Annual Progress Report for award number 80NSSC18K0829

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Proposal Title: The Virtual Planetary Laboratory: Advancing the Search for Life Beyond The Solar System.

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I) Summary of research originally proposed.

To enable and advance NASA's search for life beyond the Solar System, the Virtual Planetary Laboratory Team will focus on a compelling scientific question: "How do we recognize whether an exoplanet can or does support life?" In advance of challenging observations, the VPL will combine scientific models, observations, and field and laboratory data from many disciplines to explore how a planet becomes and remains habitable, and identify new biosignatures in the context of their environments. Five research tasks will address our scientific question. Tasks A-D provide a suite of self-consistent planetary environments based on data and models that are validated against Solar System planets. These planetary environments are then input to Task E, to simulate planetary observations and determine the detectability of signs of habitability and life. The five Tasks are: Task A:Solar System Analogs for Exoplanets, Task B:The Earth Through Time, Task C:The Habitable Planet, Task D:The Living Planet, and Task E:The Observer. This interdisciplinary research will inform target selection for JWST from K2, TESS, and ground-based exoplanet discoveries; help observers recognize the signs of planetary habitability and life; and inform upcoming NASA missions that will observe terrestrial exoplanets such as JWST, and the HabEx, OST and LUVOIR mission concepts.

II) Summary of accomplishments made during this grant period.

Our second year of efforts in **Task A, The Solar System as an Analog for Exoplanetary Systems,** included a diversity of community-focused activities. Most prominently, the forthcoming book *Planetary Astrobiology* (Meadows et al., 2020) contains a number of VPL-supported chapters that focus on Solar System analogs for exoplanet environments. These chapters—designed, in part, to help exoplanet scientists more fully understand the utility of analog studies in the Solar System—include a chapter emphasizing Venus (Arney & Kane, 2020) as a laboratory for understanding the many hot terrestrial exoplanets that have already been discovered by NASA missions (see also Kane et al., 2019). Robinson & Reinhard (2020) discuss how Earth (at all stages in its evolution) can be used to understand the spectral appearance of a habitable and inhabited world. Finally, Raymond et al. (2020) cover how the formation of the Solar System can help us understand exoplanetary systems, and Zahnle & Carlson (2020) discuss how habitable planets emerge out of these

dynamic, complex systems. Members of the VPL also participated in other work emphasizing the details of Solar System formation, volatile delivery, habitable planet formation, and links to exoplanetary systems (Ribeiro et al., 2019; Clement et al., 2019). Lastly, Glenar et al. (2019) used the VPL 3-D Spectral Earth Model (developed under Task A) to explore how reflected and emitted light from Earth can impact the thermal balance of permanently shadowed craters on the Moon, thereby demonstrating how VPL tools can influence Solar System planetary science and exploration.

In **Task B, The Earth Through Time**, we examine the co-evolution of life with its environment and examine phases of early Earth as an examples of the myriad of exoplanets we may someday encounter. For the earliest Earth history, a book chapter by K. Meech and S. Raymond reviews the origin of habitability on our planet from the perspective of how Earth received its water inventory (Meech et al. 2020). Another book chapter by J. Baross, R. Anderson, and E. Stüeken (Baross et al. 2020) reviews the environmental roots of the origin of life on Hadean Earth (before 3.7 billion years ago), describing how life's origin is inextricably linked to its geochemical setting. Life's origin was also explored in a paper by C. Cornell, R. Black, and colleagues, (Cornell et al. 2019) that examined how amino acids could stabilize fatty acid membranes on early Earth, and in a paper by J. Toner and D. Catling (Toner and Catling 2019), which probed the role of alkaline lake settings to concentrate cyanide and lead to synthesis of amino acids, nucleotides, and lipids. Cold alkaline oceans were argued to be likely for Hadean Earth in a paper by S. Kadoya, J. Krissansen-Totton, and D. Catling (Kadoya et al 2019) as a result of high meteoric impactor flux producing minerals readily weathered by carbonic acid. The Archean, about one third of Earth's history, came next, and an overview by D. Catling and K. Zahnle (Catling and Zahnle 2020) provides a comprehensive summary of what we know about the Archean atmospheric composition. Further extending our understanding of the Archean atmosphere, S. Cadoya and D. Catling (Kadoya and Catling 2019) argued that detrital magnetite particles in Archean riverbeds implies that there was $< 10^{-2}$ bar of H_2 in the Archean atmosphere, precluding it as a major greenhouse gas. Micrometeorites from 2.7 billion years ago have been previously suggested to imply an oxygenated upper atmosphere, but O. Lehmer and colleagues (Lehmer et al. 2020) show how this can also be explained by an atmosphere > 70% CO_2, which also would have provided robust greenhouse warming against the faint young sun. Moving forward in Earth history to the Neoproterozoic, Stüeken et al. (2019) reinterpreted the depositional environment of what were thought to be some of the oldest lacustrine sulfate evaporites (possibly analogous to early Mars sediments) as likely marine in nature (implying the relevance to Mars is more tenuous). Finally, Kipp et al (2019) demonstrated that cycads, a group of ancient gymnosperms that harbor symbiotic nitrogen-fixing bacteria in their roos, have N isotopic ratios that match that of the atmosphere. Their fossil record stretches back over 200 million years old, so they may inform of us how the isotopic composition of atmospheric N_2 has changed.

