Habitable Worlds
Abstracts of Selected Proposals
(NNH16ZDA001N-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. 61 proposals were received in response to this opportunity. On August 11, 2017, 14 proposals were selected for funding.

Oleg Abramov/Planetary Science Institute
Impact Bombardments on Extrasolar Terrestrial Planets: Implications for Habitability

Large impacts events deliver vast amounts of heat to planetary surfaces and upper crusts, particularly early in the history of a planet when post-accretionary bombardment rates are high. In addition, spikes in the number of impact events, similar to the Late Heavy Bombardment that the inner solar system likely experienced about 3.9 billion years ago, may become significant later in a planet's history. Signatures of both types of bombardments have been detected in extrasolar systems by the Spitzer Space Telescope. We propose to undertake a focused study of the biological effects of impact bombardments on a wide range of Earth-like extrasolar planets to further constrain conditions needed for life to arise and evolve.

The proposed work has the following tasks:

1) Prep work: (i) Improve numerical models of the thermal effects of impact bombardments developed by the PI for the early Earth. In particular, fully integrate models of post-impact hydrothermal cooling and global ejecta deposition following basin-forming impacts into a global cratering model. (ii) Compile constraints on the duration and intensity of extrasolar planetary bombardments using Spitzer Space Telescope data (Collaborator Trilling) as well as on physical structures of extrasolar terrestrial planets and radiogenic heating and thermal structures of extrasolar planets.

2) Apply the integrated model to planets with the same diameter as the Earth (equi-Earths). Parameters that will be varied are thermal structures (surface temperatures and geothermal gradients), orbital characteristics (such as being tidally locked), impactor parameters (size-frequency distributions, compositions, impact velocities), and bombardment properties (durations and intensities). Results will include total habitable volumes and habitable volumes in hydrothermal environments as a function of time. Co-I Mojzsis will assist with analyzing and interpreting the results.

3) Once baseline results have been established, we will apply the model to mini-Earths (approximately Mars-mass planets) and super-Earths (planets with up to 10x Earth mass).

Parameters that will be affected are impact velocity, impact cross-section, gravitational focusing, and ejecta distribution. To accomplish these tasks, we intend to make use of several existing numerical modeling tools: (i) HEATING (a general-purpose, three-dimensional, finite-difference heat transfer program written and maintained by Oak Ridge National Laboratory), which has been used by the PI to study the thermal effects of impact bombardments; (ii) HYDROTHERM (a three-dimensional finite-difference computer code developed by the U.S. Geological Survey), previously used by the PI to model impact-induced hydrothermal activity.

This proposal is highly relevant to the NASA Habitable Worlds program goal of identifying the characteristics and the distribution of potentially habitable environments in the Solar System and beyond, by modeling the effects of impact bombardments on planetary habitability. Theoretical and modeling studies such as this one are permitted by program rules. Proposals focused on exoplanets similar to Earth are encouraged, and we will study three types of Earth analogs (planets with conditions roughly comparable to those of Earth), which addresses the Habitable Worlds objective of searching for ancient and contemporary habitable environments and exploring the possibility of extant life beyond the Earth.

Amy Barr Mlinar/Planetary Science Institute
Sluggish Lid Convection on Icy Satellites: Implications for Habitability

Background: Icy moons Europa and Enceladus are prime candidates for future exploration. Their ice-covered oceans, and similar oceans on other satellites, have been suggested to be possible abodes for life. The ice shell serves as a barrier to nutrient transport to the ocean, and transport of biosignatures to the satellite's surface, where they could be detected by spacecraft. The habitability of the ocean, and the ability of spacecraft to detect life, depends on the geological and geophysical processes that move material between the ocean and the surface.

Solid-state ice shell convection, similar to convection in Earth's mantle, has been suggested as a means of driving vertical transport between the satellites oceans and surfaces. Until recently, it was thought that the strongly temperature-dependent viscosity of ice caused the near-surface ice to be so stiff that convective upwellings would be trapped below the surface.

Recent work motivated by Cassini observations of the south polar terrain (SPT) of Enceladus suggests that under certain conditions, convective upwellings and downwellings can reach the surfaces of icy satellites if the near-surface ice is weak, for example, weakened by cyclical flexing due to tidal forces. This style of convection also drives sluggish deformation of surface material, periodic burial of the surface via putative subduction, and emplacement of fresh sub-surface material in extensional regions. Recent work by our group and others shows that this process may have operated on Europa, as well Enceladus.

Science Goals and Objectives: The purpose of this effort is to constrain the time scale and spatial scale of surface/sub-surface transport on icy satellites via sluggish lid convection, to determine the viability of detecting ocean material on the satellites surfaces, and the amount of nutrients delivered to their oceans by convection. This work is particularly timely given that observation planning for the forthcoming Europa mission is underway.

Summary of Methodology: We will use 2D and 3D numerical simulations of solid-state convection to determine the time scale and spatial distribution of upwellings and downwellings as a function of ice shell thickness, amount of tidal heating, temperature dependence of viscosity, and yield strength. Estimates of the rheology and thickness of the ice shells based on geological observations will constrain the parameter space appropriate for each satellite. We will use tracer particles to measure transport times between the surface and ocean.

