Interdisciplinary Consortia for Astrobiology Research
Abstracts of Selected Proposals
(NNH19ZDA001N-ICAR)

Below are the abstracts of proposals selected for funding for the Interdisciplinary Consortia for Astrobiology Research program. Principal Investigator (PI) name, institution, and proposal title are also included. 30 proposals were received in response to this opportunity. On October 23, 2020, 6 proposals were selected for full funding and 2 for partial funding.

Daniel Apai / University Of Arizona
Alien Earths: Which Nearby Planetary Systems Are Likely to Host Habitable Planets and Life?

With the discovery that habitable planets may be very common, one of the most compelling and timely questions to answer is: Which Nearby Planetary Systems are Likely to Host Habitable Planets and Life? Advancing our knowledge on this question will have far-reaching implications for astrobiology: It will directly address topics central to the Astrobiology Strategy, contribute to ICAR/NExSS's primary goals, will inform the use of current and upcoming NASA missions, and will guide designs of missions concepts.

We will transform our understanding of the habitability of nearby planetary systems by combining: (a) improved statistical understanding of planet formation, (b) population-level knowledge on exoplanets, (c) data on specific nearby systems, with (d) models for atmospheric evolution and biosignature surveys, incorporating population-level information.

We propose 14 projects organized in four closely-integrated modules: In Module 1 we will advance our understanding of the conditions and timeline for planet formation, focusing on the less well-understood early stages. We will combine astrophysical observations with state-of-the-art protoplanetary disk models, and contrast model predictions with cosmochemical studies of samples from primitive Solar System planetesimals. In Module 2 we will quantify how different planet formation pathways impact planet composition and, through it, habitability. We will combine knowledge from models of planet formation in disks with large-scale structures, with observational tracers of migration of solids and planetary building blocks. We will contrast the simulated and simulated planet populations to identify connections between formation and composition. In Module 3 we will apply knowledge from Modules 1 and 2 to nearby planetary systems. We will improve the available data on these systems and assess their potential for hosting habitable zone, Earth-sized planets, also considering the possible threats and range of planet formation pathways and dynamical stability. In Module 4 we will combine knowledge from Modules 1 3 to inform current and future space missions that

characterize small planets and search for atmospheric biosignatures. We will further our understanding of the small planet population and the occurrence rate of Earth-sized habitable zone planets. We will extend our probabilistic, Bayesian interpretation of exoplanets, a powerful technique to combine well-established, planet population-level knowledge with specific but uncertain measurements of a given planet. We will assess the efficiency of different biosignature search strategies in light of coupled ecosystem-atmosphere models of living planets. In order to address aspects of habitability not included in our projects we will organize annual workshops to integrate NExSS-wide quantitative knowledge on habitability into a self-consistent, statistical, and modular framework to guide mission design. We are building on the powerful heritage of our EOS/NExSS team, that explored how volatiles and organics are delivered to forming habitable worlds. EOS published 120+ refereed papers (with over 2,000 citations), including multiple high-impact results. We will build on the effective management structure of EOS and will firmly control the schedule and budget to ensure the highest quality results and on-time, on-budget product delivery. We are combining astrophysics, planetary science, atmospheric science, cosmochemistry, biology, and mathematics to reach our ambitious goals. Each of our four modules integrates at least three of these disciplines. Our team also includes world-leading, independently-funded, international partners who will enrich the NExSS community. UArizona, is among the nation s largest Hispanic Serving Institutions and one of the leaders in astrobiology, and we will use this research opportunity to support and enhance diversity in STEM fields.

