Habitable Worlds
Abstracts of Selected Proposals
(NNH18ZDA001N-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. 60 proposals were received in response to this opportunity. On October 17, 2019, 10 proposals were selected for funding.

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Rory Barnes/University Of Washington, Seattle
The Desiccation of Habitable Worlds

Potentially habitable worlds orbiting M dwarf stars can experience extreme internal and external heating that can remove primordial water. M dwarfs may take up to 2 Gyr to reach the main sequence, during which time the star is more luminous and hence planets in the habitable zone today were interior to it early on. In addition, tidal heating can be larger than on Io, possibly sustaining a long-lived magma ocean and intense volcanic activity. Like the stellar luminosity, this tidal heating is expected to fade in most cases as orbits circularize and rotations synchronize, eliminating the sources of friction that heat the interior. Thus, the early evolution of these planets is likely characterized by a runaway greenhouse atmosphere atop an active solid body that is outgassing interior volatiles. The high XUV flux from young M dwarfs can photolyze water and the released hydrogen can escape to space. The lost water can be replaced by outgassing, but eventually the internal reservoir is depleted. Hence, it is essential that astronomers determine if these planets can retain their liquid water in spite of these processes.

We propose to self-consistently model the stellar, orbital, rotational, atmospheric, geochemical, and geophysical evolution of terrestrial planets orbiting M dwarfs to assess the likelihood that they can retain significant abundances of water. We will couple plausible astrophysical and internal heat sources (tidal, radiogenic, radiation, differentiation, solidification) with models of cooling modes (plate tectonics, stagnant lid, magma ocean, heat pipe). Tidal heating can be generated by rotational de-spinning and liberation, or by non-circular orbits that are sustained by gravitational perturbations from other planets. We will employ appropriate volatile cycling models for each cooling mode to track water through interior and atmospheric buffers, with a slow drain of water via photolysis and hydrogen escape. We will use a state-of-the-art planetary evolution code directed by a novel machine learning technique to determine what combinations of initial conditions and planetary system properties permit liquid water on known and hypothetical terrestrial exoplanets that may be habitable. For known systems, we can then identify evolutionary tracks that are consistent with current observations in order to predict the likelihood that it could still possess water. These experiments can help prioritize observations of NASA spacecraft like JWST that can detect the composition of terrestrial exoplanets in the habitable zones of M dwarfs.
Eleanor Browne/University Of Colorado, Boulder
Impact of Sulfur on Planetary Haze: Implications for Habitability

Atmospheric hazes, a common feature of planetary bodies, may impact habitability in several ways including by shielding planetary surfaces from harmful UV radiation and providing key nutrients for life. Geochemical data supports the existence of an organic haze layer on Earth at multiple times during the Archean eon (H4-2.5 billion years ago), a period covering the origin of life and start of an oxygenated atmosphere. Previous work, including our own, has investigated the formation and optical properties of organic hazes containing C, H, O, and N. An element considered essential for life and absent from these works is sulfur (S).

Sulfur isotope studies from Archean rocks indicate a critical role for atmospheric S during this important time in the development of a habitable Earth. The presence of mass-independent S-isotope fractionation (S-MIF) is thought to be evidence for an early anoxic atmosphere, while S-MIF variability in the Archean eon has been hypothesized to be related to haze formation/properties. However, few experimental constraints exist on how S species alter the elemental and isotopic composition and optical properties of organic haze. Notably, organosulfur (OS) chemistry is unexplored. Our previous work found that CH4 photolysis in the presence of SO2 produced OS. This work focused on how SO2 altered aerosol composition and yield, leaving open questions regarding the gaseous composition, the haze optical properties, and the influence of S precursors.