Michael Bland/USGS Flagstaff
Silicate volcanism and the habitability of Europa's seafloor

1. Background. Europa possesses perhaps the most suitable conditions for extant biological activity in our solar system. The presence of liquid water, the necessary elemental building blocks (e.g., CHONPS), and a stable environment provide many of the requirements for life. However, sustaining biologically-usable energy sources over time may be a major obstacle to Europa s habitability. A great number of biogeochemical cycles and metabolic pathways have been investigated for Europa [see Hand et al. 2009 for a review], but many of these depend upon hydrothermal activity and/or an influx of material to maintain chemical disequilibrium and avoid thermodynamics-driven extinction [Gaidos et al. 1999]. Thus, determining the rate at which chemical species are added to the ocean is critical to understanding the potential habitability of Europa. Two basic sources for such a chemical flux have previously been identified: (i) addition of oxidants from the surface (requiring mixing through the ice shell), and (ii) geologic activity at the seafloor (e.g., volcanism). Here we focus on the latter. The goal of the proposed work is to rigorously assess the plausibility of active volcanism at Europa s seafloor, and to evaluate the time-dependent rate at which biologically-useful chemical species are injected into the ocean.

2. Methodology. In order to evaluate the current and past levels of silicate volcanism on Europa (and thus the influx of biologically useful materials such as Fe, C, S, H2, and CH4 [e.g., Zolotov and Shock 2003, 2004]), we propose to produce robust models of the evolution of Europa s silicate interior that include the generation, segregation, and eruption of magma and crust formation. The work leverages two existing codes that have previously been applied to melting and magma transport on Io. In Task 1 we will utilize a one-dimensional model for melt formation and migration in Europa s mantle. The code self-consistently couples a melt migration model to convective scaling laws which include the effects of partial melting to calculate the radial melt profile in the mantle.

This code will be used to evaluate the range of conditions that lead to substantial melt generation, estimate eruption rates, and identify interesting regions of parameter space for more detailed investigation in Task 2. Task 2 will utilize the 3D mantle convection code StagYY [Tackley 2008] which includes magma generation, segregation and eruption to provide a more detailed examination of the evolution of Europa s silicate interior, including crust formation. Task 3 will use analytical models of magma ascent through the lithosphere (dike propagation) to evaluate the relative importance of volcanic eruption and magmatic intrusion on Europa.

3. Relevance to Habitable Worlds. The proposed work will directly assess "the processes and conditions that create and maintain habitable environments" on Europa. Metabolic pathways such as sulfate reduction and methanogenesis have great potential as energy sources for life on icy worlds, but depend on geologic activity (e.g., volcanism) to supply the necessary chemical ingredients. By constraining the rate at which volcanism can enrich Europa s ocean with these ingredients, we will specifically address whether such pathways are feasible sources of energy for life. Additionally, because we are able to model changes in eruption rates over time, we can investigate the physical and chemical evolution of potential habitats.

Nicolas Dauphas/University Of Chicago
Biotic and Photo-Chemical Pathways to the Formation of Ferruginous Acidic Waters on Mars

Objectives:
If life ever emerged on Mars it might have been similar to chemotrophic bacteria, which create mineral deposits in kinetically unfavorable conditions for the equivalent abiotic reactions. Hematite-jarosite deposits at Meridiani Planum require that ferrous Fe from weathering of Martian basalt was oxidized in acidic conditions (pH 2-4). At such low pH, Fe oxidation by O2 is very slow and the formation of similar deposits on Earth is usually mediated by bacteria. Time limits for Fe oxidation on Mars are imposed by the lifetime of standing water bodies, and if abiotic Fe oxidation rates in acid waters are found to be inadequate to account for hematite-jarosite deposits, this could make a compelling case that biology played a role in accelerating oxidation. However, Fe oxidation can also be driven by UV photons. Earlier studies suggest this may be a viable pathway for hematite-jarosite formation but the kinetics are inadequately characterized in the chemical and radiative environment of Meridiani Planum. The dependence of the quantum yield (atoms oxidized per photon absorbed) on Fe speciation and UV wavelength and has not been determined, which limits extrapolation of experimental photo-oxidation rates to acidic waters under Martian surface conditions.

Characterizing photo-oxidation rates on Mars is necessary in assessing whether iron oxidation could have been an energy source for life at Meridiani Planum. We will conduct new photo-oxidation experiments to define the quantum yield as a function of wavelength and Fe speciation, and determine rates of oxidation under a UV spectrum

relevant to the incident radiation at the Martian surface. Our experimental results will form the basis of the holistic geochemical models that we will build to determine the relative efficiency of competing biotic and abiotic pathways to Fe oxidation in acid waters.