In **Task C, the Habitable Planet,** VPL scientists participated in research that demonstrated that pebble accretion models can generate both compact multiplanet systems and the Solar System (Lambrechts et al., 2019), and showed that transient resonances during oligarchic growth can alter size distributions and constrain planetesimal formation models. (Wallace & Quinn, 2019). The team also developed and employed new machine learning models to characterize the history of high energy

radiation from TRAPPIST-1 (Fleming et al., 2020), supported the completion of the first comprehensive study of UV and X-ray emission from K dwarfs (Richey-Yowell, 2019), which we argued have potential advantages for biosignatures searches for direct imaging observations (Arney, 2019), and participated in a study that revised local M dwarf properties via GAIA observations (Martínez-Rodríguez et al., 2019). We also embarked on a significant initiative to assess intrinsic uncertainties in input data and models for coupled planetary simulations, and especially those being used to inform target selection and data interpretation for terrestrial exoplanets (Seales et al., 2019) Several research efforts focused on climate modeling to explore the limits of planetary habitability, especially for tidally-locked planets orbiting M dwarfs (Checlair et al. 2019, Yang et al., 2019, Rushby et al., 2019, Badhan et al., 2019) and for planets orbiting binary stars (Cukier et al., 2019; Haqq-Misra et al., 2019). Notably, several results (Yang et al, 2019) and initiatives focused on intermodel comparisons for exoplanet simulations, efforts that strengthen the science and modeling communities that support it. The massively interdisciplinary VPLanet terrestrial planet evolution model was also published this year (Barnes et al., 2020), and work continued on predicting telescopic observables for ocean loss and otherwise evolved terrestrial planetary atmospheres (Lincowski et al., 2019, Lustig-Yaeger et al., 2019). These and previous papers are being used to help support upcoming JWST proposals to observe the TRAPPIST-1 system and search for signs of terrestrial exoplanet evolution, habitability and life.

Members of **Task D, the Living Planet,** authored a chapter (Hoehler et al., 2019) in the Planetary Astrobiology book entitled, “Life’s Requirements, Habitability, and Biological Potential.” The chapter is intended to be a resource to the astronomy community to ultimately help characterize the life-hosting potential of environments beyond Earth. Generically, life requires energy; a supply of elements from which to construct molecules with a diversity of shapes and properties; a solvent that can support the synthesis, maintenance, and interaction of those molecules; and physicochemical conditions that support the full range of molecules and molecular interactions upon which biochemistry depends. Assessing life’s requirements offers a basis for constraining the habitability of planetary bodies — not just whether they support life, but how abundantly and robustly they could support it.

Beyond habitability, Wogan et al. (2019) assessed how disequilibrium biosignatures changed as Earth evolved from a prebiotic to chemosynthetic world. They quantified how chemical disequilibrium in an Earth-like exoplanet atmosphere (remotely detectable with telescopes) could indicate life or no life, depending on context. Volcanic gases in the atmosphere of an uninhabited, prebiotic world would be an anti-biosignature, showing that there are no microbes using the free energy of reacting those gases for metabolism. But on a planet with a biosphere, disequilibrium from a mixture of biogenic gases, which would otherwise disappear from photochemical reactions and are different species from volcanic gases, implies continuous fluxes from a biosphere. Schwieterman et al. (2019b) moved beyond the early Earth and characterized how limited the habitable zone might be for complex life. This paper compares known CO_2 tolerances for metazoans (animals) with the minimum CO_2 concentrations needed to provide sufficient warming for above freezing conditions at various locations through the habitable zone. The paper concluded that the toxic impact of very high CO_2 may limit Earth-like complex biospheres to only a portion of the

conventional habitable zone (consistent with Earth's location within it today).

