Habitable Worlds
Abstracts of Selected Proposals
(NNH17ZDA001N-HW)

Below are the abstracts of proposals selected for funding for the Habitable Worlds program. Principal Investigator (PI) name, institution, and proposal title are also included. 46 proposals were received in response to this opportunity. On August 28, 2018, five proposals were selected for funding.

Jason Barnes/University Of Idaho, Moscow
Tidal Obliquity Variations of Potentially Habitable Planets

The obliquity (axis tilt) of a planet and its variation strongly affect climate, and by extension a planet's potential for habitability. Obliquity can vary a small amount, like the Earth's in the presence of our Moon. Or it can vary wildly, like Mars', which takes values between 0 and 60 degrees over 100,000-year timescales. Each of those variation regimes assumes the present-day parameters of Earth and Mars, though, while in reality both rotation rate and obliquity itself are affected by tidal interaction with the Sun. We will investigate long-term chaotic obliquity variations and their evolution for terrestrial planets over billion-year timescales by uniting numerical obliquity tracking with tidal influences. While the obliquity of a planet in a single-planet system can be treated analytically, a more complete treatment requires a numerical approach. We will explore the climate variability resulting from obliquity over the lifetime of the Sun for early Venus, Moonless Earth, Mars, and hypothetical systems around M-dwarf stars. We expect for our results to bear on not just the instantaneous habitability but also the long-term habitability of both our Solar System planets and by extension exoplanets as well. This proposal is relevant to the Habitable Worlds program goal to "identify the characteristics and the distribution of potentially habitable environments in the Solar System and beyond" because it will help to evaluate the rotational and orbital parameters that influence long-term habitable terrestrial environments as affected by tides.

Tori Hoehler/NASA Ames Research Center
Abiotic and Biological Sulfate Reduction in Serpentinizing Systems

Fluid-rock interactions are a critical determinant of habitability on Mars and the icy moons of the outer solar system. Such interactions not only affect the evolution of global and local aqueous chemistry, but can also represent a long-term source of energy for life, through provision of substrates for redox-based metabolism. Within the broader spectrum of fluid-rock interactions, considerable attention has recently focused on serpentinization of ultramafic rocks, both for its potential relevance to the crustal geochemistry of Mars and the icy satellites and for its capacity to generate abundant

hydrogen ý a substrate that is widely utilized by microbes on Earth. Importantly, however, this H2 represents energy only if biologically-accessible oxidants are also present. Many studies initially focused on the potential for serpentinization to drive biological methanogenesis, using CO2 as an oxidant; however, this model has several drawbacks and may be limited to a narrow subset of serpentinizing conditions. Here, we evaluate microbial sulfate reduction (SR) as an alternative ý yet largely unexplored ý model metabolism that lacks the disadvantages of methanogenesis in the context of serpentinizing systems. The two main objectives of this work are to:

1. Characterize the abiotic reactivity and fate of dissolved sulfate during aqueous alteration of ultramafic rocks, across a range of conditions.
2. Determine whether, under what conditions, and at what rates microbial SR occurs in a natural serpentinizing system.

Objective 1: The potential for abiotic reduction of sulfate during fluid-rock interaction would reduce or eliminate oxidant availability, and thereby diminish the potential for microbial SR. However, the reactivity and fate of sulfate in such systems is not well constrained by existing experimental or field work, particularly for the rock types and conditions that may be most relevant for Mars and the ocean worlds. We will use a well-established experimental methodology to characterize the reactivity of dissolved sulfate in the presence and absence of Harzburgite, at temperatures ranging from 200-325C. The experiments will utilize stable isotope-labeled (34-S) sulfate to permit (i) construction of a sulfur isotope mass balance through comprehensive analysis of the distribution of oxidized and reduced sulfur phases in the experimental products; and (ii) visualization of the distribution of newly-formed sulfur-bearing minerals by microscale isotopic and mineralogic analysis.

Objective 2: The viability of microbial SR in serpentinizing systems is not well characterized. We will quantify rates of microbial sulfate reduction in freshly cored solids and recovered well fluids from the Samail Ophiolite, Oman, where decreasing sulfate concentrations along the hydrologic gradient are suggestive of active sulfate reduction. We will utilize a well-established 35-S tracer technique combined with cold chrome distillation of end products to quantify rates of microbial SR as a function of naturally-occurring variation in pH and concentrations of sulfate, hydrogen, and organic acids.