Methodology:
To assess whether Fe photo-oxidation is kinetically viable on Mars or would be outpaced by biological activity, we will perform UV photo-oxidation experiments in an anoxic chamber to quantify the quantum yield as a function of wavelength. The experimental setup to carry out this work is established in our laboratory, and was used in a recent publication that reports on the photo-oxidation of Fe at near-neutral pH. It involves a quartz reaction vessel with a central UV lamp. O2 is removed from the system by flushing with high purity Ar. We will use a xenon lamp to produce a solar-like UV spectrum, and bandpass filters to control wavelength output. Fe speciation changes with pH, so we will use an acidic (pH ~2.5) buffer solution to determine quantum yields of species present in Martian waters. Speciation- and wavelength-dependent quantum yields will be quantified by measuring the amount of Fe oxidized as a function of time, and Fe isotopes will be measured to characterize the reaction mechanism. The quantum yields will be used in geochemical models which consider photo-oxidation under Martian surface UV radiation, in competition with Fe-oxidizing bacteria, and evaporation. The work will be carried out by PhD student Andrew Heard with guidance from the PI and collaborators.

Relevance:
The overarching theme of the proposed work is to better understand what drove the oxidation of Fe in the acidic conditions relevant to hematite-jarosite deposits discovered on Mars. On Earth, this is often mediated by biological activity but UV photo-oxidation could have played a role on early Mars. Comparing the kinetics of biotic and photochemical Fe oxidation under acidic conditions is relevant to NASA s strategic objectives (solicitation NNH16ZDA001N-HW), which include the astrobiological potential of past or present environments on or in the Martian surface or subsurface (document E.4 of the solicitation, page C.4-1).

Chuanfei Dong/University Corporation For Atmospheric Research (UCAR)
Exoplanetary Space Weather, Climate and Habitability: Consequences of Atmospheric Loss

Science goals and objectives: In the last two decades, the field of exoplanets has witnessed a massive surge. Research in exoplanets now encompasses a wide range of fields ranging from astrophysics to geology and atmospheric science. One of the primary objectives of studying exoplanets is to determine the criteria for habitability, and whether certain exoplanets meet these requirements. Amongst the many factors that determine habitability, understanding atmospheric losses is of paramount importance. In particular, most of the attention has been centered around the study of exoplanets orbiting M-dwarfs,

since the latter are highly numerous in our Galaxy (and in the Universe). The study of these exoplanets has also received a major boost from the discovery of Proxima Centauri b at a distance of only 4.3 light years away. The primary objectives of the proposed work are 1) to study the atmospheric loss and evolution of both unmagnetized (Mars/Venus-like) and magnetized (Earth-like) exoplanets through their interaction with the stellar wind of the host star, and 2) to study the atmospheric loss and evolution for exomoons (Titan-like) through their interaction with the magnetospheric flow of the host planet. Consequently, this will build a model library that will benefit the exoplanetary community.

Methodology: In our Solar system, the most sophisticated codes tend to use magnetohydrodynamic (MHD) models for modeling the interactions of the solar wind with magnetized (such as Earth) and unmagnetized (such as Mars and Venus) planets, and the interactions of planetary magnetospheric flow with its moons (such as Titan). We will use a one-way coupled framework (including sophisticated 3D ionosphere-thermosphere model, 3D exosphere model, and 3D stellar wind model) centered around a well-validated 3D multi-species magnetohydrodynamic (MS-MHD) model to build a model library with a reasonable range of parameters. In the one-way coupled framework, MS-MHD adopts the neutral thermospheric profiles from the Global Ionosphere Thermosphere Model (GITM) and the exospheric profiles from the exosphere Monte Carlo model Adaptive Mesh Particle Simulator (AMPS); the latter can be directly applied to study the photochemical escape. MS-MHD, GITM and AMPS have been successfully (are being) adapted to, e.g., Mars, Venus and Titan. For the stellar wind parameters (such as the stellar wind velocity, density, temperature and interplanetary magnetic field), we will also adopt the Alfven Wave solar Model (AWSoM) model to simulate those parameters (including space weather events such as CMEs/CIRs/super Carrington-type flare events) based on the observed magnetograms (or ZDI maps) of M-dwarf stars. These three planetary models (the MHD, ionosphere/thermosphere, and exosphere models) will be adapted to exoplanet research by modifying the stellar wind inputs and exoplanetary atmospheric profiles.

Relevance: The proposal is highly relevant to the Habitable Worlds program as the proposed research on the study of atmospheric loss is crucial for understanding the atmospheric evolution, climate change of the exoplanets/exomoons, and thus offers fresh insights concerning the habitability of exoplanets and exomoons. The proposed work will enable us to explore the possibility of extant life beyond the Earth based on our understanding and knowledge of ancient and current Earth, Mars, Venus, Titan and the solar system as a whole. The "Habitable Exoplanets and/or their moons" constitute the central targets and primary objectives of the Habitable Worlds program. The proposal is also highly relevant to NASA's Planetary Science Division's current and future missions (e.g., MAVEN) for studying the Martian atmospheric loss and evolution as well as NASA's Astrophysics Division's, more specifically, Exoplanet Exploration Program's current and future missions (e.g., Kepler and JWST) for the characterization of exoplanets and the study of their habitability.