In **Task E, The Observer**, over the past year VPL has made contributions to new observations of extrasolar planets, with the discovery of an Earth-sized planet in the habitable-zone of a bright M dwarf, TOI-700d (Gilbert et al. 2020; Suissa et al. 2020a), as well as detection and characterization of a wide variety of exoplanets (Cotton et al. 2018; Kruse et al. 2019; Freudenthal et al. 2019). We developed tools for contemporary studies of exoplanets (Le et al. 2020; Windemuth et al. 2019; Morris et al. 2020), including the open source model STARRY which can produce accurate light curves of transits, eclipses, and rotational modulation with derivatives (Luger et al. 2019; Agol et al. 2020), and was used in characterizing TOI-700d. We have led the way in forecasting studies of potentially habitable planets with the James Webb Space Telescope (Lincowski et al. 2019; Fauchez et al. 2019; Komacek et al. 2020; Suissa et al. 2020b; Chen et al. 2019), featuring models for a suite of hypotheses for the molecular make-up of the atmospheres of the TRAPPIST-1 planets (Lustig-Yaeger et al. 2019b) and an initiative to coordinate JWST community studies of the TRAPPIST-1 system, co-lead by PI Meadows (Gillon, Meadows, Agol et al. 2020). In our view, JWST will set the stage for more direct studies of potentially habitable exoplanets around Sun-like stars with future coronagraphic telescopes which may include NASA's plans for HabEx or LUVOIR (Smith et al. 2020; Tolento & Robinson 2019; Lustig-Yaeger et al. 2019a; LUVOIR Report; HabEx Report; Ross & Robinson 2019; Stark 2020; Arney 2019; Kopparapu et al. 2019). Finally, VPL team members have contributed to review papers regarding on studies of exoplanets with Kepler and Spitzer (Agol & Carter 2018; Borucki et al. 2018; Deming &Knutson 2020).

VPL's Contribution to Exoplanet Astrobiology Community-Building Activities

This year we'd like to emphasize the significant community building and community leadership activities of the VPL team. These activities include editing, writing and review for the *Planetary Astrobiology* book, which was sent to the printers in March 2019 but its print run is currently delayed due to COVID-19. There was significant participation of several VPL team members in the Final Reports for the Decadal mission concepts LUVOIR, HabEx and, to a lesser extent, OST. The VPL PI and many VPL team members chaired and served on the Science Organizing Committee for the Astrobiology Science Conference 2019. The VPL PI served as the Chair of the Astro2020 Decadal Survey Science Panel on *Exoplanets, Astrobiology and the Solar System.* Several VPL team members coordinated the THAI 3-D/1-D exoplanet climate model community intercomparison, and VPL provided leadership for the organization of the joint VExAG, ExoPAG and OPAG Solar System/exoplanet synergy conference "Exoplanets in our Backyard", held in February 2020.

III) Summary of risks or obstacles, plus mitigation strategies.

The current pandemic is clearly a challenge for our research, and in particular laboratory and field work exercises. It is not clear at this point how long impacts on lab and field work will continue, but we will want to revisit and address this in the coming months. However, the majority of our team works in theoretical modeling, and this work has been able to continue, largely unaffected. The team continues to make progress

and interact virtually over Slack and Zoom. However, it is unlikely that we will be able to hold our summer REU activity for tribal college students this year, and we were already experiencing challenges in implementing this program due to conflicting advice on how to proceed, and the desired outcomes of the program. When the pandemic abates, the PI hopes to discuss this further with tribal liaisons at UW, and with NASA education personnel prior to that.

IV) Summary of plans for the coming year.

