Emerging Worlds
Abstracts of selected proposals
(NNH19ZDA001N-ROSES)

Below are the abstracts of proposals selected for funding for the Emerging Worlds 2019 program. The abstracts are listed by Principal Investigator (PI) name and include institution and proposal title. One hundred proposals were received in response to this opportunity. On October 29, 2019, 21 proposals were selected for funding.

Aaron Bell/University of Colorado Boulder
The Angrite Redox Conundrum: Shedding New Light on Angrite Petrogenesis by Testing Models of Primordial Asteroidal Melting

The angrites are an ancient (4.56 Ga), critically silica under-saturated achondrites of igneous origin. These meteorites exhibit a range of mineralogy (e.g. pyroxene-rich basalts to dunites), textures (e.g. quenched liquids, ophitic basalts, and cumulates), and isotopic systematics which imply derivation through a range of thermal and crystallization histories during the earliest stages of planetesimal differentiation. Several petrogenetic models have been proposed to explain the generation of the angrites. One family of petrogenetic models argues that the angrites originated from the partial melting of chondritic precursor material under uniquely oxidizing conditions. Alternatively, it has been argued that the angrites were generated by the melting of reduced, metal saturated chondritic precursor material that experienced a significant addition of an early high-temperature nebular condensate. In this view, the angrites are simply a product melting a parent body with unusual bulk composition rather than melting under oxidized conditions. Understanding the role that fO2 plays in producing angrite magmas is clearly critical for deciphering the conditions of their petrogenesis and expanding our understanding of primordial melting processes on asteroidal bodies. Calculations constraining the fO2 conditions of angrite melting and crystallization are sparse and have, so far, yielded conflicting results. Compounding this distinct lack of reliable redox data is the fact that many of the angrites also possess phase assemblages that provide conflicting signals about their prevailing magmatic fO2 conditions. At present there is little reliable redox data with which to directly evaluate the hypotheses proposed to explain the origin of the angrites. This study will produce a new, high quality dataset that will provide a robust, quantitative oxygen fugacity dataset for the volcanic angrites and deepen our understanding of the redox evolution of these magmas. The redox records preserved in the volcanic angrites will be quantified with synchrotron ¼-XANES measurements of Cr valence in olivine phenocrysts and Fe valence in anorthite phenocrysts. The proposed synchrotron ¼-XANES measurements from the meteorites will be complimented by a detailed petrographic and chemical characterization of the selected phenocrysts, as well as a set of redox controlled crystallization experiments performed on angritic liquids. The results of calibration experiments will be used to construct models of Cr2+/£Cr and Fe3+/£Fe systematics in olivine and anorthite phenocrysts grown from angritic liquids; these models will subsequently be used to translate the valence ratios measured in the olivine and anorthite phenocrysts of the meteorites into a spatially and temporally resolved fO2 dataset. This dataset will allow us to critically evaluate the petrogenetic models that have been proposed to explain the origin of the angrites. More specifically this proposal will shed new light on the role that 1) oxidation state and 2) a unique

accretion history and bulk chemical composition may have played in the generation of the angrites. In a broader context, this proposal addresses fundamental questions about the potential importance of fO2 variation as a mechanism for generating compositional diversity in primordial asteriodal magmas of the early solar system. The goals of this proposed work are consistent with the scope and stated objectives of the NASA Emerging Worlds program, as they address fundamental questions and the geochemical conditions under which the oldest differentiated, igneous meteorites in the solar system formed

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Lars Borg/Lawrence Livermore National Laboratory
Isotopic Studies of Lunar Primordial Planetary Differentiation: A Petrologic Approach

Goals: This work seeks to determine constrain the timing of lunar differentiation and crust formation on the Moon. This work will evaluate the relationship between various lunar magma ocean cumulates and crustal rock suites, as well as the duration of primordial lunar crust formation. This project is divided into 3 tasks:
Task 1: Age Determinations of FAS Samples 67016 and 60015. The objective of Task 1 is to date two FAS samples characterized by mineralogical and geochemical compositions distinct from previously dated samples to determine if the preponderance of previously published ~4.35 Ga FAS ages reflects a sampling bias or records the age of widespread anorthositic magmatism (i.e. the age of LMO solidification). We will complete Ar-Ar, Rb-Sr, Sm-Nd, and U-Pb chronologic investigations on two lunar ferroan anorthosite suite samples in order to establish whether they record evidence for ages older than 4.35 Ga. There are only a few large FAS samples suitable for dating with current techniques and they have proven to be difficult to date reliably. As a result, concordance will be sought from multiple chronometers. This will permit the potential effects of slow cooling in the lunar crust to be evaluated, as well as lend confidence to our age measurements.
Task 2: Chronology of Mg-suite Rocks 67667 and 15455 CTA Clast. The goal of this task is to evaluate high precision ages determined on Mg-suite and FAS samples in the context of the cooling history and closure temperatures of isotopic systems in order to establish the temporal relationship between both suites of rocks. The ages of Mg-suite sample 67667 and 15455 CTA clast will be determined using the Ar-Ar, Rb-Sr, Lu-Hf, 146Sm-142Nd, 147Sm-143Nd, and U-Pb isotopic systems. Cooling rates will be estimated from pyroxene lamellae following McCallum and O Brien by C. Shearer, as well as from the radiogenic isotope ages measured at LLNL.
Task 3: 146Sm-142Nd Isotopic Measurements of Mafic and Felsic Lunar Cumulates. The objective of Task 3 is to expand our existing Sm-Nd data set to include a more geographically and compositionally extensive sample suite in order to assess whether the 4.334±0.007 Ga 146Sm-142Nd age we previously defined is representative of all LMO cumulates thus recording the age of LMO solidification. The proposed work is based on the principal that if all available samples representative of LMO cumulates fall on the 146Sm-142Nd isochron, then the isochron is likely to record the age of solidification of a reservoir of global-scale as predicted by the LMO model of lunar differentiation. On the other hand, if some samples do not lie on the isochron, then the reservoir is of more regional scale, likely produced by localized melting potentially associated with overturn of the LMO or melting by a very large impact event.

Relevance: The work proposed in this proposal is relevant to the Emerging Worlds Program because it is focused on the chemistry of events and materials that contributed to the formation of planets, satellites, and minor bodies. Furthermore, the tasks designated here will constrain nebular, as well as planetary scale chemical and isotopic fractionation processes that occurred early in Solar System history. In particular, this proposal addresses processes associated with global differentiation that result in the separation of bodies into compositionally distinct layers.

Michael Callahan/Boise State University
Investigating Soluble Organic Compounds and Their Evolution with Aqueous Alteration in CM Carbonaceous Chondrites

Aqueous alteration may have been the most widespread of processes that have affected primitive solar system materials, and its effect on soluble (and insoluble) organic matter in meteorite parent bodies is still debated. We will directly address this outstanding problem by investigating the nature of soluble organic matter in a full range of aqueously altered CM chondrites. We will extract the soluble organic matter in ~60 CM carbonaceous chondrites and perform a comprehensive investigation of the soluble organic composition using state-of-the-art ultrahigh resolution Orbitrap mass spectrometry. We will use various data mining and visualization tools to reveal compositional changes in these highly complex mixtures of organic compounds. By utilizing a very large set of CM chondrites where the degree of aqueous alteration has been assessed, we will be able to explore the connection between soluble organic matter and the impact of aqueous alteration in a novel fashion. Our proposed research is directly relevant to the NASA Emerging Worlds program because we will conduct sample-based studies involving meteorites, which represent extraterrestrial materials related to both the formation and early evolution of our Solar System. The proposed work brings together an experienced research team, utilizes state-of-the-art instrumentation for the analysis of extraterrestrial meteorites, builds off of past research, and is budgeted at a low cost while still yielding a high science payoff.

