**Emerging Worlds 2017**
**Abstracts of selected proposals**
**(NNH17ZDA001N-EW)**

Below are the abstracts of proposals selected for funding for the Emerging Worlds 2017 program. Principal Investigator (PI) name, institution, and proposal title are also included. 128 proposals were received in response to this opportunity. On December 4, 2017, 31 proposals were selected for funding.

**Peslier, Anne/Jacobs Technology, JETS**
**Effect of shock on water in meteorite minerals via analogue impact experiments**

Science Goals
Determining how much water is contained in Solar System bodies is crucial to our understanding of Solar-System formation and the origin of life. Silicate-dominated planetary bodies incorporate water in nominally anhydrous minerals (NAM) such as olivine and pyroxene in the form of hydrogen (H) bonded to structural oxygen in lattice defects. These NAM constitute the main reservoir for water in the interiors of differentiated planets. To determine the origin of water in the latter, H can be analyzed in their building blocks, chondrites. Meteorites are our samples of the Solar System and understanding how water was first incorporated, retained and lost at various stages of the evolution of their parent bodies will establish the origin and distribution of water in the Solar System. Although it may seem simple to analyze water in meteorites, and thereby to infer the amount of water in their parent bodies, all meteorites have been shocked to some degree at various stages in their history. Shock in meteorites comprises many conditions that can potentially disturb water in minerals, i.e., high pressure and temperature, brittle/ductile deformation, amorphization, melting and degassing. The question is therefore, to what extent have the water distribution in meteorite phases been changed during impact events, potentially overprinting the initial concentrations inherited from parent-body processes such as melting, crystallization, hydrothermal activity and alteration.
The few shock experiments coupled with water analyses performed to date have been limited solely to hydrous phases. Here we propose to perform impact experiments on terrestrial olivine, pyroxene and apatite, using compositions and shock pressures (<20-60 GPa) similar to those recorded in meteorites, to determine the effects of shock on water and H isotopes of these analogues of typical meteorite minerals. If the water contents in these minerals were largely undisturbed by shock, water measured in meteorite phases could be used to calculate the amount of water in their parent bodies. If not, careful assessment of the significance of water contents in meteorite phases would be necessary before inferring parent-body volatile budgets. In either case, the results would have significant implications for understanding the role of shock in the volatile distribution and in the evolution of H-isotopic compositions in Solar-System bodies during their formation.
Approach and Methodology
Chemically homogenous olivine, pyroxene and apatite grains >1 mm in size with > 50 ppm wt H2O will be shocked in vacuum using a vertical gun (range of shock pressures in the target) and a flat-plate accelerator (uniform peak pressure throughout the target via shock reverberation) in the Experimental Impact Laboratory (NASA-JSC). The shocked minerals will be analyzed by FTIR (NASA-JSC & UC Berkeley ALS synchrotron) and by SIMS (ASU) for water content and H isotopes. The degree of shock will be assessed using a petrographic microscope, TEM, Raman spectroscopy (NASA-JSC) and micro-XRD (ALS). Mössbauer (NASA-JSC) and XANES (ALS) will be used to assess the redox state of Fe in pyroxene.
Relevance to the Emerging Worlds program
The aims of this project fall within the scope of the Emerging Worlds program which targets "the fundamental science question of how the Solar System formed and evolved" by addressing the role of

water in the "chemical and physical properties of ancient materials". This project is also multi-disciplinary, in that it combines experiments, petrology and geochemistry. Ultimately, the successful completion of this research can be expected to have a significant positive impact upon advancing the Program s goal of constraining the "dynamical evolution of the Solar System" (impact study), and the "early thermal and chemical processes occurring on small bodies" and planetary "global differentiation" by assessing their volatile budgets.

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**Canup, Robin/Southwest Research Insitute**
**Origin of the Uranian satellite system**

Ice giants like Uranus remain poorly understood, yet we now know that they are perhaps the most common type of planets, based on exoplanet detections. A satellite system can be used to place important constraints on the final stages of a planet s formation. However the origin of the Uranian satellites remains the least well understood of any of the outer satellite systems. The large satellites of Jupiter and Saturn likely formed within circumplanetary disks of gas and solids that were created as those planets accreted gas (e.g., Stevenson et al. 1986). Retrograde Triton was likely captured intact (e.g., Agnor & Hamilton 2006), which destroyed evidence of an original satellite system at that ice giant.

In contrast, basic properties of the Uranian satellite system are not easily explained by standard origin models. The challenge is that Uranus is a retrograde rotator with an obliquity of 98 degrees, and its satellites orbit in the same sense as its retrograde rotation. The nearly circular, co-planar orbits of the main Uranian satellites, and their orbital spacings and masses compared to that of the planet, are similar to Jupiter s moons. This suggests they may have formed similarly via co-accretion. However inflowing gas would form a prograde disk around the planet and a satellite system orbiting in the opposite sense to that observed. Alternatively the satellites could have formed from a disk produced by a giant impact that tilted Uranus, but the disks produced by such events appear too compact and ice-dominated to produce the outer rock-rich Uranian moons.

A promising new idea has been proposed (Morbidelli et al. 2012). The idea is that Uranus originally had a smaller obliquity and a prograde satellite system like that at Jupiter. This system was destabilized by a Uranus-tipping giant impact. The current satellites then re-accreted in Uranus new equatorial plane from debris created by disruptive collisions between the original prograde satellites. A first requirement for this scenario is that the impact must produce not only Uranus retrograde obliquity but also a massive inner disk, containing 1% or more of the planet s mass, or roughly 100 times the mass of the current satellites. The gravitational influence of this impact-generated disk is needed so that outer disk debris accretes into satellites with low inclinations, consistent with the current low inclination orbits of Titania and Oberon. A second requirement is that the massive inner disk must be lost, since no such disk nor comparably massive inner moon exists at Uranus today. Whether such conditions can be achieved is unclear.

In this proposal we will model the formation of the Uranian satellites in a co-accretion + giant impact scenario. In Task 1, we will conduct SPH simulations of impacts into Uranus to determine the type of impact needed to tilt the planet and generate a sufficiently massive inner disk. In Task 2, we will model the accretion of satellites from the post-impact system in two stages. First we will model the re-accretion of the outer regular satellites from the debris disk produced by collisions among the prior moons (Task 2a). Then we will model the later evolution of the inner, ice-rich impact-generated disk as it cools and condenses (Task 2b). The goal in Task 2 is to determine whether the post-impact system can evolve into a system of Uranus-like satellites while the massive impact-generated disk is nearly entirely lost.

Together, Tasks 1 and 2 will allow us to evaluate the viability of a co-accretion + giant impact model.

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**Ogliore, Ryan/Washington University in St. Louis**
**Investigating Nearby Supernovae through Analyses of Ancient and Contemporary Stardust**

Science Goals and Objectives

A nearby supernova exploded ~2 million years ago and sent dust grains into the Solar System, leaving a detectable trace of the radioactive isotope 60Fe globally on Earth's ocean floor, as well as the Moon and other planetary bodies. I propose to extract supernova dust from deep-sea sediments and analyze its isotopic composition and detailed structure. I will then compare these grains to presolar stardust grains that will be extracted from meteorites, which formed more than ~4.6 billion years ago, in order to constrain models of supernova nucleosynthesis and ejecta mixing. The comparison of the isotopic compositions of ancient and presolar supernova dust will shed light on the chemical evolution of high-mass stars in the neighborhood of the Sun.

Methodology

We will dissolve the deep-sea sediments in acids in Co-I Wang's clean lab at Wash U. Then we will do automated SE, BSE, and EDX imaging on a Tescan FEG-SEM in PI Ogliore's lab to identify SiC grains. We will analyze various isotope systems (Al-Mg, Si, C, Ti, O, etc.) of these grains using the Wash U NanoSIMS.

Relevance to the Emerging Worlds Program

The Emerging Worlds program covers "Studies of the materials present and processes that led to the onset of Solar
System formation." (C.2.1) Presolar grains were an important part of the solid material at the onset of Solar System formation. Comparison of presolar grains with contemporary supernova grain will allow us to understand how the Solar System's immediate galactic environment (i.e. "the molecular cloud from which the Solar System formed" per Emerging Worlds C.2.1) has changed over the last 4.6 billion years. Our proposed work will shed light on the most primitive building blocks of the Solar System, addressing "the fundamental science question of how the Solar System formed", the main goal of Emerging Worlds (C.2 Introduction).

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**Simon, Jacob/University of Colorado**
**Pebbles to Planets: The Role of Pressure Traps**

How 100 km planetesimals form from smaller mm-cm sized pebbles is one of the biggest unanswered questions in Solar System formation. With the discovery of the streaming instability, a robust candidate has emerged for clumping these pebbles to the point of gravitational collapse, allowing them to form larger bodies. However, there remain two largely unresolved issues with this process. First, the streaming instability will only trigger clumping for a sufficiently large concentration of pebbles, a condition that is not always easily met in disks with a smooth, monotonic radial structure. Additionally, the initial planetesimal size distribution that arises from numerical simulations is significantly more top-heavy compared with observed small body Solar System populations.

Another advancement in recent years has been the realization that pressure traps, i.e., local gas pressure enhancements, are likely prevalent in protoplanetary disks, arising from a variety of processes, e.g., the outer edge of planet-induced gaps. While the importance of these traps has been realized in the context of planet formation as a whole, their role in planetesimal formation via the streaming instability has only barely been explored.

Thus, studying the interaction between these pressure traps and streaming-induced planetesimal formation is essential for several reasons. First, as mentioned above, these traps are more likely than not to exist in protoplanetary disks. Second, while these traps may locally enhance the concentration of pebbles to streaming-unstable values, these effects must compete with momentum feedback from the pebbles onto the pressure trap, which could deform the trap and actually reduce clumping. Finally, if these traps can survive, they could potentially change the initial planetesimal sizes (since streaming-unstable wavelengths will decrease near the trap peak) and/or the size distribution (if the traps maintain a pebble concentration close to gravitationally instability, planetesimals may form one-by-one, each of roughly the same size, equating to a more bottom heavy distribution). Thus, we aim to test whether pressure traps will (a) survive the momentum feedback from pebbles to produce significant clumping and (b) change the resulting planetesimal sizes and/or size distribution.

Pressure traps could also play a crucial role in planet formation. For example, as Jupiter is being formed, it will open a gap that generates a pressure trap exterior to its orbit. Planetesimals formed from this trap could critically influence the evolution of the Solar System in any combination of three possibilities: These planetesimals may merge and/or accrete pebbles to eventually form Saturn, be scattered away from the planet, some of which may be deposited as volatile rich asteroids in the main belt, and/or be accreted by Jupiter, providing the source of Jupiter's observed super-Solar metallicity.