Natalie Batalha / University Of California, Santa Cruz
Follow the Volatiles: Tracing Chemical Species Relevant to Habitability from Proto-Planetary Disks to Exoplanet Atmospheres

The next decade will see the characterization of potentially habitable planets around other stars, and the search for biosignatures will begin in earnest. Much of that effort will involve observations by JWST and other telescopes to detect gases in the atmospheres of Earth- to Neptune-size planets, including planets within the compact habitable zones of M dwarf stars. In order to assess the chemical and (potentially) biological significance of these observations, we must understand the formation and evolution of the atmospheres of small planets, the pathways of volatile elements that comprise such atmospheres from star-forming clouds into protoplanetary disks and planets, the exchange of such volatiles with the interior, and their possible loss to space. Our understanding of these abiotic processes is largely based on the Solar System, but known exoplanetary systems comprise vastly greater diversity which challenges this framework and our ability to interpret any potential biosignature against the possibility of a false positive . Our interdisciplinary team proposes a synergistic program of observations, laboratory experiments, and modeling to understand the journey of planetary volatiles, particularly but not limited to carbon- and oxygen-containing species, and their manifestation in atmospheres. We will address four fundamental questions: (1) What is the inventory of volatiles in the planetary building blocks that make up protoplanetary and debris disks? We will use mm- and radio-wave interferometers and occultation techniques to detect

structures in disks that trace or influence the migration of that material and probe its size and composition. We complement those observations with measurements of volatiles in primitive material (meteorites) in the Solar System, and laboratory experiments that measure how such volatiles are released by heating and accretion. (2) Which and how much volatiles are accreted from the disk as gas or solids, and are lost to space, and how does this shape the observable population of exoplanets? We will combine models and observations of disks to map these volatiles, and use laboratory experiments to study how volatiles may be incorporated in or lost from planetesimals. We will use data from space missions to map the distribution of gas- and volatile-rich sub-Neptune vs rocky planets, informed by observations of ongoing escape of planetary atmospheres, and an improved understanding of the stellar activity that drives it. (3) How are volatiles exchanged between the atmosphere, surface and interior of a planet? We will use high-pressure laboratory experiments and models of accretional and radioactive heating to study the partitioning of volatiles between the surface and interior during the crucial early phase of differentiation of a planet, and investigate the possibility that primordial volatiles are still present in Earth and other planetary bodies. (4) How can observations of exoplanet atmospheres inform us about the volatile inventories and chemistries of exoplanets? We will lay the foundations for these observations by telescopes like JWST by measuring the masses of the TESS-detected planets that are the most suitable targets and develop strategies for detecting and robustly quantifying volatiles in objects from giant to small evaporating planets. Finally, we will develop a synthesis of our work and trace the pathways of volatile elements and their isotopes, with particular attention to C and O and their relative abundance as a widespread indicator and determinant of the chemistry leading to rocky atmospheres. Our team will work synergistically with other members of the NExSS research coordination network and our research will support the detection of biosignatures in exoplanets in support of future NASA flagship missions and is one of the principal goals of the NASA Astrobiology Strategic Plan (2015) and NASA s 30-Year Roadmap for Astrophysics (2014).

Donald Burke / University Of Missouri, Columbia
Bringing RNA to Life Emergence of Biological Catalysis

RNA world theories feature prominently in Origins-of-Life models, which propose that RNA or a similar polymer played major roles in biological catalysis, in addition to storing heritable genetic information. While some RNA world elements are well supported by experimental data, the biological viability of such ribo-organisms remains speculative or requires extrapolation well beyond the existing data. In particular, it is well-established that RNA can promote several classes of chemical reactions in single-turnover format with non-biological substrates, but it is unknown whether RNA can provide the necessary catalysis to support complex cellular functions, or how such catalysts might emerge. Indeed, the dearth of robust RNA catalysts for small molecule transformation is the single biggest bottleneck in the construction of model ribo-organisms. A long-term goal of our Consortium is to define the potential of RNA to sustain cellular metabolism and to fully bridge the gap between bottom-up and top-

down approaches to RNA world research, thereby touching on both the PCE3 and FECM Research Collaborative Networks (RCNs). The proposed research will provide experimental underpinning to a critical missing piece of the RNA world puzzle: emergence of robust, truly catalytic, multiple-turnover ribozymes as precursors to contemporary metabolic pathways.