Fred Ciesla/The University of Chicago
Exploring the Origin of Isotopic Variations in Volatiles within Solar System Objects

Objectives: Within our Solar System, primitive materials, including meteorites and comets, can be compositionally classified based on their 17O/16O, 18O/16O, D/H, and 15N/14N ratios. While variations among planetary materials are observed for other isotopic systems, they are relatively small compared to the variations seen in these elements, which are generally used to classify primitive materials into distinct groups, including meteorite classes and comet families. The fact that such variations developed within what is largely considered to be a homogeneous solar nebula is an outstanding issue in the formation of our Solar System. The variations in isotopic ratios is often attributed to photochemical self-shielding (in the case of O and N) or high temperature mixing combined with primordial enrichment from the cold pre-stellar environment (in the case D/H). The current paradigm for water presents a conflicting dichotomy where models that match the deuterium enrichment of solar system bodies require outward motion of material, while oxygen isotopic enrichments require inward motions.

Here, we propose to explore a new unifying paradigm for isotopic fractionation in the solar nebula linked to photochemical self-shielding for three major elementary reservoirs: D, H, and N. For this purpose we will unify two disparate efforts within our teams. The first is detailed exploration of the interaction of gas phase species and grains, including only sublimation and condensation, within a dynamic nebular environment where grains grow, settle to a dust rich midplane, and in some instances drift inwards. Our second effort is detailed kinetic chemical simulations of the protoplanetary disk environment using state-of-the-art radiation transfer models for ultraviolet and X-ray radiation.

We will merge these two efforts, using extant models of self-shielding and chemical kinetics from published works, to connect an evolving chemistry within our pre-existing simulations of dust growth. Our dust models demonstrate that products from chemistry in layers exposed to UV photons are captured by the grain evolution and brought to the dust rich planetesimal forming midplane. Thus the heavy element products of isotopic self-shielding in the H, O, and N reservoirs will be brought to the midplane. Using 1 + 1D vertical simulations we will will predict, for the first time, a mass weighted isotopic enrichment (D/H, 17O/16O, 18O/16O, 15N/14) along with deviations, carried within pre-planetary icy solids as a function of radius in the solar nebular disk midplane. This evolution will provide unique insights into the isotopic diversity seen in Solar System materials as a function of formation distance and within distinct reservoirs (e.g. meteorites, comets).

Relevance: The Emerging Worlds program, as stated in the 2019 ROSES call, aims to answer the fundamental science question of how the Solar System formed and evolved, including 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. The interdisciplinary research program outlined here will also support ongoing and planned NASA missions whose primary focus is on understanding the origin of planetary bodies, including JUNO, OSIRIS-Rex, Psyche, Lucy, and a possible comet sample return mission. Our goal is the development of a new and predictive paradigm for isotopic enrichment in the solar system which will have important implications for a wide range of previous, existing, and future NASA funded research and missions.

Andrew Davis/University of Chicago
The early Solar System and its precursors

Science Goals and Objectives. The general theme of the proposed work is to better understand the nature and timing of mixing and nebular processing in the early Solar System, the ultimate sources of dust in the solar nebula, stellar nucleosynthesis, and the chronology of the first few million years of Solar System history. These goals are to be accomplished by measurements of chemical and isotopic compositions of a variety of extraterrestrial samples, including: (1) presolar grains, CAIs (calcium, aluminum-rich inclusions), chondrules, and matrix in primitive chondrites; (2) differentiated meteorites; and (3) IDPs (interplanetary dust particles).

"Presolar grains have proven to be a rich source of information about nucleosynthesis in individual stars that existed prior to our Solar System. We will study the isotopic compositions

and chemical abundances of minor and trace elements in SiC, graphite, silicates, and other presolar materials, as well as search for internal heterogeneities within these grains to better understand stellar nucleosynthesis in and condensation of grains around asymptotic giant branch stars and supernovae. We will compare presolar grain compositions with isotopic components in the early Solar System inferred from isotopic heterogeneities among bulk meteorites and CAIs.

"CAIs rich in hibonite contain the largest isotopic anomalies (in Ca and Ti) of any materials that formed in the Solar System, yet these CAIs formed when little or no 26Al was present. We will measure the isotopic compositions of hibonite-rich CAIs by RIMS (resonance ionization mass spectrometry) to better resolve the sources of the isotopic components that formed our Solar System. We will also test the idea that 26Al was introduced into the solar nebula late, after the largest isotope anomalies had been partially homogenized, through Hf-W dating of isotopically anomalous hibonite-rich CAIs.

"The 182Hf-182W system has been very successful for early Solar System chronology, but nearly all previous studies have relied on high precision W isotopic measurements on bulk samples and mineral separates. We will use the high sensitivity and selectivity of RIMS to do in situ 182Hf-182W dating of CAIs from chondrites and zircons from differentiated meteorites.

"There are now known to be small variations in the isotopic compositions of many elements (Ca, Ti, Cr, Sr, Zr, Mo, Ru, Pd, Ba, Sm, Nd, Hf, W, and Os) in bulk samples of different types of meteorites; somewhat larger variations in these elements are revealed in chemical leaching experiments on primitive meteorites and CAIs. The carriers of these isotopic anomalies are unknown (except for Cr), but hold information about sources and solar nebular mixing. We will map primitive meteorites, CAIs, and IDPs at fine spatial resolution to search for the carriers of anomalies.

Methodology. CHILI, the Chicago Instrument for Laser Ionization, is a RIMS instrument that is designed for high useful yield (atoms detected per atom desorbed), and nearly complete suppression of isobaric interferences from both monatomic and molecular ions. RIMS schemes are available for all elements listed above. Also available is a TESCAN LYRA3 FESEM-FIB equipped with EDS, WDS, and EBSD.

Relevance. The proposed research is highly relevant to the goals of the Emerging Worlds program, which is targeted at improving understanding of the formation and early evolution of the Solar System, and will address many of the bulleted items listed in ROSES 2019, including: studies of the materials present and processes that led to the onset of Solar System formation; studies of all aspects of materials present and processes occurring in and affecting the protoplanetary disk, including those occurring on bodies of any size during this stage of Solar System evolution; studies related to the accretion of Solar System bodies after dissipation of the protoplanetary disk.