In this proposal we will use state-of-the-art codes ATHENA (a gas+particle dynamics code) and LIPAD (a planet formation code) to carry out the most in-depth study to date to test these critical ideas. Specifically, our proposed work is outlined into three tasks:

Task 1: Use ATHENA to test whether pressure traps will survive feedback forces to enhance clumping.
Task 2: Use ATHENA to test whether pressure traps will change the sizes and/or size distribution of planetesimals.
Task 3: Use LIPAD to determine whether planetesimals produced in a pressure trap induced by proto-Jupiter will lead to the formation of Saturn's core, be scattered into the asteroid belt, and/or enrich Jupiter's atmosphere.

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**Pasek, Matthew/University of South Florida**
**Phosphorus mineral cosmochemistry in the emerging solar system**

The element phosphorus (P) is generally classified as a minor or trace element in terrestrial and extraterrestrial samples. However, despite its relative scarcity in the Solar System, phosphorus has received a significant amount of attention from the cosmochemical community, due both to its role in capturing trace elements in phosphate mineral crystal lattices, and in the astrobiological implications of phosphorus to the development of life on the earth (e.g., Pasek 2015).

Despite the role of phosphorus in cosmochemical evolution, several facets of phosphorus cosmochemistry remain unclear, including 1) the extent of volatile forms of phosphorus present within the early Solar System, including the gas phosphine (PH3), 2) the oxidation reactions between siderophilic (metal-loving) P minerals such as schreibersite (Fe,Ni)3P and silicates and oxides to give phosphate, and 3) a detailed analysis of why specific phosphate minerals are more common in meteorites than on planetary bodies. We propose to investigate these key aspects of phosphorus cosmochemistry to better constrain the phases and forms that govern the distribution of this key element in our Solar System. This objective will be accomplished by experimental analyses that are fed into Solar System and planet chemistry models.

1. The gas phosphine (PH3) has been proposed to be the major P species in cold environments in the solar system. We believe this to be incorrect, and instead argue that phosphorus is highly reactive towards metal. We propose that metal is phosphidized by phosphorus gases at high temperatures (500-1200K), and diffusion distributes gaseous phosphorus towards this extensive phosphorus sink, and results in the depletion of volatile phosphorus throughout the solar nebula. As a result, phosphine and other volatile P forms are less likely to dominate in the outer solar system. This will be examined by detailed metal phosphidation studies that establish reactions kinetics that then apply this data to solar system models.

2. The formation of phosphates from phosphides is predicted to occur at about 800 K, and produces calcium phosphate minerals such as apatite. The kinetic controls on this oxidation are unknown. In equilibrated chondrites most of the phosphorus is in phosphates, whereas in unequilibrated chondrites, the phosphorus is more distributed between phosphates and phosphides. This suggests that oxidation timescales may be of the order of thousands of years, requiring longer-term metamorphism. Phosphate-phosphide equilibrium and kinetics will be investigated using controlled reactions in a tube furnace, and will attempt to constrain the timescale of oxidation. By doing so, this data may help constrain the metamorphic history of asteroids.

3. The phosphate minerals that are found in meteorites include apatite well known from terrestrial mineralogy and merrillite/whitlockite, which are both minerals quite rare on the earth. The dominance of calcium phosphate is surprising as recent work has demonstrated these phosphates are susceptible to alteration to Mg/NH4 phosphates. Here we will research the apatite-struvite transition using mineral reactions in a vacuum manifold under a controlled temperature, and attempt to determine the rates and specific chemistry required to form these different phosphate mineral classes.

This work is directly relevant to Emerging Worlds as it deals with the primordial chemistry that formed the initial solids in the solar system. It is part of the planet theory and primitive meteorites investigation categories, and is relevant to studies of the formation of planets, satellites, and minor bodies, including dust, and to the early history of these bodies , as highlighted within the Emerging Worlds call.

**Alexander, Conel/Carnegie Institution of Washington**
**The relationship between chondrite matrices and IDPs**

The two most primitive Solar System materials available are chondrite matrices (both interchondrule matrix and chondrule rims) and chondritic porous interplanetary dust particles (CP IDPs), and both contain presolar circumstellar grains, D-rich organic matter, fine grained crystalline silicates with similar ranges of compositions, and amorphous silicates. These common features suggest both are mixtures of materials inherited from the presolar molecular cloud and materials that were thermally processed in the nebula. Despite these common features, there is still no consensus about (1) whether matrix and CP IDPs are related, (2) how their components formed, or (3) what they tell us about processes in the early Solar System.

In the two-component model, matrix is dominated by CI-like material. Modest contributions from chondrules and inclusions, along with parent body modification, explain non-CI-like bulk matrix compositions. The higher abundances of presolar grains and organics in many CP IDPs indicate lower contributions from the thermally processed material, consistent with cometary origins. Nevertheless, for the thermally processed material to be so widespread probably requires that it formed very early when radial disk transport was most vigorous.

The alternative model is that matrix is the complement to chondrules, in which case the presolar grains, organic matter, etc. were added to matrix late in a minor primitive component. Complementarity has far reaching consequences as it suggests that chondrules and matrix formed in close proximity and were not later efficiently fractionated from one another despite their very different grain sizes. It is an argument against the X-wind model and any other grain size sensitive processes such as forming and/or transporting chondrules in disk winds or planetesimal formation by pebble accretion or the streaming instability.

These two models result in fundamentally different views of thermal processing and transport in the nebula, as well as accretion of planetesimals. It is the aim of this proposal to try to test both models by combining focused ion beam (FIB) and electron microscopy techniques in ways that minimize the potential for operator or analytical bias, as well as provide checks for the accuracy and self-consistency our protocols.

(i) We will use point counting and quantitative elemental analysis in the electron microprobe to determine the abundances and bulk compositions of: (a) chondrules, (b) isolated metal, sulfide and silicate grains (>10 um), (c) interchondrule matrix, (d) chondrule rims, and (d) refractory inclusions. To minimize the influence of parent body alteration, we will only analyze the most primitive chondrites available. A first order check of this approach will be to combine all the components in each meteorite and compare the estimated bulk compositions to the bulk compositions for their groups from the literature.

(ii) We will follow this up with high spatial resolution SEM studies of the most primitive matrix areas to determine the abundances and compositions of mineral grains >1 um. These data will be used to estimate the contributions of chondrules and inclusions to matrix, as well as to search for grains that are unrelated to chondrules and inclusions.

(iii) We will use SEM-STEM and TEM techniques to analyze FIB sections from these matrix areas to determine: (a) the bulk compositions of the FIB sections for comparison with the matrix compositions determined by EMPA, and (b) the compositions, microstructures and abundances of minerals and amorphous material >100 nm across (thickness of sections) for comparison with chondrules, inclusions

and CP IDPs. We will use exactly the same techniques to analyze FIB sections of CP IDPs so that we can make direct comparisons.

Armed with this data, we will compare the compositions and microstructures of matrix and its components to the expectations of the two-component and complementarity models.

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**Halfen, DeWayne/University of Arizona**
**Tracing the History of Molecular Phosphorus: From Interstellar Space to Planetary Surfaces**

Phosphorus plays an important role in living systems, where it is an integral part of replication, metabolism, and cellular structure. The cosmic history of this element, however, is far from transparent. Phosphorus is thought to originate in massive stars, entering the interstellar medium in the gas phase or as mineral grains through stellar winds and supernovae. The element forms interstellar molecules such as PO and PN, as traced by radio astronomy, and is also incorporated into meteorites in mineral form and as phosphonic acids. A plausible source of biogenic phosphorus may be exogenous delivery from such bodies. Establishing the connection between the interstellar and solar system carriers of this element is therefore critical to understanding life s origins.
We propose to expand our current understanding of phosphorus by examining new interstellar and solar system carriers in both the gas-phase and solid-state forms, and integrating these new data with previous studies to build a more complete, cosmochemical portrait with functionality as our chief tool. We will explore the forms in which phosphorus was delivered to the pre-solar nebula. For example, did interstellar chemistry play an important role in sequestering the phosphorus in organic form? Alternative exogenous sources of this element conveyed to planet surfaces will also be investigated. Did organophosphorus material survive solar system formation, or was it all transferred into mineral-like material?
Our multi-disciplinary approach will center on five research topics: 1) Laboratory measurements of gas-phase rotational spectra of organophosphorus and Fe/Ni/P bearing molecules, 2) Identification of these molecules in star-forming regions, circumstellar envelopes, protoplanetary disks, and comets using astronomical databases, 3) Solid-state measurements of insoluble organic material (IOM) in chondritic meteorites to determine the presence of phosphorus and its functionality, 4) Solid-state microscopy of pre-solar grains extracted from carbonaceous chondrites to examine the presence of phosphorus, in particular schreibersite, and 5) Creation of a Phosphorus Archive to synthesize all current data.
For the gas-phase studies, Fourier transform microwave spectroscopy and mm/submm direct absorption techniques will be employed. The PI and Co-I Ziurys have already successfully measured the spectrum of a variety of P-bearing molecules. This work will be extended to organophosphorus molecules with C-P, P-N, and P-O bonds to examine functionality, as well as Ni-P and Fe-P bonds to link to mineral carriers. These species will then be identified by their lab spectra in existing observational data of circumstellar, interstellar, and solar system bodies. The PI has in hand sensitive, broadband spectral-line surveys of star-forming clouds, circumstellar envelopes and planetary nebulae; the ALMA archive can be searched for data in protostellar disks and comets.
We will then link the astronomical findings to phosphorus in meteorites, in particular to the IOM in primitive carbonaceous chondrites. Co-I Zega will map type-1, 2, and 3 meteoritic samples using an electron microprobe, revealing pockets of abundant phosphorus. These areas will be probed for mineralogy and the correlation of phosphorus with elemental C, N, and O, which would signify an organic carrier. Secondary ion mass spectrometry will also be used to measure the isotopic composition (C,N) of the P-rich regions to establish interstellar origins. The functional chemistry of phosphorus will be analyzed with electron energy-loss spectroscopy, transmission electron microscopy, and X-ray absorption near-edge structure spectroscopy. In addition, pre-solar grains, extracted from carbonaceous chondrites, will be studied by ion and electron-beam microscopy to examine the presence of phosphorus, in particular schreibersite.

All data will be compiled and compared in the Phosphorus Archive, open to the community.

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**Croat, T./Washington University**

**The First Solids: Insights into Early Solar System Processes from Pristine Presolar SiC Grains**

Presolar grains were the first solid objects in the solar system, and as such they were exposed to a series of astrophysical environments of interest (circumstellar, interstellar medium, solar nebula, etc.) before incorporation into meteorite parent bodies. Pristine SiCs from meteorites (those found using x-ray mapping and not subjected to harsh acids) may preserve some clues as to this prior history in their grain surfaces. In particular, some pristine presolar SiCs have oxide coatings and amorphous surface residues of a type not seen on adjacent grains, suggesting that some effects of their alteration history prior to parent body processing has been preserved. Prior investigations with Auger electron spectroscopy (AES) and NanoSIMS have shown mainly carbonaceous coatings which in some cases also show indications of surface-correlated 15N enrichment. Since presolar grains were known to be present as solids in the ISM, these dust grains may have acted as catalytic surfaces, leading to formation of organic coatings of the type that are spectroscopically observed in the ISM.