Methods/Techniques/Approach: The Team comprises 12 faculty from 8 institutions, with expertise in RNA biochemistry, structural biology, enzymology, ribozyme selection, synthetic organic chemistry, bacteriology, synthetic biology, systems biology modeling, and informatics of evolving RNA populations.

Relevance to NASA Objectives: An RNA world could provide a bridge between bottom-up and top-down approaches that are at the heart of the PCE3 and FECM Research Coordination Networks.

Betul Kacar / University Of Arizona
What life wants: Exploring the Natural Selection of Elements

What drives the natural selection of elements in biology function or availability? The evolution of the menu of bioessential elements is determined by two key factors: each element s chemical characteristics, and its environmental availability through time. Earth s history provides a natural laboratory in which to study these factors because element availability in the environment has changed over evolutionary timescales. We can imagine a future in which quantitative and mechanistic understanding of life s selection of the elements becomes important in the interpretation of data from future exoplanetary observations, and guides exploration efforts. However, our present understanding of the evolution of life s elements is insufficient for this task.

The MUSE (Metal Utilization and Selection across Eons) team will explore the natural selection of the chemical elements during the coevolution of life and environment on early Earth, focusing on the history of metal use in the biological nitrogen (N) cycle. Our research program will address the limitations in our understanding by studying the evolution of metal use in nitrogen fixation over Earth s history. On any Earth-like world, life will need to obtain nitrogen from inorganic sources. But will the same metals be required in all cases? By deepening our ability to answer this question, our program will help us understand what makes an environment habitable, which is of high astrobiological importance.

Our research approach integrates the traditionally disparate fields of geochemistry, geobiology, paleogenetics, experimental evolution, and artificial biology toward a common goal of understanding the evolution of metal requirements in biological nitrogen fixation. These field-based, experimental, and in silico investigations will connect the planetary and molecular scales, as well as independent geochemical and molecular records of ancient life. We will test specific hypotheses targeting currently unknown

metal availabilities of the early Earth environment, the metal demands of early life, and the plausibility of alternative evolutionary scenarios in the metal requirements of nitrogen fixation.

We propose to target three interconnected aspects of this problem. First, we will place new constraints on the abundances and sources of Mo and V in Archean oceans (Initiative I). Second, we will investigate the biological demands of these metals through analogs of early diazotrophic ecosystems, as well as by the experimental reconstruction of ancient nitrogenases (Initiative II). Third, we will use experimental evolution of nitrogenases and the design of artificial nitrogenase-like systems to understand the evolutionary tradeoffs of differential metal usage, as well as the potential for radically different evolutionary possibilities by identifying the essential features of biological N-reduction in artificial nitrogenase proteins using different metal cofactors.

MUSE team research into the role of metal cofactors in the N-cycle fits squarely in From Early Cells to Multicellularity (FECM). Toward our long-term goal of a theory of planet-life coevolution, we will foster a network that includes scientists from all the RCNs and beyond interested in exploring alternative evolutionary scenarios across diverse metabolic processes.

Timothy Lyons / University Of California, Riverside
Alternative Earths How to Build and Sustain a Detectable Biosphere

Our proposed research is defined by one fundamental question: How do ocean chemistry and solid planetary processes lead to sustained habitability and the maintenance of detectable atmospheric biosignatures? Our search for the answer will require a comprehensive mechanistic understanding of Earth s past and will produce, by extrapolation, a framework for interpreting remote observations of exoplanets. We will view the stages of our planet s history over its initial four billion years as alternative Earths. These chapters will provide unique windows onto the evolution of our own planet as well as the factors that regulate the evolution of planetary habitability and the appearance, persistence, and detectability of atmospheric biosignatures on habitable worlds more generally. This effort builds on our previous results but goes much further by: (1) employing exciting new and wide-ranging geochemical and numerical approaches to deconstructing Earth s past, including extensive calibration of proxy approaches in modern analogs of ancient oceans, and (2) extending our understanding of Earth system dynamics to exoplanet observables.