Neil Dello Russo/Johns Hopkins University Applied Physics Laboratory
A comparative study of how ices are stored in cometary nuclei

The main objective of this proposal is to investigate how molecules are associated as ices in the nuclei of individual comets. Whereas most studies focus on the abundances of coma gases, how they are distributed in the coma is vital for understanding how ices are stored in the nucleus. A study of spatial distributions of volatiles in many comets with diverse properties is key for disentangling natal associations from subsequent evolution and is thus needed for understanding comets as early solar system remnants. To address this objective, we propose to use our extensive and diverse astronomical database of infrared long-slit spectroscopic observations to accurately measure and inter-compare the spatial distributions of parent volatiles (i.e. those originally stored as ices in the nucleus) released in cometary comae because: (1) Taxonomic compositional studies reveal general volatile relationships within the overall comet population, but comparison of ice associations in many individual comets of diverse properties tests which links are indicative of primitive vs. evolved processes. (2) When measured together, coma spatial distributions test whether the sampled volatiles are associated with common or distinct nucleus sources in individual comets. (3) Comparing the sources and associations for different molecules is critical to understanding how species are stored as ices in cometary nuclei, and comparing to astrochemical disk model predictions further tests whether ices retain natal characteristics and chemical relationships.

Our study addresses important and timely questions that are highly relevant to decoding the cosmogonic record in comets in the post-Rosetta era: (1) How are ices associated or sequestered in cometary nuclei? (2) Which molecular associations in a broader sample of comets are similar to (or distinct from) those found in 103P/Hartley 2 and 67P/CG by the EPOXI and Rosetta missions respectively? (3) Which molecular associations are general properties within our sample of comets and which vary from comet to comet? (4) Which volatile distributions in the coma are affected predominantly by natal vs. evolved nucleus associations?

Our primary research Task is to determine, compare, and interpret spatial profiles of volatile and dust column densities in the comae for twenty-eight comets. A secondary Task is to examine any short-term changes in the associations of volatiles in a subset of the data where signal-to-noise ratio (SNR), temporal coverage, and spatial resolution warrant further study. We will utilize publicly available datasets from state-of-the-art ground-based facilities for near-IR astronomy, covering comets with diverse chemistries, activity levels, dynamical histories, heliocentric distances, and spatial resolutions. This data diversity is needed to reveal which volatile associations are universal and which are comet-dependent, and to help disentangle natal nucleus associations from those that have subsequently evolved. To further establish the link to our early solar system, we will compare volatile relationships in comets revealed in our study to molecular associations in midplane ices predicted from state-of-the-art early solar system astrochemical models. Both instrumentation and techniques for investigating comet volatiles have recently improved, enabling sensitive studies of the spatial distributions of parent volatiles and dust.

Yingwei Fei/Carnegie Institution of Washington
Experimental Study of Planetary Differentiation and Core Composition

It is recognized that planetary bodies were differentiated at early history of our Solar System. The early accretion and differentiation processes play important roles in planet formation and redistribution of materials and energy in the interior. Metal-silicate separation in planetesimals and Moon-to-Mars-size planetary embryos occurred in a range of temperatures depending on the heat sources. We envision that liquid metal separates from silicate matrix when silicate is at solid state, partially molten, or completely molten. These three differentiation scenarios would lead to different pervolative behaviors of liquid metal and element partitioning between the percolative metal and silicate. It is essential to understand the physical process and chemical interaction during metal-silicate separation in order to model the evolution of the interior and the composition of the planetary cores.

The objectives of the proposed research are (1) to determine Fe-Ni-S-O-Si-C liquid metal percolation in solid silicate mantle in the pressure range of 0.1-8 GPa, mimicking percolative core formation in small bodies, (2) to investigate percolative behavior and element partitioning in partially molten chondritic mantle, and (3) to determine element partitioning during liquid metal and liquid silicate separation at very high temperature. The three sets of experiments represent three different differentiation scenarios depending on the accretion conditions that would lead to different core compositions and chemical signatures. The expected results will provide fundamental data to link the physical process with chemical redistribution during early core-mantle differentiation.

The proposed experiments will be conducted in the piston-cylinder and multi-anvil high-pressure devices that can simulate the pressure-temperature conditions of large planetesimals and small planetary bodies during differentiation. They are built on our experiences in planetary interior simulations and successful applications of analytical and imaging techniques such as field-emission electron microprobe and focus-ion-beam/SEM crossbeam instrument that is capable of generating 3D images of the recovered high-pressure samples. We also introduce high-temperature capability in the multi-anvil press up to 3600 K to obtain partitioning of volatile siderophile elements under extreme conditions to understand high-energy impact in the early history. We are taking an integrated approach to study mobility and chemistry of core materials in natural compositions, and have the expertise and resources to accomplish the proposed research. The expected results will provide insights into early differentiation processes in large planetesimals and small planetary bodies and core composition of differentiated bodies in general. The proposed research is within the scope of The Emerging Worlds program. The proposed study is related to the early evolution of our Solar System with emphasis on the process of accretion and differentiation within Solar System bodies at early history. Our research results will increase the understanding of the origin of the Solar System and the processes by which its planets have evolved to their present states.

Dionysios Foustoukos/Carnegie Institution of Washington

Kinetics of H and O isotope exchange during hydrothermal alteration of insoluble organic material

Proposed research will investigate alteration processes affecting the isotopic and elemental composition of water and insoluble organic matter (IOM) in chondrite parent bodies. Specifically, experiments will be conducted to constrain: (1) the kinetics of Murchison IOM

modification (H/C, N/C) and IOM-water H isotope exchange under hydrothermal conditions as a function of pH and down to lower temperatures (150-300 oC) than in previous studies; (2) the elemental/isotopic response of CR IOM at similar hydrothermal conditions to determine if all C1/2 IOM could have a common CR-like precursor; (3) the kinetics of D/H exchange at the molecular level of the functional groups in analog IOM (syn-IOM); and (4) the variation in O/C and O isotope systematics between hydrothermally altered chondritic/syn-IOM and H2O. The aim of the proposal is to develop a detailed understanding of how the elemental/isotopic composition and structure of IOM in chondrites was modified by metamorphism and aqueous alteration in the chondrite parent bodies. Experimental results will shed light on the isotopic evolution of chondrites after accretion, and the origins of the H2O and organics accreted, the thermal histories of aqueously altered and mildly metamorphosed chondrites.

Significance: Our experimental results will have implications for: (i) the formation of organics and ice, and their transport in the disk, (ii) the accretion locations, thermal histories and dynamical evolution of asteroids, and (iii) the delivery of volatiles and organics to the terrestrial planets. Ultimately, these experiments will help us to quantitatively understand the origins and evolution of water and organic matter in chondrites and their parent bodies, constrain the chemical and thermal evolution of chondrites/asteroids during alteration, and describe processes of planetesimal and planet formation. This is a multidisciplinary/collaborative effort between a hydrothermal experimentalist/geochemist, an isotope cosmochemist, an organic geochemist, and an isotope geochemist. Each year, the project will support a 8-week summer internship for one undergraduate/high school student.

