A GROUND TRUTH-BASED APPROACH TO FUTURE SOLAR SYSTEM ORIGINS RESEARCH. Rhonda. M. Stroud¹, ¹Code 6360, U.S. Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC, 20375. (rhonda.stroud@nrl.navy.mil)

Introduction: One of the most fundamental questions human researchers can strive to answer is, “How did we get here?” Part of the answer lies in understanding the conditions that lead to the formation of the Solar System. While remote sensing and lander-based measurements for exploration of the primitive Solar System bodies are essential, full knowledge of the Early Solar System (ESS) also requires detailed laboratory-based analyses. For example, our knowledge of the first solid particles in the Solar System comes primarily from laboratory measurements of refractory inclusions in meteorites [1]. Our knowledge of the gaseous components of the ESS come primarily from laboratory-based noble gas studies of dust grains, and carbonaceous extracts from meteorites [2]. We have even identified organic matter from the ESS [3] and individual dust grains that pre-date the SS formation [4]. These discoveries could not have been made through any means other than direct laboratory measurements.

Furthermore, such laboratory analyses of planetary materials provide the motivating context for, and ground truth for interpretation of, spacecraft-based missions, be these science, hazard mitigation, or commercial interest-driven.

Three essential resources are needed to carry out the laboratory analyses: samples of planetary materials from diverse primitive Solar System bodies, state-of-the-art laboratory instrumentation, and trained researchers. Over the next three decades, we can expect to dramatically expand the inventory of planetary materials. Two missions already underway, NASA’s OSIRIS-Rex [5] and JAXA’s Hayabusa2 [6], will return samples from the primitive carbonaceous asteroids Bennu in 2023, and Ryugu in 2020, respectively. Sample return from Mars is plausible in the mid ‘20’s to early ‘30’s. Comet surface and lunar South Pole Aiken sample return are among targets of the current New Frontiers competition. Cryogenic sample return missions, preserving water and organic ices from a comet, or moons of outer planets, are in the conceptual stage and could be implemented by the mid ‘30’s to early ‘40s. Earth-based sample collection of asteroidal and cometary materials is on-going, and continues to benefit from improvements in collection methods, e.g., Australian Fireball Network, for rapid meteorite fall recovery, and South Pole-based interplanetary dust particle (IDP) collection, both of which have the potential provide among the most pristine asteroid samples and cometary dust yet available. Private sector sampling of asteroids is also now in the planning stages.

Expanding the Planetary Materials Analysis Toolkit: To continue to push forward our understanding of how the Solar System, and thus humanity itself, came into being, we must also push forward the state-of-the-art in planetary materials analysis capabilities over the next three decades. The instrumentation currently available for planetary materials research is truly impressive. Isotope composition signatures that identify the ESS, interstellar, or even presolar provenance of individual particles can be imaged at scales down to 10’s of nm’s. The isotope compositions of the Solar Wind can be measured from a few implanted ions in the Genesis sample collection [7]. Imaging and spectroscopy of individual atoms with electron microscopes provide clues to the formation and processing of organics in the ESS. Focused ion beam instruments can enable site-selective coordinated analysis at the sub-micrometer scale, so that the when, where, and how are precisely determined for an individual EES sample. Measurements of the infra-red spectra of individual sub-micrometer grains can help link the extraterrestrial materials with established origins and processing histories to remote sensing of primitive solar system bodies. Molecule-specific isotope measurements allow the identification of labile organics, including amino acids, in meteorite and comet samples.

Decades of laboratory work on meteorites, IDs and samples returned by Apollo, Genesis, and Stardust, have well prepared us to handle the soon-to-be returned Bennu and Ryugu asteroid samples. And yet, new advances in analytical instrumentation occur yearly, if not daily, driven by wide range of basic and applied science and technology needs, from quantum computing, to genomic medicine to renewable energy. The planetary materials community will be only one many research communities pushing the frontiers of analytical methods development over the next three decades and it behooves us to identify emerging instrumentation championed in our own, and related fields, that can address key questions in SS origins research.

