Sun. Jul 12, 2020

[E] Oral | U (Union) : Union

9:00 AM - 10:30 AM JST | 12:00 AM - 1:30 AM UTC | Ch.1

[U-11] Planetary Metabolism: The Science of Living Worlds

convener:Anbar Ariel D(Arizona State University), John W Hernlund(Earth-Life Science Institute), Hilairy Ellen Hartnett(Arizona State University), ryuhei nakamura(Tokyo Institute of Technology, Earth-Life Science Institute), Chairperson:Ariel D Anbar(Arizona State University), Hilairy Ellen Hartnett(Arizona State University), John W Hernlund(Earth-Life Science Institute), ryuhei nakamura(Tokyo Institute of Technology, Earth-Life Science Institute)

9:00 AM - 9:15 AM JST | 12:00 AM - 12:15 AM UTC

[U11-01] Syngeosis: Application of the Principles of Symbiosis to Geological Processes

*John W Hernlund[1] (1.Earth-Life Science Institute)

9:15 AM - 9:30 AM JST | 12:15 AM - 12:30 AM UTC

[U11-02] Redox Revolutions on Earth and Beyond

*Ariel D Anbar[1] (1.Arizona State University)

9:30 AM - 9:45 AM JST | 12:30 AM - 12:45 AM UTC

[U11-03] The future life span of Earth's oxygenated biosphere and its controlling factors

★Invited Papers

*Kazumi Ozaki[1], Christopher Reinhard[2] (1.Toho University, 2.Georgia Institute of Technology)

9:45 AM - 10:00 AM JST | 12:45 AM - 1:00 AM UTC

[U11-04] Water worlds may be habitable, but not detectable

*Hilairy Ellen Hartnett[1], ASU NExSS Team (1.Arizona State University)

10:00 AM - 10:15 AM JST | 1:00 AM - 1:15 AM UTC

[U11-05] **CHALLENGES TO PREDICTING PLANETARY DIVERSITY**

★Invited Papers

*Steven J Desch[1], Hilairy Ellen Hartnett[1], Cayman T Unterborn[1] (1.Arizona State University/CSPO)

10:15 AM - 10:30 AM JST | 1:15 AM - 1:30 AM UTC

[U11-06] Planetary Dyspepsia: Finding Planets that work by understanding the planets that don’t

★Invited Papers

*Cayman T Unterborn[1], Steven J Desch[1] (1.Arizona State University/CSPO)

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[U-11] Planetary Metabolism: The Science of Living Worlds

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The geosciences are poised for transformation because of the convergence of two rapidly emerging revolutions: The advent of the Anthropocene, and the radical realization that Earth is one of countless planets in the Universe. These twin revolutions expose major gaps in our understanding of the integrated Earth-life system. The gaps are apparent when we realize that we cannot answer fundamental questions now confronting us: What are Earth's most likely future trajectories? What are the prospects for life on even the most Earth-like extrasolar worlds? The solution is to develop a truly integrated science of living worlds. Building on - 250 years of investigation across an ever-increasing range of subdisciplines, we now know the evolution of life and of Earth's biogeochemical cycles are inextricably linked to the evolution of the solid Earth. The emergence of life, the rise of an aerobic biosphere, biological radiations, mass extinctions, and even human evolution-these events and their placement in time are shaped by the trajectory of Earth's internal differentiation and dynamics, and their expression in surface tectonics and volcanism. From this vantage point, life emerged as an epiphenomenon of geophysics, and will remain coupled to the solid Earth far into the Anthropocene. Hence our greatest questions can only be answered through integration of our subdisciplines, considering the entire planet as a system. We must develop a quantitative, predictive "theory" of the Earth system that describes the mechanistic links between the interior and the surface, and how they have changed with time. Without such a theory, we cannot readily generalize from our understanding of the modern Earth system to forecast its future state, nor can we reliably model the likely states of Earth-like worlds beyond our own.

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[U11-01] Syngeosis: Application of the Principles of Symbiosis to Geological Processes

*John W Hernlund[1] (1.Earth-Life Science Institute)

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[U11-02] Redox Revolutions on Earth and Beyond

*Ariel D Anbar[1] (1.Arizona State University)

9:30 AM - 9:45 AM JST | 12:30 AM - 12:45 AM UTC

[U11-03] The future life span of Earth's oxygenated biosphere and its controlling factors

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*Kazumi Ozaki[1], Christopher Reinhard[2] (1.Toho University, 2.Georgia Institute of Technology)

9:45 AM - 10:00 AM JST | 12:45 AM - 1:00 AM UTC

[U11-04] Water worlds may be habitable, but not detectable

*Hilairy Ellen Hartnett[1], ASU NExSS Team (1.Arizona State University)