Stein Jacobsen/Harvard University
Ca, K, Nd and Mg isotopic heterogeneities in the Solar System

The proposed causes of isotope variations in the protoplanetary disk include: (1) nucleosynthetic isotope heterogeneity inherited from the protosolar molecular cloud, (2) thermal processing and irradiation of primordial molecular cloud dust in the protoplanetary disk, (3) formation in different nebular reservoirs, separated by the early-formed Jupiter and (4) continuous mixing of primordial and thermally processed materials during accretion of meteorite parent bodies and planets. However, there is a clear need for improved isotope data for different elements in the same well-characterized meteoritic constituents such as CAIs, chondrules, matrix and bulk samples. The objectives of this proposal are (1) to measure Ca, K, Nd and Mg isotopic compositions of meteoric constituents and (2) use these new data for better understanding nebular evolution and testing disk models. To achieve our objectives, the isotopic measurements will be made using our new Nu Sapphire multi-collector inductively coupled plasma mass spectrometer and our new Isotopx Phoenix ATONA thermal ionization mass spectrometer, both developed for and installed in our laboratory specifically for isotopic studies of difficult-to-analyze elements, like Ca, K and Nd. The Nu Sapphire is capable, for the first time, of achieving very high Ca sensitivity allowing high-precision Ca-isotope analyses of a variety of CAIs and chondrules, in addition to rare large inclusions analyzed so far, and a relatively high throughput of Ca isotope measurements for both small and large samples. This will greatly enhance the efficiency of mapping the most important isotope variations and understanding their relationships to the various isotope groupings of meteorites. Using our new equipment for

isotope measurements, we expect to develop a better and more extensive database for interpreting the observed isotopic variations in nebular materials suitable for better testing of various protoplanetary disk models. The proposed tasks are: (1) measure Mg isotopes, including 26Al-26Mg systematics, and elemental compositions of CAIs and classify them based on REEs, textures and mineralogy; (2) measure Ca isotopes in CAIs and chondrules aiming to achieve a clear resolution of possible Ca-isotope components and their mixing relationships; (3) measure K and Nd isotopes in selected samples to better understand the relationship between variations in all isotope systems. We will be further testing the proposed isotope groupings of meteorites by searching for simple, well defined mixing relationships between O, Ca, K, Nd and Mg isotopes among meteoritic constituents. The measured isotope variations will be used to constrain (1) nucleosynthetic sources of such groups; (2) the source of mass-dependent variations (Ca) in refractory and moderately volatile elements (K) and (3) to understand the origin of the distinct isotopic end-members in the Solar System. Specifically, we will attempt to resolve where different signatures may originate; e.g, beyond Jupiter, close to the Sun, or outside the solar nebula. Achievement of our goals will significantly advance understanding of the formation and evolution of the solar nebula and the Solar System as a whole. The proposed research focuses on one of the major goals of NASA s Emerging Worlds program that is to increase "understanding of the formation and early evolution of our Solar System.

Brandon Johnson/Purdue University
Dynamics of the early solar system and implications for the possible impact origin of chondrules

Science objectives: Understanding the origin of chondrules can provide information regarding the processes at work in the nascent solar system. Our primary objective is to explore the impact environment of the early solar system and to investigate whether impacts are an important chondrule forming process. This includes better understanding how impacts produce potentially chondrule forming melts assessing the role of oblique impacts and ice content. We will use planetary accretion models to explore the hypothesis that carbonaceous chondrites formed in the outer solar system (beyond the orbit of Jupiter). Because chondrule formation by impacts is sensitive to the dynamics of accretion, this work will lead to further insight regarding the dynamical state of the solar system during the epoch of chondrule formation.

Technical approach and Methodology: In Task 1, we will use the Lagrangian Integrator for Planetary Accretion and Dynamics (LIPAD) to simulate the accretion of giant planet cores during the first few Myr of solar system history through pebble accretion. We will also simulate planetary accretion in the region of terrestrial planet formation in the context of pebble accretion. We will compare these results to canonical planetesimal accretion models focused on the formation of the terrestrial planets. In combination with previous work on the possible impact origin of chondrules, these models will provide a sense of where, when, and how many potentially chondrule forming impacts were occurring during planetary accretion.

In Task 2, we will measure U-corrected Pb-Pb absolute ages (in collaboration with J. Connelly, U. Copenhagen), as well as Al-Mg and O-isotope systematics of chondrules from the metal-rich G chondrites NWA 5492 and GRO 95551, which may have formed in a process similar to the

CB chondrites. These measurements will allow us to explore the how and when theses meteorites formed. If the meteorites formed in an impact vapor plume produced by a hypervelocity impact as inferred for the CB chondrites, they suggest the solar system was dynamically excited at their times of formation. These results will then be compared to various accretion scenarios including rapid growth of a stationary Jupiter and scenarios that include migration of the giant planets.

In Task 3, we will use the iSALE shock physics code to explore the thermodynamic path of jetted material. Because outer solar system planetesimal likely has a substantial ice content, we will explore the role of ice content on jetting efficiency using a mix material equation of state.

In Task 4, we will use the iSALE shock physics code to produce fully three-dimensional impact simulations. This will allow us to explore the role of impact angle on the amount of potentially chondrule forming material produced by a given impact. Although thin plate theory predicts oblique impacts may produce orders of magnitude more jetted material than vertical impacts, experiments and numerical models suggest the predictions of thin plate theory cannot be trusted.

In Task 5, we will combine the results of Tasks 1, 3, and 4 to produce revised estimates of the amount of chondrules formed during planetary accretion. In combination with observations of the meteorites, these results may provide a deeper understanding of the processes at work in the early solar system. This includes a better understanding of the process of planetary accretion and the origins of chondrules.

Nan Liu/Washington University in St. Louis
Isotopic Characterization of Presolar Supernova Grains: Constraints on Dust Formation and Nucleosynthesis in Type II Supernovae

The principal goals of this project are to constrain stellar, nucleosynthesis and dust formation models for type II supernovae (hereafter SNe) by conducting multielement isotopic analysis of presolar SN grains. The fundamental importance of this study for Emerging Worlds lies in the facts that (1) all the starting materials of the Solar System (SS) came from the interstellar medium (ISM), a mixture of gas and dust originated from different types of stars, and (2) SNe are believed to be a dominant source of dust grains in the ISM and could have triggered the formation of our SS. The proposed work will build upon recent major progresses made by the PI and co-Is through their collaborative studies: (1) development of an innovative method to nondestructively identify SN grains by coordinated BSE-EDX analysis, (2) development of a novel method to reliably date grain formation in SNe using the 49V-49Ti (t1/2 =330 days) chronometer, and (3) non-destructive identification of a new group of potential supernova (PS) grains with large 13C excesses by microRaman analysis.

