# Emerging Worlds 2018
# Abstracts of selected proposals
# (NNH18ZDA001N-EW)

Below are the abstracts of proposals selected for funding for the Emerging Worlds 2018 program. Principal Investigator (PI) name, institution, and proposal title are also included. 110 proposals were received in response to this opportunity. On November 26, 2018, 30 proposals were selected for funding.

**Day, James/University of California, San Diego**
**Planetary accretion and differentiation processes investigated using highly siderophile and volatile elements**

This proposal seeks to refine understanding of the fundamental processes involved in accretion and differentiation of the Moon and asteroids. Three questions will be addressed, all targeted at the earliest stages of planetesimal and planet formation:

1. How and when were indigenous highly siderophile elements (HSE: Os, Ir, Ru, Rh, Pt, Pd, Re, Au) set in the Moon and asteroidal bodies, and what are the distributions of these elements within the silicate mantles of these bodies?
2. What are the relative timings of metal-silicate equilibrium to define core formation and the onset of post-core formation late accretion, and can differentiated meteorites be linked to some iron meteorite groups?
3. Were volatile elements lost during planetesimal differentiation and what are the potential collateral effects of 'drying out' of small planetesimals on the growth and volatile inventories of larger planets?

These questions will be investigated through four inter-related tasks using Re-Os, Rb-Sr and Zn isotopes, HSE and trace element abundances, and petrography and mineral chemistry of meteorites and Apollo samples. The tasks address the 'early evolution of the Solar System', and are directly relevant to the Emerging Worlds program.

Task 1 is designed to more fully characterize the Zn and Os isotope and HSE abundance composition of the Moon. This task will include study of ferroan anorthosites and magnesian suite rocks to assess pristinity using Os isotopes and HSE abundances and then to use this filter to refine determination of the indigenous HSE composition of the lunar crust and whether it is heterogeneous with respect to these elements. These results will be important for determining volatile and siderophile element behavior during lunar differentiation and as a baseline for indigenous HSE abundances in the lunar crust.

Task 2 will involve study of lunar "mantle" derived materials, including mare basalts and volcanic glasses. The new data will be used to assess whether the HSE are heterogeneously distributed in the lunar mantle through comparison of Apollo sites. Combined Zn-HSE data will be used to evaluate effects of post-core formation late accretion on mantle source siderophile-volatile inventories. We will also seek to address whether some magmatic materials might reflect derivation from a primordial, volatile-rich lunar mantle source.

Task 3 will examine how indigenous HSE and volatile element abundances were set in differentiated asteroidal bodies. We will extend the new 'pristinity' index that we have developed for eucrites, by

analysis of more eucrite and diogenite samples to evaluate the formation and development of the howardite-eucrite-diogenite parent body, and expand these principles to angrite meteorites. A pristinity index is fundamental to determining which samples preserve evidence for the earliest phases of formation of a parent body and for providing a chronological framework for understanding planetary accretion and differentiation processes. The work will enable quantitative assessment of silicate-metal equilibrium and post-core formation accretion additions to differentiated asteroids. The data will also be used to establish the extent and cause(s) of volatile-depletion, as evident from isotopically 'heavy' Zn and unradiogenic Sr isotopic ratios in some eucrites and angrites.

Task 4 concerns measurement of primitive achondrite meteorites, including FeO-rich achondrite (e.g., brachinite-like), and acapulcoite-lodranite meteorites using high-precision Os and HSE abundances, as well as new petrology and geochemical techniques. We will examine the processes of metal-silicate equilibrium and how this affects element distributions, including volatile element behavior. The data will be used to evaluate temporal and genetic links with primitive achondrites and some iron meteorite groups.

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**Zhang, Youxue/The University of Michigan**
**Abundances of H2O and other volatiles in the Moon**

Knowledge of the abundances of H2O and other volatiles in the Moon is fundamental in constraining the origin of the Moon, in understanding lunar evolution, and in assessing future human exploration of the Moon. In the last decade, the lunar interior was found to have higher abundances of H2O and other volatiles than previously thought (e.g., Saal et al., 2008, 2013; Hauri et al., 2011, 2015, 2017; Hui et al., 2013, 2017; Chen et al., 2015; Lin et al., 2017; Mills et al., 2017; Ni et al., 2017; and papers on lunar apatite). New data also indicate that H2O and S (with condensation temperatures TC of 182 and 704 K, Lodders, 2003) in the Moon are only depleted by a factor of 3 to 4 compared to the Earth (Chen et al., 2015), whereas Na, K and Rb (TC = 958, 1006 and 800 K) are depleted by a factor of 5 to 7, and Zn (TC = 726 K) seems to be depleted the most (Albarede et al., 2015). Debates are still intense, but these works prompted re-examination of the giant impact hypothesis for the origin of the Moon (Hartman and Davis, 1975; Cameron and Ward, 1976; Canup, 2004). New variations of the giant impact model have been constructed to accommodate a wet Moon (Pahlevan et al., 2016; Nakajima and Stevenson, 2018), but better knowledge of H2O in the Moon and the whole volatile depletion trend would provide more stringent constraints on the origin of the Moon.

With support by two NASA grants (NNX10AH74G and NNX15AH37G), my group has contributed to the recent advancements and participated in the debates to understand H2O and other volatiles in and on the Moon (Zhang, 2011; Liu et al., 2012; Hui et al., 2013; Chen et al., 2015; Ni et al., 2017; Hui et al., 2017). I propose to expand our study of volatiles in the Moon in three directions. One direction is to resolve a major debate on H2O in the Moon: whether 74220 with high H2O and normal F-Cl-S concentrations, is a local anomaly (Albarede et al., 2013, 2015), or is representative of pre-eruptive melts before H2O loss (Chen et al., 2015; Ni et al., 2017). We will investigate more Apollo samples and assess the dependence of H2O/Ce ratio on the cooling rate for systematic evaluation of H2O loss from melt inclusions. Hence, a more reliable estimation of H2O in the Moon will be obtained. The second direction is to homogenize more crystalline melt inclusions from lunar samples to gain systematics of volatile/refractory

elemental ratios, since we have demonstrated that volatile elements except for H2O can be well retained after homogenization (Chen et al., 2015; Ni et al., 2017). The third direction is further push the limit of SIMS to determine H2O concentration and D/H ratio in pyroxene that coexists with plagioclase we investigated earlier (Hui et al., 2013, 2017). In summary, we plan to expand the study to other naturally glassy melt inclusions, to crystalline melt inclusions (with known cooling rates) to be homogenized in lunar rocks, and to pyroxenes in ferroan anorthosites so as to broadly represent lunar samples. Homogenization experiments and instrumental analyses will be carried out using our established techniques (Chen et al., 2015; Hui et al., 2017; Ni et al., 2017). With a larger set of data for lunar rocks, abundances and origin of volatiles in the primitive lunar mantle or the bulk Moon will be estimated.

This proposed research is relevant to NASA's Emerging Worlds Program. As stated in guidelines, "Research in the area of 'Emerging Worlds' aims to answer the fundamental science question of how the Solar System formed and evolved", and "relevant work on Apollo samples may be submitted to Emerging Worlds." Our proposed study will focus on new approaches in studying melt inclusions and minerals in Apollo samples to characterize the budget of volatiles acquired by the early primordial Moon and using the information to constrain the origin and evolution of the Moon.

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**Chabot, Nancy/Johns Hopkins University**
**Iron Meteorites and Early Solar System Processes**

Iron meteorites provide unique opportunities to investigate the formation and evolution of metallic melts in the early Solar System - a fundamental process that led from primitive bodies becoming differentiated ones and ultimately to the terrestrial planets we have today. Iron meteorites enable a fundamental question to be asked: What early Solar System processes produced the chemical signatures in iron meteorites? Understanding these early Solar System processes is the focus of the proposed work through a series of complementary but independent tasks:

Task 1: Investigate troilite formation during melt trapping by modeling IIIAB irons, analysis of Sb and troilite nodules in Cape York and other IIIAB irons, and application of the model to four other magmatic iron meteorite groups.

Task 2: Investigate troilite formation at the Fe-Ni-S cotectic by experiments with coexisting solid metal, liquid metal, and troilite, analysis of troilite in high-Ni irons, and modeling of the expected trace element concentrations due to this process in irons with high Ni/Co ratios.

Task 3: Investigate formation of the low Ni, reduced iron meteorite parent body by modeling the crystallization of IIIF iron meteorites and measuring the Si content in low Ni irons.

The proposed work is highly relevant to the Emerging Worlds program as it will advance our understanding of the early evolution of the Solar System. In particular, the proposed work focuses on understanding the early Solar System processes that influence the chemical signatures of iron meteorites. Iron meteorites are samples of small bodies that formed in the early Solar

System, before the differentiation of the terrestrial planets, consistent with the time period covered by the scope of the Emerging Worlds program.

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**Simon, Jacob/University of Colorado**
**Planetesimal Formation in the Protosolar Disk: The Influence of Turbulence**

One of the most fundamental open questions in Solar System formation is: how do the gas dynamics in the proto-solar disk affect the earliest stages of planet formation? The settling and growth of micron-sized dust grains are directly influenced by gas motions, a result of strong aerodynamic coupling between the gas and dust. Similar aerodynamic interactions between this gas and larger, mm-cm sized solids are also the key to a mechanism, known as the streaming instability, for forming planetesimals from these smaller constituents.

Despite the powerful role that gas motions play in the earliest stages of planet formation, the nature of such motions is still not entirely understood. Given this uncertainty, planet formation has been studied within the context of several disk models, including fully turbulent disks (e.g., from the magnetorotational instability; MRI), viscous alpha disks, and the classical dead zone model, in which two active layers (driven to be MRI turbulent by external ionization sources) surround a cold, weakly ionized mid-plane region where Ohmic diffusivity quenches the MRI. However, recent years have seen the emergence of a new paradigm for gas dynamics in planet forming disks, the implications of which have not yet been explored for Solar System planet formation. This new paradigm is based on two other low-ionization effects, the Hall effect (resulting from ion-electron drift) and ambipolar diffusion (resulting from ion-neutral drift) that can fundamentally alter the gas dynamics in planet forming regions. In particular, the Hall effect (in concert with a large-scale vertical magnetic field threading the disk) can render the mid-plane region of the disk active in ways that differ from previous models: the disk mid-plane is dominated by large-scale magnetic torques, intermittent bursts of magnetic activity, or no magnetic activity at all, depending on the geometry of the magnetic field and the precise strengths of the low-ionization effects. Even in the case of no magnetic activity, turbulence appears to persist near the mid-plane. Furthermore, the large scale vertical field, which is necessary to drive accretion at observed levels, launches a strong wind that removes gas from the disk vertically.

