Habitable Worlds
Abstracts of Selected Proposals
(NNH15ZDA001N-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. 63 proposals were received in response to this opportunity. On June 3, 2016, 10 proposals were selected for funding.

Dorian Abbot / Univeristy of Chicago
Ocean and Cryosphere Dynamics and Habitability: Through Thick and Thin Ice

Overview: The habitable zone concept has been incredibly useful for developing our thinking about exoplanets, as well as guiding astronomers as they focus in on exoplanets that might potentially host life, and make rough calculations of the frequency of Earth-like planets in the galaxy. There are, however, a number of limitations to the traditional habitable zone which must be considered. First, by design the habitable zone does not consider many viable hosts for life, such as icy planets and satellites located further from their sun. Second, most calculations of the habitable zone have been done using atmosphere-only models, many of them one dimensional. This neglects potentially critical effects of ocean heat transport, which can alter cloud behavior and move heat into regions where it can be more easily radiated to space. It also neglects cryospheric feedbacks such as ice flow, which were found to be critical to the dynamics of Snowball Earth events that can serve as a model for icy planets and satellites. Third, it has recently been pointed out that the outer regions of the habitable zone may be subject to limit cycles between Snowball Earth-like states and very warm states. We have previously proposed a related alternative Snowball Earth state with a gap in thick ice near the equator, and if this state applies to the limit cycles in the outer habitable zone, they would pose much less of a challenge to habitability.

Objectives: The purpose of this proposal is to extend on and improve the concepts of habitability and the habitable zone by bringing detailed knowledge that we have gained through studies of Earth and its physical climate history to bear. Our research is organized by cryospheric regimes and the specific objectives are as follows:

1. Determine the effect of ice flow and ocean circulation on habitability under global thick ice cover (e.g., Europa or icy exoplanets).
2. Determine whether gaps in thick, near-global ice coverage can be maintained at the equator or substellar point by ocean-ice-atmosphere dynamics, and determine the consequences for observables and habitability.
3. Determine the effect of ocean circulation on the location of the inner edge of the habitable zone, which corresponds to planets with minimal ice coverage.

Methods: In order to achieve these objectives, we will use a combination of an original numerical models for the flow of thick ice that we have developed for the study of

Snowball Earth, coupled to state-of-the-art publicly available ocean-atmosphere global climate models. We will perform and analyze a large array of simulations where we vary important planetary parameters. We have assembled an expert team to do this, that will also include two graduate students who will receive training in the field. We expect this work to lead to six peer-reviewed journal publications.

Relevance: This work is highly relevant to the Habitable Worlds call since we address the habitability of icy moons and exoplanets using tools that have arisen from our studies of Earth's paleoclimate. It is also relevant to NASA more generally. It is partially motivated by the discovery of a sub-surface ocean on Europa by NASAâ€™s Galileo mission, and will provide predictions that can be tested by NASA's future Europa mission. It is also motivated by the explosion of extrasolar planet detections in recent years led by NASAâ€™s Kepler mission, will leverage future work using NASA's JWST and TESS, and will be essential for planning a future NASA mission resembling TPF or HDST.

Stephen Clifford / Universities Space Research Association
An Integrated Atmospheric and Subsurface Investigation of the Evolution of the Early Martian Hydrosphere: Implications for the Occurrence and Duration of Potentially Habitable Liquid Water Environments on a Cold Early Mars.