Various types of dust grains that condensed in presolar stars have been found in primitive meteorites. A fraction of dust that formed in SN ejecta survived destruction in the SNe, ISM and protosolar nebula before their incorporation into the host meteorites that formed early in the SS history. Supernova grains are therefore valuable tools to study nucleosynthesis, mixing and dust formation processes in SNe at a level of detail that cannot be achieved by astronomical observations. The proposed studies include:

(1) Isotopic (C, N, Si, V-Ti) characterization of SN X grains and their Ti subgrains to better constrain the previously observed 49Ti-28Si correlation and thus to better understand the timing of dust production in SNe as well as the diversity of SN grains in the early SS. A large number of X and PS grains will be quickly located by BSE-EDX and Raman characterization, respectively, of presolar SiC grains, which greatly reduces the cost, labor and time. The new Hyperion O ion source at both WashU and Carnegie will be crucial to identification of Ti subgrains as well as Ti isotope analysis at ~100 nm resolution.
(2) Multi-element (S, Mg-Al, K-Ca, Ti-Ca) isotopic characterization of X grains to constrain SN nucleosynthesis models. Our novel method for identifying the origin of 49Ti in X grains can be readily applied to investigate the origins of other isotopes, e.g., 44Ti, by avoiding complicated mixing calculations. The results will provide stringent tests to several recent proposals about SN nucleosynthesis. Moreover, the proposed research will shed new light on the longstanding debate about whether a SN might have triggered the formation of the SS from the perspective of presolar SN grains.
(3) Multi-element (S, Mg-Al, K-Ca, Ti-Ca) isotopic characterization of 13C-rich PS grains to constrain the proposed explosive H burning process during SN explosion, which greatly affects the production of short-lived nuclides, e.g., 26Al and 60Fe, in SNe and thus our understanding of the SS origin.

The proposal team will consist of PI Nan Liu from Wash U, and Co-Is Conel Alexander and Larry Nittler from Carnegie Institution. The research we propose will provide ground-truth data to constrain theoretical models for SNe with the ultimate goal of improving our understanding of the origin of dust in the Universe, the Galactic chemical evolution of various nuclides, the triggering mechanism for the SS formation, and observed isotopic anomalies in planetary materials. Our research thus supports the goals of NASA s Emerging Worlds Program to explore and observe the objects in the SS to understand how they formed and evolve , as outlined in the ROSES 2019 NRA and is therefore relevant to NASA s strategic objective to ascertain the content, origin, and evolution of the SS.

Ming-Chang Liu/University of California, Los Angeles
Tracing the formation environments of the Solar System through studies of multiple short-lived radionuclides in the early Solar System materials

Objectives:
The origins of very short-lived radionuclides (SLRs, t1/2 d 10 Myr) provide important constraints on the formation environment of the Sun. The nascent Solar System could obtain these radioactivities from one or more of following mechanisms: direct injection from a single dying star, inheritance from the parental molecular cloud already contaminated with SLRs produced by massive stars of an earlier generation, and spallation of gas/solid targets by (solar and galactic) energetic particles. In principle, radioisotopes that are synthesized by the same process and co-incorporated into the Solar System should be similarly spatially distributed and exhibit a concordant decay behavior; as such, their astrophysical sources could be constrained by a quantitative understanding of the abundance relationships among SLRs.

Beryllium-10 (t1/2 = 1.3 Myr), 26Al (t1/2 = 0.72 Myr) and 41Ca (t1/2 = 0.1 Myr), are important SLRs for reconstructing the initial astrophysical conditions surrounding the forming Sun because of their very short lifetimes compared to the age of the Solar System. The former presence and initial abundances of these SLRs in the solar nebula were primarily inferred from Ca-Al-rich Inclusions (CAIs), the oldest dateable solids in the Solar System. A wealth of data for 26Al and 10Be abundances have been acquired in the past, pointing towards homogeneity and heterogeneity, respectively, in the solar nebula. In contrast, our knowledge regarding the initial abundance and distribution of 41Ca remains quite limited mainly because of the analytically challenging mass spectrometry. Since 41Ca is the shortest-lived among the three SLRs, its relationship with 26Al and with 10Be (or lack thereof) has important implications for which astrophysical process (direct injection, inheritance, or spallation) most likely accounted for the presence of SLRs.

We propose a three-year project to carry out correlated isotopic investigations of 10Be, 26Al and 41Ca in CAIs from reduced CV3, CO3 and CM2 chondrites, with overarching goals of better addressing the relationships among the three SLRs, and then inferring the Solar System s formation environment.

Methods:
We will focus on CAIs enriched in fassaite, melilite and/or hibonite found in reduced CV3 (e.g., Vigarano), CO3 (e.g., NWA2187), and CM2 (e.g., Murchison) chondrites to minimize the potential effects from parent body thermal metamorphism. Isotopic analyses for 10Be-10B, 26Al-26Mg and 41Ca-41K isotope systems will be carried out by using the CAMECA ims-1290 ion microprobe at UCLA, which features high transmission and high spatial resolution. Some of the inclusions have been characterized for 26Al and/or 10Be abundances by the research teams led by our collaborators, Profs. MacPherson, Davis, and Wadhwa, so only 41Ca-41K will be measured in such samples. Once isotopic measurements are finished, calculations of expected SLR abundances based on stellar nucleosynthesis and charged particle spallation models will be performed to compare with the isotope measurements.

Significance:
The objective of this proposed work is to obtain constraints on the formation environment of the Solar System by using the abundances and distributions of various short-lived radionuclides inferred from refractory inclusions. It is therefore highly related to NASA s strategic objectives Studies of the materials present and processes that led to the onset of Solar System formation.

Isamu Matsuyama/Lunar and Planetary Laboratory
Early dynamical evolution of the Moon with a subsurface magma ocean and finite rigidity

Objectives: The primary objective of the proposed work is to advance our understanding of the early evolution of the Earth-Moon system (EMS), during the first few tens of Myr of solar system history. The evolution of the EMS is a coupled thermal-orbital problem; the orbital parameters change due to tidal dissipation in the Earth and Moon and the amount of energy dissipated due to tides depends on these evolving parameters. While many studies have looked at the evolution of the EMS, only Chen & Nimmo (2016) have explicitly included tidal dissipation

in the liquid magma ocean due to obliquity forcing, which can generate large energy dissipation. However, they do so assuming a surface, liquid, magma ocean and ignoring the evolution of the shape of the Moon, which affects the large obliquity variations during Cassini state transitions (CST). We will develop a coupled thermal-orbital evolution model that takes into account the feedbacks between energy dissipation in liquid, partial melt, and solid regions; and a fossil figure preserved by an interior with finite rigidity

Methods: We have developed a preliminary ocean energy dissipation model that is applicable to both surface and subsurface liquid magma oceans. This model will be extended by taking into account energy dissipation in all the liquid, partial melt, and solid regions oh the Moon. We have also developed a preliminary CST model that takes account the effects of a fossil figure with finite rigidity and obliquity feedback. This model will be extended by considering a more realistic viscoelastic response of the solid regions. Finally, we will extend an existing coupled thermal-orbital evolution model by taking into account the effects described above.

Significance: Tidal energy dissipation in a crystallizing magma ocean is an important long-term energy source that plays a major role in the early evolution of the EMS. An interior with finite rigidity changes the gravity field and the corresponding CST, which in turn affects tidal dissipation. Therefore, there is a critical need for developing the proposed thermal-orbital evolution model that takes into account these effects. We will be able to investigate which regions of parameter space allow the correct present-day shape, thermal and orbital state of the Moon, advancing our understanding of the early thermal and orbital evolution of the EMS.

Relevance: The proposed study supports the objectives of the Emerging Worlds program and NASA overall by developing a greater understanding of the processes responsible for the early dynamical evolution of Solar System bodies. This work will focus on the early evolution of the EMS. Therefore, it will be of direct relevance to the goals of the Emerging Worlds program, as it directly addresses two bullets in Appendix C.2 (dynamical processes that happened and were most prominent between the time of Solar System formation, and studies of the planetary bodies during the period of planetary evolution through the end of the major period of accretion or the time of global differentiation, whichever is later) of the ROSES 2019.