If these additional low-ionization effects alter the gas dynamics in such a critical way, as numerous studies have suggested, we must address the implications of this new paradigm for the earliest stages of planet formation. Here, we propose a series of calculations to pursue this endeavor and to answer two questions critical to the earliest stages of planet formation in our Solar System: (1) How do complex gas flows that result from magnetic fields acting on the low-ionization environments of the early protoplanetary disk influence the settling of dust grains and (2) how do these gas flows affect the growth of mm cm sized particles into planetesimals via the streaming instability?

In order to answer these questions, we will use the state-of-the-art, hybrid magnetohydrodynamics, particle dynamics code ATHENA to carry out three tasks:

Task 1: Determine the strength of both magnetically-launched winds and magnetically stirred turbulence and their influence on the settling of protoplanetary disk solids.

Task 2: Test whether magnetically-driven gas dynamics inhibit or aid the clumping of solids via the streaming instability.
Task 3: Determine whether magnetically-driven gas dynamics change the initial mass function of planetesimals formed via the streaming instability.

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**Dobrica, Elena/E&PS**
**Hydrothermal alteration experiments of primitive materials to demonstrate the early fluid-assisted processes on asteroids**

Iron-rich olivine is one of the most abundant phases in the matrices of ordinary and carbonaceous chondrites. Although there are a lot of studies of the occurrence of FeO-rich olivine, its origin is poorly understood. This proposal aims to understand the hydrothermal alteration and fluid-assisted metamorphic growth of FeO-rich olivine on the parent bodies of ordinary and carbonaceous chondrites through detailed analysis of the mineralogy, texture, chemical composition, and crystallography of olivines formed during experiments. The experiments will be conducted at optimal conditions of asteroidal parent bodies. We will synthesize FeO-rich olivines and constrain the conditions of their formation at different temperatures, water-to-rock (W/R) mass ratios, durations and bulk rock compositions. The proposed research will have important implications for understanding the chemical reactions and the role of fluids in the fluid-assisted metamorphism that affected the matrices of ordinary and carbonaceous chondrites. Additionally, we will investigate the effect of dehydration treatments of the hydrothermal alteration products to understand the kinetics of recrystallization of secondary phases.

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**Heck, Philipp/The Field Museum**
**Underexplored aspects of the history of our solar system s presolar starting material**

The knowledge of the origin of the starting material of our solar system is an issue of fundamental interest in planetary science. After the discovery of presolar grains (PSG) in 1987 it was possible for the first time to study solid samples of stars in the laboratory. This provided a unique perspective on the origin and composition of the material from which the solar system formed. We propose to use atom-probe tomography (APT) to study the compositions of presolar nanograins that are too small to study with NanoSIMS. The goal is to better understand the origins of these understudied samples, information not obtainable otherwise (task 1). We also propose to extend the small number of known presolar exposure ages of large presolar SiC grains. Our approach is to use He and Ne, and Li isotopic analysis in conjunction with improved nuclear recoil corrections and production rates for cosmogenic nuclides to study the presolar chronology of the solar system s starting material (task 2).

Task 1: Much fruitful effort was devoted to the analyses of PSG in the um-size range to determine stellar sources and to gain unprecedented insight into processes operating within those stars. While PSG in this size range are readily accessible to ion probes, they are not necessarily representative of smaller PSG. The smallest size fraction of presolar Cr-rich spinels was discovered to carry the largest isotopic anomalies. The small fraction of presolar nanodiamonds has not yet been quantified. Even with the latest generation of the highest resolution ion probe, the NanoSIMS, samples smaller than 50-100 nm are difficult to analyze due to limitations in

spatial resolution and sensitivity. To address this issue we developed methods to apply APT to extraterrestrial samples. The near atomic-resolution and high sensitivity makes APT the ideal technique to analyze the elemental and isotopic compositions of samples that are too small for the NanoSIMS (<50 nm). We successfully performed APT of meteoritic nanodiamonds, a lunar dust grain, an iron meteorite, and quantified instrumental bias. We can now reliably analyze with APT small samples, incl. presolar nanograins the goal of our proposed investigation (task 1). Compared to NanoSIMS the tomographic approach of APT provides an undiluted sample analysis without contributions from the underlying substrate or surrounding matrix. The objective of this task is to perform APT on presolar nano-oxides and nanodiamonds to obtain elemental and isotope data to provide new insights into stellar origins, formation processes, and possibly alteration in the early solar system.

Task 2: The knowledge of the time span between the formation of PSG and their incorporation into forming planetesimals is still limited. We have successfully measured cosmogenic He and Ne in large presolar SiC grains, applied nuclear recoil loss corrections, and calculated presolar cosmic-ray exposure ages using presolar production rates of cosmogenic nuclides. So far, a total of only 40 PSG have been dated. Most grains had presolar ages <300 Ma and only a few had higher ages up to ~2 Ga. The knowledge of the production rates in the interstellar medium is one of the most critical elements in the calculation of presolar exposure ages. Since our last publication more realistic production rates have been developed. For the first time, these rates use the galactic cosmic-ray spectrum as observed outside the heliosphere by Voyager. We propose to measure presolar cosmogenic nuclides of He, Ne and Li in large presolar SiC. We will use our new data to test the hypothesis that the dominance of young presolar ages is a consequence of a starburst event and to explore the presolar chronology of the starting material of our solar system. While our method has large uncertainties compared to radiometric chronometers, it is currently the only method that provides ages of PSG, the oldest material available for study in the solar system,

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**Hesse, Marc/University of Texas at Austin**
**Multi-phase melt percolation during core formation**

Chemical differentiation in planetesimals in the early solar system leads to melting of both metallic and silicate phases. The segregation of these melts with opposite buoyancy occurs either in a compacting porous medium or in a magma ocean. The process of core formation imprints distinct geochemical signatures on the differentiated body and affects the thermal history of the planetesimal and therefore the cooling history of the core. Hypotheses about the latter will become testable for the first time with the upcoming NASA mission to metal asteroid 16 Psyche. To determine the timing of core formation in planetesimals we propose to improve the description of simultaneous metal and silicate melt percolation in a compacting porous medium. The dynamics of this process involve a complex coupling across the scales. The large-scale redistribution of energy and mass depends on pore-scale interactions between the two melts. Therefore, we propose the development of novel a multiscale model, where the constitutive laws for the macroscopic evolution equations are determined by pore-scale simulations.

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**Davidsson, Bjorn/Jet Propulsion Laboratory**
**Volatile Loss During Collisional Cascades**

Introduction:
According to the current paradigm of Solar System formation the bodies now known as comets, Centaurs, and Kuiper Belt Objects (KBOs) experienced a violent collisional cascade in the Primordial Disk before it was dispersed by the giant planets. Such collisions lead to heating and potentially the loss of highly volatile ices such as CO and CO2. Yet, such molecules are abundant in active comets and Centaurs. Whereas it is possible that some CO and CO2 are protected during heating episodes by being hosted within substantially less volatile water ice, this is likely not the case with the bulk of these species. The Rosetta mission to Comet 67P/Churyumov-Gerasimenko has shown that CO2 itself is a major independent condensed species that hosts CO, CH4, H2S, and HCN. If so, massive loss of condensed CO2 and/or its trapped species in the early Solar System is inconsistent with observations. This provides an opportunity to test hypotheses regarding the intensity and duration of the collisional cascade, because it must have taken place under conditions that conserved condensed CO2 and trapped supervolatiles.

Science Objectives:
1) Determine the loss of supervolatiles during catastrophic disruption of medium-sized parent bodies
2) Determine the effect of including subcatastrophic, shapechanging, and cratering collisions on the supervolatile loss
3) Determine constraints on Primordial Disk population size and lifetime

Methodology:

The Numerical Icy Minor Body evolUtion Simulator NIMBUS is used to calculate the thermophysics of porous bodies subjected to protosolar and collisional heating while accounting for heat conduction, multi-species sublimation, gas diffusion, recondensation, and outgassing. NIMBUS is used to answer the following questions;
i) What is the baseline core temperature of bodies of various size at different heliocentric distances, with and without the cooling effect of sublimating condensed CO
ii) Is the temperature elevation above the baseline in catastrophic collisions sufficient to volatilize CO2 and release the supervolatiles it traps?
iii) CO2 itself is expected to recondense near the rapidly cooling surface but can this blockage be removed by the smaller continuous heating provided by subcatastrophic, shapechanging, and cratering collisions?

Relevance:
The proposed project is relevant to the C.2 Emerging Worlds Program Element because;
1) it concerns the composition of the material that occurred on small bodies that formed at an early stage of Solar System evolution;
2) it considers thermal processing of small bodies that took place before the large planetary bodies had reached their modern configuration.

Specifically, the Decadal Survey Important Questions that are addressed directly in this project are the following Important Questions:
a) "What is the relationship between large and small KBOs? Is the population of small KBOs derived by impact disruption of the large KBOs?"
b) "How is the surface composition of comets modified by thermal radiation and impact processes?"