The proposed work is directly relevant to ROSES element E.4, Habitable Worlds, specifically by evaluating energy availability in the context of global geochemical cycling. The process considered, serpentinization, has relevance for understanding the geochemical evolution and habitability of both Mars and the icy satellites.

Leslie Rogers/University Of Chicago
Quantifying the Effect of Oceans on the Atmospheric Composition of Habitable Water Worlds

We propose to combine models of planet interiors, climate, phase equilibria, and photochemistry to delineate the habitable zone boundaries and atmospheric compositions of water world exoplanets (with at least 1% water by mass). Kuchner (2003) and Leger et al. (2004) first proposed the possibility of water worlds - water-rich super-Ganymede exoplanets that formed from volatile ice-rich material beyond the snow line but that never attained masses sufficient to accrete or retain large amounts of H/He nebular gas. This pathway for producing low-mass water-rich planets has played out as a robust prediction of planet formation simulations. If located at an appropriate orbital separation from their host star, water worlds may host a global surface water ocean. Habitable water worlds are especially timely and relevant because 1) water worlds formed from remnant cores of evaporated mini-Neptunes could be one of the dominant formation mechanisms for volatile-rich habitable zone planets around M dwarf stars (Luger et al. 2015), and 2) their larger sizes relative to terrestrial planets make them more amenable to observations with current and upcoming telescopes such as HST and JWST.

The classical habitable zone does not apply to water worlds with global oceans. Water worlds lack exposed landmass for continental silicate weathering feedback, and may host a layer of high pressure ice (ice phases VI and VII) that separates the liquid ocean and atmosphere from the planet's crust and interior. In the absence of a carbonate-silicate cycle, the formation of clathrates and the solubility of CO2 in the ocean determines its concentration in the water world's atmosphere. To date, studies of the solubility-mediated habitable zones of water worlds have only considered liquid-vapor equilibria in the H2O-CO2 system (Kitzmann et al. 2015, Levi et al. 2017), whereas water worlds are expected to form from a comet-like mixture of astrophysical ices (including H2O, CO2, CH4, H2S, N2, NH3, H2S, and CH3OH). Due to chemical interactions in the liquid phase, the presence of other chemical species that dissociate in water could have an order unity effect on the solubility of CO2 (and consequently the atmospheric concentration of CO2 and the planetary surface temperature). A more thorough exploration of the solubility-mediated habitable zone of water worlds is needed.

We propose to improve upon existing models for water-world exoplanets 1) by developing the first self-consistently coupled models of exoplanet interior structure, atmospheric radiative transfer, liquid-vapor thermochemical equilibria, and photochemistry and 2) by substantially expanding the range of compositional parameter space considered. We will apply these models to assess how partitioning of species between the liquid, hydrate, and vapor phases affects the atmospheric composition, transmission spectrum, and thermal emission spectrum of ocean-covered planets. We will also delineate the solubility-mediated habitable zone for water worlds, and how it depends on the composition of volatiles accreted by the planet. One of the primary results of this project will be predictions for atmospheric abundance patterns that are signatures

of global water oceans. This modeling effort is necessary if we are to identify potentially habitable planets with global oceans using JWST observations.

This proposal is directly relevant to the NASA Habitable Worlds Program because it addresses the habitability of water-rich exoplanets. This work involves modeling water body physics and chemistry as they pertain to habitability and habitability over time. By developing observational diagnostics of the presence of global oceans on water world exoplanets, this project will inform target and operational choices for current NASA missions (i.e., HST, Spitzer, JWST, TESS) and will be essential for the planning of a future space-based exoplanet direct imaging mission (e.g., LUVOIR, HabEx).

Jonathan Toner/University Of Washington, Seattle
The Composition and Habitability of Enceladus' Ocean

Cassini has found evidence for a subsurface ocean erupting plumes of material from Enceladus' south pole. Analyses of the plumes suggest a moderately saline, high pH ocean environment containing organics, carbon dioxide, methane, ammonia, argon, and molecular hydrogen. This composition suggests a potentially habitable environment that may be favorable for origin-of-life scenarios. The ability to sample the subsurface ocean via the plumes makes Enceladus a strong candidate for proposed missions, e.g. the 'Enceladus Life Finder' (ELF) and 'Enceladus Life Signatures and Habitability' (ELSAH) missions.

