.

We consider C; extension to S and N would be similar. Stellar abundances suggest a factor-of-2 variations in C/Mg and thus C/rock ratios in disks [1]. Earth's mantle has up to 120 ppm C, yielding 8×10^{-5} M_E or $40,000 \times 10^{18}$ moles of C in the mantle, plus 7000×10^{18} moles of C is in the crust and surface [3]. This represents a decrease by a factor of 40,000 below the solar C/rock ratio [3.5], due to a combination of disk processes and sequestration of C in the core. The plausible range of C contents of Earth's core, ~0.1 - 1wt% C [4,5], suggests a mass 3×10^{-4} –3×10^{-3} M_E, so C in the Earth's mantle was reduced by a factor of 4-40 during core formation. Solubility of C in metal is sensitive to the pressure of core formation, varying by a factor of 3 for pressures between 0 and 44 GPa [6]. Variations in mantle oxygen fugacity during core formation likely lead to significant differences in the C partitioning [5]. The partitioning of N into the core decreases by two orders of magnitude across the plausible range of mantle oxygen fugacities, ΔIW=-5 to 0 [7]. Mantle redox must play a role in setting the CH_4/CO_2 ratio of outgassed C. We conclude that the largest determinants of C content and CH_4 outgassing are snow line-like disk processes, followed by a planet's mantle redox. Stellar abundances, circumstances of core formation, near-surface mineralogies, and mode of volatile exchange (stagnant lid vs. plate tectonics) also play important roles.

Understanding the geochemical cycles of a nominally Earth-like exoplanet requires constraining its formation history and its redox state. This demands an interdisciplinary approach to solve.

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