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**Chiang, Eugene/UC Berkeley**
**Feeling the Heat: Planet Formation in Massive Star Clusters**

MOTIVATION: Most planetary systems, including our Solar System, formed in stellar clusters centered on massive O/B-type stars. In such clusters, ultraviolet (UV) radiation emitted by high-mass stars photoevaporates protoplanetary disks hosted by lower-mass stars like the Sun. This process of external photoevaporation works by heating circumstellar gas to escape velocity. Blowing off the gas also reduces the dust content of disks in two ways: either by entraining dust in the gas outflow directly, or by weakening dust-gas coupling to enable solids to undergo faster orbital decay onto the host star. The UV environments in OB clusters also better ionize disks, which may indirectly accelerate gas disk dispersal via magnetically driven winds or disk turbulence. Additionally, supernovae in massive star clusters seed disks with radioactive elements that are critical for the heating of planetary interiors. For all these reasons, planetary systems born in the vicinity of massive stars likely look different from those born farther away.

METHODOLOGY: Emission at sub-mm to mm wavelengths probes the outer regions of circumstellar disks, which are most prone to UV photoevaporation. Continuum and CO line observations at these wavelengths provide fundamental measurements of disk masses and sizes, both in dust and in gas, which are key diagnostics of the impacts of external photoevaporation. To study the effects of clustered environments on disk evolution, we are conducting complete

surveys of protoplanetary disk populations in OB clusters using the Atacama Large Millimeter Array (ALMA); continuum and line data have been obtained or are in the queue for A-ranked (i.e., guaranteed observation) programs. Our surveyed regions span a critical range of ages, from ~1 Myr (Orion + NGC 2024) to ~3 Myr (sigma Orionis) to ~5 Myr (lambda Orionis), allowing us to probe how the ionizing effects on disks accumulate with time and even accelerate as intra-cluster cloud material disperses (via, e.g., a supernova, as may have occurred in lambda Orionis). Our proposed reduction and analysis of these mm-wave datasets will be complemented by a full suite of radiative-hydrodynamic simulations of photoevaporating disks, enabling inferences of mass loss rates as functions of UV environment, stellar mass, disk mass, and disk radius. These same disk models can be used to calculate aerodynamic drift rates of solid particles and the degree to which dust is drained from the outside in, which will be key to interpreting our mm continuum observations. Additionally, we will obtain VLT/X-Shooter spectra, which uniquely cover UV to optical wavelengths at high sensitivity and moderate spectral resolution, to confirm enhanced levels of disk ionization (via forbidden line diagnostics) and increased stellar mass accretion rates, as expected in elevated UV environments.

IMPACT/RELEVANCE: Although many studies of Solar System formation assume for simplicity that the protosolar nebula evolved in isolation, the meteoritic record, the demographics of star-forming regions, and the dynamically excited state of the Kuiper belt/inner Oort Cloud all point clearly to planet formation within a cluster containing several thousand stars, of which the most massive members will be prodigious emitters of UV light. Measuring the gas and dust mass distributions of protoplanetary disks within such Orion-like environments aligns directly with the Emerging Worlds mission to "study all aspects of materials and processes ... in the protoplanetary disk." Such processes as we will study include UV-powered photoevaporative winds; magnetically driven disk accretion enabled by UV ionization; and the transport and distribution of solids, the raw materials from which planetary cores are built.

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**Goodrich, Cyrena/USRA/LPI**

**Physical and Compositional Structure of Heterogeneous Asteroid 2008 TC3 from New Samples of the Almahata Sitta Meteorite**

Asteroid 2008 TC3 was tracked and studied for ~19 hours before it impacted in Sudan in October 2008. Search campaigns in the predicted fall area, led by Co-Is Shaddad and Jenniskens, recovered ~600 stones (~0.2-400 g each) that were named the Almahata Sitta (AhS) meteorite. AhS is the first meteorite observed to originate from a spectrally classified asteroid, and provides an unprecedented opportunity to correlate properties of a meteorite with properties of the asteroid from which it was derived. 2008 TC3 was also the first near-Earth object (NEO) detected before it impacted Earth, which makes it unique for studies in planetary defense.
The main AhS collection is curated at the University of Khartoum (UoK) by Co-I Shaddad, documented with find coordinates for each stone in the strewn field. Studies of 85 of these stones (61 by our team under a 1-year proof-of-concept grant from Emerging Worlds) have shown that AhS is a remarkable meteorite. Approximately 80% of the stones are ureilites (carbon-rich ultramafic achondrites), while ~20% are various types of chondrites, so AhS is classified as an anomalous polymict ureilite. Far from being a coherent, monolithologic rock in space, asteroid 2008 TC3 was a loosely aggregated, heterogeneous object that disintegrated in the atmosphere, with its clasts landing on Earth as individual stones. Determining the physical and compositional

structure of this asteroid is critical to understanding its formation, the provenance of its components, its orbital and collisional history, and the fate of related asteroidal fragments. It is also of paramount importance to the goals of the NEO program and missions to asteroids. Complete classification of the UoK collection is needed to determine the physical and compositional structure of 2008 TC3. Our proof-of-concept work showed that AhS is extremely heterogeneous, and revealed the first AhS stones to consist of both ureilitic and chondritic materials. It is virtually certain that the rest of the collection harbors new materials. Furthermore, the documentation of find coordinates for each stone allows determination of the spatial distribution of different materials in the asteroid.

We propose to select and study ~150 new stones (in 3 years) from the UoK collection. The objectives are:

1) To determine the full diversity and proportions of rock types among AhS stones;
2) To determine the physical and compositional structure of asteroid 2008 TC3, including grain size and distribution, and rock type distribution;
3) To constrain the origin and history of 2008 TC3, including mechanism(s) and timing of formation, provenance of constituent materials, collisional events, orbital evolution, and identification of related asteroids.

To accomplish these we will use a battery of analytical and modeling techniques including: FE-SEM, EMPA and FIB/TEM (mineralogy and petrology); bulk and SIMS oxygen isotope analysis; VNIR, MIR and micro-FTIR reflectance spectroscopy; Cr isotope analysis; Ar-Ar dating; noble gas and cosmogenic nuclide analysis; least-squares modeling of the 2008 TC3 reflectance spectrum, and; predictive modeling of reflectance spectra of related asteroids.

The proposed work is a serendipitous asteroid sample return mission relevant to the strategic science goal of EW to explore and observe the objects in the Solar System to understand how they formed and evolved. It is an interdisciplinary effort uniting meteorite petrology and geochemistry with asteroid spectroscopy and meteor astronomy to address the key question of how a heterogeneous, rubble pile-like asteroid formed, evolved, and eventually impacted Earth. Results will aid in the development of missions to asteroids. The work addresses processes of accretion, collisional mixing of inner and outer solar system materials, and regolith formation in the early Solar System before the planets were in their modern configuration, and is thus relevant to EW.

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**Pravdivtseva, Olga/Washington University**

**I-Xe dating of alteration in CK and CV carbonaceous chondrites**

Mineralogical, petrographic and isotopic observations indicate that most groups of chondritic meteorites experienced asteroidal alteration to various degrees, resulting in the formation of secondary minerals. The alteration occurred in the presence of aqueous solutions under variable conditions, and in many cases was multistage. Based on Al-Mg, Mn-Cr and I-Xe ages of secondary minerals, the chondrite parent bodies must have accreted 2 4 Ma after the collapse of the protosolar molecular cloud and the alteration may have lasted for up to 15 Ma.

The I-Xe chronometer is based upon decay of now-extinct 129I where the ratio of the accumulated daughter 129Xe to stable 127I reflects the iodine isotopic ratio at closure of the host mineral. The short half-life of 129I (15.7 Ma) gives the I-Xe chronometer the precision needed for high temporal resolution within the formation time period of the first solids and the subsequent onset of metamorphic changes. Relative I-Xe ages are normalized to an absolute time

scale through the chronometry of the I-Xe standard Shallowater aubrite. It s absolute age of 4562.4 ± 0.2 Ma is derived from the observed correlation between I-Xe and Pb-Pb ages in a number of samples and was recently re-evaluated by our laboratory.
Our study of the onset of the alteration and its I-Xe chronology is an ongoing project; I-Xe dating of magnetites, refractory (CAI) and dark inclusions from CI, CM, CV and CO chondrites have been especially fruitful. We propose to extend I-Xe studies of aqueous alteration to CK magnetites and coarse- and fine-grained Allende (CV) CAIs. Our previous I-Xe isotopic studies of 3 fine-grained Allende CAIs demonstrated the I-Xe system closure between 3.0±0.2 and 3.7±0.2 Ma (later than Shallowater). For the work proposed here we have assembled a unique set of 12 fine-grained and 12 coarse-grained Allende CAIs. One of them, Curious Marie, is characterized by an extremely large 235U excess, proving that 247Cm was alive in the early Solar System. We recently reported Xe isotopic composition and the I-Xe chronometry of Curious Marie, both essential for the determination of the initial abundance of 247Cm in the Solar System. The I-Xe system survived in two different mineral phases in Curious Marie, contrary to what we previously observed for Allende CAIs. Studies of the additional CAIs will help to better delineate the aqueous alteration sequence in Allende. CK and CV chondrites are closely related based on petrology, bulk chemical and oxygen isotopic compositions, thus their alteration histories may overlap. The CK chondrites are one of the most oxidized groups of carbonaceous chondrites, and the I-Xe age of Karoonda (CK4), ~ 5 Ma after the formation of CV CAIs, suggests that oxidation of CKs started early. We plan to chemically separate and study magnetites from type 3, 4, 5, and 6 CK chondrites to determine the onset and duration of aqueous alteration on CK parent body in relation to CV3 magnetites and CAIs. The proposed study will improve understanding of the genetic and historic evolution of CK chondrites.
Our laboratory is exceptionally well suited for this application we have four noble gas mass-spectrometers, including a high-sensitivity, high-transmission mass-spectrometer, designated for the I-Xe studies, and low-background extraction systems. This allows us to do analyses of the mg-sized samples, critical for small CAIs that have to be divided for multifaceted research. We irradiate our samples at the Missouri University Research Reactor that has a well-thermalized reflector area, ideal for slow neutron capture on 127I.
The proposed research is aimed at improving the understanding of alteration in carbonaceous chondrites through the high-precision I-Xe chronology of specific mineral phases and well characterized refractory inclusions, in line with the strategic science goal of the Emerging Words program to understand how the objects in the Solar System formed and evolved .