Christopher Doughty/Northern Arizona University
Testing methods to detect 3D vegetation structure on exoplanets

Over the next few decades, NASA and ESA are planning a series of space-based observatories (HabEx) to measure the spectral characteristics of Earth-sized extra-solar planets in regions where liquid water may be present. If they succeed in finding a planet with both biogenic gasses in the atmosphere and a red-edge characteristic of life, we would want to know whether the land-based life on this planet is similar to the green photosynthetic slime common for most of Earth s history, or whether this life has evolved to be diverse and multi-cellular. Multi-cellular photosynthetic organisms on Earth (trees) have a distinct bidirectional reflectance distribution function (BRDF) causing differing reflectance at different sun/view geometries. In previous work, we examined whether the BRDF could detect the existence of tree-like structures on an extra-solar planet, by using changes in planetary albedo as a planet orbits its star. We used a semi-empirical BRDF model to simulate vegetation reflectance at different planetary phase angles and found that even if the entire planetary albedo were rendered to a single pixel, the rate of increase of albedo as a planet approaches full illumination would be measurably greater on a vegetated planet than on a non-vegetated planet (Doughty and Wolf 2010 Astrobiology). We hypothesized that depending on how accurately planetary cloud cover can be resolved and coronagraph design, this technique could theoretically detect tree-like multi-cellular life on exoplanets in 50 stellar systems. However, such theoretical work needs empirical validation. We next carried out a proof of concept of this technique in a manner similar to Sagan et al. (1993) by using Galileo data to determine if multicellular life on Earth could be detected. However, we were unsuccessful, likely because there was no change in phase angle with these Galileo data and the technique requires a large change in phase angle (Doughty and Wolf 2016 PLOS One).

We propose here to further advance this technique with an improved proof of concept study by using existing data from the space probes EPOXI and OSIRIS-REx (with complementary variability in phase angle) to determine if 3D vegetation structure can be detected on Earth from a distance. Next, we plan to use Earthshine (light reflected from Earth off the moon and back to Earth) at different phase angles to determine if 3D structure can be detected. Finally, we will try the same technique on the nearby planets of Mars and Venus to measure the false positive effect. All such measurements are simple and can be completed with existing data or using our campus telescope with undergraduate astronomy students.

Next, we propose to further refine the technique with ground-based measurements. Near Northern Arizona University and Flagstaff USGS Astrogeology, NASA created cratered fields to mimic the moon for Apollo astronaut training. Also nearby are the landscapes of Sunset and Meteor craters, which mimic extraterrestrial landscapes. We propose to use drone-based spectrometers (operated by collaborator Sankey) to compare these non-Earth-like landscapes to the local vegetation landscapes. With these data, we will determine at which spectral wavelengths the BRDF differences between vegetation and non-Earth-like landscapes are maximized.

Overall, we feel the proposal will fit within the Habitable Worlds call because the work will help identify the characteristics (multicellularity) of potentially habitable environments on exoplanets which could be used to inform future targeting and/or operational choices. Our work will include quantitative terrestrial field experiments that improve scientific understanding of this process. We are asking for funding to support a graduate student for three years to work on this project, which includes participation of NAU's Department of Physics and Astronomy and NAU's School of Informatics.

Jacob Haqq-Misra/Blue Marble Space
Constraining the Habitable Zone for Binary Star Systems

Nearly 50% of Sun-like stars in our galaxy are in binary stellar systems. Recent discoveries by the Kepler mission and ground-based surveys have shown that dynamically stable planetary systems exist and are abundant around many binary stars. Future missions, such as TESS and PLATO, will discover nearby planets in binary systems, which could be further characterized spectroscopically with JWST. The recently launched GAIA astrometry telescope, which observes 1 billion stars in our Galaxy (1% of the Galactic stellar population), is providing unprecedented positional and radial velocity measurements that can reveal further planets in binary systems. As with planets around single stars, these planets in binary systems continue to raise questions about their potential habitability. Previous studies of the habitable zone (HZ) of binary systems considered only the effect of changes in the peak of the combined spectral energy distribution (SED) of the two stars; however, the spectral energy distribution (SED) for planets in binary systems should be a superposition of both host stars. Habitability is defined as the ability of a terrestrial planet to sustain liquid water on its surface, which is determined by the energy balance of a planet s atmosphere. Greenhouse gases like water vapor and carbon dioxide absorb radiation at both long (infrared) and short (ultraviolet) wavelengths, which makes the climate sensitive to the full combined SED of both stars. We expect that the HZ for planets in binary systems should be a function of the SED of the binary system, which will depend upon the evolutionary history of each stellar system. We will also study the differences in diurnal patterns of solar insolation caused by both P-type and S-type planetary orbits within binary systems. We expect the orbital configurations of binary systems to play a significant role in the definition of habitable zones.

METHODS
This research will constrain the HZ for planets in binary systems by using a hierarchy of existing climate models. We will use observed stellar spectra and stellar evolutionary models to develop several scenarios for the combined SED of both P-type and S-type binary systems. We will first study the effect of superposition of multiple stellar spectra using a line-by-line radiative transfer model. These calculations will set benchmarks for evaluation of the correlated-k radiative transfer codes used subsequently. We will then evaluate the HZ for binary system in combinations of F, G, K, and M types using a one-

dimensional radiative convective climate model, which will provide a basis of comparison against classic single-star HZ calculations in the literature. We will next use this 1-D model to parameterize the radiative transfer in a 2-D latitudinal energy balance model, which will allow us to consider the contributions to habitability of non-circular orbits and ice-albedo feedback. We will then examine the effect of binary SED on atmospheric dynamics by using full three-dimensional general circulation models to quantify changes in large-scale circulation that affect habitability. By using these 3-D models, we can self-consistently simulate all aspects of climate, which includes geophysical and orbital properties, radiative transfer, dynamics, and clouds.