Several key instrumentation improvements are already under development or commercially available, but not yet widely adopted. These include improved ion sources for SIMS machines; resonant ion mass spectrometers with sub-10 nm spatial resolution; a time-
of-flight sputtered neutral mass spectrometer with non-resonant laser post-ionization system for in-situ mapping of all elements in solid materials down to 10’s of nm; atomic-force microscope-based infra-red microscopes for sub-100 nm-scale IR characterization of polished thick samples; monochromation for electron microscopes that enable characterization of IR properties at spatial scales to ~1 nm for thin samples; higher sensitivity detectors for imaging and spectroscopy in electron microscopes that enable high-resolution characterization of highly beam sensitivity samples, e.g., organic molecules; and a single-stage accelerator mass spectrometer with multiple ion sources, for high sensitivity, molecular-interference-free elemental and isotopic analysis. Each of these new tools will enable planetary scientists to reveal previously hidden signatures of Early Solar System processes in extraterrestrial samples, such as interfacial reactions between sulfide nanoparticles are fluids on asteroids affected the inventory of prebiotic chemistry.

Two key additional expected needs for future sample analysis are: (1) sample storage, handling, preparation and coordinated multi-instrument analyses, all under vacuum or inert gas to prevent air, water and/or ambient organic exposure; (2) cryogenic sample handling and analysis capability for liquid and other volatile sample analyses. Although storage of valuable planetary materials are under inert gas is standard practice, the sample handling, processing, and transfer between instruments typically requires air exposure. This can lead to alteration of space weathered surfaces on returned asteroid samples, and molecular cross-contamination of Martian samples with terrestrial matter. The longer term goal of sampling volatiles from the outer solar system, which have key roles in ESS processes from providing “glue” to aid in the planetesimal formation to serving as key ingredients for the emergence of life, will require to ability preserve, process, and analyze volatile samples under cryogenic conditions. Some such capabilities exist, e.g., cryo-SIMS has been performed on individual liquid-bearing halite crystals, cryo-TEM is widely used in the biological microscopy community, and cryo-FIB lift-out has been demonstrated. However, in most cases, the samples are handled first at ambient temperature, and cooled to cryogenic temperatures either during sample preparation, or only after loading in the vacuum instrumentation. Further research into cryogenic sample storage, sample handling, instrumentation, and transfer between instruments for coordinated analysis will be required in advance of cryogenic sample return, but also in the near term, to advance our understanding of the preserved ESS volatiles in our existing suite of meteorite samples.

Developing the Planetary Materials Analysis Community: Visionary planetary science necessarily includes experts in planetary materials. The real driving force behind the new discoveries in SS Origins will be not the samples or instrumentation, but the next generation of expert researchers. Planetary science is an inherently interdisciplinary endeavor, which benefits from a great deal of international cooperation. Developing a ground-truth based approach to visionary planetary science means ensuring that the next generation of researchers draws broadly across disciplinary and demographic boundaries. More specifically, it means ensuring that researchers have training opportunities in state-of-the-art analytical laboratory methods on real planetary materials samples, and that the skills and knowledge gained from these studies continue to provide a basis for the sound conceptualization, implementation, and interpretation of the full suite of planetary science goals.

Summary: An essential goal of planetary science research is to connect the dots spanning the roughly billion years from the proto-solar molecular cloud to the emergence of terrestrial life. Equally compelling goals are the need to protect Earth from potential devastating asteroid or cometary impacts; and the desire to explore beyond the boundaries of Earth. In addressing these goals over the next three decades, we should not forget that the microscope is as an important tool as the telescope. Laboratory analysis of recovered, e.g., meteorites and interplanetary dust, and returned, e.g., Stardust, and Hayabusa samples have, and will continue, to provide some of the strongest scientific evidence for the pathways of the evolution of gaseous, rocky, and organic materials in the SS. In the next decade, SS origins researchers, using a full complement of advanced analytical laboratory instruments, will connect the dots from remote sensing C-class of asteroids to amino acid, water, and even rare earth and refractory metal contents. In two decades, we could have analyses of actual samples of Martian water, and perhaps even direct evidence of prior life on Mars. In three, we could be distinguishing the interstellar organic components from the SS components in cometary ices to identify whether there is evidence for extra-solar life.