In the coming year, a major focus for the VPL will be on providing the theoretical predictions, observations and tools needed to support JWST and ground-based observations of terrestrial exoplanets in the near-term, and direct imaging observations in the longer term. We will continue to focus on models of M dwarf planet formation, evolution and detectable characteristics, looking in particular at the impacts of star-planet interactions, and we will continue to obtain critical information on stellar properties and evolution that are needed to interpret upcoming observations of terrestrial planetary environments. We will continue to develop our suite of algorithms and tools for exoplanet detection, mass determination and spectral interpretation, including updating current climate/photochemical models and the development and testing of new retrieval models for terrestrial exoplanet spectra. We will also continue to push the frontiers of biosignature science, by developing a more probabilistic approach to biosignature retrieval and interpretation, including the ongoing identification of false positives, as well as identification of novel biosignatures and their detectability (including reflectance spectra and chirality). We also plan to explore isotopic methods to understand the onset and evolution of metabolism throughout Earth's history and the impact of life and weathering on geochemical cycles. We will also focus on surface photosynthesis (atmosphere climate feedbacks in a 3D climate model) and its limits.

V) Publications produced during the past year

Peer Reviewed Articles

Agol, E., & Carter, J. A. (2018). Discovery And Characterization Of Kepler-36B. New Astronomy Reviews, 83, 18–27. https://doi.org/10.1016/j.newar.2019.03.004.

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Suissa G., Wolf, E.T., Kopparapu, R.k., Villanueva, G.L., Fauchez, T., Mandell, A.M., Arney, G., Gilbert, E.A., Schlieder, J.E., Barclay, T., Quintana, E.V., Lopez, E.D., Rodriguez, J.E., and Vanderburg, A. (2020). The First Habitable Zone Earth-Size Planet From Tess. Iii: Climate States And Characterization Prospects For Toi-700 D. In revision at The Astrophysical Journal, https://arxiv.org/abs/2001.952.

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Walker, S. I., Cronin, L., Drew, A., Domagal-Goldman, S., Fisher, T., Line, M., and Millsaps, C. (2020). Probabilistic Frameworks for Life Detection. In Planetary Astrobiology (V. S. Meadows et al., eds.), pp. 477-504. Univ. of Arizona, Tucson, DOI: 10.2458/azu_uapress_9780816540068-ch018.

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Windemuth, D., Agol, E., Carter, J., Ford, E. B., Haghighipour, N., Orosz, J. A., & Welsh, W. F. (2019). An Automated Method To Detect Transiting Circumbinary Planets. Monthly Notices of the Royal Astronomical Society, 490 (1), 1313–1324. https://doi.org/10.1093/mnras/stz2637.

Wogan, N. (2019). When Is Chemical Disequilibrium In Earth-Like Planetary Atmospheres A Biosignature Versus An Anti-Biosignature? Disequilibria From Dead To Living Worlds. http://arxiv.org/abs/1911.06852 arXiv:1911.06852.

Wolf, E.T., Kopparapu, R.K., and Haqq-Misra, J. (2019). Simulated Phase Dependent Water Vapor And Cloud Spectra Of Synchronously Rotating Aquaplanets Near The Habitable Zone. The Astrophysical Journal, 877, 35 (18pp). https://doi.org/10.3847/1538-4357/ab184a.

Yang, H., Komacek, T. D., & Abbot, D. S. (2019). Effects Of Radius And Gravity On The Inner Edge Of The Habitable Zone. The Astrophysical Journal, 876 (2), L27. https://doi.org/10.3847/2041-8213/ab1d60.

Yang, J., Leconte, J., Wolf, E. T., Merlis, T., Koll, D. D. B., Forget, F., & Abbot, D. S. (2019). Simulations Of Water Vapor And Clouds On Rapidly Rotating And Tidally Locked Planets: A 3D Model Intercomparison. The Astrophysical Journal, 875 (1), 46. https://doi.org/10.3847/1538-4357/ab09f1.

Zahnle, K. J., and Carlson, R. W. (2020). Creation of a Habitable Planet. In Planetary Astrobiology (V. S. Meadows et al., eds.), pp. 505–516. Univ. of Arizona, Tucson, DOI: 10.2458/azu_uapress_9780816540068-ch001.

- Abstracts and extended abstracts

We are providing a list of VPL AbSciCon Abstracts with VPL team members as first authors. Additionally, VPL team members contributed to another 46 extended abstracts as co-authors.

Anderson, R.. (2019, June 24-29). When students become the teachers: Astrobiology as a STEM recruitment tool for both undergraduates and K-12 students. Astrobiology Science Conference 2019, Seattle, WA, United States.