RELEVANCE
This proposed research is relevant to NASA s Habitable Worlds program as a theoretical study of the climates of extrasolar terrestrial planets and their ability to sustain the presence of water. The results of this research will help to identify the characteristics and the distribution of potentially habitable environments in the Solar System and beyond (C.4-1) by using a hierarchy of existing climate models to constrain the HZ of planets in binary star systems. The scope of this research focuses on the habitability of extrasolar planets, so this proposal is not relevant to the Emerging Worlds program, the Exobiology program, or any existing data analysis programs.

Renyu Hu/Jet Propulsion Laboratory
Constraining Early Mars s Atmosphere and Habitability with Isotopic Measurements

We propose to study the evolution pathways of the atmosphere of Mars since the mid/late Noachian period (about 3.8 Ga ago), as constrained by the isotopic composition of the current atmosphere. The objectives are (1) to constrain the abundance of CO2, N2, and Ar in Mars s atmosphere in the mid/late Noachian period and the Hesperian period, and (2) to constrain the amount of hydrogen that has been lost to space in the past 3.8 Ga. Recognizing that the evolution of a planetary atmosphere involves a poorly understood trajectory in a multi-dimensional phase space of many variables, we design a million-model approach to rigorously perform quantitative tests against the isotopic composition of the atmosphere and the size of crustal volatile reservoirs. The key processes controlling the evolution of the Martian atmosphere include outgassing, surface deposition, and atmospheric escape. The precise isotopic compositions of carbon, nitrogen, argon, and hydrogen from Curiosity allow us to quantitatively assess the strength of these processes.

We construct a model to simulate the atmospheric evolution with surface deposition and atmospheric escape as the two sinks and magmatic activity as the sole source. Our study of the Martian atmospheric evolution goes beyond previous work, particularly in four aspects. First, we will assimilate the measured atmospheric isotopic composition and the abundance of carbonates, nitrates, and hydrated or hydroxylated minerals in soils and rocks. In situ and remote sensing in the past decade have detected and quantified the

extent of these secondary minerals and salts on Mars. Because they are sinks of atmospheric volatiles, the surface measurements provide constraints of the atmospheric evolution. Second, we will model the evolution of nitrogen taking into account the effects that have not been included before, including nitrate formation and its isotopic effect, fractionation in escape via photodissociation of N2, and a changing CO2 background pressure that affects both the escape rate of nitrogen and the fractionation factor of photochemical nitrate formation in the atmosphere. We will refine and utilize the evolutionary scenarios of CO2 recently published by our team. Third, we will perform a joint analysis of the isotopic evolution of carbon, nitrogen, and argon to minimize uncertainties in the history of magmatic activity and the solar wind particle flux. Last but not least, we will evaluate the fractionation factor of thermal escape of hydrogen in a realistic atmosphere with evolving CO2 and N2 partial pressures. This way, we will refine previous interpretation of the D/H evolution and assess the near-surface water inventory in the Noachian and Hesperian periods. Out of this multi-functional and multi-elemental synthesis, we should be able to derive quantitative assessment of the volatiles that were lost.

The study of Mars using simulations proposed here will produce the best possible constraint of the mass and the composition of the atmosphere in the mid/late Noachian and Hesperian, based on the latest isotopic measurements and the geologic record. The volatile budgets resulted from the proposed research will be foundational for evaluating whether Mars was once a habitable planet (Earth-like) or uninhabitable (e.g. too cold) during the late Noachian and Hesperian periods. Our effort will also produce results that are testable by continuing observations of Mars, and will predict isotopic signatures detectable by ongoing and future in situ exploration. This investigation is directly relevant to NASA's mission because it will address a key objective in the NASA NRA: Mars - the astrobiological potential of past or present environments on or in the Martian surface or subsurface.

Avi Mandell/NASA Goddard Space Flight Center
The Habitability of Collisionally Formed and Tidally Heated Trans-Neptunian Objects

Observational evidence has shown that icy bodies in our Solar System beyond the snow line possess dynamic and potentially habitable surface environments. Cryovolcanic activity, unexpected evidence of crystalline water ice, and surface dynamics that necessitate a significant reservoir of internal energy all point to a wider environment of potential habitability in our solar system than previously anticipated. This study will examine the depth and longevity of liquid water in the interiors of TNOs in the context of their evolving internal heat budgets. This includes monitoring the retention of liquid water as bodies cool in a tidal and radiogenically heated environment.

Given the low insolation environment they reside in, the heat budget of TNO s has primarily been thought to have been driven by radiogenic heating. However, there is

increasing evidence that the larger TNOs in the Solar System have undergone dynamical interaction with secondary bodies - either through gravitationally bound moons or other interactions with other TNOs. While radiogenic heating is still likely to be the dominant term in the heat budget of these bodies, tidal interactions with these secondaries after a collision, capture scenario or mutual accretion may be an important term in understanding evidence of previous or extant habitability proxies on these bodies. Tidal interactions have been demonstrated to have potentially been important to the habitability of the Pluto-Charon system and to Enceladus and may be important for similar and smaller sized TNOs. We will examine the effects of these tidal interactions on the heat budget of these bodies by assessing the contributions of eccentricity, spin and obliquity tides in addition to evolving radiogenic and other heat contributions.