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**Zega, Thomas/University of Arizona**
**Thermodynamic origins of refractory dust in the early solar system and ancient stars**

Refractory dust is among the building blocks of our solar system. Its microstructure, atomic structure, and chemical composition contain clues to the dust-condensation conditions of our solar nebula and ancient circumstellar environments. Here we propose measurements from the micrometer scale to the atomic level, supported by a computational effort, aimed at understanding the origins and thermodynamic environments of the first nebular solids and ancient circumstellar dust. Our proposed work builds on advances and productivity from our previous effort and is crafted around our new capabilities in state-of-the-art microscopy and computational materials science. Our proposed effort is divided into three distinct but related

tasks that examine meteoritic components which deviate from established equilibrium thermodynamic predictions.

Calcium-aluminum-rich inclusions (CAIs) in meteorites are the oldest solar system solids and are believed to have formed within the inner solar protoplanetary disk. We have identified mineral assemblages within CAIs that are not consistent with long-standing equilibrium thermodynamic predictions. In Task 1, we propose detailed study of these assemblages, at scales ranging from the micrometer to the atomic to understand their thermodynamic origins.

Circumstellar (presolar) grains were discovered in meteorites just over 30 years ago, and since then, many types of grains have been identified. Their structures and compositions hold important clues to the nucleosynthetic and thermodynamic processes that occurred in and around their parent stars. In Task 2, we propose to examine the origins and condensation conditions of grains that appear to deviate from established thermodynamic predictions, particularly SiO2 grains, Fe-rich silicates, and Fe-bearing oxides. We will probe such materials down to the atomic level to determine whether condensation occurred via equilibrium processes in circumstellar envelopes.

In Task 3, we propose to perform thermodynamic modeling, informed by quantum-chemical calculations, to determine thermodynamic parameters for solid solutions relevant to identified CAI and presolar-grain phases. Microstructures that are inconsistent with established predictions, whether for the early solar nebula (Task 1) or circumstellar environments (Task 2), raise fundamental questions as to whether available thermodynamic descriptions are incomplete, the presumption of equilibrium is wrong, or some combination of the two. We will use the results of these calculations to determine the conditions under which such materials condensed and hence the pressure-temperature conditions, i.e., thermodynamic landscapes, of the inner solar protoplanetary disk and circumstellar environments. We will place these results into the context of dynamical models of the transport and evolution of protoplanetary and circumstellar dust.

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**Lissauer, Jack/NASA Ames Research Center**
**Formation & Internal Structure of Jupiter, Saturn, Uranus and Neptune**

Science Goals and Objectives: We propose to attack, mainly through numerical modeling, some major outstanding problems in the core nucleated accretion theory of the formation of the giant planets in the Solar System. This work will account for important physical processes heretofore neglected and thereby provide a much more realistic model for the formation and early evolution of the giant planets. During the early stages of giant planet accretion, with a rocky core of around an Earth mass, the basal temperature of the hydrogen atmosphere above this growing core can already exceed a few thousand degrees, su fficient to allow evaporation of accreted planetesimals within the envelope. This may affect the growth of the giant planet, primarily by increasing the mean molecular weight of the envelope (reducing the pressure scale height), and it may also produce a wider range of possible outcomes for giant planet formation than those previously studied. The consequences may be partially preserved throughout subsequent evolution and influence the internal structure of the giant planets today. To study the effects of this process, we will compute the amount of mixing of the constituents within the planets during their growth. This additional physics will be incorporated into detailed

numerical studies of the concurrent accretion of solids and gas, including an improved treatment of interactions of the growing planets with the surrounding protoplanetary disk.

The proposed work will address the following questions: How much H and He was mixed with material from the heavy element cores of the planets during the formation epoch? How much planetesimal material was dissolved into the H/He envelope? How long did Jupiter, Saturn, Uranus, and Neptune take to form? What was the solids surface density in the region of the protoplanetary disk where these planets accreted? Do Jupiter and Saturn retain most of the angular momentum of the circumplanetary subdisks through which much of their mass was accreted, or did they shed most of this angular momentum?
Methodology: Accretion of solids will be modeled using the PSI Multizone Code. The internal structure and evolution of each planet will be modeled with an adapted 1D stellar evolution code. Gas accretion will be followed with a 3D hydrodynamic code when appropriate.
Relevance to NASA's Emerging Worlds Program: Our simulations will provide a substantially improved physical model of the formation of the four giant planets in our Solar System, particularly regarding the mixing of light and heavy components within the planet and in our treatment of the fi nal stages of accretion when the planets' ultimate masses and heavy elements content were determined. We will determine whether or not a realistic amount of mixing of light gases with heavy constituents within Uranus and Neptune can yield planet structure models that match the planets' measured gravity fields without invoking super-solar ice/rock ratios. The interior structures of Jupiter and Saturn that we compute using mixing of constituents will be useful to interpreting the gravity data sent back by the Juno and Cassini Solstice missions.
As the giant planets formed in the presence of the protoplanetary disk, our proposal is for research that addresses "processes occurring in and affecting the protoplanetary disk, including those occurring on bodies of any size that may have formed at this stage of Solar System evolution"
(quote from Appendix C.2 of ROSES-18).

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**Tarduno, John/University of Rochester**
**External magnetization of undifferentiated carbonaceous chondrite meteorites: Constraints on the nature of the protoplanetary disk**

Meteorite magnetizations can provide rare information about the ambient Solar System environment. To read these magnetizations, however, we must first evaluate whether fundamental physical requirements of magnetic recording on billion-year times scales are met. These requirements include the need for non-interacting small (<< 1 micron) magnetic grains with single domain-like behavior. Given the presence of these ideal magnetic grains, the directional and paleointensity information in a meteorite denote an internal (core dynamo) or external (nebular or solar wind) origin. For external magnetizations, the magnitude of the paleointensity can be used to constrain orbital distance during magnetization.

These data take on new importance given the recognition of two broad classes of meteorites and the likelihood that these were once separated by Jupiter and subsequently mixed into the asteroid belt. The new information on orbital distance encoded in some meteorite magnetizations, that can contribute to this history of origin and dispersal, focuses on the magnetization age. That is,

while geochemical data can provide foundational information on meteorite parent body formation, meteorite magnetizations can be imparted millions of years later. In the case of carbonaceous chondrites, the magnetization age is most often a parent body alteration event during which magnetic minerals were either formed or taken to higher than ambient temperatures. Thus, meteorite magnetizations can provide orbital distance constraints for times different from those of parent body formation, providing further context for early Solar System evolution.

However, it is also important to emphasize that there are currently two contrasting viewpoints on the origin of some chondrite meteorite magnetizations. One proffers the CV and CM parent bodies as differentiated, with magnetizations resulting from core dynamos. In contrast, in our view the CV and CM meteorites come from undifferentiated bodies, and their magnetizations are of external origin. There is a further debate on whether magnetizations are of solar wind origin. Resolving these debates is important because they bear on the fundamental nature of parent bodies as well as critical early Solar System events (principally the transition from nebular to solar wind fields which marks clearing of the proto-planetary disk).

The specific goals of our work hence are as follows: 1. To develop new rock magnetic and paleomagnetic tests aided by electron microscopy to assess the magnetic recording fidelity of meteorites in light of core dynamo, nebular and solar wind magnetization mechanisms; 2. To apply these new methods to carbonaceous chondrites to determine if their magnetizations indicate internal (core dynamo) or external (solar wind) magnetization processes; 3. To apply these methods to other achondrites formed in near surface environments to build a data set with which the carbonaceous chondrites can be compared; 4. To develop the theoretical basis of solar wind and nebular magnetizations supported by numerical simulations; 5. To use the results of theory and simulations, constraints provided by radiometric age data and our new magnetic data to provide constraints on the time of dust and gas clearing in the proto-planetary disk and on the orbital distance of meteorite parent bodies when they were magnetized. We hope to test our working hypothesis that the CV and CM parent bodies had already been scattered to the location of the present-day asteroid belt by Jupiter by the time of their aqueous alteration where they were magnetized by the young solar wind.

Our goals address the origin and nature of meteorites groups, differentiation, and early processes

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**Young, Edward/University of California Los Angeles**
**Developing Isotopic Signatures for Planetesimal Evaporation**

OBJECTIVES: Recent advances in our ability to measure stable isotope ratios of light, rock-forming elements, including isotope ratios of Zn, K, Fe, Mg, and Si, among others, has resulted in an emerging hypothesis that collisions among rocky planetesimals, planetary embryos, and/or

proto-planets caused losses of moderately volatile elements (e.g., K) and "common" or moderately refractory elements (Mg, Si). If correct, this hypothesis would argue for a prevalence of magma oceans exposed to space during planet formation. The primary motivating evidence is in the form of heavy isotope enrichments in several rock-forming elements relative to chondrites. Our goal is to assess the meaning of heavy isotope enrichment of moderately refractory elements in rocky solar system bodies by calibrating self-consistent models for multi-element isotope fractionation during evaporation using experiments on relevant starting materials.

APPROACH: Experiments will be performed under a variety of conditions (temperature, enveloping gas molecular weight, oxygen fugacity) to explore the factors controlling the relative fractionations in the different isotope systems. These new data will be used to evaluate recent hypotheses that enrichment in the heavy isotopes of Mg, Si, and Fe in differentiated rocky bodies in the solar system (e.g., Earth, Mars, Moon, and the angrite parent body) resulted from evaporation of magma oceans on planet precursors. We propose a series of experiments to evaporate carbonaceous and enstatite chondrite starting materials at various temperatures and oxygen fugacities. We will:

1. Heat samples with an infrared laser as they are aerodynamically levitated in gases of controlled composition;
2. Measure bulk chemical compositions of synthetic and natural chondritic starting materials and their evaporative residues using EPMA;
3. Calculate mass loss rates and evaporative fluxes;
4. Define reference fluxes for specified compositions, T, Ptotal, and PO2;
5. Use the derived evaporative fluxes to derive relevant evaporation parameters;
6. Measure Fe, Mg, Si, and O isotope ratios for the starting materials and evaporation residues at different degrees of mass loss using MC-ICPMS and laser-heating assisted fluorination;
7. Use the results to assess competing models for evaporation of molten silicates as the cause of heavy isotope enrichment in Earth, Mars, Moon, and meteorite parent bodies (e.g., the angrite parent body).