Bradley Meyer/Clemson University
Chemical Evolution of the Building Blocks of the Solar System

The overarching aim of this research is to understand how isotopes form in stars, how they condense into dust grains, and how they travel through the interstellar medium to the solar nebula. By providing insight into this history, the proposed research will yield theoretical estimates of the initial building blocks of the Solar System. By comparison with existing Solar System samples, these estimates will in turn help provide constraints on the origin of the Sun, on the evolution of the proto-planetary disk, and on the formation of planetary bodies.

To address the question of the chemical evolution of the building blocks of the Solar System, the PI proposes to use and extend his nucleosynthesis, stellar evolution, Galactic chemical evolution, multi-zone mixing, and chemical network and condensation codes to focus on two main topics.

The first is to constrain the the initial chemical state (that is, the types of molecules and dust grains) in which isotopes are injected into the medium between the stars. The second is to explore the evolution of dust grains and their isotopes as those grains sputter away and shatter in hot regions of the interstellar medium and then recondense in the colder regions. The goal will be production of public and extendable databases of theoretical initial Solar System building blocks that the PI and others can use in considerations of the early evolution of the Solar System.

Where possible, all computer codes and related resources the PI develops as part of this research will be publicly released as open-source, free software available to all interested parties. Furthermore, the PI and his team will work to make easily executed versions of those codes available either as machine images on cloud-computing resources or as Docker images that can be downloaded and run on any local computer. The PI will continue to provide documentation on how to use the codes and other resources he makes available. A full-time graduate student and one or more part-time undergraduate students will participate in the research by carrying out calculations and helping to develop codes, documentation, and databases.

The "Emerging Worlds" program seeks to answer the fundamental question "how the Solar System formed and evolved." By studying the history of the isotopes and their carriers in the Galaxy, this work will constrain the initial building blocks of the Sun and planetary bodies; thus, the projects proposed by the PI will contribute to our understanding of the initial chemical state of the Solar System and the processes that alter that initial state to form primitive Solar System objects.

David Nesvorny/Southwest Research Institute
Formation and Evolution of the Kuiper Belt

We propose three themes related to the formation and early evolution of the Kuiper belt:

Theme 1: Constraining Dynamical Models with OSSOS.
OSSOS is a wide-field imaging program that detected 838 outer Solar System objects. The OSSOS team has also developed a survey simulator, providing a straightforward way to account for OSSOS biases. This offers an exciting opportunity to test different dynamical models of Kuiper belt formation/evolution. Here we perform dynamical modeling to tease out the dependence of the results on the radial profile of the original trans-Neptunian disk. The radial profile has two effects: it (i) controls the nature and timescale of Neptune's migration, and (ii) determines the availability of source planetesimals at different orbital radii. We will be able to constrain the radial profile, because both (i) and (ii) are reflected in the present-day orbital distribution of KBOs (as characterized by OSSOS). The proposed work will provide fundamental insights into the early evolution of the outer Solar System.

Theme 2: The Meaning of KBO Colors.
Observations show that KBOs can be divided into two color groups, hereafter red (R) and very red (VR), reflecting a difference in their surface composition. This is thought to imply that KBOs formed over a wide range of radial distance, r. The cold classicals (CCs) at $42<r<47$ au are predominantly VR and Neptune Trojans at $r = 30$ au are mostly R. Intriguingly, however, the

dynamically hot KBOs show a mix of R and VR colors and no correlation of color with r. Here we propose that these observations can be best understood if R objects formed at r<r* and VR objects at r>r*, with 35<r*<40 au. To explain the distribution of colors, we will use the results of Theme 1, where the Kuiper belt is populated from a source planetesimal disk extending from below r* to above r*, and determine the VR/R ratio in each population as a function of r*. The results will help us to identify possible causes of the color bimodality.

Theme 3: Planetesimal and Binary Formation.
A large fraction of 100-km-class CCs are binaries with similar sizes and a wide separation of components. Recent work suggests that KBOs probably formed by the streaming instability (SI), when clouds of locally concentrated solids collapsed under their own gravity. The CC binaries emerge in the gravitational collapse model when an excess of angular momentum prevents the agglomeration of available mass into a solitary object. Here we use high-resolution SI simulations to determine the initial physical structure of gravitationally collapsing clouds and follow each cloud's collapse to completion with PKDGRAV. The results will reveal how planetesimal sizes/binary properties depend on local disk conditions. With an eye to the contact binary 2014 MU69, our PKDGRAV simulations will also determine the shape of the accreted objects. This project will lead to a better understanding of planetesimal formation in the outer Solar System.

Relevance Statement
The proposed research is fundamental to understanding the formation and early evolution of the Solar System. This is a central theme of NASA's Strategic Goals and the Emerging Worlds program. Specifically, the NRA for the Emerging Worlds program states that the program “aims to answer the fundamental science question of how the Solar System formed and evolved", and that the program objectives include “formation, accretion, and evolution of Solar System bodies" and “early dynamical evolution of the Solar System". Here we propose theoretical investigations of the formation and early dynamical evolution of the outer Solar System. This includes the planetesimal accretion processes, early dynamical evolution of planetesimals, and planetary migration/instability. These themes are directly relevant to the NASA Strategic Goals and Research Objectives, and to the Emerging Worlds program in particular.

Sune Nielsen/Woods Hole Oceanographic Institution
Tracking the distribution and abundances of water in the early solar system: Systematic differences between carbonaceous and non-carbonaceous parent bodies?

Water is one of the most important molecules in the solar system. It is essential for life, a necessity for human space exploration, and is critical to geologic and planetary processes. All the major differentiated bodies in the solar system have been shown to contain significant amounts of water and volatile elements. However, large uncertainties persist in our understanding of how and when these volatiles got there.
Recently, a reclassification of meteorites into a carbonaceous and non-carbonaceous grouping based primarily on the nucleosynthetic anomalies in Ti and Cr isotope systems has suggested that the early solar system consisted of two distinct chemical reservoirs that were physically separated for long enough to establish the isotopic dichotomy that has now been observed in

other isotopic systems such as Mo and Ru. In addition to carbonaceous chondrites, the carbonaceous group includes an increasing number of ungrouped achondrites many of which appear to be igneous rocks from small differentiated planetesimals. The non-carbonaceous group includes the terrestrial planets, ordinary chondrites, HEDs, ureilites, angrites, brachinites and igneous meteorites that represent fragments of other differentiated bodies. The physical separation between the carbonaceous and non-carbonaceous bodies could be related to accretion of Jupiter, the presence of which would have effectively prohibited significant mixing between the two reservoirs at least until giant planet migration brought them into contact with one another.

Based on these hypotheses it follows that carbonaceous bodies likely accreted in the outer solar system, and thus would have been characterized by very high water and volatile element concentrations, whereas non-carbonaceous bodies likely accreted in the inner solar system, which may have been significantly drier and volatile element-poor. We propose to test this hypothesis by measuring volatile element concentrations and D/H in carbonaceous and non-carbonaceous achondrites. These analyses will address the questions: 1) Was there also a dichotomy in highly volatile element contents between carbonaceous and non-carbonaceous bodies in the early solar system? 2) Were the source(s) of volatiles different between carbonaceous and non-carbonaceous bodies? 3) Can we trace these two volatile element source materials in present-day bodies of the inner solar system (e.g., Earth, Mars, the Moon and 4-Vesta)?