By developing heat budget informed interior models of known TNO s that incorporate radiogenic and tidal heating effects, we can determine the depth at which these bodies would possess liquid water. By creating time evolving coupled thermal-orbital models of these bodies we can then track the depth and width of these liquid water layers through time. For captured and bound multi-body systems we will use a modified Andrade rheological model to describe the tidal response of water-ice, and mantle material, to explore how the heat budget of these systems influence the phase state of that water. While it is an open question whether or not Andrade fits responses from silicate dominated bodies (the Moon), it has been used accurately for icy bodies such as planetary satellites and has outperformed the current most used rheological model, Maxwell, in both planetary studies and lab experiments. The inclusion of spin and obliquity tides will represent a novel and previously understudied additional component of these bodies heat budgets. We will also be able to examine the thermal-orbital evolution of bodies that may have formed from a collision process. Our team will be able to use appropriate SPH simulations to inform tidal response simulations with the appropriate initial interior properties of the collisionally formed bodies.
Our team includes Joe Renaud and Wade Henning, experts in examining the interior and surface evolution of terrestrial bodies due to tidal evolution, and Prabal Saxena and Avi Mandell, who are experts in the orbital, atmospheric and bulk characteristic evolution of planetary systems. It will also include Martin Jutzi, an expert in collisions of silicate and icy bodies.

This proposal is relevant to the Habitable Worlds Program because it addresses the fundamental question of the habitability of icy worlds in the Solar System. We will apply knowledge of the fundamental physical processes involved in radiogenic and tidal heating of small icy bodies to constrain the evolution of habitable environments on icy satellites and dwarf planets.

Edgard Rivera-Valentin/Universities Space Research Association, Columbia
The biologic potential of the martian subsurface via brine production through atmosphere-regolith interactions

The biologic potential of the martian subsurface via brine production through atmosphere-regolith interactions

Background: The potential for liquid water environments on the surface of present-day Mars is enforced by observations of mass movement events, such as recurring slope lineae (RSL), and the identification of hydrated mineralogy within these features. A viable process for the liquid source is deliquescence, which has been shown to be a biologically and geologically relevant process in arid terrestrial environments, and may be active on Mars as demonstrated recently by the Mars Science Laboratory s Rover Environmental Monitoring Station. However, habitability requires more than the presence of liquids; tolerable temperature, salinity, and radiation conditions must be present. The radiation environment on the martian surface, though, has been shown to not be conducive to life as we know it; therefore, investigations focusing on subsurface environments are of import in the search for present-day habitable abodes on Mars. In this project, we propose to investigate the biologic potential of the martian subsurface by incorporating our fully coupled atmosphere-regolith heat and mass transfer model with Global Circulation Modeling (GCM) as well as recent experimental constraints, to study and characterize liquid water environments via deliquescence.

Science Goals and Objectives: The science questions we propose are motivated by recent spacecraft data analysis and experimental results. We seek to answer: 1) What is the temporal and spatial distribution of subsurface liquid water environments on present-day Mars? 2) When do subsurface liquid water environments meet the conditions that permit biological activity, such as metabolism and replication? 3) How do subsurface liquid water environments change with local-scale geology, such as topographic effects? 4) How much water is available for potential biological processes?

Summary of Methodology: We propose to combine our established, fully coupled heat and mass transfer model, which simulates transport processes between the planetary boundary layer and the subsurface, down to several meters, with GCM results to simulate the global martian environment. From lander observations, it is clear that only salts with the lowest eutectic temperature will form liquid brines on Mars; therefore, we will conduct kinetic simulations of such Mars relevant salts, grounded by experimental results and focusing on deliquescence. These results will be paired with our environmental modeling to conduct a global search, in latitude, longitude, depth, and time, for the conditions that permit for deliquescence. When liquids are present, we will investigate if these conditions (e.g., temperature and salinity) are habitable. Additionally, we will conduct high resolution, local-scale modeling, including geologic effects such as topography, to investigate the amount of liquid available in sites known to be favorable to liquescence, such as RSL sites.

Relevance to Habitable Worlds Objectives: The proposed work would identify and characterize the distribution of potentially habitable liquid water environments in the subsurface of Mars by investigating the availability of liquids through deliquescence. Our proposed modeling work would investigate the physics and chemistry of potential

subsurface liquid water environments as it pertains to habitability by characterizing the processes that may influence the nature and degree of habitability on present-day Mars, such as temperature and water activity. By applying recent experimental results on brine stability and terrestrial field studies on the habitability of deliquescence-based habitats to our models, the proposed work would improve our understanding for the potential of the martian environment to support life.