Arney, G. N. and The LUVOIR Concept Study Team. (2019, June 24-29). Telling the Story of Life in the Cosmos: The LUVOIR Telescope Concepts. Astrobiology Science Conference 2019, Seattle, WA, United States.

Barnes, R., Luger, R., Deitrick, R., Driscoll, P., Fleming, D., Smotherman, H., Quinn, T., McDonald, D., Wilhelm, C., Guyer, B., Meadows, V. S., and Barth, P.. (2019, June 24-29). VPLanet: The Virtual Planet Simulator. Astrobiology Science Conference 2019, Seattle, WA, United States

Black, R. A., Cornell, C. E., Xue,M., Litz, E. H., Ramsay, A., Gordon, M., Mileant, A., Cohen, Z., Williams, J. A., Lee, K. K., Drobny G. P., and Keller, S. . (2019, June 24-29). Prebiotic Amino Acids Bind to Prebiotic Fatty Acid Membranes and Stabilize Them Against Mg2+, and Dehydration Enhances This Effect. Astrobiology Science Conference 2019, Seattle, WA, United States.

Bott, K., Meadows, V. S., and Guez, I., Lincowski, A., Bailey, J., and Kedziora-Chudczer, L. . (2019, June 24-29). The Practicality of Polarimetry for Judging Planetary Habitability. Astrobiology Science Conference 2019, Seattle, WA, United States.

Brosius, A. L., Arney, G. N., and Kopparapu R., Kostov, V., Barclay, T., Quintana, E. V., Kasting J. F., and Domagal-Goldman, S. D.. (2019, June 24-29). L98-59 system as test bed for evaporated mini Neptunes and the “Venus zone”. Astrobiology Science Conference 2019, Seattle, WA, United States

Catling, D. C. and Zahnle, K. J.. (2019, June 24-29). The early Earth's environment. Astrobiology Science Conference 2019, Seattle, WA, United States.

Cohen, Z., Nguyen, J., Lalic, G., Black, R. A., and Keller, S.. (2019, June 24-29). Fatty Acid Membranes Boost Peptide Yield: Implications for the Origin of Cellular Life. Astrobiology Science Conference 2019, Seattle, WA, United States.

Currie. M., Meadows, V. S., and Lustig-Yaeger, J.. (2019, June 24-29). Detecting False Positives with O2: A Feasibility Study. Astrobiology Science Conference 2019, Seattle, WA, United States.

Davis, C. E., Lustig-Yaeger, J., and Meadows V. S., Kopparapu, R., Guzewich, S. and Gupta, P.. (2019, June 24-29). A New Framework for Generating Simulated Observations of 3D GCM Planetary Environments. Astrobiology Science Conference 2019, Seattle, WA, United States.

Eggl, S. (2019, June 24-29). Habitable Zones in Binary Star Systems: A Zoology. Astrobiology Science Conference 2019, Seattle, WA, United States.

Fauchez, T., Wolf, E. T., Pidhorodetska, D., and Kopparapu R.. (2019, June 24-29). The Impact of Background N2 Pressure on the Habitability of Tidally Locked Rocky Exoplanets Around Cool Stars. Astrobiology Science Conference 2019, Seattle, WA, United States.

Felton, R., Neveu, M., and Domagal-Goldman, S. D. and Arney G. N.. (2019, June 24-29). A Study of a Lifeless Archean Earth as an Analog for Abiotic Terrestrial Exoplanets. Astrobiology Science Conference 2019, Seattle, WA, United States.

Fleming, D., Barnes, R., and Luger, R.. (2019, June 24-29). Constraining the Water Loss Histories of the TRAPPIST-1 Exoplanets: Comparative Habitability Using the Exoplanet Habitability Index. Astrobiology Science Conference 2019, Seattle, WA, United States.

Guez, I. and Bott, K.. (2019, June 24-29). Polarimetric Differentiation of Super-Earths and Mini-Neptunes. Astrobiology Science Conference 2019, Seattle, WA, United States.

Haqq-Misra, J. D., Welsh, W. F.,Wolf E. T., Kopparapu, R., and Kostov, V., and Kane, S.. (2019, June 24-29). Climate Extremes and Habitability Constraints for Circumbinary Planets. Astrobiology Science Conference 2019, Seattle, WA, United States.