We plan detailed studies of pristine SiCs concentrating on their surfaces with a battery of microanalytical techniques (FESEM, AES, FIB/TEM, and NanoSIMS). We will look for correlated 15N and D excesses on pristine SiC surfaces that are suggestive of low temperature irradiation in the ISM or outer solar system. We will use several strategies to deconvolve any interstellar or nebular signatures from effects of parent body processing: Close comparison of presolar SiC surfaces with those of nearby matrix grains will help to identify parent body and other processes that were universally experienced by all matrix grains. We will also compare SiCs found within a range of carbonaceous meteorite groups (CM2, CO3, CR3) in an attempt to deconvolve primary effects in the ISM and solar nebula from any later parent body processing effects. FIB/TEM studies of presolar SiCs found in-situ in several CR meteorites that largely escaped aqueous alteration should provide less processed material for comparison with the pristine SiCs from Murchison (CM2) and Dominion (DOM) Range 08006 (CO3). The FIB/TEM studies of SiCs found in-situ will also preserve their petrographic context and could reveal more complex grain assemblages, possibly giving clues as to how the SiCs survived in the oxidizing solar nebula. We will also attempt to detect partially-altered presolar SiCs in the more-altered Murchison CM2 material using x-ray spectral imaging (rather than isotopic imaging). FIB-TEM studies of their structure followed by NanoSIMS measurements should aid in understanding of the pathways for presolar grain destruction and modification in the more-altered meteorites (in which fewer presolar grains are detected). The higher SiC abundances in DOM 08006 should permit discovery of pristine SiC-X grains, which can retain processing features from SN environments that are not preserved in acid-etched SiC-X grains.

The proposed research is relevant to the goals of the Planetary Science Decadal (Visions and Voyages) in that it seeks to decipher the record in primitive bodies of epochs and processes not obtainable elsewhere . Since it deals with studies of the materials present at the onset of the Solar System , it is directly relevant to the Emerging Worlds program.

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**Sandford, Scott/NASA - Ames Research Center**
**Radiation Processing of Ices and Organics in Space: Searching for Links with Meteoritic Materials**

Science Goals - Ices and organics are routinely exposed to ionizing radiation in space. This leads to the creation of new organics and the alteration of existing ones. Such processing occurs in interstellar clouds and protostellar disks and likely played important roles in establishing the composition of organics in the early Solar System. We propose to carry out laboratory studies designed to compare the organics in meteorites and other extraterrestrial samples with the organics made during laboratory experiments on ice/organic irradiation designed to simulate conditions in the protosolar nebula.

Our primary tasks will be to:

1) Evaluate the extent to which organic molecules are formed and restructured as they and their icy precursors were irradiated by UV photons, X-rays, and cosmic rays in the solar nebula. Specifically, we will carry out laboratory experiments to evaluate the consequences of the sorts of irradiation doses seen by ices and organics in the protosolar disk predicted by the model of Ciesla & Sandford (2012). The detailed consequences of this irradiation, as well as the rates and fluences required to drive changes in the chemistry and physical structure of organics, will be determined by experiments and analytical studies.

2) Explore the extent to which noble gases resident in original astrophysical ices are trapped in the organic residues that result from exposure to ionizing radiation and how the population of trapped gases is modified as the organics are subsequently exposed to additional radiation. We will seek to see if the trapped gases replicate properties of the meteoritic phase Q carrier of noble gases in terms of trapped gas abundance, and elemental and isotopic fractionations. This effort will explore the history of noble gases in ices and organics in the outer solar nebula as ices are formed, irradiated, and destroyed in the solar nebula.

3) Determine the extent to which isotopic effects in C, H, and N can be induced in ices and organics via irradiation. We will carry out experiments to determine how isotopic fractionations are passed forward from ices into organics and the extent to which irradiation itself results in intrinsic isotopic fractionation.

Methodology - We plan to perform lab experiments that expose astrophysical relevant ices to energetic radiation followed by subsequent warming to produce complex refractory residues. Portions of these residues will be further irradiated to monitor the evolution of organics with further exposure to radiation. The primary analysis techniques we will use to study the resulting samples at ARC and GSFC are IR spectroscopy, HPLC, GC-MS, GC-MS/IRMS, and C,N,O-XANES. Our Collaborators will also apply the techniques of TEM, SIMS, and noble gas analysis to the samples. Results will be compared to meteoritic organic materials to see if they share similar properties with regards to chemical and physical structure, noble gas retention, and isotopic fractionations.

Relevance - This research focuses on the chemical processing of ices and the formation and processing of organic molecules in space as outlined in the Emerging Worlds solicitation. The lab studies proposed here are designed to model processes that are expected to occur in the protosolar nebula. This will allow us to explore the connection between the radiation processing of mixed molecular ices and organics of astrophysical relevance and the organic materials found in meteorites and samples returned from comets and asteroids.

**Huss, Gary/University of Hawaii at Manoa**
**Timescales of Aqueous Alteration in Primitive Chondrites as Determined from 53Mn-53Cr Systematics and Validating the 60Fe-60Ni Chronometer**

The 53Mn-53Cr chronometer has great potential for dating aqueous alteration in chondritic meteorites. Aqueous alteration produces minerals such as calcite and fayalite with very high Mn/Cr ratios, and secondary ion mass spectrometry (SIMS) can easily measure the 53Cr excesses in these phases. Until recently, the SIMS measurements have not been properly standardized, and the inferred chronology has been confusing. Recently, however, our group and Dr. Sugiura s group in Japan have put a lot of effort into producing matrix-matched standards for Mn-Cr measurements. With the new standards, the dates for secondary phases in UOCs, CM, CV, and CR chondrites have converged on ~ 4 myr after CAIs. We want to take this work to the next level.

1) We will develop new standards for calcite and dolomite, and, perhaps, other carbonates to reduce the uncertainties from the Mn/Cr relative sensitivity factors. The new calcite standard developed by Sugiura s group is zoned, which makes it difficult to use.

2) We will improve the precision of 53Mn-53Cr measurements. Currently the ages determined from carbonates have uncertainties of 20% - 33%. This is because of limited numbers of measurements on a given sample and relatively poor precision of the measurements. We will take special care to obtain high-precision data. A new Hyperion II ion source, which is the subject of a PME proposal to Emerging Worlds, would greatly facilitate this work. Together, improved standards and improved measurement precision should reduce the uncertainties in initial 53Mn/55Mn ratios to <10% (<~0.5 myr in the ages).

3) We will put the measurements of carbonates and fayalite into a better petrologic context. For example, we will look for multiple generations of carbonates such as has been described in MET 01070, and we will look for relationships among phases. Oxygen isotopes will be useful in this work.

The new high-precision data and detailed petrologic context should permit us to extract detailed information on the timing of alteration among meteorites of a given class, and perhaps among lithologic units within a given meteorite. We will initially concentrate on carbonates from CM chondrites, with samples representing levels of aqueous alteration from CM2.7 to CM2.0. We will also try to extend and improve the data on carbonates from CR chondrites. We will then turn to UOCs, looking primarily at fayalite.

In a closely related study, we will investigate the 60Fe-60Ni system in secondary minerals from primitive chondrites. There is currently no consensus on the abundance of 60Fe in the early solar system. SIMS measurements suggest initial 60Fe/56Fe ratios as high as 1x10^6, while bulk measurements of meteorites and chondrules suggest initial ratios below 3x10^-8. The main problem seems to be that Fe and Ni are mobile under the conditions experienced by most meteorites (Telus et al., 2016). We propose to get around this problem by measuring secondary Fe-rich minerals (fayalite, magnetite, hedenbergite) that were produced by the same alteration events that disrupted the 60Fe-60Ni system in the primary phases (olivine, pyroxene). If the initial 60Fe/56Fe ratio in the solar system was as high as ~(1-2)x10^-7, we should be able to detect evidence of 60Fe in secondary minerals. Preliminary measurements in fayalite and magnetite from Semarkona (LL3.0) and Kaba (CV3) have not given resolved initial ratios, although the upper limits on the initial ratios are consistent with values of (0.5-2)x10^-7. We have identified a large number of small fayalite grains in Kava and in several UOCs. Although the grains are small, can measure many of them. If our PME proposal for a new Hyperion II O- source is funded, we will easily be able to

measure a large number of these small fayalite grains and determine the level at which 60Fe was present in the early solar system.

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**Bermingham, Katherine/University of Maryland**
**A SEARCH FOR TECHNETIUM IN THE EARLY SOLAR SYSTEM**

The main goals of the proposed work are to constrain the provenance of material comprising the solar nebula, and potentially provide new constraints on the timing of very early Solar System fractionation processes. We will obtain siderophile element chemical and isotopic data from cosmochemical materials to address a long-standing question: Is there direct evidence of Tc in the early Solar System?

TASK 1: The focus of this task is to investigate the presence of now extinct radioactive nuclides 97,98,99Tc in the early Solar System. Many astrophysical models predict that Tc was present in the solar nebula, however, conclusive evidence for Tc has yet to be identified. If evidence were to be found for Tc, important constraints on the timing of very early metal fractionation processes in the early Solar System would be provided, including condensation of material in the solar nebula and early core formation. The short-lived 97Tc-97Mo (t1/2 ~4 Myr), 98Tc-98Ru (t1/2 4 ~ 10 Myr), and 99Tc-99Ru (t1/2 ~0.21 Myr) decay systems are associated with Tc. Published studies have resolved Mo and Ru isotope anomalies in refractory inclusions and whole rock meteorites, however, these have been attributed solely to nucleosynthetic effects. As contributions to these variations by the radiogenic decay of radioisotopes of Tc would be minor, high precision techniques are required to detect daughter products of Tc decay. We propose to search for direct isotopic evidence of Tc decay through the analysis of Mo and Ru isotopes in calcium aluminum rich inclusions and bulk meteorites (iron meteorites, diogenites, and angrites). These materials are chosen because the processes related to their formation likely fractionated Tc/Mo and Tc/Ru thus allowing appreciable daughter products to accumulate. Subtask 1 will focus on 97Tc-97Mo. Using our state-of-the-art analytical techniques which allows for 97Mo/96Mo <5.4ppm (2SD) precision, we are in the unique position to discriminate between nucleosynthetic isotope signatures and Tc decay products, and identify the presence of radiogenic Tc decay signatures evident by <10 ppm enrichments in 97Mo/96Mo. Subtask 2 will focus on the 98Tc-98Ru and 99Tc-99Ru by applying the same approach used in Subtask 1. We will use our experience with high precision isotope analysis of Ru isotopes to refine methods to resolve small radiogenic contributions from the decay of Tc. Because an estimate of chemical fractionation between Tc/Mo and Tc/Ru is desirable to interpreting the isotope data, a pilot study in collaboration with Dr. Elizabeth Cottrell (Smithsonian Institution National Museum of Natural History) will see the collection of partitioning data on Tc/Mo and Tc/Ru fractionation during metal-silicate fractionation (Subtask 3). The proposed work will provide the highest resolution constraints on 9xTc0 by virtue of the improved levels of analytical precision obtainable using N-TIMS and the new chemical constraints from the proposed partitioning experiments. In Subtask 4, the refined 9xTc0 data will be incorporated into models of Tc nucleosynthesis to address questions of Tc isotope synthesis and introduction into the Solar System in collaboration with Prof. Bradley Meyer (Clemson University).