We propose to investigate the occurrence and duration of potentially habitable liquid water environments on early Mars, by integrating the Laboratoire de MÃ©tÃ©orologie Dynamiqueâ€™s (LMD) 3D Mars Global Climate Model (GCM), MOLA topography, and enhanced subsurface thermal and hydrologic models, to investigate the effects of a cold early climate on the evolution of the Martian hydrosphere. This first simulation of a hydrologic cycle of a cold early Mars, will be used to investigate the effects of a broad range of planetary water inventories (200-1000 m GEL), atmospheric surface pressures (0.01-3 bars), obliquities (0-60 degrees), and Martian crustal properties, on the existence and survival of subpermafrost groundwater, ice-covered lakes, seas, and a northern ocean. The LMD GCM includes a complete simulation of the atmospheric water cycle, calculating surface temperatures and pressures, wind speed and direction, geographic and temporal variations in sublimation and precipitation, and many other climate-related factors. Recent applications of this GCM have demonstrated the inability of the early Martian climate to raise mean annual surface temperatures above freezing, without invoking volcanic greenhouse gas emissions or atmospheric heating by large impacts.
In our application, the LMD GCM is combined with a model of the thermal evolution of the crust, and an advanced model of regional and global subpermafrost groundwater flow (based on the latest unstructured grid implementation of the US Geological Surveyâ€™s groundwater modeling software, MODFLOW-USG) â€“ an approach that represents the current state-of-the-art in modeling the evolution of the Martian hydrosphere. The simulation begins when surface ice, present in thermodynamically unstable reservoirs, is sublimed and ultimately precipitated in high altitude snowpacks and polar ice sheets. Groundwater recharge occurs when the accumulation of H2O, predicted by the GCM, becomes great enough to undergo basal melting. The resulting increase in local hydraulic

head drives the flow of groundwater beneath a global cryosphere, a system that is depleted as groundwater is: (1)cold-trapped into the cryosphere in response to the long-term decline in planetary heat flow, and (2) discharged to the surface by local breaches of the cryosphere (from impact, tectonic and igneous activity or the development of superlithostatic hydraulic heads). These discharges, combined with the flow of groundwater into ice-covered lakes, replenish surface reservoirs of H2O which freeze, sublime, and reprecipitate in response to the GCM.

The participation of groundwater in the cycle ceases when surface accumulations of snow and ice are no longer thick enough to undergo basal melting or enough groundwater is cold-trapped into the cryosphere to break hydraulic continuity. Given the complexity of this investigation, our initial effort will be limited to consideration of the sub-freezing early Mars conditions predicted by the LMD GCM. Mean annual temperatures >273 K (resulting from volcanic emissions or large impacts) are beyond the scope of the present study. Likewise, our groundwater simulations will be limited to investigations of the effects of recharge, discharge, and crustal heterogeneity. Consideration of other processes, such as hydrothermal activity, crustal deformation, diagenesis, groundwater aqueous geochemistry, rainfall, surface runoff, ponding, and infiltration, will be pursued in future studies. Investigation models and results will be presented at professional meetings, submitted to peer-reviewed journals, and made available on the web.
This proposal is relevant to NASAâ€™s Habitable Worlds program because it uses knowledge of the Earth as a guide for determining the processes and conditions (including the presence of water) that create and maintain habitable environments and supports theoretical studies of water body physics that pertain to habitability and the evolution of water with time.

Shawn Domagal-Goldman / NASA Goddard Space Flight Center
Organic Habitable Worlds: Simulating Habitable Zones for Organic-Rich Atmospheres

Science Goals and Objectives: In this proposal, we will study the habitable zones of organic-rich atmospheres on planets around different star types. The feedbacks between organics in the atmosphere and the climate at the surface is complex: organic gaseous species absorb outgoing IR radiation and act as a greenhouse gas; however, condenses organic aerosols absorb and reflect incoming UV radiation and act as an anti-greenhouse species. The process of aerosol formation is itself a function of the photolysis of the gaseous species, which depends on the amount and spectral distribution of the energy flux hitting the top of the planetâ€™s atmosphere. We propose to study the complex feedbacks that result from this process around a variety of star types, calculate the net climatic effects of the presence of these atmospheric organics, and assess the habitable zone (HZ) boundaries for worlds with such atmospheres. This will affect the HZ in different ways for planets around different type stars, and so will add nuances to the concept of the HZ.

Methodology: We will simulate organic-rich atmospheres and the resulting climates with 1-dimensional (altitude-dependent) photochemical/climate codes and 3D global circulation models (GCMs). We will use the coupled 1D photochemistry-climate model we have used to study organic-rich atmospheres in the past, the ROCKE-3D (Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics) global climate model (GCM) that is based on the ModelE2 Earth GCM, and with the Community Atmospheric Model (CAM) GCM. A critical input to these codes will be updated optical constants, obtained from measurements of products from our aerosol generation laboratory.