10:00 AM - 10:15 AM JST | 1:00 AM - 1:15 AM UTC

[U11-05] **CHALLENGES TO PREDICTING PLANETARY DIVERSITY**

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*Steven J Desch[1], Hilairy Ellen Hartnett[1], Cayman T Unterborn[1] (1.Arizona State University/CSPO)

10:15 AM - 10:30 AM JST | 1:15 AM - 1:30 AM UTC

[U11-06] Planetary Dyspepsia: Finding Planets that work by understanding the planets that don’t

★Invited Papers

*Cayman T Unterborn[1], Steven J Desch[1] (1.Arizona State University/CSPO)

Syngeosis: Application of the Principles of Symbiosis to Geological Processes

*John W Hernlund[1]

1. Earth-Life Science Institute

The ultimate aim of geology is to understand the role of natural processes in shaping a terrestrial planet. A process is that which animates and transforms matter, driven by available energy. Rock deformation, tectonics, mantle convection, partial melting, differentiation, orogeny, weathering, erosion, geodynamo, and even life are all processes that operate on a living planet, which involve many of the same materials and energy sources. Symbiosis, the intricate interplay of the collective processes carried out by a community of organisms, is widely established in ecological science. Less well-understood, however, is the extension of these emergent communal behaviors to include non-biological processes operating across the planet scale through deep time, something I term "syngeosis." In this presentation I will examine the interplay of abiotic processes from the viewpoint of ecological dynamics, and attempt to establish the difference between "life on a planet" and a "living planet."

Keywords: Ecology, Symbiosis, Habitability, Evolution, Dynamics

Redox Revolutions on Earth and Beyond

*Ariel D Anbar[1]

1. Arizona State University

The molecule O_2 looms large in the search for life on extrasolar planets, because Earth’s O_2-rich atmosphere is a consequence of biology. Commonly, it is assumed that an Earth-like planet on which oxygenic photosynthesis evolves will inevitably accumulate O_2 in its atmosphere and pervasively alter the surface environment –that biological redox innovations inexorably lead to environmental redox revolutions. However, close examination of Earth’s environmental redox history challenges this assumption.

Increasingly, it appears that evolution of the solid Earth played a key role in modulating the oxygenation of Earth’s surface environment. Multiple lines of evidence now suggest that O_2 was being produced biologically hundreds of millions of years before its accumulation in the atmosphere during the Great Oxidation Event (GOE), ca. 2.4 Ga, and hence that Earth’s surface redox revolution was substantially delayed. This delay can be accounted for by interactions between the atmosphere and the solid planet, because the biological production of O_2 is ultimately balanced by consumption through reaction with reductants derived from Earth’s interior. In particular, recent examinations of oxygen fugacity during the formation of Precambrian basalts and komatiites suggest that large volumes of the mantle underwent a secular increase of oxygen fugacity through the Archean and early Proterozoic. The cause(s) of this secular shift remain unclear, but when translated into a secular evolution of the redox state of volcanic gases, the observed mantle trend can account for a shift from net O_2 consumption to net O_2 production at about 2.4 Ga.

This emerging understanding of Earth’s redox revolution raises important questions about the likelihood of similar revolutions on other worlds even in the presence of large biospheres powered by oxygenic photosynthesis. Even modest differences in mantle compositions or tectonics might substantially alter the timing of surface oxygenation. On some worlds, atmospheric O_2 accumulation might be impossible. This realization highlights the need for far better understanding of solid Earth processes - and how these processes might operate on other nominally “Earth-like” worlds - as a key part of a new science of living worlds.

The future life span of Earth's oxygenated biosphere and its controlling factors

*Kazumi Ozaki[1], Christopher Reinhard[2]