METHODS: We will mainly use proven techniques for this study.

RELEVANCE: All of the proposed work is directly relevant to the aim of the Emerging Worlds program and falls within the scope of the Emerging Worlds program.

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**Zolensky, Michael/NASA**
**Characterization of Early Fluids and Regolith Processes on C-Class Asteroids**

This proposal has two tasks, both directed towards furthering our understanding of C-class (and related) asteroids with respect to the nature and activity of aqueous fluids on these carbonaceous asteroids during their formation and early history (first few 10s of million years).
In Tasks 1 and 2 we will continue our search through carbonaceous chondrites to locate aqueous fluid inclusions and measure the isotopic and chemical composition of the trapped fluids, and determine the mineralogy, organic chemistry, composition, structure and chronology of associated solid inclusions in the fluid-bearing crystals and associated secondary phases resulting from the fluids, by a coordinated and phased suite of analyses including scanning electron microscopy, X-ray computed micro-tomography, secondary ion mass spectrometry, laser ablation inductively coupled mass spectrometry, nanoscale liquid chromatography with Fourier transform mass spectrometry, two-step laser desorption/laser ionization mass spectrometry, confocal Raman spectroscopy, electron back-scattered diffraction, electron microprobe analysis, transmission electron microscopy, carbon X-ray absorption near-edge spectroscopy, and synchrotron X-ray diffraction. We are testing three hypotheses. (1) Direct samples of early solar system aqueous fluids ( water ) have survived in a variety of primitive meteorites and can be analyzed to provide critical information on the nature and activity of water in the c-class asteroids, which straddled the snow line in the early solar system. (2) The Monahans and Zag halite formed from hydro-volcanic plumes, and through analysis of the fluid and solid inclusions in the halite, especially the organic fraction, and comparison of these results to spacecraft observations of icy Saturnian and Jovian moons and, potentially the asteroid Ceres, we can confirm or disprove this origin, and if proven characterize the fluids and the rocky mantles and surfaces of the parent C-class asteroids. (3) Carbonaceous chondrite clasts in Zag, Carancas, Tsukuba, Plainview and NWA 8369 (all H chondrites) provide larger samples of the mantle and crust of the water-bearing world that produced the halite in Zag and Monahans  a water and organic rich world in the early Solar System.
The proposed work will provide new information on major processes affecting water- and organic-bearing planetesimals in the first few Ma of Solar System history, and therefore is directly relevant to the goal of "Emerging Worlds" to understand "the formation and early evolution of the Solar System" (ROSES 2017). In particular, it addresses  accretion of small bodies  and  early thermal and chemical processes  on these bodies. Our proposed research will also provide information on asteroid surfaces that will be critical to the OSIRIS-REx and Hayabusa2 missions.

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**Kaib, Nathan/University of Oklahoma**
**Understanding the Evolution of the Primordial Kuiper Belt During the Solar System's Early Years**

This proposal aims to develop additional constraints on the timing of the giant planet instability, conditions in the primordial Kuiper belt prior to this, and reassess the dynamical lifetimes of Kuiper belt binary objects. These goals will be accomplished through three research tasks focused on dynamical and collisional modeling. First, we will use dynamical models to reassess whether ultra-wide Kuiper belt binaries can in fact survive for the age of the solar system and, by extension, whether their modern existence offers robust constraints on the early solar system. Second, we will use a collisional and orbital simulation code to model accretion, fragmentation and the time evolution of the overall Kuiper belt size distribution within a massive primordial disk to determine the time required to generate the Kuiper belt size distribution and 1000+ Pluto-sized objects as a function of initial conditions. Finally, we will study how long primordial KBO binaries can survive within the massive pre-instability Kuiper belt as it grows and whether conditions in the primordial belt can explain the rarity of equal-mass binaries outside of the cold classical Kuiper belt. This proposed work will clearly advance the Emerging Worlds program's larger goal of understanding the formation and early evolution of the solar system.

**Nimmo, Francis/UC Santa Cruz**

**Driving asteroid dynamos by solidification and delamination**

Understanding the early thermal histories of small bodies (asteroids) forms an important part of inferring the initial stages of solar system evolution. Recently, it has become clear that some asteroids - those which underwent differentiation - also generated early dynamos. The aim of this proposal is to investigate a novel mechanism for generating asteroid dynamos. This mechanism makes predictions for asteroid dynamo characteristics which differ from previous models in terms of dynamo strength, duration and temporal variability. As such, it is testable with existing meteorite samples, and potentially with future spacecraft mission observations (e.g. Psyche).

We will focus on asteroid parent bodies which are primarily metallic and which, after differentiating, solidified from the outside in. The importance of this situation is that the outer, solid iron crust can record magnetic fields which are being generated by dynamo activity in the still-molten interior. Although several modes of solidification are possible, we will concentrate on the situation in which the dense crust undergoes delamination, with sections of the crust sinking as discrete blobs (diapirs). Such a mechanism has not been considered hitherto.

We will carry out an analytical treatment of this situation. Our objectives are to understand how the magnetic field strength and duration, depth and time of acquisition of magnetization, and the associated crustal cooling rate vary as a function of control parameters such as parent body size, initial sulphur content, and thickness of the overlying mantle.

The significance of this work is that it makes quite different predictions to existing theories: in particular, strong magnetic fields of brief duration and rapid asteroid solidification with high cooling rates are predicted. Measurements of meteorite characteristics can thus discriminate between the theories. Furthermore, we argue that for asteroids lacking a silicate mantle, a conventional thermally-driven dynamo is unlikely to operate. Our proposed delamination mechanism provides one possible way to explain how such bodies still acquired a remanent magnetization.

Cooling, solidification and elemental partitioning within meteorite parent bodies is a central aspect of our proposed work. As such, it is relevant to the Emerging Worlds theme ``Early thermal and chemical processes occurring on small bodies regardless of whether or when they differentiated."

**Korycansky, Donald/University of California Santa Cruz**
**Hydrodynamical simulations of crust and water redistribution by planetary impacts**

We will perform a series of calculations relating to the Moon-forming and other planetary impacts to focus on two issues. The first issue is the extent to which contamination of the Moon by the Earth s crust took place. The second is the amount of water from terrestrial oceans that was incorporated into the protolunar disk, or which escaped during the Moon-forming and other large impacts on the Earth.

We will use the well-tested SPH/tree-code of Fryer and Warren (2004). SPH (Smoothed Particle Hydrodynamics) is a Lagrangian method that represents matter by freely-moving particle elements. In combination with a tree structure for gravity calculation and neighbor finding, SPH/tree-codes are exceptionally well-suited for tracking material provenance and have been parallelized to make efficient use of multiprocessor machines with distributed memory. These properties make them the ideal choice for the challenge of simulating the Moon-forming impact. Complementary calculations will be performed using the Eulerian code CTH from Sandia National Laboratory to investigate impacts and escape on smaller scales and to assess the robustness of the SPH results.

The resolution of the proposed SPH simulations will for the first time make it possible to include planetary crusts and oceans self-consistently, for which 20 km resolution is the minimum requirement to resolve the shock at the planet's surface. Because the Earth s proto-crust was enriched in incompatible elements, addition of too much crustal material to the protolunar disk would violate the available constraints on lunar trace element bulk concentrations. This criterion provides a novel additional test of Moon-forming models.

Zircon evidence suggests the presence of liquid water at the surface of the Hadean Earth. Although surface oceans can not yet be fully resolved, we will carry out preliminary studies to investigate how much water is transferred from the surface to the protolunar disk. Doing so is important because of abundant recent evidence for at least locally high water concentrations in lunar magma source regions. The SPH simulations will use 10^8 to 10^9 particles and achieve spatial resolutions on the order of 10 km in the Earth and 100 km in the Moon-forming disk. These resolutions are 10 times finer than those in state-of-the-art simulations published to date, which typically deploy only 10^5-10^6 particles.

Our simulations will also provide a qualitatively and quantitatively better description of the Moon-forming disk, by vertically resolving the disk and reducing numerical viscosity into the estimated range of physical viscosities. Preliminary calculations done by us using 10^8 particles have shown that the proposed research using hundred-million and billion particle simulations is not only timely but can provide a quantitative improvement in our understanding of the origin of the Moon

Relevance to the Emerging Worlds Program: This proposal is relevant to the goals of the Emerging Worlds research program, as laid out in section C.2, section 2, of the ROSES 2017 document. Specifically, under the Program Scope, our proposal addresses theoretical and modeling investigations of formation and global differentiation of solar system bodies and processes that occur during that event. The proposed work is concerned with collision processes that had significant effect on the structure of the target bodies (Earth and Moon), and will address key geochemical and geophysical processes in early planetary evolution and terrestrial history in terms of general Solar System processes.

**Hirschmann, Marc/University of Minnesota**

**Hydrogen, water, and fluorine during accretion and magma ocean differentiation of the terrestrial planets and the Moon**

To better understand the accretion of volatiles to terrestrial planets, small planetary bodies, and the Moon and their distribution owing to initial differentiation, we propose two projects. The first focuses on the role of magmatic H2 in the acquisition of hydrous components in accreting planets and protoplanetary embryos. The second extends our studies of H and F in silicate minerals from the Moon.

Magmatic molecular H2 in early planetary differentiation
Key Objectives: We will determine the solubility of H2 in planetary magmas in order to better understand H mass transfer and associated chemical reactions during differentiation of small and large bodies in the early solar system.

Both hydrogen gas and silicate magmas were abundant during planetesimal and protoplanet accretion and differentiation. Under reducing conditions, magmas dissolve H in part as molecular H2, which allows direct ingassing of nebular H2 to planetary embryos and protoplanets and may facilitate outgassing of magma oceans to primordial atmospheres. Some ingassed H2 may be retained in early planetary mantles and some may partition into metallic cores. Redox reactions between the different forms of magmatic H (H2O and H2) and Fe (FeO, metallic Fe) have important consequences for sequestration of H in cores and for the oxidation state of mantles. Solubility of H2 in magmas remains poorly quantified. No data are available on compositions relevant to early planetary differentiation, and the temperature dependence is not known. Crucially, analytical quantification remains highly uncertain. Previous experiments were quantified using FTIR absorption coefficients calibrated from SiO2 glass, but the calibration could be quite different for natural aluminosilicate glasses.