The combination of tools will allow us to update our codes, simulate a range of planets with the 1D code, and simulate each type of planet at a high degree of detail with GCMs. Intermodal comparisons will enable constraint of total model uncertainties, and a better understanding of the 1D modelâ€™s ability to accurately simulate a wide range of planets. This will enable a wider set of simulations by the 1D code than is feasible for the 3D GCMs, and enable a broader set of simulations.

Predictions from all these models will be used as inputs to the SMART (Spectral Mapping Atmospheric Radiative Transfer) model, a line-by-line radiative transfer tool. This will produce model spectra, simulating future exoplanet observations.

Relevance to Exoplanets Program: The results of this work will be relevant to the exoplanets program in three ways: 1) it will improve our understanding of the impacts of hazes on planetary climate; 2) it will demonstrate how the habitable zone will shift for anoxic atmospheres as a function of star type; and 3) it will make predictions on the observations needed to test the hypotheses associated with these new/expanded habitable zone boundaries. Thus, it will lay the foundation for an improved understanding of habitability and leverage that understanding to develop new hypotheses testable by future space-based exoplanet observations.

Bryana Henderson / Jet Propulsion Laboratory
Microbial Habitability and Diagenesis on Europa's Surface under Radiation

Scientific Objectives: We will experimentally determine radiation product signatures (both volatile and nonvolatile) of distinct classes of organics upon bombardment with electrons under simulated Europa conditions (microbes embedded in ice at 100 K and with radiation doses with energies spanning from 10 keV to 100 keV). To accomplish this, we will irradiate ices containing organics, biomolecules, and microbes with and without salts at ~100 K with lethal electrons, and estimate organic flux expelled into Europaâ€™s tenuous atmosphere by each class of molecules. For the microbes, we will use survival data from several different doses combined with radiation penetration models to estimate their survival depths under Europaâ€™s ice shell at various latitudes and longitudes on Europa. We will detect all organic byproducts produced during the irradiation of microbes both in water-rich and salt-rich environments using an in-situ

laser-ablation and laser-ionization mass spectrometry technique that has been successfully demonstrated in our laboratory [1, 2]. The deliverables include identification of volatile and non-volatile organics produced from microbial systems in a Europa-like environment and quantification of the radiation dose required to completely denature our microbes/spores at ~100 K on Europa's surface. Our work is critical for habitability assessment and mission design for potential orbiter and lander science return for the upcoming Europa mission.

Methodology: Leveraging on the collaborative expertise and infrastructure at JPL's Ice Spectroscopy Lab (ISL) and Microbial Survival Assessment (MSA) facilities, we will produce samples containing five categories of organics (including microbes) in Europa-relevant ice-salt mixtures, expose them to varying electron irradiation doses, and determine products formed. We will use a 10 keV - 100 keV electron gun as the radiation source (sufficient to penetrate through microbial cells), and will measure the production organic molecules that could potentially act as unambiguous tracers of life. We will also monitor the production of volatiles such as CO2 using a combination of in-situ laser-ablation and evolved gas mass spectrometry. We will study temperature ranges that are relevant to Europa's surface: 50 K in the polar regions to 150 K in potentially warmer regions, with an average surface temperature of ~120 K.

Relevance to Habitable Worlds: This proposal is highly focused towards the habitability of Europa, addressing the Habitable Worlds call: Icy Worlds - the astrobiological potential of icy worlds in the outer solar system, including Europa, Ganymede, Enceladus, and Titan. Our studies will determine whether and where potential life can survive at the surface of Europa and what organic products can be expected by flyby and lander instruments, further addressing the Habitable Worlds call: Research areas include, but are not limited to, the presence of water and/or exotic solvents, sources of energy for life, presence of organics and their reactivity, and water body physics and chemistry as they pertain to habitability and habitability over time.

Funded Team Members: Dr. Bryana L. Henderson; Dr. Murthy S. Gudipati; Dr. Parag Vaishampayan.