We propose a comprehensive study of the chemical and optical properties of haze analogs, formed via far UV irradiation of N2/CH4/CO2/O2 mixtures, in the presence of H2S and/or SO2. Starting gas compositions will be based on early Earth as a habitable planet analog. We will characterize the chemical composition of gaseous compounds, including OS, with a chemical ionization mass spectrometer. Haze chemical composition will be probed with an aerosol mass spectrometer. A unique aspect of this work is that the above measurements occur in real-time with on-line instruments directly coupled to the reaction chamber. Molecular information on aerosol composition will be obtained by collecting filter samples and analyzing the samples off-line with the chemical ionization mass spectrometer. Once the chemical controls of haze formation are quantified, we will repeat select experiments to collect samples of bulk aerosol and residual S-bearing gases to monitor the S isotopic consequences of haze formation.

Based on comparisons to Earth's present day aerosols, we hypothesize that fundamentally new atmospheric organic chemistry, such as the formation of OS and the promotion of acid-catalyzed reactions, occurs in the presence of inorganic S. As such, an important source of organic haze, biomolecule, and nutrient production is missing from current models of early Earth and exoplanet atmospheres.
The proposed work is directly relevant to the overall goal of Habitable Worlds to use knowledge of the history of the Earth and the life upon it as a guide for determining the processes and conditions that create and maintain habitable environments. In particular, organic hazes may have played a key role in the habitability of early Earth by influencing the temperature, UV flux, and nutrients available to early life. A more complete picture of haze impacts on habitability will be explored by simultaneously using multiple analytical techniques to constrain the SSA and chemical composition of gases and particles.

Vincent Chevrier/University of Arkansas, Fayetteville
Experimental study of brine production in the Martian regolith: Insights into present-day habitability

Objectives
The existence of present-day liquid water environments on Mars has significant implications for its biologic potential and for future exploration by both rovers and crewed missions. Several active mass movement events, such as recurring slope lineae (RSL) and gullies, have notably suggested the potential for ongoing liquid water processes. Observations by landers (e.g., the Phoenix lander and the Mars Science Laboratory) have also indicated the presence of environments favorable to brine formation through either water ice-salt interactions or atmosphere-regolith interactions (e.g., deliquescence). However, such processes are strongly dependent on temperature and water vapor and thus affected by the diurnal and seasonal cycles and the diffusion of these cycles through the Martian regolith. Experimental work thus far has focused on defining the phase space for Mars-relevant brines, but not much work has been done to define the stability of these brines under Mars-like diurnal conditions. Here we propose to investigate the stability and properties of Mars-relevant brines under Mars-like conditions in our unique environmental chamber. The proposed work would experimentally simulate the effect of thermal cycles on water vapor diffusion in complex situations involving adsorption, and deliquescence / hydration in a shallow regolith column. Our experiments will replicate both equatorial and polar conditions as well as investigate the effect of an ice table.

Methods
We will use our unique Martian environmental chamber to reproduce the behavior of regolith columns of various compositions, and salt components and concentrations to evaluate the behavior of water vapor, ice, and liquid undergoing Martian diurnal cycles under different seasons. The regolith columns will be analyzed using an array of analytical techniques including hygrometers (identical to those onboard MSL) and thermocouples at different depths, combined with electric conductivity, optical microscopy and FTIR spectroscopy (1 to 4.5 microns) to fully understand the behavior of water phases as a function of depth. We will also use these experiments to validate our numerical model specifically designed to investigate the habitability of the Martian shallow subsurface. We will compare the results of the model with our experimental data.
on the behavior and stability of liquids as well as the behavior of water vapor on diurnal scales. This unique approach will help us better define the potential present-day subsurface habitability of Mars.

Relevance to Habitable Worlds
The proposed experimental and modeling work will improve our understanding of liquid water formation on Mars and the potential for such environments to support life. Specifically, our proposed work focuses on the present-day subsurface habitability of Mars by experimentally constraining the behavior of brines under Mars-like diurnal conditions and applying these results through a numerical model to present-day Mars. The proposed work leverages our knowledge of life on Earth to determine if conditions leading to liquid formation on present-day Mars also lead to habitable environments by defining the characteristics (e.g., temperature, salinity, longevity) of brines produced under Mars-like diurnal conditions.