Methods and Techniques: We propose the first measurement of IR absorption coefficients for aluminosilicate glasses by gravimetry and SIMS (Task 1) and new H2 solubility experiments to calibrate an ionic porosity model that will predict H2 solubility as a function of pressure, temperature and melt composition (Task 2). We will apply these to ingassing and outgassing of H2 during protoplanet and planetary accretion and differentiation.

Lunar F and H from study of silicate minerals
Key Objectives: We will document the volatile inventory of the Moon in its earliest stages of differentiation by highly sensitive analysis of F and H in lunar silicate minerals.

The abundances of lunar volatiles, their delivery and retention remain controversial. In contrast to early FTIR results, our SIMS analyses indicate that plagioclase from ferroan anorthosites are now chiefly dry, though they may have contained greater H during their formation. In contrast, the plagioclase retain small amounts of F. Given appropriate partition coefficients, this would allow calculation of the F content of the LMO, and constrain the acquisition of moderately volatile elements during lunar accretion. Paired with OH/F ratios determined from apatite, direct determination of F in lunar magmas from plagioclase and pyroxene could provide refined constraints on H2O in important lunar reservoirs.

Methods and Techniques: In Task 3, we will use SIMS to determine F (and, if present, H) in Mg-suite rocks and K-rich and Al-rich basalts to constrain the F and H2O content of KREEP-related magmas. In task 4, we will conduct high temperature and high pressure partitioning experiments of F that are needed to convert observations from plagioclase to magmas of the LMO and therefore to understand the origin and fate of volatiles on the early Moon.

Relevance to Emerging Worlds  Interactions between hydrogen and molten silicate  are a key mode of mass transfer during formation and differentiation of planetesimals, embyros, and protoplanets.  Evidence of abundances of F and H in the early Moon documents the acquisition and retention of volatile material during formation and differentiation of the Earth-Moon system

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**Telus, Myriam/UC Santa Cruz**

**60Fe-60Ni systematics of chondrules: Constraining the conditions and timing of solar system formation**

The former presence of 60Fe in the solar system has been detected in meteorites. However, in order to use the 60Fe-60Ni system to address fundamental questions about the astrophysical conditions and chronology of the solar system s formation, the initial 60Fe /56Fe ratio of the solar system must be constrained. Progress toward constraining the initial abundance of 60Fe in the solar system has been hindered by discrepancies between in situ and bulk analyses and likely stem from late-stage open-system Fe-Ni mobilization. The (60Fe/56Fe)SS ratios inferred from bulk chondrule analyses are all consistent with <3×10-8. An initial ratio at this level is more consistent with 60Fe being inherited from the galactic background during the Sun s formation. In situ analyses of chondrules often infer initial solar system ratios that are an order of magnitude higher than estimates based on bulk data.  Telus et al. (2017) infer an (60Fe/56Fe)SS between 5×10-8 and 3×10-7 based on 60Ni excesses of 200 to 700 in chondrules from unequilibrated ordinary chondrites. However, isochrons for chondrules that have resolved excesses in 60Ni are often significantly disturbed based on the poor correlation between excess 60Ni and the Fe/Ni ratios. Synchrotron X-ray fluorescence mapping of unequilibrated ordinary chondrites chondrules shows evidence for extensive open-system Fe-Ni redistribution between chondrules and the surrounding matrix material (Telus et al., 2016), providing an explanation for the poorly correlated internal isochrons and the discrepancies between in situ and bulk Fe-Ni data.

To better understand the 60Fe-60Ni systematics in chondrules and to constrain the initial abundance of 60Fe in the solar system, we will carry out coordinated in situ and bulk Fe-Ni analyses in chondrules from various chondrites. This study is divided into 5 parts:

1.) We will first thoroughly characterize chondrules from various chondrites using synchrotron X-ray fluorescence prior to isotope analyses.

2.) We will synthesize matrix-matched standards.

3.) We will carry out in situ Fe-Ni secondary ion mass spectrometry using the new Hyperion duoplasmatron source on a large geometry SIMS, which makes it possible to measure Ni isotopes in situ to higher precision and spatial scales than before, allowing us to target areas in between Fe-Ni alteration veins.

4.) A subset of samples will be analyzed for in situ Fe-Ni isotopes using resonance ionization mass spectrometry.  This technique provides higher Ni yields and little to no interferences.

5.) A subset of samples will be analyzed for high precision bulk Fe-Ni analyses using ICPMS.

Combining detailed 3-dimensional synchrotron X-ray mapping of the Fe-Ni distribution in chondrules with coordinated in situ and bulk isotope analyses is the most effective way to finally constrain the initial 60Fe/56Fe ratio of the solar system. This study has broad implications for the stellar source of short-lived radionuclides, the conditions of the solar system s formation, and the chronology of early solar system

processes. It is relevant towards NASA Emerging Worlds goal to address fundamental questions about how the Solar System formed and evolved.

References:

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Telus M., Huss G. R., Nagashima K., Ogliore R. C., and Tachibana S. (2017, in review) In situ 60Fe-60Ni Systematics of Chondrules from Unequilibrated Ordinary Chondrites

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**Liu, Ming-Chang/University of California, Los Angeles**
**Probing solar nebula environments: Isotopic heterogeneity in the earliest condensates**

We propose to carry out coordinated petrologic, mineralogical and isotopic investigations of early-formed nebular condensates preserved in chondritic meteorites in hopes of better constraining the earliest environments in the solar nebula. This project is aimed to shed light on the (astro)physical and chemical processes that resulted in the formation of Solar System s first solids, and the isotopic inventories in which these solids condensed. This is directly relevant to the goals of Emerging Worlds solicitation to understand the formation and early evolution of the Solar System and the research areas of 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 .

Ca-Al-rich Inclusions (CAIs) are the oldest dateable solids in the Solar System, with a radiometric age of 4.567 billion years determined on a few large CAIs. In this proposed work, we plan to study two subtypes of CAIs. The first subtype, namely fine-grained CAIs, consists of aggregates of micron-sized dust that directly condensed out of the nebular. Therefore, the chemical and isotopic characteristics of the fine-grained CAIs reflect the conditions of the nebular gas in which these CAIs formed. The second subtype of CAIs, which are also early nebula condensates, is hibonite (±corundum) bearing inclusions. They are thermodynamically predicted to be the first mineral phases directly condensing from a cooling gas of solar composition around 1600 1770 K at ~10-3 bar. Such inclusions provide an excellent opportunity to study the environment in the hottest stage of the Solar System history; however, they have not been well studied due to their rarity and small sizes (usually 50 microns or less).

In this proposal, we will focus on the CO 3.0 chondrites, as they are known to be more pristine, and have been reported to have more enriched in fine-grained CAIs and hibonite (±corundum) bearing inclusions, than other groups of carbonaceous chondrites. Our collaborators, Prof. Brearley, Drs. Krot, Keller and Han, have identified some fine-grained CAIs and hibonite (±corundum) bearing inclusions in CO3.0 chondrites. We will also perform in-situ searches for more of these rare inclusions and petrological studies of them on thick sections with scanning electron microscopy, followed by oxygen isotopic measurements with the new CAMECA ims-1290 at UCLA to better constrain the oxygen isotope reservoirs in the gas. Once the oxygen isotope analyses are finished, measurements for 26Al-26Mg (chronology) and 10Be-10B (irradiation histories of dust and gas) systems will be also performed on the ims-1290 ion microprobe by using a radio-frequency oxygen ion source, whose small yet intense primary ion spot will allow for isotope analysis of individual phases within a small inclusion. When isotopic analysis is accomplished, peculiar samples (e.g., carry unusual isotopic anomalies) will be sent to our collaborators laboratories for transmission electron microscopy (TEM) study. A comprehensive picture of the formation environments

of fine-grained CAIs and hibonite (±corundum) bearing inclusions will be constructed by using all the mineralogy, petrology and isotopic characteristics obtained in this proposed work.

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**Weisberg, Michael/Kingsborough College City University New York**
**Origin and Thermal History of Enstatite Chondrites**

The enstatite chondrites are important for understanding the evolution of the inner Solar System. They have stable isotope compositions similar to the earth and moon, suggesting a genetic relationship and may be analogues of the primitive materials that accreted to form the Earth or are possibly products of the event that formed Earth s moon. The enstatite chondrites are extremes in the conditions that resulted in the properties of primitive meteorites having mineral assemblages that suggest highly reducing conditions. Their constituent components (chondrules, metal, sulfides, matrix) are markedly different from those of any other chondrite groups. The origin of EH3 and EL3 enstatite chondrites and their components is highly controversial and the Solar System environment in which their unusual properties developed is poorly understood. EL3 chondrites and their components have been interpreted to be the result of brecciation and impact melting and they have also been interpreted to be primitive Solar System materials. The proposed research is focused on the origin and evolution of enstatite (EH3 and EL3) chondrites and the planned analyses are targeted at testing hypotheses for the origin of their components (chondrules, fragments, metal-rich nodules and matrix) and relationship to other chondrite groups and Earth-Moon. The PI s goals are to (1) decipher the pre-accretionary and asteroidal evolution of enstatite (E) chondrites, (2) evaluate the thermal histories of E chondrites, determine which ones are the most primitive and establish petrologic (metamorphic) grades for EH3 and EL3 chondrites, (3) unravel age relationships of E chondrite components, (4) understand the relationship between EH and EL chondrites and their parent asteroids, (5) assess the role of impact in the evolution of E chondrites, their components and parent asteroids. The PI proposes a program that will include petrologic-geochemical consortium studies employing a variety of analytical techniques. Five closely related tasks targeted at evaluating the origin of chondrules, matrix and metal-rich nodules in enstatite chondrites are proposed. These include: (1) Petrology and micro-distribution of oxygen isotopes in ALH 81189, a primitive EH3 chondrite, (2) Petrologic and isotopic study of chondrules in the EL3 chondrites. (3) Age relationships (26Al chronology) of chondrules in EH3 and EL3 chondrites. (4) Petrologic, trace element and isotopic studies of metal-rich nodules in EL3 chondrites and (5) Study of matrix and insoluble organic matter (IOM) in EH3 and EL3 chondrites.

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**Durda, Daniel/Southwest Research Institute**
**Particle Aggregation in Microgravity: Parabolic Aircraft Experiments**

Science Goals and Objectives

The primary goal of the proposed research is to achieve a better understanding of the dust aggregation stage of planet formation in protoplanetary nebulae. A crucial step in the earliest stages of planet formation is the growth of solid bodies in the millimeter to meter size range by the aggregation of millimeter- to sub-millimeter-scale dust grains. The process by which dust aggregated into planetesimals is not well understood; experiments without the effects of gravity are needed to investigate it. The primary science objectives of the proposed work are as follows: to determining the effects of: (1) particle size; (2) number density; and (3) composition on the aggregation (accretion) of dust-scale grains in microgravity conditions.

Methodology

The investigation would build on our previous record of successful microgravity experiments with granular materials (Love et al., 2014) to extend these results to additional materials and particle containers, using more advanced methods and analyses. The proposed work focuses the bulk of its experimental investigation on granular media relevant to protoplanetary environments, such as various silicate minerals and powdered ordinary and carbonaceous chondrite materials. The results of the proposed work would greatly constrain particle aggregation and cluster growth in the early protoplanetary disk.