Because Earth is the only known inhabited world, it provides a unique opportunity to ground-truth conceptual and predictive models for planetary habitability and associated, remotely detectable biosignatures against an empirical rock record spanning billions of years. We will emphasize a diversity of planetary states and the transitions between them, prioritizing stages of Earth s history that are markedly different from our current world,

including those with very different (and variable) levels of atmospheric oxygen and methane.

To meet this goal, we have constructed an interdisciplinary team with broad expertise across Earth system science, marine biogeochemistry, microbial ecology, climate modeling, and observational astronomy. Our scientific objectives are structured specifically around four alternative Earths that allow us to interrogate carbon cycling and related nutrient controls, climate dynamics, and the emergence and maintenance of atmospheric biosignatures across a range of planetary configurations with clear relevance to a broad array of potential exoplanetary scenarios.

The highly interdisciplinary nature of our team allows for a novel vertical integration of approaches. We will begin by characterizing the diversity of planetary states of our past using cutting-edge geochemical proxies first developed in modern oceans and lakes to reconstruct past environments. These efforts, including rate measurements in the field and controlled experimental settings, will provide the boundary conditions for rigorous 3-D models for ocean biogeochemistry that will yield gas fluxes to simulated atmospheres. Our combination of expertise with modern and ancient oceans is a novel if not unique strength of the team. Coupled climate and photochemical models will then be used to predict steady-state atmospheric composition, which can be translated to synthetic spectra generated by radiative transfer models. Finally, the remote detectability of the simulated atmospheres by present and future telescopes will be explored using instrument simulators, thus solidifying our connection to ongoing NASA missions and future mission concepts.

The Alternative Earths team will strive to integrate techniques and insights both within and among NASA s new Research Coordination Networks (RCNs). More specifically, our efforts and outcomes will bridge effectively with the three RCNs called out in this solicitation and more generally lie at the focal point of all existing RCNs. Those connections will be facilitated by the already strong involvement among the team in NExSS and PCE3, including participation as members on the steering committees and as an RCN co-leader. Finally, the research of the Alternative Earths Team aligns in diverse and substantive ways with the goals outlined in the NASA Astrobiology Strategy.

Burckhard Seelig / University Of Minnesota
Emergence of a Complex Biochemical System:
Evolutionary Aspects of the Path to Coded Protein Synthesis

Complex biological systems must emerge through the evolution of simpler intermediate forms, which themselves need to be advantageous to an organism in its environment. A major evolutionary transition out of the RNA World and toward the earliest cells is defined by the emergence of the genetic code of protein translation. However, the emergence of the genetic code remains conceptually mysterious, largely because, while the advantage of a fully instantiated code is clear, the evolutionary advantage of simpler