Hoehler, T. M.. (2019, June 24-29). Research and outreach and missions (Oh my!). Astrobiology Science Conference 2019, Seattle, WA, United States.

Kane, S., Arney, G. N., and Crisp, D., Domagal-Goldman, S. D., Glaze, L. S., Goldblatt, C., Grinspoon, D. H., Head III, J. W., Lenardic, A., Unterborn, C. T., Way M., and Zahnle, K. J.. (2019, June 24-29). Venus as a Laboratory for Exoplanetary Science. Astrobiology Science Conference 2019, Seattle, WA, United States.

Kipp, M.. (2019, June 24-29). Electron acceptors, nutrient recycling and biological productivity prior to the Great Oxidation Event. Astrobiology Science Conference 2019, Seattle, WA, United States.

Koehler, M. C., Stüeken, E. E., and Prave, T.. (2019, June 24-29). A three-dimensional view of carbon and nitrogen cycling across the Ordovician-Silurian boundary. Astrobiology Science Conference 2019, Seattle, WA, United States.

Kopparapu, R., Kane, S., Wolf E. T., Haqq-Misra, J. D. and Cukier, W.. (2019, June 24-29). Habitable Zones Around Circumbinary Stars with a 1-D Climate Model. Astrobiology Science Conference 2019, Seattle, WA, United States.

Krissansen-Totton, J. and Catling, D. C.. (2019, June 24-29). Understanding the climate evolution of Earth and exoplanets with a coupled carbon-silica cycle model. Astrobiology Science Conference 2019, Seattle, WA, United States.

Larsen, D. and Meadows, V. S.. (2019, June 24-29). The University of Washington Astrobiology Program. Astrobiology Science Conference 2019, Seattle, WA, United States.

Lehmer, O., Catling, D. C., Buick, R., Brownlee, D. E., and Newport, S.. (2019, June 24-29). Atmospheric CO2 Levels from 2.7 Billion Years Ago Using Micrometeorite Oxidation. Astrobiology Science Conference 2019, Seattle, WA, United States.

Lincowski, A., Lustig-Yaeger, J., and Meadows, V. S.. (2019, June 24-29). Constraining Past Ocean Loss From M Dwarf Planets with Transit Transmission Spectroscopy. Astrobiology Science Conference 2019, Seattle, WA, United States.

Luger, R., Agol, E., Foreman-Mackey, D., Fleming, D., and Lustig-Yaeger, J. and Deitrick, R. (2019, June 24-29). Analytic Techniques for Mapping the Surfaces of Habitable Worlds. Astrobiology Science Conference 2019, Seattle, WA, United States.

Lustig-Yaeger, J., Lincowski, A., and Meadows, V. S.. (2019, June 24-29). TRAPPIST-1 and Beyond: Strategies for Characterizing Terrestrial Exoplanets and their Habitability. Astrobiology Science Conference 2019, Seattle, WA, United States.

Lyons, T. W., Olson, S., Reinhard C. T., and Schwieterman E.. (2019, June 24-29). How Earth’s Early Oceans and Atmosphere Help Guide the Search for Life Beyond our Solar System. Astrobiology Science Conference 2019, Seattle, WA, United States.

Meadows, V. S.. (2019, June 24-29). The Virtual Planetary Laboratory. Astrobiology Science Conference 2019, Seattle, WA, United States.

Meadows, V. S., Lincowski, A., Lustig-Yaeger J., and Tovar, G. (2019, June 24-29). Prospects for Biosignature Detection with JWST. Astrobiology Science Conference 2019, Seattle, WA, United States.

Parenteau, M. N. and Jahnke, L. L.. (2019, June 24-29). Production and Preservation of Lipid Biosignatures in Planetary Analogs: Distinguishing Biotic from Abiotic Signals. Astrobiology Science Conference 2019, Seattle, WA, United States.

Pidhorodetska, D., Fauchez, T., and Villanueva, G. L., and Domagal-Goldman, S. D.. (2019, June 24-29). Detectability of Habitability Signatures on TRAPPIST-1e with Current and Future Ground- and Space-Based Observatories. Astrobiology Science Conference 2019, Seattle, WA, United States.