Relevance to Call

The Scope of Program for Emerging Worlds includes "investigations related to understanding the formation and early evolution of our Solar System". This proposal is focused on research directed at "protoplanetary disk formation and evolution, physical processing of dust, and the formation and accretion of solar system bodies" by conducting microgravity experiments on the aggregation of millimeter- to sub-millimeter-scale grains under conditions relevant to those in the early protoplanetary nebula. The proposal also explicitly involves the subsequent analyses and publication of these experimental data.

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**Sharp, Thomas/Arizona State University**
**Investigating the early impact history of the solar system in meteorites**

Impact processes are an important part of the early history of the solar system, and the resulting shock effects in meteorites provide a record of impacts and solar system dynamics (Scott 2002; Consolmagno and Britt 2004). However, most of what we have learned about shock metamorphism in ordinary chondrites and Martian meteorites represents relatively late solar system impact events (Swindle et al. 2014; Moser et al. 2013). Our knowledge of highly shocked meteorites is strongly influenced by the large quantity of shocked L chondrites, which were predominantly shocked in a large impact event at 470 Ma (Turner 1969; Bogard et al. 1976; Korochantseva et al. 2007; Heck et al. 2008; Weirich et al. 2012). As a result, we know relatively little about shock effects from solar system impact events older than 4150 Ma. 40Ar/39Ar ages of impacts in ordinary chondrites (Turner 1969; Bogard et al. 1976; Turner 1978; Bogard 1995; Korochantseva et al. 2007; Swindle et al. 2009; Swindle et al. 2014) demonstrate that many chondrites have experienced impact events > 4150 Ma. The goal of the proposed study is to investigate shock effects, shock conditions, annealing and impact ages in the earliest shocks recorded in ordinary chondrites to better understand impact processes in the first 400 Ma of solar system history.
Shock effects in meteorites are well preserved in rapidly quenched samples, but they can be partially or completely annealed after shock or during thermal metamorphism. Deformation and transformational microstructures that survive can be used to investigate both shock and post-shock processes. 40Ar/39Ar ages provide a chronological history of impact events in meteorites in addition to constraints on time-temperature histories (Swindle et al. 2014). We propose to perform detailed mineralogical and microstructural analysis of chondrites shocked in the oldest post-accretion impact processes. We will use polarized-light microscopy to classify the shock stage and map out local shock melting and transformation in samples that have 40Ar/39Ar ages > 4150 Ma. We will use Raman spectroscopy and synchrotron X-ray diffraction to identify high-pressure minerals formed by shock. We will use backscattered electron imaging and energy dispersive analysis with our field-emission SEMs to characterize nano-scale deformation, melting and reaction microstructures. We will use the focused-ion-beam lift-out technique to prepare samples for analytical transmission electron microscopy (TEM). TEM will be used to identify and characterize nano-mineralogy, nanometer-scale reaction structures, deformation microstructures and annealing effects. Finally, we will use 40Ar/39Ar dating to refine the ages of some of the oldest shocked samples to better evaluate the timing of early impact processes. These data, combined with published 40Ar/39Ar age data, will be used to provide a detailed record of shock

effects, shock conditions and post-shock annealing in the oldest shocked materials in the solar system. This data will provide new insights into the role of impacts and shock in the metamorphism of asteroids in the early history of our solar system

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**Lyons, James/**
**O, N, and C-isotope fractionation due to self-shielding of CO and N2 in the solar nebula**

NASA Emerging Worlds Step 1 proposal (2017)

Title: O, N, and C-isotope fractionation due to self-shielding of CO and N2 in the solar nebula

PI: James Lyons, ASU; CoI: Glenn Stark, Wellesley Coll.; CoI: Cheuk Ng, UC Davis

Introduction: Self-shielding of CO is presently the preferred mechanism for explaining the 60 permil enrichment in 17O and 18O measured in terrestrial planets and meteorites relative to the solar photosphere. Previous self-shielding models have used a wavelength-independent approximation known as shielding functions to compute O isotope fractionation in the nebula. Through previous NASA grants, we have compiled a set of very high quality FUV cross sections for CO isotopologues. With these data, we can quantitatively evaluate CO self-shielding for a range of nebular locations and for any stellar FUV spectrum. To do this we must first complete the reduction of our isotopic CO cross section data. We also need quantum yield measurements for the very important CO E(0) band. As a parallel effort, and with collaborators, we will develop a coupled-channel (CSE) model for CO isotopologue cross sections informed by our data that will allow us to model CO isotopologue absorption spectra at the full range of temperatures needed for solar nebula modeling. With our CO isotopic cross sections, we will evaluate O and C isotope effects due to self-shielding. A CSE model already exists for N2, and will be used to model N2 self-shielding to predict d15N for HCN and NH3 produced photochemically in the nebula. Our nebula models will be run with several forms of turbulent transport to reflect the recent work arguing that the magnetorotational instability may be less important than previously believed due to dissipative effects. Finally, we will make a preliminary assessment of the transfer of O isotope signatures in water to nebular silicates.

Proposed research:
1. O isotopes. This task is composed of several subtasks. i) Complete analysis of our isotopic CO cross section data. This is in collaboration with our colleagues in the US and France. ii) Measure isotope-dependent quantum yields for the E(0) band of CO. This is the strongest dissociating CO band, and the present uncertainty in quantum yields is introducing large uncertainties into nebular model results. iii) Measure the absorption spectrum of 12C16O at 1000 K. iv) Develop a CSE model for CO cross sections from 90 to 110 nm. This will performed in collaboration with European collaborators. v) Run solar nebula model with full O isotope CO cross sections.
2. C isotopes. Add C isotopes to solar nebula model. Run using full CO cross sections.
3. N isotopes. Evaluation of 15N enrichment due to N2 self-shielding in the solar nebula. The d15N enrichment of the terrestrial planets and meteorites including hot spots is well known. We will model these effects due to N2 self-shielding using highly precise N2 cross sections.
4. Nebular silicates. Evaluate O isotope exchange of nebular water with silicates and CAIs. To explain the inner solar system via self-shielding, nebular silicates had to exchange O with H2O. We have previously argued that such exchange is slow for CAIs. Here we will evaluate exchange quantitatively for chondrules and CAIs.

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**Steckloff, Jordan/Planetary Science Institute**
**Early Evolution and Survivability of Amorphous Water Ice Within Small Icy Bodies**

Goals

Amorphous water ice (AWI) is expected to form in the outer solar disk and later incorporated into larger bodies in the outer Solar System. The transformation of water ice phases and their stability conditions are major contributors to the thermal balance and chemical reservoirs of surface and sub-surface materials. Because the crystallization of pure AWI is highly exothermic, it has been often proposed to be the energy source driving activity and alteration of cometary bodies (outgassing, outbursts, breakup). Additionally, AWI can trap highly volatile species (CO, N2, CH4) and noble gases (Ar, Xe, etc.) and release them upon crystallization. Therefore, AWI would allow highly-volatile species to be present within comets under relatively warm conditions, consistent with observations. Thus, any surviving AWI could significantly affect the thermal balance and chemical reservoirs of cometary bodies in the present day.
However, the ultimate fate of amorphous water ice is uncertain. Planetary migration scenarios early in the Solar System dynamically destabilize icy populations and emplace icy bodies in distinctively different thermal and collisional environments. These environments may significantly affect the survival of AWI (and its trapped volatile species), altering its distribution within a given object and across the Solar System. However, the combined effects of these processes have never been systematically studied. Additionally, cometary activity and chemistry may be explained by proposed mechanisms that do not rely on the presence of AWI. This knowledge gap is particularly acute now that high-resolution observations and in-situ exploration of icy bodies (e.g., comet nuclei, KBOs and icy moons) have revealed these worlds to be diverse in volatile species and activity. Therefore, to understand the dominant physical processes driving cometary activity and evolution, it is critical to determine if amorphous water ice can even survive early Solar System evolution.

Methodology

We propose to create sets of models that track the conditions of water ice phase alteration as a function of physical, thermal, and dynamical conditions. We will first explore the effects of collisional processes on the survival of AWI using laboratory experiments to understand the energetics and phase change behavior of both pure and impure AWI (without/with the presence of silicate dust and volatiles). We will then use numerical thermophysical models and the iSALE hydrodynamics code to investigate the conditions under which AWI within and at the surface of small icy bodies survives impact-induced shock processing and thermochemical evolution early in the Solar System s history.

Relevance

ROSES 2017 states that the Emerging Worlds program [EW] solicits research proposals to conduct scientific investigations related to understanding&the early evolution of our Solar System. The call further clarifies that for studies of processes that occurred on small bodies, the intent is to cover processes that can be reasonably inferred to have occurred and were most prominent up to the time that large planetary bodies were in or near their modern configuration. The scope of EW therefore clearly includes studies of evolutionary processes of small bodies (such as collisions) that directly resulted from planetary migration, during which the planets of our Solar System were reaching their current configuration. The supported investigations may include theoretical studies, analytical and numerical modeling&[and] laboratory studies. As our proposed work is a combination of theoretical, analytical, numerical and laboratory studies, our proposed investigation is within the scope of EW. Finally, because our proposed investigation focuses on the early evolution of AWI within small, icy bodies, (up to the time at which the planets obtained their current configurations), our proposal is specifically excluded from the Solar System Workings program.

**Ehlmann, Bethany/California Institute of Technology**

**Isolating and Understanding Spectrally Active Constituents in Carbonaceous Chondrites: Linking Meteorite to Telescopic and Spacecraft Data**

Carbonaceous chondrites are naturally delivered samples from asteroid parent bodies. Linking these meteorites to asteroids and, more fundamentally, understanding the causes of observed variations in asteroid spectral properties requires understanding how spectral attributes are affected by the presence and absence or prevalence of phases (mineral, mineraloid, and volatile) and chemical indicators of alteration. Studies of most- and least-altered carbonaceous chondrites show variations in the presence/absence of a 0.7 µm absorption due to iron in phyllosilicates, 1.0-1.5 µm absorptions due to mafic minerals, 2.7-3.0 ¼m absorptions due to OH/H2O, and silicate features from 8-12¼m. Similarly, telescopic and spacecraft spectral data of primitive asteroids show these absorptions are present. They are used to classify and understand processes affecting primitive solar system bodies; there is also substantial, less understood spectral diversity in absorption features from 2.5-4.5 ¼m, attributed to metal-OH, NH3, carbonate, and possibly organics and water ice. Spectroscopic work with meteorites to link with the asteroids has, to date, focused on the spectral properties of ground, bulk powders, the preparation of which has destroyed or homogenized any pre-existing heterogeneity.