Our approach takes advantage of a new method for melting and evaporating materials under controlled conditions. The results will be a self-consistent set of experimentally-determined evaporation parameters relevant to the problem of planetesimal evolution.

RELEVANCE TO EMERGING WORLDS: The proposed experiments will provide essential and definitive data necessary to construct detailed models for evaporation from chondritic-like melts that in turn can be used to test quantitatively the proposal that evaporation imparted isotopic signatures for these elements to rocky bodies in the solar system. The "Emerging Worlds" program has the stated goal of fostering our understanding of the formation and early evolution of the solar system, including the formation and evolution of planet precursors (ROSES Appendix C.2). Our work is directed towards achieving a fuller understanding of how rocky bodies acquired their chemical and isotopic characteristics and so is relevant to the stated goals of the program.

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**Willacy, Karen/JPL**

**Following the multi-isotope trail to understanding the formation and early evolution of our Solar System**

Isotopic ratios are commonly used to trace the origin of Solar System bodies. This is fundamental but still a highly-debated topic. It is still unclear whether most of the organics are inherited from the cold and dense molecular parent cloud of our Sun, or if they are the result of chemical processing within the solar nebula protoplanetary disk. We will put a particular focus on nitrogen and oxygen fractionation, whereas carbon and deuterium fractionation will be the side products of the project.

We will undertake following studies:

(1) We will build a first consistent isotopic fractionation chemical network of D, C, N, and O both for the gas phase and surface including spin-state chemistry.

(2) We will model the isotopic ratios for a range of protoplanetary disks using a state-of-the-art gas-grain-mantle 3-phase chemical code with proper physical structures.

These studies will aim to shade light on following puzzles:

(a) In meteorites, some micron-sized zones called hotspots are highly enriched in 15N or D. Although the lack of correlation between these 15N and D anomalies could naively be used as an argument against a chemical fractionation process in the protosolar nebula (deuteration and nitrogen fractionation should correlate if they occur at low temperature), different carriers for N-enrichment may be the main reason for this non-correlation. This was indeed shown for the Isheyevo carbonaceous chondrite by van Kooten et al. 2017, Geochimica et Cosmochimica Acta 205, 119: the H-clasts which are 15N-poor (similar to the solar value) and D-rich are dominated by amine groups (NH), while the A-clasts which are enriched in 15N and D are associated with nitrile functional groups (CN). We will be able to address the origin of this non-correlation for the first time with the developed model.

Correlated 13C and 15N enrichments have also been observed by Bose et al. 2012, Geochimica et Cosmochimica Acta, 93, 77. With the same model, we will be able to address this possibility as well.

(b) We will be able to determine the dominant mechanism responsible for enhancements of 15N and 18O: low-temperature exchange reactions or isotope-selective photodissociation. This will help to explain the origin of the high 15N enrichments observed in the rocky planets, comets, and meteorites whereas 18O enrichment in chondritic meteorites.

(c) We will also generate the spatial distribution of 14N/15N and 16O/18O ratio within the planet and comet-forming region in the protoplanetary disks. A constant ratio across disks would favor a scenario where disks inherit their organics from the natal cloud, while a gradient would strongly suggest that the chemistry is modified during the disk phase.

ALMA data from the archive is also available for a some of the disks (which covers 12C18O, 13C18O, and 13C16O J = 3-2; H13C14N, H12C15N, 12C14N, and 12C15N J=3-2 transitions) and potentially could be used and analyzed with DiskFit (Pietu et al. 2007, A&A, 467, 163) radiative transfer code to verify our results.

The proposed research is highly relevant to the Emerging Worlds Program as it focused on the Early Evolution of the Solar System by considering studies on the protosolar disk, multi-isotope chemistry, chemical and physical structure of gas and ice, and understanding the chemical and physical properties of ancient materials (such as comets and meteorites).

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**Hofmann, Amy/NASA Jet Propulsion Laboratory**
**Using isotopic evidence from Orbitrap mass spectrometry to elucidate the formation conditions of PAHs in carbonaceous chondrites**

Polycyclic aromatic hydrocarbons (PAHs) are among the most abundant organic molecules in the universe: they are observed throughout the interstellar medium and in molecular clouds from which stars form, are dispersed throughout the organic material in carbonaceous chondrites (CCs), and are ubiquitous on Earth as the products of combustion. CCs are undifferentiated meteorites whose chemical and isotopic compositions are thought to be representative of the bulk composition of their primitive parent body and thereby reflect the composition of the solar nebula within which that parent body formed. It has long been postulated that the stable carbon and hydrogen isotopic compositions of extraterrestrial PAHs found in meteorites may provide insight into what the precursor building blocks of individual PAH species were as well as under what conditions those individual species may have formed. The prevailing hypothesis for extraterrestrial PAH formation invokes high-temperature reactions in the outer envelopes of carbon-rich stars; however, results from our pilot study on PAHs extracted from the Murchison meteorite strongly suggest alternative mechanisms, at least for CC PAHs.

The goal of this work is to identify the formation conditions (and, hence, provenance) under which the precursor molecules of PAHs in CCs formed. As such, this work presents an opportunity to investigate the origins of organic matter during the early stages of Solar System formation and evolution. Given that our pilot study supports a hypothesis for meteoritic PAH formation counter to the most commonly invoked mechanism, the results of the proposed work in which we will analyze PAHs from multiple CCs will inform our understanding of chemical processes on primitive bodies relative to those occurring within stellar envelopes.

Previous attempts to elucidate reaction pathways for extraterrestrial PAH formation in CCs were limited by available instrumentation resolution as well as the need for relatively large samples. In this study, we will use high-precision, high-accuracy Fourier transform mass spectrometry (FTMS) with an Orbitrap mass analyzer to measure compound-specific isotopic differences among the most abundant PAH molecules (and their fragments) found in CCs as well as the proportions of multiply-substituted isotopologues of each. Due to its exceptionally high mass resolution, large mass range, and capability for simultaneous evaluation of multiple peaks, Orbitrap-based MS is uniquely positioned to resolve isobaric interferences that other MS techniques cannot, including the quantitative resolution of multiply-substituted species (i.e., those with more than one minor isotope), while requiring only sub-nanomolar samples. The

analytical capability of this novel method to resolve multiply-substituted isotopologues to a high degree of precision and accuracy has been demonstrated on various gases and organic compounds, including amino acids [1].

Given its foundation in disentangling the chemical processes by which some of the earliest organic materials in the Solar System formed, the proposed study is directly aligned with NASA s Emerging Worlds program goal  to conduct scientific investigations related to understanding the formation of our Solar System . As described in the text above, the proposed work is an investigation into  materials present [at] the onset of Solar System formation  and  aspects of materials and processes occurring in the protoplanetary disk  as well as "[during] the accretion of Solar System bodies after dissipation of [that] disk .

[1] Eiler, J. et al. (2017)  Analysis of molecular isotopic structures at high precision and accuracy by Orbitrap mass spectrometry.  International Journal of Mass Spectrometry 422: 126 147.

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**Cuk, Matija/SETI Institute**
**Early Dynamics of the Inner Solar System**

In this proposal we will explore the intertwined dynamics of the planets, their satellites and small bodies in the Inner Solar System. Our goal is to produce a self-consistent picture of the inner Solar System's evolution in the first few tens and hundreds of Myr, before it reached its present dynamical configuration.

Hungaria asteroid group is a slowly eroding remnant of a much-larger initial population, which was likely responsible for the Late Heavy Bombardment of the Moon (Cuk 2012, Bottke et al. 2012). However, there is still a factor of a few shortfall between the projected numbers of proto-Hungarias compared to lunar impactors 3.9 Gyr ago. Here we propose to use recent results of Cuk & Nesvorny (2018) on the sensitive dependence of Hungarias' stability on Martian eccentricity, and test if an excess of late lunar impacts could be due to low initial eccentricity of Mars, which relaxed to the present state over the first few hundreds of Myr after Mars' formation. In Task 1 we will use numerical simulations to study the evolution of a primordial Mars-crosser population that evolves into Hungarias in the presence of chaotically changing orbit of Mars.

In Task 2, we will compare different realizations of the early Solar System with varying time-histories of Mars in terms how they would be reflected in the early lunar record. We will build on recent work of Co-I Minton and his collaborators at Purdue who have developed new models that start with an impactor population and show a variety of impacts records that can result from stochastic bombardment by this population. Our goal is to identify models of early dynamics of terrestrial planets and proto-Hungarias that are consistent with the available constraints from the Moon, including basin and crater numbers, their relative chronology as well as formation time for the Imbrium basin 3.9 Gya.

In Task 3, we will model the 2-degree orbital inclination that the Martian moon Deimos should have obtained from encounters with passing planetesimals, a mechanism previously proposed for Iapetus (Nesvorny et al., 2014) and the Moon (Pahlevan & Morbidelli 2015). Using direct

numerical methods and a realistic model of the late planetesimal population, we will quantify the amount of orbital excitation that can be expected for Deimos from passing planetesimals that would not at the same time disrupt Deimos and erase the orbital inclination. We will use the lunar cratering record to constrain the size-distribution of planetesimals and their fragments.

Pahlevan and Morbidelli (2015) have shown that planetesimal encounters can in some cases produce the observed lunar inclination. However, their lunar orbital evolution model was not self-consistent and may violate constraints from lunar eccentricity. In Task 4 we will revisit this issue, and we will also introduce fly-bys into the tidal evolution scenarios of Cuk & Stewart(2012), Tian & Wisdom(2016) and Cuk et al.(2016), which all achieve angular momentum (AM) loss by the Moon spending some time in resonant, near-resonant or equilibrium-state orbits which may be unstable against "kicks" from planetesimal flybys.