References Cited:

1. Gudipati, M.S. and R. Yang, In-Situ Probing of Radiation-Induced Processing of Organics in Astrophysical Ice Analogs-Novel Laser Desorption Laser Ionization Time-of-Flight Mass Spectroscopic Studies. Astrophysical Journal Letters, 2012. 756(1): p. L24.

2. Henderson, B.L. and M.S. Gudipati, Direct Detection of Complex Organic Products in Ultraviolet (Ly Alpha) and Electron-Irradiated Astrophysical and Cometary Ice Analogs Using Two-Step Laser Ablation and Ionization Mass Spectrometry. Astrophysical Journal, 2015. 800(1): p. 66.

Simone Marchi / Southwest Research Institute
Environmental Consequences of Asteroidal Bombardment on Early Mars

Background.

The past habitability of Mars is inextricably linked to its climate history. Geomorphological evidence has shown that Mars likely experienced episodes of widespread liquid water during its early history, prior to ~3.5 Ga. During this key period in Martian history, asteroidal impacts were much more numerous and energetic than during subsequent evolution, and may potentially have played a key role in influencing coupled surface-atmosphere evolution and climate. Here we will calibrate the magnitude and timing of these early impacts, we will quantify the extent of impact-induced melting and outgassing, and we will explore the consequences of this outgassing for atmospheric evolution and environmental conditions relevant to habitability.

Proposal Summary.

Our scientific goals are to develop the most comprehensive model thus far for i) the early bombardment history of Mars, and ii) the environmental effects of this bombardment, with emphasis on factors that affect life and habitability (e.g., surface temperature and volatile inventory). The work is divided into three major tasks. In Task 1 we will develop a model for the earliest martian bombardment, prior to ~ 3.5 Ga. This will be achieved by extrapolating our recent lunar impactor flux (Morbidelli et al. 2012) to Mars. In doing so we will calibrate our model against available geochemical constraints (e.g., highly siderophile elements recorded in martian meteorites), as done in recent work for the Earth (Marchi et al. 2014). In Task 2 we will study the heating and melting induced by the collisions we expect from Task 1 with the aid of dedicated hydro-code impact simulations. In particular, we will use iSALE hydrocode simulations to improve estimates of target temperature generated during large collisions, and we will account for a range of impact conditions. We will focus our attention on computing realistic estimates for the volume of impact-generated melt (as in Marchi et al. 2014). In Task 3, we will combine results from Tasks 1-2 to quantify the first-order environmental effects of ancient collisions. In particular, in Task 3.1, we will estimate the magnitude of carbon, water, and sulfur outgassing from melt pools. This will follow our recent successful model applied to the early Earth and derived from terrestrial large igneous provinces (Marchi et al. submitted). Here the outgassing model will be based on the available constraints from martian meteorites and calculations of volatile behavior during melting and degassing. In Task 3.2, we will use 1D photochemical atmospheric models to investigate the first order climatic and chemical effects of outgassing. We will consider the effects of varying starting atmospheric conditions and varying volcanic gas compositions. The ultimate goal of the proposal is to determine the environmental consequences of the early collisional history of Mars, including predictions of the amount of surface and atmospheric water due to outgassing, the amount of surface and atmospheric carbon dioxide due to outgassing, and the fraction of the martian surface melted by impacts.

Aaron Noell / Jet Propulsion Laboratory
Near-surface habitability of icy worlds

Science Goals and Objectives
Interfacial regions, such as ocean/rock or ocean/ice, are typically focused on when exploring the habitability of Icy Worlds. However, very little is known about the habitability of the near-surface/exosphere interface, as well as its potential coupling to the ocean below. While the near-surface environment is â€œextremeâ€ by nearly any measure, there is the possibility of micro-environments where radiation shielding by ice/salt mixtures could permit the survival of dormant organisms until they are recycled into more favorable conditions below. Furthermore, radiation processing and oxidation of possible microbes at the surface could be an important source of oxidized organic material to the subsurface. This material could be combined with reduced species from the planetâ€™s interior to allow chemotrophic organisms to survive.