Jacob Haqq-Misra/Blue Marble Space
Constraining the Climate Trajectory of Early Mars using an Optimized Ensemble of Climate Calculations

Evidence for fluvial features and standing liquid water indicate that Mars was a warmer and wetter place in its past; however, climate models have historically been unable to produce conditions to yield a warm early Mars under the faint young sun. Some models invoke thick greenhouse atmospheres to produce continuously warm conditions, while others argue that impacts during the Late Heavy Bombardment caused transient warming on an otherwise cold Mars. A third option suggests that early Mars experienced climate limit cycles between short periods of warmth and prolonged periods of glaciation, due to modulation of greenhouse warming by the carbonate-silicate cycle. Aspects of all these models may have operated during Mars' history: the Noachian experienced heavy impacts and large-scale volcanic activity, with the earliest signs of fluvial features, while the Hesperian was less geologically active and indicates evidence of standing liquid water. This research will investigate the confluence of available hypotheses for warming early Mars with an ensemble modeling approach to the evolution of climate across the planet’s geological history.

METHODS
This research will calculate observationally-consistent trajectories for the climate history of Mars using an optimized ensemble of energy balance model (EBM) climate calculations. This EBM has been used in previous studies of planetary habitability to identify the contribution of factors such as incident stellar flux, volcanic outgassing rate, planetary obliquity, greenhouse gas inventory, and atmospheric mass loss. This study will examine the confluence of all these factors to the history of liquid water on Mars by using an optimization algorithm that iteratively improves an ensemble of EBM simulations, with constraints based upon key characteristics during the Noachian, Hesperian, and Amazonian. Candidate trajectories will be evaluated against general circulation model
(GCM) calculations to assess the robustness of the EBM approach. The results of this climate model optimization will provide several trajectories for how these quantities have changed with time over the history of Mars from the Noachian to the present.

RELEVANCE
This proposed research is relevant to NASA's Habitable Worlds program as a theoretical study of plausible climate trajectories to explain the past presence of surface liquid water on Mars. The results of this research will constrain "the astrobiological potential of past or present environments on or in the Martian surface or subsurface" (E.4-1) by using an optimized ensemble of climate model simulations constrained by observations. The scope of this research focuses on the habitability of early Mars, so this proposal is not relevant to the Emerging Worlds program, the Exobiology program, or any existing data analysis programs.

Shannon MacKenzie/Johns Hopkins University
The Interior Life of Dunes

Dunes are often found in the hottest, driest environments on Earth, but dune interiors are not as devoid of life as may be expected. A dune's interior can be relatively benign, with smaller temperature gradients, higher humidity levels, and decreased radiation exposure than the surrounding environment. Active dunes experience influxes of new material consistent with the rate of dune motion and seasonal rainfall. Thus, dune interiors are oases of which terrestrial microbial life has taken advantage.

Water content has previously been established as an important environmental condition for life to thrive within dunes. Monitoring of a single mobile barchan in Qatar showed that microbial abundance within the dune was more closely related to humidity, which varies within the dune. Studies of Sonoran Desert soils, however, have shown that bacterial population diversity is also significantly correlated with other properties like pH and carbon content. But several questions remain that are key to understanding what environmental conditions promote habitability. How these factors vary within a dune or across a dune field? How does such variance affect the growth and detection of the microbiome? What aspects of habitability are most closely tied with environmental factors?

Answering these questions is critical to assessing the potential of dunes across the solar system as habitable niches (past or extant). The dunes of Mars and Titan, where surface liquids were or are conceivably interacting with the dune interior, are particularly compelling astrobiological targets. Adsorbed water was detected by Curiosity at an inactive dune and pits left by possibly flooded ancient dunes have been identified. Huygens landed in Titan's equatorial desert but gathered evidence suggesting liquid methane was present in the near subsurface and, later, Cassini observed surface wetting from rainfall.
This proposal will leverage knowledge of behavior of life in dunes on Earth to answer the questions above by conducting a quantitative terrestrial field experiment in a US dune field. In Task 1, we will measure the following environmental conditions at four discrete depths within four dunes: temperature, moisture, grain size, nitrogen, oxygen, and total organic carbon. Discrete layers will be determined on site using ground penetrating radar. For Task 2, we will establish a more nuanced measurement of habitability within the dune interiors by examining not only bacterial abundance, but also metabolic activity and gene expression. Genomic, metabolomic, and metatranscriptomic analyses will be performed on samples procured along with the measurements of Task 1. This information is critical to interpreting the relative importance of the environmental conditions measured in Task 1.