Inferring the deep ocean composition from plume analyses is vital for proposed missions, and represents a gap in knowledge between proposed instrument suites and science return. Measurements of Enceladus' plume may not directly reflect the ocean composition because equilibrium and non-equilibrium processes will fractionate oceanic waters during transport to the surface. Efforts to model equilibrium and non-equilibrium fractionation processes in the plume are hindered by a lack of experimental data at low-temperatures and high salt concentrations relevant to Enceladus. To address these issues, we propose three tasks to: (1) measure low-temperature properties of gases and aqueous solutions relevant to Enceladus, (2) incorporate experimental and literature data into predictive numerical models, and (3) apply a box model to understanding the subsurface ocean and plume composition.

The experimental measurements in Task 1 target processes that form Enceladus' plume and key knowledge gaps that hinder numerical modeling efforts. We will measure heat capacities of aqueous solutions to constrain the temperature-dependence of aqueous chemistry models. To understand the potential preservation of organics within glasses in plume particles, we will measure glass transition temperatures and crystal nucleation rates in aqueous solutions. Finally, we will directly investigate processes that form Enceladus' plume in gas solubility, dissolution, and exsolution experiments. In Task 2, we will incorporate the new data into numerical models of aqueous chemistry. In Task 3, we will apply new experimental data and aqueous models to Enceladus using a box

model that accounts for plume fractionation and mass fluxes from its source in the deep ocean to the erupted plume in space. Our goal is to constrain which deep ocean compositions are consistent with plume measurements by Cassini (and future spacecraft), and the potential habitability of the ocean.

The outcomes of this research will address fundamental questions about Enceladus' ocean, including: (1) What do plume measurements indicate about the ocean composition? (2) What are the habitability parameters of the ocean, such as pH, salinity, water activity, and freezing temperature? Are there chemical gradients in the ocean important for life? (3) What do solid phases in the plume imply about conditions in the parent fluid? Could aqueous glasses preserve organics in Enceladus' plume? This research is also relevant for understanding aqueous solutions on other icy worlds such as Ceres, Europa, and Titan, as well as low-temperature aqueous chemistries on Earth and Mars.

Our proposed research is timely because our work will better constrain the ocean chemistry and potential habitability using existing Cassini data, inform future planning of Enceladus missions, and allow a rapid and more accurate interpretation of results returned from future missions. Experimental work will directly measure gas exsolution processes that fractionate plume materials, and allow the development of aqueous models to understand the chemistry of Enceladus' ocean. Overall, our modeling efforts will result in better constraints on the composition of Enceladus' plume, and habitability parameters in Enceladus' ocean, including gas composition, salinity, pH, water activity, and temperature.

Michael Way/NASA Goddard Space Flight Center
The Role Of Land/Sea Boundary Conditions On Climates Of Habitable Worlds And Implications For Future Space Observations

At present, exoplanet community studies that apply global climate models (GCMs) to understand the climate dynamics of other worlds typically make use of scenarios such as aquaplanets/desert planets, idealized block continents, or present-day Earth topography. In most cases, these scenarios also employ thin (50-100m) mixed-layer oceans with zero horizontal heat transport. While such an end-member approach is straightforward and computationally advantageous, it is not necessarily optimal to the eventual detection of life elsewhere. Planets with oceans and some exposed land appear more likely to have a carbonate-silicate feedback cycle that regulates CO2 and promotes climatically stable habitable conditions and to produce abundant life whose spectral signature is less likely to be confounded by abiotic signals. We suggest that the use of realistic and scenario-appropriate topography for solar system terrestrial planets with a dynamic ocean with more physically representative heat transports than a mixed-layer ocean provides a more useful baseline from which to explore climatic processes not seen on modern Earth, as well as factors leading to regionally habitable conditions that are likely to exist on the

inner and outer edges of circumstellar habitable zones. By extension, this approach is likely to lead to an improved assessment of planetary habitability.