We will investigate the habitability at the near-surface of Icy Worlds by determining the viability of bacterial spores after irradiation (UV-B,C, e-, etc.) under relevant temperatures, pressures, and matrices (ice, hydrated salts, etc.). We will also investigate the ability of spores to shield biomolecules and enhance their preservation under these conditions, even after the spores have been inactivated.

Methodology
For these experiments, we will use an ultra-high vacuum chamber equipped with a rotating cryostage to create low temperature ~ 30 â€“ 150 K H2O and H2O:X (X = e.g., CO2, Ar, N2, CH4, H2O2, SO2) matrices doped with spores, or spore biomolecules (e.g., dipicolinic acid, DNA). This temperature range will allow surveying the habitability within ices on bodies like Europa and Enceladus. A selection of discharge lamps, an Ar arc lamp, and appropriate wavelength filters will be used to UV irradiate the species and an electron gun will provide e- irradiation. Real-time monitoring of the matrices will be performed by reflectance FTIR to assess irradiation damage. At the completion of irradiation, the substrates with spores will either be cultured to determine the viability of the spores, or the spores will be collected and the biomolecules extracted to determine their degree of degradation. Substrates with the bare biomolecules applied will be similarly extracted and analyzed for comparison.

Relevance
This proposal will help â€œto search for . . . contemporary habitable environments and explore the possibility of extant life beyond the Earthâ€ by investigating the astrobiological potential of the near-surface environment on Icy Worlds. The work will explore the timescale of survival at the surface, therefore also placing constraints on turnover rates required for the habitability of the coupled surface and subsurface system.

Norbert Schorghofer / University of Hawaii
Seasonal frost as source of liquid water on Mars

The possible presence of liquid water on present-day Mars continues to receive extraordinary attention among planetary scientists and the public, as liquid water is suspected an agent in many surface processes and considered a universal prerequisite for microbial activity. Recurrent Slope Lineae (RSL) form during the warm season on Mars and are widely believed to be caused by liquid water. However, the source of the water (aquifers, ground ice, deliquescence, seasonal frost, or other) remains unknown and the physical mechanism of how ice can melt, under adverse physical conditions such as rapid sublimation, remains highly controversial.

We propose to quantitatively study one specific mechanism that we consider particularly promising: Melting of seasonal water frost in alcoves. In areas within alcoves that are seasonally shadowed, water frost will accumulate, and when the sun rises again, temperature increases rapidly and melting can occur. We will use HiRISE-stereo derived DEMs and three-dimensional modeling of shadows, surface temperature, near-surface temperatures, and sublimation in RSL alcoves. The goal is to quantitatively assess the full cycle of frost accumulation, warming, and melting in these local environments. The investigation will answer the following profound question: Can liquid water form by melting of seasonal frost in alcoves at present-day Mars conditions?

Our model results will be compared to a suite of observational constraints. We will take the model surface temperature output and compare it to 1) measured RSL growth/retreat timescales (at what temperatures are the RSL changing?) and to 2) freezing point depression calculations for chloride, perchlorate, and sulfate solutions and/or brines. The modeling component of the proposed work will build on existing model code for the energy balance on three-dimensional topography. The model calculates horizons and field of views for each topographic element; it evaluates solar incidence angles, multiple reflection, and subsurface heat conduction to determine surface temperature as a function of time and location. The model will be augmented to better represent relevant physics. The model source code will be shared on Github, where existing code is already archived.

Everett Shock / Arizona State University
Mechanisms of Organic Compound Reactivity in Habitable Worlds

Goals & Objectives
The goal of this work is to support the exploration of the habitability of Icy Worlds such as Europa by enhancing current understanding of the timescales and mechanisms of organic reactions in hydrothermal systems. Considerable data from experiments already exist for lower-temperature conditions that are applicable to the warming and melting of comets, and the low-temperature aqueous alteration documented in carbonaceous meteorites. In contrast, experimental constraints on mechanisms and rates of organic reactions at higher-temperature hydrothermal conditions are far less abundant.