For Task 3, we will determine correlations between the environmental and biological factors and variance of that correlation with dune interior position or position in the dune field. These results will specifically inform the design and interpretation of future measurements, i.e. establishing how representative a shallow sample or sample at the edge of a dune field is of the entire dune or the entire dune field.

Our proposal directly responds to the Habitable Worlds solicitation as our results will improve scientific understanding of how in situ measurements at analog sites can [...] improve our understanding of the potential for the environment to support life elsewhere. Our findings of how environmental and biological factors vary within a dune and between dunes of the same field will have implications for sampling strategies at Mars or Titan. Furthermore, by tying the environmental factors to different aspects of biological activity within dune interiors, we will determine processes and conditions that create and maintain habitable environments, providing new insight for investigating dunes as targets for the possibility of extant life beyond the Earth.

Roy Price/State University Of New York, Stony Brook
Habitability of Saponite-rich Hydrothermal Systems of Early Mars.

Of all the potential sites in the solar system that may harbor life, those with hydrothermal vents have perhaps the greatest potential for creating environments conducive for life's origin and continued habitability. Energy production and availability is key: The disequilibria generated during water-rock reactions and the mixing of vent fluids with the overlying water column provides an energy-rich environment for chemosynthetic life to thrive. Studies of different types of hydrothermal vents on Earth have revolutionized our understanding of how life on Earth might have emerged, and how and where life might exist. But, modern Earth analogs for ancient Mars systems are uncommon.

Iceland rocks are similar to those found on Mars, and many authors have compared Iceland hydrothermal vents with putative vents thought to have once existed on early Mars. Environments where Iceland’s iron-rich rocks are being altered by hot springs were suggested to reflect conditions on Mars more than three billion years ago. This
makes Iceland a valuable analog site for upcoming missions to Mars, including that of the Mars 2020 rover. Set to launch in 2020, this mission will, among other things, search for evidence of extraterrestrial life, and will target environments that were similar to those found in Iceland.

Our target analog site, the Strytan Hydrothermal Field (SHF), is an exceptional terrestrial analog for past hydrothermal systems on Mars because of its basaltic setting and associated water-rock chemistry. The SHF is one of the only places on Earth where massive, hydrothermal saponite is being deposited in an anoxic, alkaline environment, making it an ideal locality for investigating the habitability of similar clay-rich deposits on Mars. Our overarching goal for this proposed work is to evaluate how, and to what extent, energy generated by ancient, saponite-rich, alkaline hydrothermal settings on Mars could have supported biological processes. Our focused objectives are to: 1) model the bioenergetics of SHF and compare to similar putative habitable sites on early Mars; 2) evaluate the electrical energy generated by Strytan vents and laboratory simulated vents that could support habitability via direct electron transfer from precipitates; 3) evaluate the amount of trapped organic matter in natural and synthetically generated laboratory vent precipitates and relate the results to the energy available for heterotrophic metabolisms.

The information gained by this project can be applied directly to the primary goals of the Habitable Worlds program: 1) to search for contemporary habitable environments relevant to exploring the possibility of extant life beyond Earth, and 2) to contribute to our understanding of the characteristics and the distribution of potentially habitable environments in the Solar System and beyond. It will use field experiments that improve scientific understanding of how in situ measurements at analog sites can or will improve our understanding of the potential for the environment to support life; it will investigate sources of energy for life, using Mars as a target body; and it will evaluate the astrobiological potential of past or present environments on or in the Martian surface or subsurface. The proposed work is not relevant to Exobiology because it is not an evaluation of biosignatures and does not evaluate phylogeny, physiology, or adaptations of extant terrestrial organisms to extreme environments, or PSTAR, as it is not designed to develop technical or scientific basis to conduct planetary research.