We therefore propose a planetary systems science modeling approach that combines data-driven paleo-Earth simulations, hypothetical paleo-Venus simulations, and theoretical Earth analogue exoplanet simulations to explore the effects of spatially distinctive land-ocean distributions on climatological diversity and patterns of surface habitability, and their remotely detectable characteristics. These simulations will involve the construction of realistic new surface boundary conditions, either from geological data (for paleo-Earth) or based on current topography (Venus). Our initial sets of boundary condition data (BCDs) will be used in turn as the foundation for further sensitivity studies exploring the effects of land/ocean fraction and depth and topographic controls on habitability. These new scenarios will provide informative, fully-coupled atmosphere-ocean scenarios that are vital for the next generation of community GCM studies, specifically those intended to help scientists interpret observations from proposed future direct imaging missions such as HabEx and LUVOIR.

As a community service, we will package the new BCDs that we create for distribution to the planetary climate community, with the goal of making possible model inter-comparisons that can lead to the further improvement of our modeling tools. The BCDs may also form the experimental basis of a future exoplanet modeling inter-comparison project (ExoMIP), similar in concept to other model inter-comparison projects that have proven so useful to the modern- and paleo-Earth climate communities.

This proposal is responsive to the cross-divisional Habitable Worlds program in two ways: 1) By expanding researchers' capabilities to explore the parameter space of BCDs, we offer the Planetary Science community the opportunity to take a more sophisticated approach to characterizing global to regional-scale habitable surface environments of potentially habitable (Earth analog) exoplanets and/or their moons. 2) The habitability studies supported by the proposed atlas will be accompanied by synthetic transit transmission spectra as well as reflected light and thermal emission phase curves, ultimately assisting the Astrophysics community by expanding the scope of studies that can inform targeting and/or operational choices for current and future NASA Astrophysics missions.

Mikhail Zolotov/Arizona State University
Aqueous Environments and CO2 on Exoplanets

In the coming decade, new orbital and ground telescopes will be able to detect atmospheric compositions of terrestrial exoplanets in Habitable Zones (HZ) of their stars. Although compositions of surface rocks and aqueous phases may not be observed in foreseeable future, atmospheric gases could constrain habitable planetary environments if gas-solid-aqueous links are understood. On solid HZ exoplanets, chemical interactions between gases, surface water and rocks could affect the composition of volatile-bearing

planetary envelopes. The atmospheric CO2 abundance is set by a balance between sinks and a supply through degassing. Sinks of CO2 to liquid and solid phases are affected by dissolution in waters and precipitation of carbonates and/or clathrates, which are influenced by the temperature, composition and acidity (pH) of solutions. In turn, chemistry of aqueous solutions is mainly affected by the composition of altering rocks and dissolution of atmospheric gases. The apparent diversity of star compositions together with complex scenarios of planet formation and evolution imply a wide range of rock compositions. These coupled influences could be quantified by methods of equilibrium chemical thermodynamics constrained by fundamental constants and mass balances in gas-water-solid systems on HZ exoplanets.

This study is aimed at understanding effects of rock composition and water/CO2/rock ratios on aqueous acid-base chemistry, secondary mineralogy and abundance of atmospheric CO2 on HZ exoplanets. We will consider water/CO2/rock interactions on water-poor (desert) and water-rich (ocean) exoplanets. We will model water-gas-rock type chemical interactions at specified water/CO2/rock ratios through calculations of chemical equilibria in closed systems and systems open with respect to CO2. We will calculate atmospheric concentrations of CO2 and link compositional characteristics of rocks with buffering capacities of rocks with respect to CO2. Rock will be presented by representative terrestrial rocks and compositions evaluated from compositions of stars. The water/rock ratio will be chosen to reflect the oceanic depth and permeability of rocks. The results will be discussed in terms of observable atmospheric CO2 linked to chemistry, mineralogy and habitability of aqueous systems.

Significance. This proposal links aqueous processes on exoplanets with quantitative assessments of habitability related to CO2 and inorganic chemistry of gas-water-rock systems in the vicinity of exoplanetary surfaces. The work will explore how the composition of rocks on diverse exoplanets and rock/CO2/water ratios affect the inorganic chemistry of aqueous environments. The work is relevant to the Habitable Words program because it deals with potentially habitable exoplanets and considers water physics and chemistry as they relate to habitability.