Aomawa Shields/University Of California, Irvine
The effect of salt- and land-albedo feedback on the climate and habitability of M-dwarf planets

Overview: Hundreds of millions of dollars are being invested in technology to directly detect M-dwarf planets and search for signs of life. However, the interaction between the unique spectral energy distributions (SEDs) of M-dwarf stars and their planets' complex atmospheres and surfaces defy simple modeling prescriptions. One of these possible surface types is sodium chloride dihydrate, or hydrohalite ($NaCl \cdot 2H_2O$), which could form on cold, dry M-dwarf planets as a result of salt within brine inclusions in bare sea ice precipitating in crystal form at low-enough temperatures. Exposed land surfaces may also be widespread, given the low potential water inventory on M-dwarf planets. The impact of these surface albedo feedback mechanisms on the climate of M-dwarf planets has not been explored, and must be quantified to inform observational interpretation. I propose to calculate the effects on M-dwarf planet habitability of hydrohalite and land surfaces, using sophisticated 3D global climate models. I will also produce a realistic assessment of the habitability, as a function of these possible surface types, of two of the most scientifically interesting M-dwarf planets discovered to date, given a range of plausible atmospheric compositions and rotation rates for these planets.

Specific Science Objectives: This proposal addresses the effects on habitability of different surface albedo feedback processes that may be possible on M-dwarf planets. In the course of this work we will: (1) Quantify the effects on planetary climate and habitability of the interaction between the M-dwarf SED and hydrohalite and land surfaces on orbiting planets, as compared with ocean-, ice-, and snow-covered surfaces. (2) Determine the effect of different atmospheric compositions and planetary spin states on a planet s climate sensitivity to these surface feedback processes. (3) Simulate the climates of M-dwarf planets Kepler-186f and Proxima Centauri b, to explore and quantify the habitability of these systems as a function of this suite of surface types.

Proposed Methodology: To meet our goals, we will use albedo spectra for pure water ice and snow (without salts), hydrohalite, and land as input to climate simulations of Earth-sized planets orbiting M-dwarf host stars, using 3D global climate models adapted by the PI to simulate the climate of planets orbiting stars of different spectral types. We will explore a range of atmospheric compositions and planetary spin states in these simulations to identify atmospheric levels that may mask these surface albedo feedback processes, and quantify the effect of rotation rate on a planet s climate sensitivity to these

surface interactions. Next, we will apply these results to simulations of the climates of Kepler-186f and Proxima Centauri b, two recently discovered potentially habitable M-dwarf planets.

Relevance: This proposal explores the surface types possible on exoplanets, and their radiative effects on the habitability of M-dwarf planets in particular. Therefore it is directly relevant to the Habitable Worlds call. Our work will add much-needed complexity to theoretical simulations, and has direct implications for experimental design. These results will be critical to providing an accurate assessment of the potential habitability of exoplanets as they are discovered and characterized by missions such as NASA s Transiting Exoplanet Survey Satellite and NASA s James Webb Space Telescope, respectively, as well as the next generation of space-based missions.

Henry Sun/Desert Research Institute
Limits of life due to chaotropic ions

This proposal is based on a preliminary experiment with freshwater alga Chlorella which indicates that a Ca brine can be uninhabitable even though its water potent is biologically permissible. This result is consistent with Franz Hofmeister s 1888 discovery that Ca is a chaotropic ion that destabilizes proteins and biological molecules, whereas Na is harmless (beyond creating osmotic stress) or stabilizing, i.e. kosmotropic. In other words, the term water potential does not capture all aspects of the ionic stress inherent in a Ca brine. The proposed one-year pilot study will expand this inquiry to include fifteen halophilc cyanobacteria, bacteria, and archaea that have been isolated or to be isolated from Lake Vida in the Antarctic Dry Valleys, Hot Lake in Washington State, and the Dead Sea. Our goal is to test the predicted halophilic Hofmeister series Ca>Mg>Na (from the most chaotropic to the most kosmotropic) and to show that the presence of Na can mitigate the chaotropic effect of Ca and Mg. Specifically, we will determine each isolate s osmotic tolerance for NaCl, MgCl2, and CaCl2, and in the latter two cases, both in the presence and absence of NaCl. Virtually all astrobiologically interesting environments on Mars and Europa are high Ca or Mg saline environments. If our thesis is correct, habitability assessment there must take into consideration the degree of chaotropicity, as well as the osmotic potential, of the brines.

Steve Vance/Jet Propulsion Laboratory
Vital Signs: Seismic Investigation of Icy Ocean Worlds

SCIENCE GOALS: The overarching goal of this work is to assess seismic activity on ocean worlds to evaluate the ability to the constrain habitability through ocean composition and redox fluxes, thus improving our understanding of their potential for supporting life. We need to distinguish sources of redox flux, an active or inactive ice shell, and resulting high- or low-pH ocean.

METHODOLOGY:
Objective 1 (OBJ1): Construct a range of chemical and thermal models of icy world interiors. Using self-consistent physical models of radial structure for Europa, Ganymede, Callisto, Enceladus, and Titan, we will model variations in density, sound speed, and seismic attenuation due to heat flux, ocean composition, the configuration of ice layers, the presence of liquids in the ice, and the thermal and compositional state of the mantle and any metallic core.