Venus is in a very slow retrograde rotation, and models require an initial rotation period >40 hr if Venus was spun down by solar tides. In Task 5, we will explore a possibility that Venus had a satellite and a high obliquity (80-100 degrees), which would lead to a rapid early AM transfer to heliocentric orbit due to Laplace plane instability (Tremaine et al. 2009, Cuk et al. 2016). We will also explore large swings in obliquity that are expected from planetary perturbations once Venus has been partially despun, and a relatively small moon has evolved outward. Resulting large and chaotically changing mutual inclination between the moon and the planet's spin would lead to further AM drain. We will explore a range of initial conditions to determine if the drastic AM loss as observed for Venus is a common dynamical outcome.

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**Jenniskens, Peter/S E T I Institute**

**Physical and chemical properties of outer solar system dust in late stages of accretion towards planetesimal formation**

Science goals and objectives: The objective of this work is to study the diversity of physical and chemical properties of mm-cm sized cometary dust, both the diversity of materials within comets and from one comet to the next. The proposed work studies the mm-cm sized material created during late stages of solar nebula accretion, which are then collected to make much larger bodies. This work is likely to demonstrate that such materials gained different physical and chemical properties at different places in the solar nebula, from solar nebula processes or during comet formation.

Methodology: Short of sample return, the cohesion and elemental compositions of mm-cm sized cometary matter can only be studied by meteor observations. Meteoroid cohesion and elemental compositions can be derived from meteor lightcurves and spectra. The Cameras for Allsky Meteor Surveillance (CAMS) project measured over 250,000 meteor lightcurves and trajectories in the period 2011-2015. The lightcurves measured the manner in which these grains fragment while entering Earth's atmosphere. The trajectories identify the source: a range of Jupiter-family and Oort-cloud comets that pass near Earth's orbit, including some active asteroidal objects such as 3200 Phaethon. An associated spectroscopic survey collected over 1,000 meteor spectra of these same sources, which will provide main-element abundances. The proposed work will analyze this data. This will require new models of meteoroid fragmentation in the atmosphere and new software tools to extract relevant physical parameters from the measured data. The

results will be used to interpret the processes of accretion during solar system formation, in particularly addressing the question how large dust may have grown before accumulating into comets. As part of this study, it will be necessary to study how the dust evolves since ejection from the comet from exposure to heat and radiation. The latter will require dynamical models of meteoroid stream evolution.

Relevance to the solicitation: Emerging Worlds aims to understand the formation and early evolution of the solar system, including the accretion of small bodies and early thermal and chemical processes. While studies of meteorites show that the early stages of accretion included the formation of chondrules in the inner solar nebula, processes in the outer solar nebula that affect such grains during the first few Ma of solar system history remain unknown.

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**Nakajima, Miki/University of Rochester**
**Volatile Escape from Giant Impact Ejecta**

The Moon has been a major focus in planetary science. The observation that terrestrial and lunar rocks have strikingly similar isotopic ratios contributed to the now leading hypothesis that the Moon formed by a giant impact. Additionally, the observation that lunar rocks are generally depleted in volatiles relative to the Earth has motivated studies that suggest that volatiles were preferentially removed from the protolunar material as the Moon formed (e.g., Canup et al., 2015). However, recent measurements suggest that at least portions of the Moon were initially water-rich, with perhaps Earth-like volatile contents (e.g., Hauri et al. 2015). Unraveling how the Moon s volatile content relates to its formation by a giant impact remains an open and important question of importance to future lunar exploration.

The only other terrestrial moons are Mars moons Phobos and Deimos. Originally, these moons were thought to be gravitationally captured asteroids, based on the similarity of their spectra to those of D-type asteroids. However, intact capture is difficult to reconcile with the small inclinations and eccentricities of the moons orbits. Recent studies instead suggest that Phobos and Deimos accreted from a disk produced by a large impact (e.g. Canup & Salmon, 2018), which can naturally explain their regular orbits. However, we still lack a clear connection between these origin hypotheses and observable quantities that would allow us to distinguish between them. Of particular importance is whether the moons would be expected to be volatile rich if they formed by an impact. Understanding this question will be key to determining their mode of origin based on anticipated results from the future sample return mission, Martian Moons eXploration (MMX), and to determining their resources for potential future exploration.

Moreover, volatile loss by impact during the planetary accretion stage may have significant consequences on the chemical and isotopic compositions of planetary bodies. The cause of the observed depletion of volatile elements and enrichment in isotopically heavy elements within differentiated bodies has been actively debated. This could have been caused by partial melting and vaporization during the Moon-forming impact (Norris and Wood, 2017), or volatile loss during the accretion stage (Hin et al., 2017). Thus, a better understanding of the behavior of volatiles during impacts may provide improved constraints on early planet formation conditions and timing of volatile delivery.

We propose to investigate volatile loss/retention during and after large impacts based on hydrodynamic simulations. Previously, we have found that volatile loss to space is negligible from a hydrostatic and circular lunar-forming disk (Nakajima & Stevenson, 2018), however, volatile loss could occur before the system reaches a hydrostatic state especially if the ejecta speed is large. We will here investigate volatile escape during the very early stages of an impact when ejecta is on on highly eccentric orbits, and predict chemical and isotopic signatures expected in the Moon.

For Mars, we will consider the consequences of an impact origin for Phobos-Deimos. Our preliminary calculations on volatile escape from a Martian moon-forming disk suggest that water and sodium vapor would have been vulnerable to escape in the first 10 hours after the impact. We predict that water vapor would escape before it adiabatically cooled sufficiently to condense, whereas sodium vapor would have condensed before it escaped from the Martian gravitational well, thus allowing sodium to eventually be incorporated in the moons. Consequently, the bulk water abundances of Phobos and Deimos may differentiate among the origin hypotheses, with impact-induced moons being dry, whereas gravitationally captured moons could be as water-rich. Finally, we will estimate volatile loss from a growing planetesimals and protoplanets undergoing large impacts.

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**Canup, Robin/SWRI**
**Evaluating the Tungsten Constraint on Lunar Origin**

There is broad agreement that the Moon formed via a giant impact, but the nature of this event remains highly debated. More than a half-dozen scenarios have been proposed involving impact energies that vary by more than an order-of-magnitude. Determining which is most likely is key to understanding the conditions of the Moon s formation, and to providing constraints on late terrestrial planet accretion.

The lunar origin debate is driven by difficulty in explaining the identical isotopic compositions of the silicate Earth and Moon. A collision of two large planetary bodies, each having their own distinct composition, would generally be expected to produce an Earth and Moon with compositional differences. Instead the Earth and Moon are isotopically identical across many elements, leading to an isotopic crisis for the impact model (e.g., Melosh 2014). Among the Earth-Moon isotopic similarities, oxygen has often been considered the most constraining for lunar origin. However, a number of explanations now exist for how the Earth-Moon similarity in O and other lithophile elements may have arisen.

Instead, tungsten (W) has now emerged as the most restrictive constraint (e.g., Pahlevan 2018). A planet s W isotopic composition is sensitive to the timing and nature of its core s formation. Thus even a giant impactor that was Earth-like in O would be unlikely to have an Earth-like W composition. But remarkably, current works argue that the initial Earth and Moon had identical W isotopic compositions (Touboul et al. 2015; Kruijer et al. 2015; Kruijer & Kleine 2017). This requires either a very improbable impactor composition (< few % likelihood; Kruijer & Kleine 2017), or disk-planet equilibration (Pahlevan & Stevenson 2007), itself an incompletely understood process (e.g., Melosh 2014).

The overall goal of this proposal is to perform a new evaluation of the W constraint on lunar origin. Mantle abundances of highly siderophile elements (HSEs) imply that Earth accreted the final percent or so of its mass after the Moon formed. Prior works assume that this late accretion delivered a chondritic W abundance to the Earth s mantle. It is this assumption together with the measured W compositions of the current Earth and Moon that has led to the conclusion that the initial Earth and Moon had equal W compositions. However, we argue that large, differentiated impactors expected during this early time would deliver a highly non-chondritic composition to the Earth's mantle, because most impactor core material descends to Earth s core (e.g., Dahl & Stevenson 2010; Marchi et al. 2018). This could allow for a much larger Earth-Moon difference in W isotopic composition than previously assumed (i.e., up to 100 ppm vs. < 15 ppm assumed previously).

In Task 1 we propose state-of-the-art SPH simulations of impacts with the Earth by D e 1000-km projectiles to determine the fraction of their HSE-rich cores delivered to the terrestrial mantle. In Task 2, we propose Monte Carlo simulations to determine how the Earth s W composition would evolve as it accreted such bodies, and estimate corresponding probability distributions for the initial Earth-Moon W isotopic difference. In Task 3, we use these results to re-evaluate the likelihood that current lunar origin models can explain the Earth-Moon W compositions.

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**Hodyss, Robert/JPL**
**Constraining small molecule ice-gas partitioning in presolar environments**

The chemical composition of planetary bodies, including those in our own Solar System, is related to that of the icy planetesimals that make-up these bodies and/or enriched them in molecular species at a later stage of their evolution. A key process that regulates ice chemical composition is the ability of water ice to trap volatile species. Laboratory experiments are used to quantify this process, though no consistent and quantitative survey exists and experimental conditions employed cannot entirely reproduce the ice morphology encountered in space. To remedy to this, we propose a combined laboratory and simulation study of volatile entrapment by amorphous water ice.

Our objectives are to:
1) Measure trapping fractions in mixed and layered amorphous water ices for chosen volatiles ($CO_2$, $H_2S$) and noble gases (Ar, Kr, Xe) with respect to thickness, heating rate, mixing ratio (when applicable), and ice structure.
2) Use these laboratory data to calibrate an off-lattice Monte-Carlo ice model to provide entrapment fractions of volatiles by amorphous water ice under relevant conditions found in star- and planet-forming regions.
Ices will be deposited on the electrode of a quartz crystal microbalance and ice desorption will be followed by the microbalance and a quadrupole mass spectrometer positioned close to the surface. The microscopic chemical kinetics model uses a so-called off-lattice treatment where the arrangements of all atoms and molecules are determined by their local interactions with other atoms/molecules. Model parameters will be fitted to the experimental data. Once the experimental results are well matched, the model will be run under interstellar conditions to derive relevant trapping fractions.