We will use knowledge gained from characterizing diverse hydrothermal vent systems in Iceland as a guide for determining the processes and conditions that create and maintain habitable environments in hydrothermal systems broadly. This will provide significant insights into understanding the habitability of ancient hydrothermal systems on Mars.
Tyler Robinson/Northern Arizona University
Pathways to Habitable Worlds: Direct Imaging Observing Strategies for Recognizing Habitable Exoplanets

Future terrestrial exoplanet direct imaging missions (e.g., the Large UltraViolet-Optical-Infrared Surveyor, LUVOIR, or the Habitable Exoplanet Observatory, HabEx) propose to use a variety of different instrumentation and observing approaches to target characterization. For example, one approach may be to initially detect worlds with a coronagraph instrument and a broadband filter. Following this detection, narrow-band filters would be used to search for signs of atmospheric absorbers (such as, e.g., water vapor, which is a key indicator of habitability). Then, for the most interesting targets, spectroscopic characterization would ensue using a coronagraph paired with one (or more) Integral Field Spectrograph(s). An alternative approach is to rapidly follow up an initial photometric detection with spectroscopic characterization using an external occulter (i.e., starshade). In either of these scenarios, target orbital parameters may (or may not) be constrained via precursor radial velocity data and/or astrometric data from a sequence of earlier photometric observations of the system.

The examples given above highlight the many pathways that mission concept teams have described towards detecting terrestrial worlds and, subsequently, characterizing these planets for signs of habitability. However, for the variety of proposed direct imaging mission architectures, it remains unclear which observing sequence is the most efficient route to recognizing a potential exo-Earth. Furthermore, we also do not understand how the various steps in an observing sequence may yield false positives in the quest for habitable exoplanet environments. For example, a narrowband photometric search for water vapor could falsely indicate that warm, non-terrestrial worlds are strong candidates for follow-up spectroscopy.

To meet the need for describing the most effective pathway(s) to recognizing habitable exoplanets with future direct imaging missions, we propose a three-part investigation. First, we will define a set of observing sequences that are consistent with the HabEx and LUVOIR concepts. Next, we will pass a variety of worlds (both real and simulated) through these sequences, thereby gaining an understanding of how the observing sequences can yield false positives as well as which steps in a sequence are most important for rapidly identifying an exo-Earth. Finally, we will make recommendations for the instrumentation and operational strategies of future HabEx- or LUVOIR-like missions for most effectively detecting and characterizing Earth-like exoplanets.

Our proposed work is relevant to both NASA’s Strategic Plan 2018 and to the Habitable Worlds Program. Critically, we aim to shed light on the various signatures of habitability that appear in spectra of Earth-like planets. As part of this work, we will address observing strategies that provide the most effective route to confirming the habitability of a directly-imaged exoplanet and for ruling out false positives for habitability that non-terrestrial worlds may present. All of these goals are relevant to NASA’s Strategic Plan, whose Strategic Goal 1 highlights the search for life elsewhere, including research in the habitability of [&] potentially habitable worlds around other stars. As discussed in the
Strategic Plan, the strategy for meeting this objective includes improving techniques and ideas for discovering and characterizing habitable and/or inhabited environments on exoplanets. Our work in detailing observing strategies for characterizing potentially habitable exoplanets with future space-based direct imaging facilities falls under NASA Astrophysics Divisions considerations described in the Habitable Worlds funding call. Specifically, the call solicits investigations that are focused upon the characterization of potentially habitable exoplanets [and] in order to provide targeting, operational, and/or formulation data for future Astrophysics observatories.