Nevertheless, geophysical models of Europa, Pluto, Ceres, Enceladus, and other Icy Worlds indicate that long-lived hydrothermal conditions prevailed on these bodies, and may continue to the present. Not knowing the consequences of hydrothermal organic transformations hampers scientific understanding of processes that determine the habitability of Icy Worlds. Furthermore, as NASA prepares to send mass spectrometers and other analytical equipment to Europa, there are pressing needs to be able to interpret planetary processes from data on the relative abundances of organic compounds. Such interpretations will be greatly improved with the results of the proposed experiments.

Methodology

Hydrothermal experiments, using methods we have already developed to study reactions of organic compounds in the Earthâ€™s crust, will constrain the reactivity (reaction products and rates) of organic compounds expected to be present on habitable Icy Worlds. Experiments will reveal mechanisms and rates in hydrothermal water, with and without the presence of minerals, for organic reactions involving carbon-carbon and carbon-nitrogen bond making and breaking. Experiments will be conducted using a variety of reaction vessels depending on temperature and pressure, and results quantified by various techniques including gas chromatography, ion chromatography, and molecular mass spectrometry.

Relevance to the Habitable Worlds Call for Proposals

The proposed research is directly relevant to the Habitable Worlds program described in Appendix C4 of ROSES 2015. Specifically, the proposed research relates to the â€œpresence of organics and their reactivityâ€□. New experimental constraints on reaction mechanisms resulting from this research will enable new interpretations of analytical data from molecular mass spectrometers and other analytical equipment sent to icy worlds. Data of this type are in hand from Enceladus, as well as asteroids and comets. The MASPEX instrument on NASAâ€™s mission to Europa will also return data of this type. The goal is to provide guidelines for using organic analyses of Icy Worlds as the means to probe planetary processes. Armed with data from the proposed experiments, researchers will be able to interpret ratios of various organic compounds to determine whether hydrothermal processes are likely to have occurred on icy worlds. In the case of Europa, much of the current enthusiasm for its habitability stems from the likelihood of hydrothermal processing of ices and organic compounds either in the past or continuing on to the present. In addition, since the proposed experiments will generate fundamental data concerning mechanisms, reaction products, and rates, they will help to constrain new model calculations applied to the interior evolution of Icy Worlds. Although not the main targets, the fundamental nature of the proposed research will permit similar models of early Mars, and plausible conditions on habitable exoplanets or their moons as observational data improve.

Owen Toon / University of Colorado
Habitable climates on early Mars

The habitability of early Mars and perhaps current Mars, is directly tied to its early climate. Was early Mars warm and wet, or cold and dry? Numerous theories have been proposed to warm Mars using CO_2, CO_2+CH_4, CO_2+ SO_2, but each of these fails even to bring Mars near the freezing point. Several bars of CO_2 plus H_2 may work, but evidence suggests such high levels of CO_2 did not occur, and an atmosphere of CO_2 + H_2 requires complex geochemistry since one is oxidized and one reduced. Our goal is to better understand the cloudy greenhouse solution of the faint young sun problem for Noachian Mars. Urata and Toon (2013a,b) show stable climate states with global average temperatures near the freezing point, as well as substantial tropical precipitation rates, can be maintained on ancient Mars by water clouds, assuming that carbon dioxide levels exceed a few hundred mbars. Unlike previous proposed solutions, carbon dioxide is not a major greenhouse gas in this model, but rather is important for carrying heat to the pole. Water ice clouds provide the greenhouse warming. We are now able to predict where rain fell and runoff amounts, which allows us to link climate models directly to the geologic record. This work may resolve the longstanding debate about how Martian river valleys formed, and whether lakes and seas were stable as liquids, or only short-lived before freezing. Unlike all other solutions to the early Mars climate problem, we only require modest amounts of carbon dioxide, and we know the greenhouse gases, CO_2 and H_2O, are present, and do not invoke gases for which we do not have observational evidence.