Objective 2 (OBJ2): Generate a data set of global synthetic seismograms for each interior model. Using outputs from OBJ1, we will obtain global propagation characteristics, creating libraries of axially and spherically symmetric models of seismic wave propagation as reference data for further analysis using both normal mode (YSpec, MINEOS) and spectral element (AxiSEM) methods. We will also examine the ability to infer the 3D structure and activity of the ice and ocean from observed topography on Europa using finite element modeling (SpecFEM).

Objective 3 (OBJ3): Use the seismograms in conjunction with estimates of seismic activity to simulate the background seismic noise. We will use the seismograms produced under OBJ2, in combination with likely magnitudes and frequencies of occurrence of events, in order to bound the level of background seismic noise in icy ocean worlds.
Objective 4 (OBJ4): Establish seismic sensitivity requirements for individual ocean worlds based on modeled signals. We will compare signal strengths modeled under OBJ2 and OBJ3 against candidate instrumentation to evaluate the ability to discern details of interior structure and signatures of habitability. These will be used to determine the detectability of vital signs , signatures of fluid motion and other activity linked to the redox fluxes in icy world oceans.

PERCEIVED SIGNIFICANCE TO NASA AND HABITABLE WORLDS: Planetary interiors determine habitability. Our knowledge of Earth s interior comes almost entirely from seismic observations. With prior knowledge from planned missions, seismology could be a powerful tool for constraining ocean compositions and redox fluxes by characterizing the detailed state of the ice, ocean, and deeper interior. Prior studies of icy moon seismology did not address many science questions that seismology might answer about habitability, and have only examined Europa in detail. The new application of thermodynamic data for fluid and mineral phases seeks to bring fresh attention to the unique features of icy ocean worlds that can arise from chemical and physical processes not occurring on Earth. The new application of modern computational seismology techniques will test for the first time the detection and characterization of active features on icy ocean worlds in ways that are needed for designing seismic experiments to characterize the habitability of ocean worlds.

Jie Xu/University Of Texas, El Paso

Can Phototrophy-Driven Sulfur Cycling Make Crystallization Water of Gypsum Bioavailable? Defining a New Habitability Index for Gypsum-Dominated Extreme Environments

The verified presence of hydrated minerals on Mars has greatly piqued mankind s curiosity about the red planet s potential of being a new habitat. In the past decade, most of the effort in searching for habitable niches on Mars has been directed towards constraining the geochemical conditions under which the hydrated minerals formed and towards the potential existence of liquid water. What has been largely neglected, in contrast, is the possibility of a more straightforward relationship between these minerals and life, namely whether the minerals structural water may become bioavailable for life activities under water-restricted conditions.

We propose a combined field and experimental study to investigate if a fundamental link exists between the bioavailability of gypsum (calcium sulfate dihydrate) and the habitability of gypsum-dominated (i.e., gypsic) environments. Specifically, we hypothesize that phototrophy-driven sulfur cycling is an essential mechanism to transform gypsum into a bioavailable source of both water and energy, thereby turning water-deficient gypsic environments into sustainable habitable niches.

To test our hypothesis, we have chosen two field sites, the gypsum dunes of the Tularosa Basin, New Mexico and Badwater salt flats of the Death Valley, California, because of their similarities to the north polar dunes (i.e., Olympia Undae) and the equatorial canyon (i.e., Juventae Chasma) on Mars, respectively. We will systematically collect microbiological, mineralogical and geochemical data of the endolithic microbe-gypsum assemblages isolated from the various locations within the two sites to diagnose the presence or absence of phototrophy-driven sulfur cycling. Based on this information, we will assess the environmental conditions that allow/favor the development of phototrophy-coupled sulfur cycling and quantify the water availability derived from the gypsum transformation driven by this process. By conducting simulation experiments in laboratory settings, we will also test if Mars surface-relevant conditions (i.e., carbon dioxide-dominated atmospheric compositions, low atmospheric oxygen content, and intense solar radiation) positively stimulate the phototrophy-coupled sulfur cycling, thereby enhancing the setting s habitability. Ultimately, the goal of the proposed project is to define a new index or several indices for gauging the habitability of gypsic environments building on the field-analysis and experimental data.

As the core task of the proposed work is to evaluate the role of a plausible mechanism in tackling the water crisis restricting the habitability of most gypsic environments, the work aligns perfectly with the major goal of the Habitable Worlds program, which seeks to use knowledge of the life on Earth as a guide for determining the processes and conditions that create and maintain habitable environments . The chosen sites and simulation experiments are relevant for Mars surfaces, and the results may have direct implication for the current and past habitability of the Martian surfaces dominated by gypsum deposits. The research approach and methodology established for this proposed project

are also applicable and transferable to similar studies at other analog sites and of other hydrated sulfate systems (e.g., magnesium- and iron-sulfates).

The proposed work will be mainly carried out within the NanoGeoBio Laboratory in the Department of Geological Sciences at University of Texas at El Paso (UTEP), as well as in the facilities of and the backing from UTEP s Center for Earth and Environmental Isotope Research and Border Biomedical Research Center. The external collaborators at the Carnegie Institution of Washington and Virginia Tech s National Center for Earth and Environmental Nanotechnology Infrastructure will also complement the expertise of the PI s and Co-PIs .