Leslie Rogers/University Of Chicago
Hot and Steamy, Cold and Icy, or Temperate and Habitable: Modeling the Early Evolution of Water World Exoplanets

We propose to model the post-accretion cooling of water-rich exoplanets (with at least 1% water by mass) to assess the conditions under which the planets will cool sufficiently to condense liquid water oceans.

Planets with global water oceans have been the subject of intrigue both in Hollywood and in the exoplanet scientific community. Kuchner (2003) and Leger et al. (2004) first proposed the possibility of water worlds - water-rich (>1% water by mass) exoplanets that formed from a comet-like mixture rock and ice from the outer reaches of the protoplanetary disk (beyond the water 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 since played out as a robust prediction of planet formation simulations. Habitable zone water worlds are especially timely given the discovery and characterization of the TRAPPIST-1 planetary system, hosting seven Earth-sized, temperate transiting exoplanets orbiting a nearby ultracool dwarf star. Transit timing variation mass measurements indicate that the TRAPPIST-1 planets may contain several percent to several tens of percent water by mass.

Studies of the habitability of water worlds have so far taken it for granted that the planets can cool sufficiently for a liquid ocean to condense. Models have not yet demonstrated the evolution of water worlds from an initial post-accretion hot state to habitable conditions (with surface or subsurface water oceans). Indeed, studies of the interior structure of water-world exoplanets have either assumed that the planets are relatively cold (with most of their water condensed in high-pressure ices, like scaled-up versions of Jupiter’s moon Ganymede) or that the planets are relatively hot (with most of their water in extended envelopes of vapor and supercritical steam). The question of whether a water-world will be icy or steamy has important implications for both the habitability of the planet (whether or not it can host a liquid water ocean) and its observable characteristics (e.g., apparent transit radius, mean planet density, and atmospheric spectra). Detailed models of the thermal evolution of water worlds are needed to assess the scenarios that will lead to cold and icy, hot and steamy, or temperate and habitable water world outcomes.
We propose to combine models of planet interior structure, phase equilibria, atmospheric radiative transfer, and ab initio simulations of H2O-CO2 mixtures to simulate the post-accretion evolution of water world exoplanets. We will apply these models to delineate the regions of planet parameter space (i.e., orbital separation, planet mass, and volatile mass fraction) within which planets are likely to remain hot and steamy or cool sufficiently to form high pressure ice mantles and/or liquid water oceans. This study is necessary to establish whether habitable zone water worlds (such as TRAPPIST-1 f and g) can develop liquid water oceans and conditions potentially favorable to life.

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 delineating the range of planet parameter space (masses, radii, and orbits) over which water world exoplanets may plausibly condense liquid oceans, 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).

Henry Sun/Desert Research Institute
UV and Oxidation Resistance in Desert Lichens and the Habitability of Mars

Desert cyanobacteria, lichens, and bryophytes (mosses) possess three adaptations critical to their existence near the dry limit of habitability. These include 1) poikilohydry, the ability to survive dehydration in a vegetative state; 2) sun screens, the ability to fortify their thallus or cell surface with pigments that are optically opaque to ultraviolet rays (UV) but relatively transparent to photosynthetically active radiation; and 3) antioxidants, which are necessary during long periods of dehydration and metabolic inactivity. In a preliminary study initiated to determine whether or not these adaptations have a limit, we challenged dried cyanobacteria and lichens to wet-dry cycles, UVC (254 nm, 4.7 watts/m2), and 5% O3. Afterward, we rehydrated the organisms and monitored their photosynthetic recovery using a pulse-amplitude-modulated chlorophyll fluorometer (PAM). Results thus far indicate that the organisms are effectively insensitive to wet-dry cycles and UVC, but they are susceptible to extreme oxidation. In oxidation resistance, lichens outperformed cyanobacteria presumably because they have a more sophisticated thallus with a multi-layered antioxidant defense. This proposal seeks to evaluate these insights with three species from each group by determining their tolerance under more controlled conditions, including 1) a rapid sequence of wet-dry cycles in an anaerobic glovebox in the dark without opportunity for repair, 2) high-intensity UVC irradiation (9 watts/m2) in ambient air, 3) high-intensity UVC irradiation in CO2 to keep out O3, and 4) 5% O3. Photobiont viability will be assessed using PAM chlorophyll fluorometry and 14CO2 labeled uptake. In O3-killed specimens, oxidation biomarkers specific to polysaccharides, lipids, and proteins separating cytosolic and DNA/nucleus-associated proteins will be quantified to understand death by oxidation at the molecular level.
Results are expected to challenge the notion that a UVC-attenuating atmosphere is a necessary condition for surface biota; to show that dry limits are because of oxidation rather than desiccation; and to reveal the possibility that anaerobic worlds are without dry limits.