It is surprising that clouds can cause planetary warming since clouds cool Earth. However, we have also found that on Archean Earth clouds may have provided warming. We seek to understand these two radiative behaviors of clouds, which we believe represent new fundamental planetary physics with implications for other planets. The Mars modeling group at NASA Ames finds similar solutions to ours, but others have not duplicated our results. We plan to use a more sophisticated aerosol and cloud model than we used in the past to eliminate some assumptions and clarify the requirements to obtain these warm climate solutions. We also plan to address such questions about ancient Mars as whether oceans would freeze over, whether a strong hydrological cycle requires only polar ice deposits or also midlatitude ones, and whether impacts are needed to initiate long-lasting warm climates caused by clouds, or instead high obliquity states will work. We will also explore several issues related to modern Mars including the physics of high altitude clouds, and the interaction of nighttime frost with the soil, which may lead to liquid formation in some locations now.

Methodology: We plan several tasks. First, we will simulate current Mars clouds and climate with a new climate model that has advanced aerosol and cloud modules. We will explore little studied phenomena for current Mars, such as high altitude clouds, and the condensation of water and CO_2 at night, which is widespread even in the tropics, and may lead to liquid water formation now. Once we have confidence the model is reproducing current data on dust and ice clouds and their interactions with the surface, our second task will be to simulate ancient Mars so that we can confirm the Urata and

Toon work, use better physics to eliminate a number of assumptions in the older model, and improve our understanding of the cloud physics. Finally, we will use the model to tie into the geologic record, by predicting precipitation and runoff patterns on early Mars and the stability of lakes and seas.

Relevance: Our proposed work is directly related to an objective of Habitable Worlds research â€œMars-â€¨the astrobiological potential of past or present environments on or in the Martian surface or subsurface.â€□

Robin Wordsworth / Harvard University
Atmospheric collapse and volatile transport on rocky M-star planets

Red dwarf (M-class) stars offer some of the best opportunities to find and characterize Earth-like exoplanets in the near future by either space- or ground-based instrumentation. However, the processes that shape the atmospheres of potentially habitable worlds around M-stars are still very poorly understood. To optimize mission planning and gain the maximum insight from future observations, more detailed theoretical study is required. Most potentially habitable rocky planets around M-stars will have close orbits, leading to low orbital obliquities and in many cases tidal locking, with permanent day and night sides. They will also suffer extended periods of atmospheric and volatile erosion early in their evolution. In combination, these effects may have diverse consequences for climate and habitability, including extreme surface temperature variations, collapse of volatile species into cold trap regions, and extensive planetary oxidation via hydrogen loss. All of these processes have important observable consequences, but most are still very poorly understood.

Here we propose a numerical and theoretical investigation of a key process governing the habitability of rocky planets around M-stars: atmospheric volatile transport. We plan to take a universal approach, treating two key volatiles (H2O and CO2) on an equal footing theoretically in order to maximise the generality of our results. At each step of the project, analysis and basic theory will be used to obtain a deep understanding of the results.

First, we will use a 3D general circulation model with accurate multiband radiative transfer developed by the PI to study atmospheric heat transport and volatile collapse on planets with a range of masses, orbits and atmospheric compositions. General empirical formulae will be constructed from the results to aid future research. Next, we will use the 3D model to study volatile equilibration in the collapsed case. Besides its fundamental theoretical importance, this second phase of the project will have two direct implications for understanding planetary habitability. First, it will allow us to assess the extent to which water-poor, desiccated M-star planets may locally have habitable surface conditions. Second, it will allow us to calculate the long-term stability of planetary water inventories against upper atmosphere H2O photolysis and hydrogen loss to space. Besides its implications for long-term habitability, this will allow assessment of the

potential for abiotic oxygen atmospheres to emerge on such planets --- an issue of vital importance to remote biosignature detection.

This proposal addresses the fact that most potentially habitable exoplanets will not be Earth-like by including a range of planetary masses, orbits and atmospheric compositions in its scope. The universality of the atmospheric condensation problem means that this work also has potential to help advance understanding of volatile redistribution in the solar system (e.g., the CO2 cycle on Mars or the N2 cycle on Triton). The empirical collapse formulae resulting from this study will serve as a valuable resource for future observation/mission planning and subsequent studies of planetary habitability, making it important to NASAâ€™s wider goals. Finally, the work will have implications for the search for life around other stars by testing scenarios under which false positives for life (such as an abiotic O2-dominated atmosphere) may arise.