Recent work has shown that there are several broad types of achondrites (e.g., eucrites and acapulcoites/lodranites) that plot in both the carbonaceous and non-carbonaceous fields. Hence, if the carbonaceous and non-carbonaceous meteorites originate from the outer and inner solar system, respectively, then it would be expected that achondrites that plot in the carbonaceous field exhibit significantly higher volatile contents than do non-carbonaceous eucrites.

To address these questions, we propose to characterize the H isotope compositions and volatile contents (C, F, S, and Cl) of primitive igneous minerals in a diverse suite of carbonaceous and non-carbonaceous achondrites. By analyzing petrologically similar meteorites that are distinct in terms of nucleosynthetic isotopes, we will be able to test if the nucleosynthetic dichotomy between the carbonaceous and non-carbonaceous groups of meteorites, as the nomenclature implies, extends to a difference in volatile element contents as well.

Larry Nittler/Carnegie Institution of Washington
Presolar stardust in the early solar system

Presolar grains of stardust are a trace constituent of primitive meteoritical materials and provide crucial information about the starting materials of the Solar System, the astrophysical context of solar system formation, transport and processing of dust in our protoplanetary disk and planetesimal alteration during the earliest stages of planet formation. All of these topics are highly relevant to the Emerging Worlds program specifically and NASA research goals in general. We propose coordinated microanalytical (NanoSIMS, TEM, Raman, RIMS, SIMS-SSAMS, APT) studies of presolar grains in meteorites designed to address scientific questions of high relevance to the Emerging Worlds program. The work will build upon our strong record of presolar grain research and many of the tasks are motivated directly by discoveries made with our current Emerging Worlds support. It will benefit from state-of-the-art instrumentation, most

of it developed or obtained with NASA support, across several institutions, and also from collaboration with world experts in stellar evolution and nucleosynthesis theory to aid in interpretation of isotopic data. The proposed studies include: 1) Isotopic and microstructural characterization of presolar SiC grains, and their sub-grains, in meteorites. We will take advantage of new nondestructive (Raman and SEM-EDS based) methods we have developed for identification of rare sub-populations of SiC grains, our new high-resolution NanoSIMS O ion source (to measure isotopic compositions of sub-grains), the CHILI instrument at the University of Chicago (to measure trace-element isotopic compositions of important elements including Mo, Zr, Ba, Fe, and Ni), and the NAUTILUS instrument at the Naval Research Laboratory (for REE and W isotopic measurements). This work will provide ground-truth on the nucleosynthetic processes responsible for isotopic variability observed in planetary materials and on galactic chemical evolution processes responsible for the bulk Solar composition and provide new insights into dust condensation processes. 2) Presolar carriers of neutron-rich isotope anomalies. With current EW funding we discovered extreme 54Cr-rich grains in the Orgueil meteorite, and hypothesized an origin in electron capture supernovae with potentially important implications for the origin of the solar system. We will test this hypothesis through identification of more grains and additional elemental and isotopic characterization (e.g., O, Fe, Ti, Mn) both by NanoSIMS and atom probe tomography, and TEM microstructural and chemical characterization. We will also search for 54Cr and 50Ti rich presolar grains in situ in primitive meteorites. 3) Presolar silicates. Our new O ion source will enable isotope measurements of key elements (Mg, Si, Ca, Fe, K, &) that have thus far been technically challenging or impossible. Moreover, we will provide samples to collaborators for high-resolution electron energy loss spectroscopy to characterize the infrared spectra of individual presolar silicate grains in order to provide ground truth for remote-sensing observations of circumstellar, interstellar and cometary dust.

Kathleen Vander Kaaden/Jacobs Technology
Elemental Distribution in Reduced Planetary Bodies: Insights from Experimental Petrology and Aubrite Meteorites

The presence of highly reduced celestial bodies in our Solar System was revealed by novel orbital data from the MESSENGER mission that has confirmed Mercury s status as a geochemical endmember among the terrestrial planets and by the presence of highly reduced meteorites, namely aubrites, in our meteorite collection. With this combination of orbital data and hand samples, we now have our first opportunity to directly investigate the behavior of elements in oxygen-starved systems. Compositional information from Mercury s surface indicates high amounts of S and relatively low amounts of FeO, consistent with magmatism occurring under highly reduced conditions (-2 to -7 delIW; iron-wüstite buffer). Similarly, aubrite meteorites exhibit a low FeO content and are dominated by very-low-FeO enstatite, indicative of formation also under highly reduced conditions (~ -5delIW). Oxygen fugacity (fO2) plays a critical role in the physical properties of magmas and minerals as fO2 has a substantial impact on the partitioning behavior and solubility of elements among and in those phases. In fact, interpretations of geochemical behavior and magmatic processes on Mercury and the aubrite parent bodies (APB) are restricted due to an overall lack of experimental studies relevant to the extremely low fO2 of these bodies. At such reducing conditions, elements deviate from their conventional geochemical behavior displayed at higher oxygen fugacity. Therefore, there is

a critical need to determine the behavior of elements under reduced conditions and the role of S in the melt structure of these bodies, in order to interpret the thermal and magmatic evolution of reduced bodies in our Solar System.

The combined experimental and analytical study proposed here will seek to elucidate the evolution of these planetary bodies through the time of global differentiation. With the successful completion of these tasks, we will be able to answer: under what conditions do typically lithophile elements become either chalcophile or siderophile? How does the melt structure change when the solubility of S is exceedingly high? Do the behaviors we see experimentally mimic those we observe in nature? What can the partitioning of elements under highly reduced conditions tell us about the geochemical evolution of reduced parent bodies up to the time of global differentiation? The combination of these experimental and analytical results will shed light on the distribution of elements within Mercury and the APB and how reduced bodies in our Solar System differentiated. This proposal will consist of three tasks:

Task 1: Experimentally determine the partitioning behavior of major, minor, and trace elements between silicate melt, sulfide melt, and metal under highly reduced conditions.

Task 2: Determine S speciation in silicate and sulfide melts using XANES at the S K-edge to better understand melt structure and refine sulfur concentrations at sulfide saturation models.

Task 3: Conduct textural and chemical analyses of major, minor, and trace elements within silicates, metals, and sulfides found within a representative suite of aubrites.

Relevance to NASA and Emerging Worlds: At the completion of this project, we expect to have determined the chemical affinity of all major and minor elements relevant to reduced planetary bodies, as well as geochemically significant trace elements. By combining this experimental data with our analytical work from aubrite meteorites, this proposal will address outstanding problems in the origin and evolution of our Solar System . Ultimately, successful completion of this research will have a significant positive impact upon advancing the goals of the Emerging Worlds program to explore and observe the objects in the Solar System to understand how they formed and evolve through experimental petrology and analytical studies and examining the period of planetary evolution through&the time of global differentiation.