1. Toho University, 2. Georgia Institute of Technology

Detecting atmospheric biosignatures on Earth-like exoplanets is one of the primary objectives of ongoing and future exoplanetary observational surveys. Significant gaps, however, remain in our understanding of the atmospheric evolution of exoplanets, and in particular the cause-and-effect relationships with an evolving biosphere. Many of these gaps arise from a lack of quantitative frameworks for interpreting atmospheric biosignatures. Construction of such a framework is a subject of broad inter-disciplinary interest. Numerous potential atmospheric biosignatures have been proposed, but molecular oxygen (O_2) (and commensurately abundant ozone, O_3) is still on top of the list of remotely detectable exoplanet biosignatures. However, a fundamental question of how much longer the remotely observable O_2/O_3 in Earth's atmosphere would be sustained on Earth remains uncertain. Solving this question has great ramifications not only for the future of our planet but also for the search for life beyond our planet. Here, we examine this problem using an Earth system model of biogeochemistry and climate that tracks the coupled carbon, oxygen, phosphorus, and sulfur cycles, and captures the global redox (O_2) budget between the exogenic system (atmosphere, ocean, and crust) and the mantle. Our model, which builds upon previous similar Earth system models, incorporates a variety of biogeochemical processes, such as biological productivity in the surface oceans and on land, a series of respiration pathways under oxic and anoxic conditions, an explicit calculation of carbonate system in the seawater, and terrestrial weathering processes, allowing an examination of biogeochemical response to changes in the O_2 levels over geologic timescales. We also include a global biogeochemical CH_4 cycle (methanogenesis, methanotrophy, a parameterized O_2-O_3-CH_4 photochemistry, and the radiative impact of CH_4 on global energy balance) in this study. The model is designed to capture the major components of the biogeochemistry and climate of Earth (and Earth-like planets more broadly) with oxic/anoxic biosphere, but is abstracted enough to allow for a stochastic approach involving large model ensembles that are run for billions of years. Implementation of a stochastic approach reveals that the mean lifespan of Earth's oxygenated biosphere (atmospheric pO_2 >1% of the present atmospheric level, PAL) is $0.81^{+0.08}_{-0.10}$ Gyr (1*sigma*), with a most probable value of 0.78 Gyr. The model predicts that a 'great deoxygenation' of atmosphere, with atmospheric pO_2 dropping sharply to levels reminiscent of the Archaean Earth (<<0.01% PAL), could conceivably be triggered within the next 1 Gyr. We also find that the future lifespan of oxygenated atmosphere depends mainly on an exchange flux of reducing power between the mantle and the exogenic (i.e., ocean-atmosphere-crust) system. We estimate that total duration of Earth's oxygenated biosphere would be ~1.5 Gyr, or roughly 25% of Earth's whole history as an inhabited planet, emphasizing the need for robust atmospheric biosignatures for anoxic exoplanet atmospheres.

Keywords: Atmosphere, Oxygen, Biogeochemical cycle

Water worlds may be habitable, but not detectable

*Hilairy Ellen Hartnett[1], Group ASU NExSS Team

1. Arizona State University

Water worlds and pelagic planets with extensive surface liquid water, are intriguing types of planet to consider in the search for life beyond Earth. They fall squarely within the traditional definition of habitable because they have surface oceans. However they may have many times more water than the Earth, which has implications for their biogeochemical cycles. We define a Detectability Index to quantify the likelihood that oxygen (O_2) could be assigned a biological vs. non-biological origin and apply it to the case of O_2 on Earth-like planets with varying amounts of water. On Earth-like exoplanets with just 0.2wt% water, i.e., no exposed continents, a reduced flux of bioessential phosphorus limits O_2 production by photosynthesis to levels indistinguishable from abiotic O_2 production due to photolysis of water vapor plus hydrogen escape. Higher water contents, > 1wt%, lead to high-pressure ice mantles and even lower rates of oxygen production. The counter-intuitive conclusion that planets with more water may be more difficult targets for life detection, highlights the importance of a biogeochemical framework for assessing biological process rates in context with geochemical and geophysical process rates.

CHALLENGES TO PREDICTING PLANETARY DIVERSITY

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

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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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Planetary Dyspepsia: Finding Planets that work by understanding the planets that don’t

*Cayman T Unterborn[1], Steven J Desch[1]

1. Arizona State University/CSPO

In our search for life outside of our solar system, the all-important question is “Where to look?” With more than 4000 exoplanets discovered, nature has revealed a diversity of rocky worlds. From exo-Mercuries to super-Earths, the vast majority of rocky planet discovered to date are unlike anything found in our Solar System. Our current data set reveals planets with masses smaller than Mercury to ten times that of Earth. For these rocky planets, the diversity increases even more so with the relative abundances of rock-building elements in stars showing factors of two difference relative to the Sun and Earth. In the building a predictive model of the trajectory a planet can take, the Earth offers our best data set to benchmark these models. The Earth, however, is unique, even in our Solar System as it undergoes plate tectonics, underwent remelting to produce continental crust and, of course, is abundant with life. We are presented with a problem: how to reconcile the need to know where to best point our telescopes to find life, the large and decidedly non-Earth parameter space of rocky exoplanet and our best source of benchmark data for any predictive models of exoplanet evolution being exceedingly complex and unique in the Earth. Given the problem’s scale coupled with the inherent need for a cross disciplinary approach to solve it, where do we start? Underlying each of these questions is a want to search for “Earth-like,” habitable planets with temperate climates over geologic timescales. As such, knowing which planets based on their observable properties are less likely to produce these conditions tell us where not to look for life. Here I present a series of examples of rocky planet compositions, ages and formation environments that outline the parameter space of planetary conditions over which emergence should be explored. By taking an “outside-in” approach to mapping the parameters for which planets stop behaving in an Earth-like manner, many of the complexities present in our models for the Earth evolution are much less relevant. By concentrating on only the most basic aspects of a planet’s evolution, we can quickly trace the planets with trajectories that are not fruitful for expensive observational follow up time in our search for life. Indeed, by mapping those planets which are more likely to be non-Earth-like can provide us with a much more robust data set to understand the population of planets to which Earths and non-Earths belong.