Steve Vance/Jet Propulsion Laboratory
Did solid tides prevent the thermodynamic death of Europa?

Aqueous environments in chemical disequilibrium are candidate locations for the emergence and existence of life. Europa’s ocean could be one such location in the Solar System, but questions remain as to the persistence of chemical disequilibria within Europa’s ocean through geologic time. High pressures at the seafloor (150–200 MPa; Vance et al., 2018) may seriously restrict the hydrothermal venting and water-rock interaction required for element fluxes and redox disequilibria favorable for life (e.g. McCollom 1999).

We aim to test whether this thermodynamic death of Europa’s seafloor and ocean could be avoided through a sustained element flux to the ocean that is enabled by orbital evolution. Europa’s geologic history controls the interior structure and the likelihood of extant silicate ocean chemical exchange. Recent simulations of Europa’s interior explored the parameter space of interior structure for present-day Europa, bound by Galileo measurements of the gravity, moment of inertia and plausible geophysical and thermodynamic constraints (Vance et al., 2018). This work noted opportunities for improving the geochemical/petrological model of the rocky interior with time-resolved phase changes and reactions, including volatile fluxes. By analogy to Earth’s mid-ocean ridges, metamorphic reactions and silicate melting, if they ever occurred within Europa, would have affected the trapping and releasing of volatiles and other elements via reversible and irreversible chemical reactions.

OBJECTIVES:
1) To resolve through models the evolution of Europa’s interior structure (the distribution of its spherical shell components, including silicate and ocean layers) as a consequence of its accretion and orbital history in the Jupiter system.
2) To determine the changing composition of the interior’s geochemical reservoirs (silicate, ocean and core) and the flux of elements between reservoirs, with a special focus on determining the flux of elements at the water–rock interface, relevant to habitable environments.
3) To constrain the habitability of Europa’s interior throughout its history, to determine whether it has been continuously habitable and remains so today, or whether Europa’s interior has been thermodynamically dead for extended periods of time because chemical fluxes were stymied by geology, and ultimately, its orbital evolution.
We will achieve our goals by:
1) Using accretion-structure-composition simulations that will determine the composition and starting state of Europa post-accretion, and the early geochemical reservoirs.
2) Subjecting the candidate initial Europa models to an orbital-thermal model from post-accretion until the present that resolves tidal dissipation in the silicate interior, petrological/geochemical changes with Gibbs energy minimization, rheological and structural changes with a geodynamic code, and water-rock reaction. Our model will be iterated, as the changing mass distribution resulting from outgassing and eruptions from the interior to the ocean may subsequently affect the orbital and tidal response of Europa.
3) Integrating the element and energy fluxes throughout Europa’s orbital history, and assessing the habitability potential of Europa’s ocean and seafloor, comparing free energy and redox conditions to known biological requisites.

SIGNIFICANCE: Examining the hypothesis that the thermodynamic death of Europa’s interior may be prevented (or accelerated) by tidal dissipation in the silicate will lead to a suite of predicted ocean salinity and pH, which trace to measurements planned by the Europa Clipper mission. This work is relevant to the Habitable Worlds Program because we aim to identify the characteristics and distribution of potentially habitable environments in the Solar System. Specifically, we will carry out theoretical work on the presence of organics, fluid-rock chemistry and sources of energy as they pertain to past and present habitability in Europa.