Here we will use microimaging reflectance spectroscopy to characterize not only the bulk properties of carbonaceous chondrite samples, but also to examine the heterogeneity of chondrite and matrix mineral assemblages, recognizing small (hundreds of microns to mm) zones of spectrally distinct materials. Our study will focus on a subset of key primitive materials, presently postulated to be the most directly related to primitive asteroids and carbonaceous mission-target asteroids (Ceres, Bennu, Ryugu), specifically, C1, ungrouped C2, CM2, CR and CV samples. C-chondrite clasts of diverse degrees of alteration are known to occur in brecciated non-carbonaceous meteorites and in carbonaceous chondrites. We will identify and provide spatially resolved maps of absorption band depths and band positions, focusing on all variability with special attention to that also observed in the asteroids. We will focus on characterization of matrix, clasts, and chondrules, identifying and mapping heterogeneous spectral classes, and identifying specific mineral phases via follow-on microprobe analyses to understand, at pixel to subpixel scales, the constituents responsible for observed spectral variability.

This study examines the results of early thermal and chemical processes occurring on small bodies to understand the origin of meteorites link these to asteroid compositional groups. We hypothesize that this study may refute or conform to and extend correlations between some chemical indices of alteration and visible and infrared features (Takir et al., 2013; McAdam et al., 2015), confirming or refuting the hypothesized species responsible. Alternatively or additionally, this study will reveal whether observed differences in spectral properties and aqueous-alteration metrics in C-chondrites are the result of (a) mixing in different proportions of clasts from multiple source regions or parent bodies with diverse, pre-assembly alteration states, or (b) different degrees of homogenizing alteration on the parent body(ies) of the post-assembly chondritic breccias. Such may allow the recognition of Ceres- or 52 Europa-like spectral classes within the existing meteorite collection. By determining the linkages between spectral properties and phases responsible, we will enable improved interpretation of telescopic and spacecraft data from primitive bodies.

**Nimmo, Francis/UC Santa Cruz**
**Implications of early mass loss from small, warm bodies**

The processes of early volatile retention or loss in small bodies have a direct influence on the final volatile budgets of outer solar system moons and dwarf planets. The main objective of this proposal is to carry out theoretical models of a novel mass-loss pathway which was likely important: vapor outflow driven by high surface temperatures. Model results will be compared with available observational constraints to identify bodies in which this particular process was important.

The mass loss rate depends on the vapor thermal velocity compared to the escape velocity, so that small, warm bodies are most vulnerable. The loss rate also depends on the power available. The principal power source that we will consider is that from accretion. This can be substantial if formation is rapid, e.g. via pebble accretion (for Kuiper Belt Objects). The mass loss happens early (as defined by the Emerging Worlds call): it happens while accretion is still occurring. Mass loss is thus potentially early enough that nebular gas is still present - which could significantly change the outcome.

We will calculate the mass loss rate and the attendant changes in bulk density and isotopic fractionation - all of which are potentially measurable effects - under various scenarios for both large Kuiper Belt Objects and the Galilean satellites. The calculations will be based on similar approaches which have been applied in the past to terrestrial planets and to exoplanets.

For Kuiper Belt Objects, our approach will provide a test of the hypothesis that they formed via pebble accretion. Rapid accretion drives volatile loss and may help to explain the density increase from Charon to Pluto to Triton. For the Galilean satellites, our mechanism can explain why there is a regular progression in density with semi-major axis, and also explains the lack of such progression for the Saturnian and Uranian satellites.

There are several potentially significant outcomes of our work. First, we are proposing a novel mass loss mechanism. Second, we can test particular accretion scenarios (e.g. pebble accretion for Kuiper Belt Objects). Third, we can test our hypothesis by investigating whether more volatile substances (e.g. N2) can be retained during accretion. Our proposal investigates the early volatile evolution of small bodies, and is thus highly relevant to the Emerging Worlds theme of early evolution, and the overarching science question of how the Solar System formed and evolved.

**Lapen, Thomas/University of Houston**
**U-Th-Pb chronology of HED meteorites: Implications for the magmatic evolution and early thermal history of asteroid 4 Vesta**

Scientific Goals and Objectives: The proposed research consists of two tasks that address fundamental uncertainties in the absolute duration of magmatic activity and uncertainties in the nature and timing of metamorphic processes operative in the howardite, eucrite, diogenite (HED) parent body (asteroid 4 Vesta).

" Task 1 will investigate the duration of magmatism and the deep-crustal thermal history of asteroid 4 Vesta with high-precision U-Pb dating of petrologically and geochemically characterized zircon in basaltic eucrites and a zircon-bearing diogenite using chemical abrasion, isotope-dilution thermal ionization mass spectrometry (CA ID-TIMS).

" Task 2 will investigate the thermal evolution and timing of volatile-rich material mobility in HEDs by in situ U-Th-Pb (thermo)chronology of Ca-phosphate minerals using laser ablation, inductively-coupled plasma mass spectrometry (LA-ICPMS). We will address these questions: Did the period of late heavy bombardment (~4.1-3.3 Ga), as observed on the Moon, also occur on the eucrite parent body (4 Vesta and its remnants)? What is the significance of global versus discreet thermal events affecting the HED parent body? And, is the age of volatile-rich veining in eucrites early (coeval with magmatism) or late (related to subsequent thermal events)?

Both tasks will rely heavily on existing and new petrological characterizations of the samples selected for study. The proposal team has the equipment and expertise to facilitate all aspects of the proposed research, including assisting in the mentoring of the graduate student.

Methods: Task 1: Zirconium-rich minerals will be documented in the samples by X-ray chemical mapping of polished thin/thick sections. Petrologic imaging and high spatial resolution (50 nm) EBSD analyses will be conducted to search for evidence of microstructural damage associated with shock deformation related to impact. In situ trace element concentration and preliminary U-Th-Pb dating of 2-3 representative zircon grains from each sample will be done by LA-ICPMS High-precision U-Pb dates of zircon will be obtained through state-of-the-art chemical-abrasion ID-TIMS analyses applied to such initiatives as calibrating the Geological Time Scale Gradstein et al., 2012). The U isotopic composition of NWA 10666 will be measured by MC-ICP-MS at the University of Houston using established sample digestion, chemical separation, and U isotopic analyses by double spike (IRMM-3636). The sample solutions remaining after U-Pb chemistry of digested zircon contain the Lu and Hf from the digested minerals which can be further processed for isotopic analyses.
Task 2: Petrologic characterizations of samples will use light and e-beam imaging and EPMA for chemical analyses of constituent phases. U-Th-Pb isotope analysis, with precisions similar to or better than that of an ion probe, will be used to date Ca-phosphate minerals with very high spatial resolution (7-10 ¼m).

Relevance: The Emerging Worlds program seeks proposals that answer the fundamental science question of how the Solar System formed and evolved and explore and observe the objects in the Solar System to understand how they formed and evolve. The proposed study is relevant to the Emerging Worlds program in that we are trying to understand the timing of differentiation in early solar system bodies and the timing of formation of planetary crusts. In this case, we will investigate the timing of igneous processes in the HED parent body. We are also investigating the timing of volatile addition to the inner Solar System and thermal processes associated with impact heating that occur early (perhaps coeval with igneous activity).

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**Humayun, Munir/National High Magnetic Field Laboratory**
**Isotopic studies of siderophile elements in the early solar system**

The isotope compositions of siderophile (iron-loving) elements (e.g., Mo, Ru, Pd, W, Re, Os, Ir, Pt) contain a record of the processes that built the parent bodies of the numerous asteroids sampled by iron meteorites and chondrites. The Hf-W chronometer allows the precise determination of the time of chemical differentiation of the earliest-formed bodies in the solar system. The resolution with which W isotope ages can be determined is limited by the extent of the correction of cosmogenic neutron capture effects. How close in timing was the differentiation of the various bodies that lead to forming iron meteorites and chondritic metal? Is chondritic metal younger than that of iron meteorites?

Nucleosynthetic isotopic anomalies of elements heavier than the Fe-peak (e.g., Mo, Ru, Pd) reveal that meteorites exhibit deficits in the s-process isotopes relative to the Earth. We have recently shown that Pd isotope anomalies correlated with Mo-Ru isotopes exhibit evidence that the presolar carriers of these anomalies have been modified by thermal processing in the solar system. New measurements of the Ru-Mo system show distinct groupings of irons into those associated with carbonaceous chondrites and those associated with the enstatite and ordinary chondrite classes. How does Pd fit into this picture? How wide spread is the Pd-Mo correlation in meteorites, and does it remain constant when extracting the carriers by acid leaching of primitive chondrites? Recent work has revealed the presence of s-process excesses of Os isotopes in some ureilites, which likely occurred when the carriers of these anomalies underwent processing on the parent body of the ureilites. Did this also create Pd isotope anomalies? We propose the following tasks:

Task 1: Origin of nucleosynthetic isotope anomalies in the Pd and Os isotopic abundances in meteorites. We propose to search for correlated Pd-(Mo-Ru)-Os anomalies in ureilites, iron meteorites and chondrites.

Task 2: Early chronology of the solar system from W-Re-Os isotope abundances in meteorites. We propose to exploit the fact that neutron capture on W isotopes produces Re isotopes, which we measure precisely to correct the cosmogenic effects, and obtain higher fidelity W isotope chronology of irons.

Methodology: The proposed tasks will be accomplished by the analysis of the isotopic compositions of Pd, W, Re, and Pt by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) at Florida State University, and of Os by Thermal Ionization Mass Spectrometry (TIMS) with collaborator Alan Brandon at the University of Houston. We have published methods for Pd, W, Re, Os and Pt isotope measurements using these facilities. The MC-ICP-MS at FSU is under the control of the PI. Collaborator Thorsten Kleine will provide Pd cuts from their Mo-Ru studies.

Relevance: The proposed studies of nucleosynthetic anomalies and refined Hf-W geochronology help to answer the Strategic Science Goal  explore and observe the objects in the Solar System [meteorites, planets] to understand how they formed and evolve . The proposed research involves  studies of chemical and isotopic properties of planetary materials  and  studies of radiometric ages  including Hf-W and Re-Os ages. Nucleosynthetic isotope anomalies inform us about the  chemistry of events . . . relevant to the formation of planets, satellites, and minor bodies  and  to the early history of these bodies . As such, the proposed research falls squarely within the scope of the Emerging Worlds (EW) program at NASA.

**Young, Edward/University of California Los Angeles**
**Volatility in the Early Solar System**

OBJECTIVES: The overarching objective of the research outlined in this proposal is to elucidate the processes that lead ultimately to formation of Earth and other terrestrial-like planets in the solar system. Our primary focus will be on the sorting of elements and their isotopes by their relative volatilities. Two projects are proposed: 1) experiments simulating the chemical and isotopic effects of collision-induced melting of planet precursors; and 2) explication of possible crystal chemical controls on high-precision oxygen isotope ratios that could influence our interpretations of these data in extraterrestrial samples.