Our proposed work is directly responsive to the Emerging Worlds call, advancing our understanding of both the formation of the Solar System and its early chemical evolution. The Emerging Worlds program seeks proposals that address "processes occurring in and affecting the protoplanetary disk." We focus on the volatiles that migrate into the mid-plane of protoplanetary disks, and shape the chemical composition of planetesimals. Specifically, with this combined experimental and theoretical work, we will provide the community with a parameterized model that can easily be integrated to large-scale chemical simulations of protostellar envelopes and disks and get an accurate description of the ice-gas portioning for volatile species.

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**Stroud, Rhonda/Naval Research Laboratory**
**Formation and Processing Histories of Presolar and Early Solar System Nanomaterials**

We seek to constrain the conditions of the formation of the Solar System and its early evolution through analysis of individual dust components, with state-of-the-art transmission electron microscopy (TEM) methods in conjunction with isotopic measurements made by our co-investigators. Our primary focus will be on two materials: nanodiamonds and presolar silicates. Our secondary focus will be on constraining the parent body and preaccretionary histories of nanoparticles preserved in insoluble organic (IOM) residues, including chromites and silica-rich grains. The questions we will address are:

(1) Can a Solar System origin be inferred for individual meteoritic nanodiamonds based on a combination of structural, elemental, thermal transformation characteristics and comparison with laboratory analog samples?

(2) Can specific presolar sub-populations of nanodiamonds be identified on the basis of thermal stability, impurity content, or encapsulation in isotopically anomalous organic matter? If so, are the identifying features consistent with a specific interstellar or circumstellar formation scenarios?

(3) To what extent do the structural and elemental compositions of presolar silicates reflect initial condensation conditions, and how much is overwritten with processing in the interstellar medium, solar nebula, and asteroid parent bodies?

(4) How can we use monochromated electron energy loss spectroscopy as a tool for infrared spectroscopy of sub-diffraction-limited grains, to better link individual silicates to astronomical spectra of preserved grain in comets, grains condensing in circumstellar space, and those in the interstellar medium?

(5) What is the distribution of oxygen-rich nanoscale dust preserved in IOM residues, particularly chromites, and silica, and how does this reflect formation in presolar and early Solar System environments?

This proposal directly addresses the goals of the Emerging Worlds program, (ROSES 2018 C2 ): Studies of the materials present and processes that led to the onset of Solar System formation; and studies of all aspects of materials and processes occurring in and affecting the protoplanetary

disk, including those occurring on bodies of any size that may have formed at this stage of Solar System evolution.

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**Gammie, Charles/University of Illinois**
**Magnetized Models for the Formation of the Moon**

In the giant impact theory the Moon formed in the aftermath of an off-center collision between a planetary sized body and the proto-Earth. The collision lofts a ring of debris into orbit around the Earth, and this proto-lunar disk then cools and coalesces to form the Moon. In the canonical giant impact models (see Canup 2004) the impactor mass is comparable to Mars and the angular momentum of the Earth-Moon system is conserved. This models suffers from an "isotope crisis" (e.g.Melosh 2014): the Moon and Earth are isotopically similar, which is unexpected since the Moon should contain a material from an impactor that likely originated elsewhere in the solar system. In noncanonical models (Cuk & Stewart 2012; Canup 2012) angular momentum of the Earth-Moon system is removed via an evection resonance. Recent work (Lock et al. 2018) considers high energy and angular momentum impacts in which the collision outcome is a rapidly rotating, well-mixed "synestia".

Existing giant impact simulations use smoothed particle hydrodynamic techniques or an Eulerian grid code with maximum resolution ~ 100km (see Canup et al. 2013). We propose to develop and apply a fast, Eulerian scheme based on the athena++ code that is capable of high linear resolution. Our code will include the option to evolve an embedded magnetic field in the magnetohydrodynamic (MHD) approximation, motivated by recent work (Gammie et al. 2016, Carballido et al. 2016) that shows that magnetic fields couple to hot, vaporized parts of the protolunarc disk.

We propose the following novel investigations of the giant impact hypothesis using numerical experiments: (1) by what factor can a giant impact amplify the magnetic field of the target and impactor? (2) how does a magnetized model differ from an unmagnetized control model? (3) can a giant impact remnants lose angular momentum through magnetized wind? (4) what is the structure (run of density, temperature, composition, and field strength) of the boundary layer between the protolunar disk and Earth? (5) what is the rate of mixing through the boundary layer? (6) what is the rate of mixing in a protolunar disk that is in contact with a dynamically active boundary layer? We will answer these questions using a special branch of the athena++ astrophysical MHD code that we will build, test, and publicly release. We hope to create a tool that is useful to communities interested in Moon formation, giant impacts, exoplanet formation, and other impact problems that can be treated in a fluid approximation. The PI has a record of developing and publicly releasing codes that are widely used in other contexts.

The athena++ code is a rigorously tested, highly optimized framework for simulating astrophysical fluids. It is fully vectorized and therefore fast in scalar mode, and it also scales efficiently to hundreds of thousands of cores. This will enable numerical investigation at higher resolution than heretofore possible. We have added tabular equation of state capability to the athena++ code, and are in the process of adding material tracking capability. The work will constitute the PhD thesis of Illinois graduate student Patrick Mullen. PI Gammie has extensive experience with numerical methods, astrophysical fluids, and disk dynamics.

The proposed work is within the scope of the program element because "Emerging Worlds" aims to discover how the Solar System formed and evolved, and this year the Planetary Science Division is particularly soliciting proposals that focus on the Moon.

Canup, R. M. 2004, ARAA, 42, 441.
Canup, R.M., Barr, A.C., Crawford, D.A. 2013, Icarus 222, 200.
Carballido, A., Desch, S. J., Taylor, G.J. 2016, Icarus 268, 89.
Cuk, M., & Stewart, S., Science, 338, 1047.
Gammie, C.F., Liu, W.-T., Ricker, P.M. 2016, ApJ, 828, 58.
Lock, S.J., et al. 2018, arXiv:1802.10223.
Melosh, H. J. 2014, PTRSA, 372, 2013.0168.

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**McKeegan, Kevin/University of California, Los Angeles**
**High precision chronology of the oldest Apollo zircons: deciphering the meaning of the 4.3Ga peak in lunar ages**

We will perform new high-accuracy, high-precision coupled U-Pb and Lu-Hf isotopic analyses of individual lunar zircons with the overall goal of constraining the timing of lunar primary silicate differentiation thereby providing a refined date for the crystallization of the Lunar Magma Ocean.The project requires completion of three separate but coordinated tasks: (1) electron beam characterization and in situ SIMS analyses of U-Th-Pb isotopes, REE, Hf, and Ti concentrations in a suite of Apollo zircons(done at UCLA); (2) chemical-abrasion and dissolution of selected zircons with crystallization ages in the 4.3 Ga peak followed by high precision U-Pb analysis by Isotope Dilution-Thermal Ionization Mass Spectrometry(done at Princeton University); (3) measurement of REE concentrations and Hf isotope compositions of the dissolved zircons by MC-ICPMS(done at the University of Chicago).

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**Parker, Eric/NASA Goddard Space Flight Center**
**Searching for Extraterrestrial Amino Acids in Cosmic Dust Particles: Tracing the Origin and Evolution of Organics in the Solar System**

Scientific Goals and Objectives:

Carbonaceous meteorites, micrometeorites (MMs), including a carbon-rich subclass of MMs known as ultracarbonaceous Antarctic MMs (UCAMMs), and interplanetary dust particles (IDPs) are fragments of comets and asteroids that contain primitive chemical records of the Solar System. The deposition of these materials to planetary surfaces, with the combined masses of MMs and IDPs representing the primary mass accretion fraction on Earth, for example, have likely influenced the chemical inventories of celestial bodies since their formations. To better understand the diversity of organic matter delivered to Earth and other planets, the chemistry of comets and asteroids must be studied by investigating the organic content of cosmic dust particles.

Meteorite studies indicate extraterrestrial amino acids can help characterize processes that likely occurred on comet and asteroid parent bodies. Many target amino acids possess the property of chirality, measurements of which help distinguish between terrestrial and extraterrestrial origins.

Additionally, a suite of non-protein amino acids are rare on Earth, and their detection can serve as evidence of extraterrestrial synthesis. Therefore, amino acids are key targets in cosmic dust particles.

Amino acid detection has been reported in batches of large (~100-400 ¼m) Antarctic MMs, however, UCAMMs (~30-200 ¼m), and IDPs (~10-40 ¼m) have not been studied for amino acids, due to their small sizes and limited sample availability preventing their organic analyses. This problem will be addressed by analyzing newly acquired UCAMMs, and IDPs for amino acids using a highly sensitive nanoliquid chromatography-high resolution mass spectrometry (nLC-HRMS) technique recently developed in our laboratory. This technique is 100-1000x more sensitive than existing methods.

We propose to: 1) analyze UCAMMs, and IDPs for amino acids using nLC-HRMS, 2) evaluate extraterrestrial origins by measuring amino acid chirality and detecting non-protein amino acids, and 3) compare amino acid distributions in UCAMMs and IDPs to previous analyses of cometary material and carbonaceous meteorites.

Methodology:

Use of a Waters nano-ACQUITY ultra performance liquid chromatograph coupled to a Thermo Scientific LTQ Orbitrap XL hybrid mass spectrometer will provide unambiguous amino acid detection. Identification will be based on comparison of sample chromatographic retention times and accurate masses to those of amino acid standards. Calibration curves will be generated for quantification purposes.

Relevance:

The proposed work will address one of the core initiatives of the Emerging Worlds program, to better understand the early evolution of the Solar System. By investigating the amino acid content of comet and asteroid fragments, this project will provide new insights on processes that can be reasonably inferred to have occurred [on small bodies] and were most prominent up to the time that large planetary bodies were in or near their modern configuration (§2.2 of the Emerging Worlds call).