Rodolfo Garcia, Barnes, R., Driscoll, P., Meadows, V. S., and Luger, R.. (2019, June 24-29). Atmosphere-Interior Coupling: Outgassing Effects on Runaway Greenhouse Desiccation Timescales. Astrobiology Science Conference 2019, Seattle, WA, United States.

Schwieterman, E., Reinhard, C. T., Olson S., Harman, C. E., and Lyons, T. W.. (2019, June 24-29). A limited habitable zone for complex life. Astrobiology Science Conference 2019, Seattle, WA, United States.

Shkolnik, E. L.. (2019, June 24-29). Blast from the Past: The Evolution of Ultraviolet Emission and Flaring from Low-Mass Stars and its Implications for Habitable Zone Planets. Astrobiology Science Conference 2019, Seattle, WA, United States.

Som, S. M. and Haqq-Misra, J. D.. (2019, June 24-29). Blue Marble Space and NAI: Building a Distributed Non-profit Community. Astrobiology Science Conference 2019, Seattle, WA, United States.

Som, S. M., Alperin, M. J., and McCollom, T. M., and Hoehler, T. M.. (2019, June 24-29). Cell-specific energy availability for methanogenesis in serpentinizing versus traditional methanogenic environments. Astrobiology Science Conference 2019, Seattle, WA, United States.

Swingley, W., Nuccio, D. A., and Gautam, D., Wolf, B., Blankenship, R. E., Chen, M., Parenteau, M. N. and Kiang, N. Y.. (2019, June 24-29). Genetic Clues to the Origin and Evolution of Far-red Oxygenic Photosynthesis. Astrobiology Science Conference 2019, Seattle, WA, United States.

Trainer, M. G., Freissinet, C., and Hand, K. P., Horst, M. S., Lorenz, R. D., MacKenzie, S., McKay, C. P., Brinckerhoff, W. B., Cable, M. L., Neish, C., Szopa, C., and Barnes, J. W.. (2019, June 24-29). In Situ Investigation of Titan's Prebiotic Chemistry and Astrobiological Potential. Astrobiology Science Conference 2019, Seattle, WA, United States.

Wilhelm, C., Barnes, R., and Deitrick, R., and Bitz, C. M.. (2019, June 24-29). Stability of Ice Belts on High Obliquity Earth-Like Planets around Main Sequence Stars. Astrobiology Science Conference 2019, Seattle, WA, United States.

Windemuth, D. and Agol, E.. (2019, June 24-29). An Automated, Homogeneous Search for Transiting, Terrestrial Circumbinary Worlds and Implications for Occurrence Rates. Astrobiology Science Conference 2019, Seattle, WA, United States.

Wofford, A. R., Arney, G. N., and Domagal-Goldman, S. D., Rushby, J. A., and Hoehler, T. M., and Som, S. M.. (2019, June 24-29). Revisiting Early Earth's Methanogenic Biosphere. Astrobiology Science Conference 2019, Seattle, WA, United States.

Wogan, N. and Winebrenner, D. P.. (2019, June 24-29). Exploring chemical disequilibrium biosignatures in icy moon oceans with Antarctic subglacial lake analogs. Astrobiology Science Conference 2019, Seattle, WA, United States.

Wolf, E. T., Kopparapu, R., and Haqq-Misra, J. D.. (2019, June 24-29). Simulated Phase Dependent Spectra of Terrestrial Aquaplanets in M-dwarf Systems. Astrobiology Science Conference 2019, Seattle, WA, United States.

Wong, M. L.. (2019, June 24-29). Podcasting: In the Classroom & Across the Stars. Astrobiology Science Conference 2019, Seattle, WA, United States.

Wong, M. L. and Yung, Y. L.. (2019, June 24-29). Inverse Phototrophy: A Hypothetical Metabolism for Highly Reduced Worlds. Astrobiology Science Conference 2019, Seattle, WA, United States.

Wong, M. L., Meadows, V. S., and Gao, P., Bierson, C. J., and Zhang, X.. (2019, June 24-29). Abiotic Oxygen on Venus-Like Exoplanets Around M-Dwarfs. Astrobiology Science Conference 2019, Seattle, WA, United States.

Zahnle, K. J.. (2019, June 24-29). Limits to Creation of Oxygen-rich Atmospheres on Planets in the Outer Conventional Habitable Zone. Astrobiology Science Conference 2019, Seattle, WA, United States.

VI) E/PO activities (optional).

VII) Science highlights (optional).