APPROACH: For the first project (the largest of the two), our approach is to test the emerging hypothesis that the isotopic compositions of rocky bodies in the solar system are the result of collisions. We propose a program of experiments to measure the chemical and isotopic consequences of melting and evaporation using chondritic starting materials. The 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 isotope fractionation during evaporation. Experiments will be performed by heating samples with an infrared laser as they are aerodynamically levitated in a gas of controlled composition. Bulk chemical compositions and isotope ratios for Si, Mg, Fe, and O will be measured in the evaporative residues produced under a variety of conditions (e.g., different values for fO2). Results from these experiments can be used to test quantitatively the hypothesis that evaporation during collisions was the primary control on the isotopic compositions of Si, Mg, Fe, and O (mass dependent only) comprising Earth, Mars, Vesta, and other bodies.

For the second project, we plan to followup on our earlier studies of lunar highland rocks showing that these samples have curiously low mass-independent oxygen isotope signals compared with lunar basalts. We have found a correlation between signals of this nature in terrestrial analogs and crystal chemical parameters, including bulk modulus and thermal expansivity. If this oxygen isotope signal is crystal chemical, it places a limit on the usefulness of ultra-high-precision oxygen isotope ratio measurements as a means for identifying distinct sources of oxygen in extraterrestrial samples. Ultra-high-precision oxygen isotope ratio measurements in lunar and terrestrial minerals representing different structures (e.g., orthosilicates vs. tectosilicates) are planned to resolve this issue.

RELEVANCE TO EMERGING WORLDS: 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. 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 goals of the program.

**Keller, Lindsay/NASA Johnson Space Center**
**Coordinated Analyses of Presolar and Early Solar System Materials**

This proposal requests support for a research program entitled Coordinated Analyses of Presolar and Early Solar System Materials, under the PI-ship of L. Keller. The work proposed is a natural progression of our ongoing collaborative studies of interplanetary dust particles (IDPs) and Ca- and Al-rich inclusions (CAIs) in primitive meteorites. The major focus of Task 1 will be a study of the nature and origin of presolar and early solar system materials preserved in anhydrous (cometary) IDPs. We propose detailed mineralogical, microstructural and chemical studies of circumstellar, interstellar and nebular grains that will be combined with coordinated isotopic measurements in order to elucidate their origins and histories as the building blocks of the solar system. This work will provide new constraints on solar nebular and interstellar processes and new insights into the nature of the earliest formed solids in the solar system.

Task 2 will build on our coordinated transmission electron microscopy (TEM)/ion microprobe analyses of hydrated IDPs rich in carbonaceous matter that are proposed to have a cometary origin. We have shown that some of these particles contain the products of reaction between 16O-poor water and anhydrous silicates that formed in the inner solar system as predicted by self-shielding models. Our preliminary oxygen isotopic compositions obtained from hydrated IDPs fall on a slope 1 line above the terrestrial fractionation line, as predicted for interaction with cometary heavy water. We will determine the mineralogy and chemical compositions of additional hydrated IDPs along with coordinated ion microprobe measurements of their O, N and H isotopic compositions. These studies may provide direct evidence for self-shielding in the early nebula as well as insights into oxidation and hydration reactions on comets and other outer solar system icy bodies.

Task 3 will focus on coordinated mineralogical, chemical and isotopic studies of ultra-refractory CAIs and Wark-Lovering rims. Our work has shown that non-equilibrium condensation reactions are prevalent in these materials. In particular, the complex microstructures in hibonite point towards a series of high temperature thermal events that occurred after CAI formation but prior to accretion into their parent bodies. We are focusing on ultra-refractory grains that have prior ion microprobe analyses for several isotopic systems including O and Al/Mg systematics. Building on our previous work, we will use a coordinated TEM/ion microprobe/focused ion beam approach to elucidate the origins and histories of these oldest solar system grains and processes involved in Wark-Lovering rim formation.

Our analytical approach utilizes nanometer-scale chemical mapping and microstructural studies using TEM analyses of focused ion beam (FIB) sections. The mineralogical, microstructural and chemical analyses are correlated with isotopic measurements from several isotopic systems on the same samples. With this approach, we determine the physical conditions of their formation and later alteration (e.g. T, P, fO2, phase assemblages) coordinated with time scales for these events from Al-Mg systematics and insights into isotopic reservoir interactions (H, N, O). The research proposed here builds upon our extensive development work on coordinated analyses by TEM and NanoSIMS in concert with other microbeam instruments. Together, these studies will provide new insight into long standing questions about the origins of the first solar system materials.

**Hauri, Erik/Carnegie Institution of Washington**
**Evolution of Hydrogen in the Inner Solar System: Volatile Abundances and Isotopic Compositions in CAIs and Chondrules from Primitive Carbonaceous Chondrites**

The abundances and isotopic composition of hydrogen in glasses & minerals from chondrules and CAIs can potentially provide information on the immediate environment in which they formed and/or subsequent modification in their parent bodies. In the inner solar system, end member volatile sources include the solar nebula gas and water ice; these two sources have D/H ratios that differ by up to an order of magnitude, and are also characterized by very different O isotope compositions. Additionally, coupled data on degree of hydration and O isotope compositions of chondrules and CAIs can potentially identify open-system behavior in phases that are used for Al-Mg, Pb-Pb, Sm-Nd and Hf-W chronometry.
Objectives: We will examine chondrules and CAIs in the most primitive (i.e., the least metamorphosed and aqueously altered) CO, CM, CR and CV carbonaceous chondrites, and the ordinary chondrites Semarkona, and MET00526, to determine if they (A) preserve evidence for volatiles incorporated from the solar nebula, potentially recording the partial pressure of hydrogen during their formation; and (B) record open-system behavior for H, O in their parent bodies. Nebular signatures can be overprinted by later interactions with low-temperature, H2O-rich fluids in chondrite parent bodies, accompanied by hydration and formation of molecular H2O in glass that is far in excess of the H2O/OH ratio typical of quenched high-temperature melts. This excess molecular H2O is readily observed by FTIR (so much so that it has formed the foundation of an H2O-diffusion-based dating method for obsidian tools in archaeology). We will use SEM, EPMA, SIMS, FTIR and Raman spectroscopy to focus on documenting the relationship between concentrations and isotopic compositions of H and O in chondrules and CAIs, and the H2O/OH ratio in chondrule glasses, in the least altered and metamorphosed chondrites, in order to determine the sources of hydrogen present in the earliest inner solar system. Our ultimate aim is the detection of nebular H in chondrules and/or CAIs. This will be challenging as not only do we expect concentrations to be low (though likely within the SIMS detection limits of our ~0.1 ppm), but we must also exclude the potential overprinting by thermal metamorphism and/or aqueous alteration. This study will provide constraints on the various models that exist to explain chondrule and CAI formation, and the sources of altering fluids and the mechanisms of fluid-rock interaction in the chondrites.
In past work, we have demonstrated a unique ability to detect very low levels of hydrogen silicate minerals and glasses by SIMS, with detection limits better than 0.1 ppm. Additionally, our prior work on lunar volcanic glasses and melt inclusions has demonstrated that we can obtain reliable data on H isotopes at total H concentrations <0.6 ppm (5.4 ppm H2O), and spatially-resolved analyses of hydrogen isotopes at the micron scale obtained by scanning ion imaging SIMS. We are thus in the best possible position to address the problem of identifying and characterizing the volatile signatures of the high-temperature components in carbonaceous chondrites.
Relevance: This study will address several objectives of the Emerging Worlds program, including: (1) protoplanetary disk formation and evolution, (2) nebular transport mechanisms, (3) large-scale chemical and isotopic fractionation processes, (4) chemical processing of gas, dust and ice, (5) the chemical properties of ancient materials (CAIs, chondrules), (6) early thermal and chemical processes occurring on small bodies, and (7) processes that occur on solar-system bodies during the period of global differentiation. The project will support a postdoc at the Carnegie Institution of Washington and provide analytical support for a graduate student at Northwestern University.

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**Hartlep, Thomas/NASA Ames Research Center**
**Collisional growth of aggregates in the turbulent protoplanetary nebula**

GOAL:

This proposal aims at investigating the conditions under which particles in the protoplanetary nebula, and perhaps the dense molecular cloud that preceded it, can form the very first aggregates by collisional sticking, in an effort to explain the observational evidence from meteorites and interplanetary dust particles (IDPs).

METHODOLOGY:

Chondrites (stony meteorites) contain apparently size-selected 0.1-1mm-(or so) particles (chondrules), and in at least one example (NWA 5717), there is preliminary evidence for aggregates of chondrules which differ significantly from each other in their chemical and isotopic composition but have nearly identical size distributions. Other examples of aggregates come from cometary IDPs. Based on the several cases so far studied, IDPs are apparently made out of monomers with approximately the same radius-density product, indicating similar aerodynamic stopping times. The case is even stronger than previous studies of metal and silicate particles in chondrites, because several different IDPs present a wide range of well-defined radius-density product even though within each IDP, the radius-density clustering is quite strong. Whether IDPs and their GEMS (non-crystalline) constituents are formed in the protoplanetary nebula or in the immediate precursor interstellar medium remains a subject of intense debate, to which this proposal will contribute. The intensity of turbulence in the nebula has also been debated for decades, but it is not hard to find regions in the nebula where chondrules have gas drag stopping time on the order of the Kolmogorov (smallest) eddy time (Stokes number St of unity). Similarly, one can find conditions in the outermost solar nebula, perhaps scale heights above the midplane, or even in the dense core of the precursor molecular cloud, where IDP monomers may have St~1. Recent numerical simulations and theoretical work suggest that St~1 particles show enhancements in their local volume density given by the radial distribution function (RDF), and reduction in their relative velocities V_rel (which would aid in sticking if V_rel is close to the sticking limit), compared to both larger and smaller particles. The RDF and V_rel (and the associated sticking coefficient) are ingredients for the collisional sticking kernel, which determines the growth rate of aggregates, and except for a few pioneering papers (which reach conflicting results regarding the kernel) have not been studied in detail. In this project we will use new, large numerical simulations of particles in turbulence, and new theoretical models of the physics involved, to focus on the effects of preferential size-dependent aerodynamics on the very first stage of the growth of primitive solid particles.

RELEVANCE:

Our results will have implications for the very first stages of growth in the chondrule/chondrite formation region, the IDP/comet formation region, and perhaps even the dense molecular cloud, where some aggregates or sub-aggregates of IDPs might have formed. It has recently been found that collective-growth born-big models of asteroids cannot succeed in moderately turbulent nebulae unless some degree of growth into aggregates can proceed to at least a few cm size. Thus, growth by sticking now becomes an inescapable, fundamental bottleneck that must be understood. There are observations of chondrites and IDPs that support some degree of growth by sticking, and will constrain our modeling, but they are hard to understand using only conventional models with currently accepted collision and sticking velocities because growth tends to stall at a bouncing barrier . Our work will illustrate how the next level of sophistication in growth physics which is already being studied in the larger fluid dynamics community - might explain the IDP and chondrite observations, and allow primary accretion of inner and outer solar system planetesimals to proceed by a combination of collective effects.