Richard Walker/University of Maryland
Linking Genetic and Chemical Characteristics of the Early Solar System

Proposal Summary: The goal of the proposed research is to advance understanding of the chemical/isotopic structure and evolution of the protosolar nebula, particularly as it led to the formation of differentiated planetesimals, and ultimately the rocky planets. To accomplish this we will explore the nucleosynthetic genetic diversity of early Solar System objects as revealed by isotopic anomalies present in bulk planetary bodies and meteorite components. These anomalies resulted from the incorporation of variable proportions of matter, produced by diverse nucleosynthetic processes, into the building blocks of early-formed solids. This goal will be pursued primarily through the integrated analysis and interpretation of siderophile (iron-loving) element isotopic compositions and abundances as applied to 2 tasks.

1) We will determine nucleosynthetic mass independent variations in Mo, Ru and W extracted from iron meteorites in order to explore genetic variations that were initially present in the protosolar nebula. Where necessary, these data will be corrected for the effects of cosmic ray exposure using either Os or Pt dosimeters. The genetic isotope data obtained from the iron meteorites will be teamed with chemical data we will generate for the meteorites in order to infer details regarding the chemical composition of the respective bulk parent bodies. Where iron groups or grouplets are examined we will investigate crystal-liquid fractionation and other processes that may chemically relate the irons. As part of sample characterization, the 187Re-187Os long-lived isotopic system will be used to assess whether closed-system behavior of siderophile elements prevailed, subsequent to primary crystallization. Finally, the genetic and chemical data generated will be coupled with chronologic information about the thermal evolution of the parent bodies, especially with respect to the timing of metal-silicate segregation, using the 182Hf-182W system (t½ = 9 Myr). This will enable us to assess the progression of formation of early solids, including the extent of chronologic overlap of genetically diverse regions of the nebula. We anticipate that this task will require ~80% of our work effort.

2) Allied with Task 1 we will analyze residues and leachates from low metamorphic grade primitive meteorites for mass independent isotopic characteristics of Mo and Ru in an attempt to improve understanding of the diversity and origins of nucleosynthetic components that contributed to the creation of genetically diverse parent bodies. Molybdenum and Ru isotopes are particularly valuable for this task because of the spectrum of nucleosynthetic processes they can be used to identify. We will mainly examine chemical fractions that remain from leaching experiments previously performed for Os isotopic analysis. We anticipate that this task will require ~20% of our work effort.

Methodology: We will use proven techniques for precisely measuring siderophile element abundances and isotopic compositions using thermal ionization mass spectrometry and inductively-coupled plasma mass spectrometry.

Relevance: All of the proposed work is directed towards the stated goals of the Emerging Worlds program which aims to answer the fundamental science question of how the Solar System formed and evolved .

Andrew Westphal/U. C. Berkeley
Measurement of the oxidation state of Fe in the interstellar medium

The oxidation state of iron in the interstellar medium (ISM) provides constraints on the processes that operated on material in the protosolar disk, because it likely defines the initial oxidation state. We have developed a technique to combine synchrotron-based X-ray absorption spectra of mineral standards and primitive extraterrestrial materials with X-ray observations of Fe-L ISM absorption from the Chandra X-ray Observatory to constrain the oxidation state and mineralogy of the host-phase of ISM Fe. We have demonstrated the value of this technique with a set of mineral standards and X-ray observations of Cygnus X-1. This work was recently published in the Astrophysical Journal. Our approach is one of the most direct methods to

determine early solar system processes. Nearly every other study of early solar system material examines meteorites, comets, and other samples that have already been altered by solar system processes. Instead we directly measure the properties of contemporary material akin to protosolar material as it would have existed before nebular processes altered it. Here we propose to extend synchrotron-based Fe L-edge absorption measurements of Fe-bearing amorphous silicates to compare with astronomical observations, to understand the range of constraints provided by them. We present detailed experimental protocols for preparation and analysis of amorphized standards amorphized by ion bombardment, including fluences and ion ranges.
We will also explore the diversity of ISM Fe chemistry in other lines of sight in addition to Cygnus X-1, using other X-ray binaries as continuum X-ray sources.
We will use XMM-Newton observations as well as those from Chandra. This work constrains the nebular and parent-body processes that eventually led to the remarkable diversity of oxidation states of primitive Solar System materials. Our study shows that oxidation of cometary material appears to have taken place in the nebula, before incorporation into cometary nuclei, although the mechanism is as yet unknown. We will evaluate systematic uncertainties due to uncertainties in the size distribution of IS dust.
Finally, in exploratory effort, we will assess the applicability of this approach to X-ray absorption near-edge spectroscopy of other major elements, particularly S, Si, Mg, and Al, with the goal of expanding our understanding of chemistry and grain-size distribution of interstellar dust, and thus the initial starting materials of the solar system.

Chao-Chin Yang/University of Nevada, Las Vegas
Following the Gravitational Collapse of Forming Planetesimals

Recent exploration of the Solar System begins to reveal more and more detailed structure of asteroids, Kuiper Belt objects (KBOs), and comet nuclei. For example, the Rosetta mission found that the nucleus of the comet 67P is irregular and appears to be two attached solid bodies. The New Horizons spacecraft found that the KBO 2014 MU69 (Ultima Thule) is also irregular and identified as a contact binary. These bodies are believed to be the relic planetisimals in the formation history of the Solar System, and it is imperative to understand their origin.

The streaming instability has been a promising mechanism to drive the formation of kilometer-scale planetesimals in the early Solar System. With computer simulations, we are able to study the initial mass function of planetesimals resulting from this mechanism and even have some hint of their rotation and binary fraction. However, even with the best available resolution (~10^3 cells per gas scale height), there still exists at least two orders of magnitude scale separation between the resolution and the sizes of planetesimals. It remains challenging for computer simulations to resolve and follow the process of gravitational collapse of forming planetesimals, let alone planetesimal binaries.

For this purpose, therefore, we plan to employ the recently developed Athena++ simulation code with our newly implemented particles module. Athena++ uses the finite volume methods to evolve the gas dynamics on an Eulerian grid. It is capable of adaptive mesh refinement (AMR), with which we can resolve any region of interest in high detail. It is also capable of simulating dust-gas dynamics by populating Lagrangian solid particles. To activate self-gravity between

particles, we will complete the ongoing development of the multi-grid method with AMR. Using these tools at hand, we will be able to simulate the streaming instability and follow the collapse of mm--cm-sized pebbles into planetesimals in its finest detail by continually refining high-density regions.

In this investigation, we propose to use the local shearing box with AMR self-gravity to simulate the formation of planetesimals down to the scale of about 100 km. This will allow us to properly follow the process of gravitational collapse of the pebble clumps with much higher resolutions than ever before. From the simulation data, we can obtain a significantly better statistics on the properties of the newborn planetesimal binaries, or planetesimals in general, which will help us to answer the following key questions:

(1) How is the initial mass function of planetesimals shaped, especially toward the very low-mass end (~1km sized)?
(2) What is the distribution of the rotation periods of the newborn planetesimals?
(3) What is the fraction of planetesimal binaries and what are their properties?
(4) Are the properties of the planetesimals formed by the streaming instability consistent with those observed in the Solar System, especially in the new and upcoming data from the New Horizons spacecraft?