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**Pahlevan, Kaveh/Arizona State University**
**Evolution of primordial atmospheres on the terrestrial planets: linking models with observations**

Evolution of primordial atmospheres on the terrestrial planets: linking models with observations

Science goals and objectives: Magma oceans were ubiquitous during planet formation; observable links between magma oceans and the subsequent history have, nevertheless, proved somewhat elusive. We aim to develop models that describe the evolution of terrestrial planet atmospheres from: (1) the high temperature equilibrium regime relevant to outgassing from a magma ocean, to (2) cooling through the quench temperature into the kinetic regime, (3) condensation of the water vapor from the steam atmosphere, and (4) the loss of the transient atmosphere and the transition to a geological steady-state. The isotopes of hydrogen and carbon

are uniquely suited to constrain this earliest stage of planetary evolution (e.g. Genda and Ikoma, 2008, Galimov, 2000). We will apply H and C isotopes as tracers with the goal of constraining early planetary evolution on Earth and Mars, in order to: (1) to constrain the redox state of the terrestrial and Martian magma oceans and thereby the redox state of the earliest atmospheres on the post-accretion planets, (2) to develop the H and C isotopic consequences of primordial atmospheric evolution and loss, and (3) to determine whether the distinct early evolutions of the Earth and Mars were due to subtle differences in the redox chemistry of magma oceans.

Description of methodology: We will construct 1D pseudo-adiabatic and radiative-convective atmosphere models that capture the behavior of outgassed planetary atmospheres from the equilibrium states at high-temperature to the quenched states characterizing low-temperature. The methods are analytical and numerical. Following this description of evolutionary states, we will incorporate the partitioning behavior of H and C isotopes as passive tracers under equilibrium and kinetic regimes in post-processing fashion. The output of the D/H and 13C/12C compositions of planetary volatile envelopes will be compared to that of the source materials. Similarities between observed and modeled planetary reservoirs are used to identify viable evolutionary sequences for early planetary atmospheres and hydrospheres.

Relevance to program: This project is relevant to the Emerging Worlds program goal to understand how objects in the Solar System formed and evolve and also involves major interdisciplinary efforts to solve key questions . The composition of the terrestrial planets early atmospheres has been a long-standing problem in planetary science. While early atmospheres have been extensively studied, previous research has neglected coupling the evolution from impact-degassed and magma ocean outgassed atmospheres to the large and rapidly attained equilibrium isotopic fractionation between H-bearing (H2O-H2-CH4) and C-bearing (CO-CO2) species on transient early atmospheres with the goal of limiting evolutionary process. This proposal represents an interdisciplinary effort to constrain the composition of these ephemeral atmospheres using the physics of magma oceans, primordial atmospheres, and well-preserved isotopic abundances of D/H, 13C/12C. The contrast between the early evolution of Earth and Mars directly contributes to understanding the reasons for differences in evolution among the various planetary bodies.

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**Farquhar, James/University of Maryland**
**Study of signatures of nebular chemistry preserved by CM chondrite sulfur compounds**

Sulfur is the tenth most abundant element in the galaxy and spectroscopic observations reveal a range of different species some are ionized, some are radicals, some are ground state. All of these species have the potential to be affected by photochemistry. Sulfur also has a rich chemistry with many different bonds,making ideal for producing a number of different types of isotopic signatures.Two findings with CM chondrites indicate that sulfur compounds in these meteorites preserve signatures of this chemistry - a singular finding of water-soluble sulfonic acids by Cooper et al. (1997) and another finding by Labidi et al. (2016) involving elemental and other zero valent sulfur species. These signature implicate photochemical reactions, point to a low temperature origin, but their origin is poorly understood. The team on this proposal will isolate these compounds from CM chondrites, refine the range of compounds that have been isolated, and explore the implications of the compounds (their existence and composition) to place constraints on the necessary conditions for their formation, transfer, and preservation.

These constraints will provide direct insights into conditions that prevailed in the regions of the solar nebula where these compounds were formed and about how sulfur is speciated in primitive meteoritic materials - information that is necessary to understand the processes that ultimately delivered sulfur to different types of solar system materials. The work will include a variety of laboratory and petrographic studies of meteorite samples. It will use state of the art techniques for isolation of these compounds and sulfur, carbon, hydrogen, and oxygen isotope analyses.

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**Ruzicka, Alex/Portland State University**

**The deformation-heat connection: Evaluating hot accretion, lithification mechanisms, and heat sources in ordinary chondrites**

The interplay between deformation and heat is at the nexus of important questions in planetary science research today. Among these is whether chondrules could have collided while hot to form primordial aggregates, such as proposed for so-called cluster chondrite lithologies (Metzler, 2012). If primordial hot chondrule aggregates were produced, it would have important implications for both chondrule formation mechanisms and for planetesimal accretion. Also not established, but critical to understanding the growth of planetesimals, is how collisions compacted, compressed, and heated already-formed planetesimals to form indurated and lithified rocks. Finally, the relative importance of different heat sources (hot chondrule accretion, exogenic, endogenic via short-lived radionuclides) in planetesimals and asterodal-sized bodies at different times in solar system history is fundamentally important for understanding the physiochemical evolution of primitive materials.

The answers to these questions can be evaluated in part by considering specific crystallographic deformation-heat signatures, textures, and physical properties in chondritic rocks that were collisionally processed in different ways at different times. An innovative approach will be used to study a suite of carefully chosen ordinary chondrites with different characteristics. Samples will include petrographic type 3 chondrites that contain cluster chondrite lithologies; type 3 and 4 chondrites of differing shock stages, porosities, and metal grain fabrics that appear to have been variably affected by shock compaction and compression; and some type 6 chondrites that could have been shocked under very different conditions, either in warm parent bodies or in cold ones. EBSD-SEM techniques will be used to map the spatial distribution of deformation, mineralogy, crystal orientations, and composition of all phases, and to assess deformation temperature and post-deformation annealing extent in olivine. These data will be used to target areas for detailed TEM studies that will provide critical information on microstructures and that will serve to validate EBSD results. Some samples not yet dated for impact ages nor measured for porosity and metal 3D petrofabrics will be analyzed with 40Ar/39Ar stepwise heating and microtomography, and all suitable meteorites will be measured for porosity.

The proposed project will 1) test whether hot chondrules accreted to form cluster chondrites, and provide estimates of the accretion temperature, relative annealing extent, and shock pressure involved in their formation, 2) evaluate how type 3 and 4 chondrites were compacted, heated, and lithified by collision-related processes, and constrain their deformation and thermal histories, 3) assess the relative importance of different heating mechanisms and conditions at different times in solar system history, including constraints on the duration of endogenically heated asteroidal bodies in the early solar system and the ability of shock events to heat and anneal chondritic rocks. This project also will provide an unprecedented characterization of how

minerals respond to shock across a range of shock stages, and will utilize methodologies that can be used to characterize the deformation and thermal histories of returned samples from asteroids. It is highly relevant for NASA.

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**The following proposal was deemed out of scope for Emerging Worlds, but was selected by the Selecting Official, and will be funded with discretionary funds:**

**Asphaug, Erik/University of Arizona**
**Application of Machine Learning to Giant Impact Studies of Planet Formation**

Understanding the role that bombardment by large projectiles played in the formation of the inner planets is prioritized in the Decadal Survey. Our group uses Smooth Particle Hydrodynamics (SPH) to model giant impacts on planetary bodies such as the Moon, Mercury and Mars (e.g. Asphaug & Reufer, Nature Geo. 2014; Emsenhuber et al., Icarus 2018). As of today, our dataset is composed of 1500 simulations spanning a wide range of parameters (composition, size, mass ratio, impact angle and velocity). Each SPH outcome is a complex 3D state (final planets, clumps, their characteristics, and unconsolidated ejecta, and their thermodynamic states) that requires detailed analysis.

The proposed investigation aims to apply machine learning to giant impact studies, both to streamline the generation of data sets to most efficiently explore the large parameter space, and to efficiently analyze outcomes, where human operators show limits in efficiency and reproducibility. Modern machine learning schemes do not suffer this big data problem; they take advantage of it to spot new and sometimes unexpected correlations.

The first objective is to design classifiers to categorize input parameters into different collisional regimes (e.g. merger, disruption, hit-and-run). As a pilot study we have developed a preliminary version of the classifier based on a subset of 100 simulations; even with few examples, the algorithm learned how to discriminate with 98% accuracy between planetary accretion and no accretion, already providing guidance for future SPH simulations.

The second objective is to design a surrogate SPH model, which is an algorithm able to learn giant impact physics through association between impact parameters (predictors) and model outcomes (responses). While a classifier provides a qualitative characterization of the outcome, a regressor predicts continuous responses, such as the mass and velocity vectors of the largest remnants. These can be consequently inputted in N-body simulations for post-collisional dynamical studies. Running the surrogate model drastically reduces the computational time and cost with respect to full SPH simulations, without downgrading the accuracy of the results. Furthermore, the surrogate SPH model can be inverted to constrain the conditions that led to observed post-collisional configurations in the solar system, i.e. the Earth-Moon. We will also apply unsupervised learning to the dataset, going beyond what humans perceive as patterns.

The third objective is to use a canonical N-body simulation as a driver for testing the utility of the surrogate models. Where model predictive confidence is low, more runs will be done.

The fourth objective is to systematically extend all these studies to the more realistic situation where friction becomes important, bodies smaller than a few 1000 km.

The long-term scientific goal is to use machine learning to enable systematic approaches towards the solution of problems such as Earth-Moon system formation, and metal-dominated worlds like Mercury and asteroid Psyche, and the overall diversity of planets, dwarf planets, KBOs and satellites. The proposed investigation is in line with the scope of Emerging Worlds because it aims to shed lights on the early evolution of the solar system, especially, to provide tools for moving from beginning states to end states, embryos to planets. We will focus on the physics of collision and impacts and their role in setting the modern configuration and structure of planetary bodies. Furthermore, the Emerging Worlds program values the potential of interdisciplinary efforts to solve key scientific questions. The combination of giant impact studies and machine learning is new research that will enhance the scientific relevance of giant impact modeling to questions of planet formation.