forms and smaller parts of the system is not obvious. In other words, what good is 5% of the genetic code? Our goal is to understand the evolutionary advantages and dynamics of the molecular parts and simpler forms of the genetic code. Evolutionary advantages may be similar to the function of the ultimate system, or selection may have been initially for completely different functions, with evolution co-opting the molecules and subsystems for the later function (a molecular bricolage). We hypothesize that parts and intermediate forms leading to coded protein synthesis could have conferred advantages to a primitive cell initially unrelated to protein translation, such that the apparatus of the genetic code emerged as a co-option of these parts. Once a minimally required complexity was reached by these intermediates, a very primitive system could be directly selected for protein translation. We propose to study three general stages of this process: 1) Experimental and computational determination of evolutionary advantages of translation parts in a protocell context; 2) Theoretical modeling of the evolutionary dynamics of the transition from selection for parts to selection for higher function, inspired by mechanisms and parameters discovered experimentally; 3) Experimental measurements and computational simulations defining possible evolutionary advantages of the earliest translation systems. Methods used in this proposal include in vitro selection, bioinformatic analysis, biophysical and biochemical assays, dynamical modeling, and computer simulations. Accordingly, we will employ an interdisciplinary team of researchers to study this complex topic. To accomplish our proposed goals, we will integrate the knowledge and methods from our investigators who are experts in: functional RNA and protocells, mathematical modeling of evolutionary processes, peptide evolution and the genetic code, bioinformatics and simulations of prebiotic systems, and biogeochemistry and mineral in prebiotic chemistry. In this project, we propose a synthesis of laboratory experiments and theoretical approaches. The project will address multiple key research questions posed in the 2015 Astrobiology Strategy. In particular, relating to Synthesis and function of macromolecules in the origin of life (Chapter 2), our proposal directly addresses the key research questions : How did the genetic code originate? and What led to macromolecular complexity? . Relating to Early life and increasing complexity (Chapter 3), we directly address the key research questions: How do evolutionary innovations originate? and What are the pressures and mechanisms for the increase in complexity? If successful, the outcome of this interdisciplinary project will be a concrete and conceptual understanding of the evolutionary driving forces leading to the emergence of the genetic code.

Kevin Stevenson / Johns Hopkins University
The M-dwarf Opportunity: Characterizing Nearby M-dwarf Habitable Zone Planets

Identifying habitable (and possibly inhabited) planets around other stars is one of NASA's greatest long-term goals. Significant resources have gone into first finding these planets, with great success. Ground-based surveys, the Kepler/K2 missions, and TESS have found >1,000 terrestrial (<1.75 Earth radii) exoplanets. Of these worlds, the most scientifically-compelling targets in the search for extrasolar life are known to orbit M-

dwarf stars, which are cooler (2600 K - 4000 K) and smaller (<0.5 Solar radii) than our Sun (5800 K). They are also the most numerous stars in the Galaxy, accounting for 75% of our closest neighbors. Systems such as Proxima Centauri, TRAPPIST-1, and LHS 1140 represent our best (and only) opportunity this decade to reveal the prevalence of life around nearby stars. This is because only habitable worlds orbiting M dwarfs may yield detectable molecular signatures with current technology.

With the forthcoming launch of JWST (and soon-to-be commissioned ground-based extremely large telescopes), detailed atmospheric characterization of terrestrial M-dwarf planets is imminent. However, it remains to be seen if the community will have the comprehensive modeling framework necessary to correctly interpret the data and avoid making premature claims of detecting signs of life. This study will help guard against errant interpretations by addressing one of the most pressing exoplanet questions in the era of JWST: Can M-dwarf planets support life, and if so, how do we best observe and characterize them?

There are several key factors that influence habitability, particularly for planets around M dwarfs. For example, unlike Sun-like stars, M dwarfs have fully convective envelopes, emit peak radiation in the near-IR, differ in stellar activity and evolutionary histories, and have tidal-locked habitable-zone planets that experience atmospheric circulation regimes and chemistry that differ from that on Earth. Thus, in order to determine how best to detect biosignatures on M-dwarf planets, a multifaceted study is required to explore the effects of coupled physical processes (e.g., mantle-atmosphere) on M-dwarf habitability, investigate the diversity of terrestrial exoplanet atmospheres around M dwarfs, and analyze M-dwarf star-planet interactions and their influence on habitability.

This study will develop the initial framework needed to accurately assess the habitability of terrestrial planets in or near the habitable zone of M-dwarf stars as observed by JWST. Our team will then generate a focused set of 1D and 3D terrestrial atmospheric simulations that uniquely integrate planet formation, interior structure, oxidation state, outgassing, climate, photochemistry, and atmospheric escape, and incorporate star-planet interactions using high-resolution, broad-wavelength stellar spectra. We will then use JWST data to complete the feedback loop and place initial constraints on the likelyhood function of M-dwarf planet parameter space. Our team will share our high-level data products with the community to guide future observations and inform the resulting retrievals and subsequent interpretations.