In Situ Science and Instrumentation for Primitive Bodies

Final Report

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1.0 EXECUTIVE SUMMARY

Our study began with the goal of developing new methods to test the radically new understanding of solar system formation that has recently emerged, and to identify innovative instrumentation targeted to this purpose. In particular, we were seeking to test predictions of dynamical models such as the Nice model (after the founding research group in Nice, France), and to do so through interdisciplinary collaboration between the planetary dynamics communities that have formulated (and largely dominated discussion of) these new ideas, and the meteoritics and cosmochemistry communities who will be most involved in any *in situ* mission to an outer solar system body. Our study was principally focused on coming up with explicit tests of the predictions of these new dynamical models of solar system evolution.

The key outcome of our first workshop was the realization that fundamental work is needed before these two communities—dynamics and meteoritics/cosmochemistry—are really ready to come to a collective understanding of early solar system evolution. Planetary dynamics examines solar system history through the orbital properties of large populations of bodies, but says little specific about any one of them. In fact, at present it appears that there is nothing you could learn about any one body that this community would consider to be a concrete test of the Nice model (or another similarly broad model of solar system evolution). On the other hand, people who study planetary materials through meteoritics and *in situ* missions are strongly focused on the idiosyncratic properties of individual bodies but don't actually know how to identify the properties of a primitive body that depend upon its orbital evolution. Without such tools, it isn't clear how this community can turn insights regarding one body into statements about broad classes of related bodies. **This is a frustrating moment in the study of solar system evolution—both the dynamics and meteoritics/cosmochemistry communities have well developed and consequential hypotheses about solar system evolution, but it isn't obvious that either knows how to make a concrete statement that is testable by the other.**

Our reaction to this impasse was to step back from the narrow problem of testing the Nice model as a whole (or similar specific dynamical models) and ask whether there might be specific instances—particular bodies or groups of bodies—where we could forge a link between the dynamical and meteoritic/cosmochemical approaches. If so, this could serve as a foundation that will eventually lead to a synthesis of the dynamical and cosmochemical understanding of solar system evolution. The key, we imagine, is to find a case where dynamical approaches lead to clear predictions about mineralogical or chemical properties of individual bodies, so that mineralogical or cosmochemical approaches could test those predictions through *in situ* or remote observations.

There was consensus amongst our team that we should be able to use dynamics to predict the chemistry of a primitive body based on knowledge of where the body originated in the solar nebula and the thermal history it has undergone. We are in a unique position to make this new type of connection between dynamical models and chemistry because of the diverse backgrounds represented in our group, which includes dynamicists, astronomers, geochemists, cosmochemists, spectroscopists, mineralogists, and instrument developers. For our second workshop, we further expanded our team to address new directions, specifically drawing on expertise in geochemistry of returned samples and meteorites.

Throughout our study, we had extensive discussions about the composition of primitive bodies, where in many cases little is known from telescopic observations. Moreover, there is no known meteorite collection of materials from the most relevant group of parent bodies (e.g., D-types – Trojan asteroids, irregular satellites, Phobos and Deimos, and some outer main belt asteroids). Trojan asteroids were identified as the most interesting target because they represent a large reservoir of D-types that can potentially be linked to origins in the outer solar system (primitive Kuiper belt). Dynamical histories have not yet made specific predictions about the chemistry of these bodies because the field is still in its infancy and there has been little interaction between dynamicists and chemists. We concluded that we need to develop our own theoretical framework starting from the beginning—what are the starting materials? How were they processed during and after migration? Then, we need to actually do the lab work to simulate these materials and look for markers. A search for these markers would be the basis of the science motivation for future missions to these bodies.

Because of the current lack of knowledge about the compositions of these bodies, we found that choosing a specific suite of *in situ* instruments to develop for such a mission would be premature at this point. (For a primer on *in situ* instruments for planetary surface exploration, see Appendix B). It is understood that any mission to the Trojans would operate under extreme constraints of mass and power so that it would not be possible to send all possible instrumentation to characterize the surface. Hence, we must develop the theoretical and laboratory framework first so that we can tailor the instruments to the most important measurements.

The expected significance of the identification of these markers (the topic of our follow-on proposal) is that it would have implications for all future missions to small bodies (not just the Trojans). It is understood that in order to gain the most detailed knowledge of both chemical and isotopic compositions of small bodies, sample return would be preferred. However, if we can identify one or several very specific markers, it will become feasible to search for these with a small suite of *in situ* instruments at a number of target bodies. Or, even better, it may be possible for us to identify spectral properties that can be observed remotely. Our goal is to work our way to an understanding of these sorts of dynamically important signatures.

2.0 BACKGROUND

Our radical new understanding of solar system formation and migration comes from very recently developed models, such as the Nice model (Gomes et al. 2005, Tsiganis et al. 2005, Morbidelli et al. 2005). The Nice model proposes a large-scale architecture of the solar system driven by planetary migration that predicts the origin of the Kuiper belt, Oort Cloud, near-Earth objects (NEOs), Jupiter's Trojan asteroids, and irregular satellites, and a scenario for the formation of Mars (Figure 1). This theory also bears profound implications for the origin of volatiles and organics on Earth. As a result, the planetary science decadal survey report (NRC 2011), *Visions and Voyages*, has identified primitive bodies as the most important targets for understanding origins. Along with that comes support for relevant Discovery and New Frontiers missions such as Trojan Tour and Rendezvous and Comet Surface Sample Return, and an ultimate flagship mission Cryogenic Comet Sample Return. In addition, the last decade has witnessed incredible technology advances in both observational capability and instrument miniaturization. *However, there still remains a strong disconnect between the dynamical theories and the sorts of information that can be collected on the surfaces of these primitive bodies.* While the Nice model has a demonstrated record of explaining astronomical observations, such as the dynamical properties of migrated populations (irregular satellites, Trojan asteroids), validation of the theory remains to be achieved. This is therefore an important time for us to identify the strategies that can both lead to the development of the best instrumentation as well as guide the development of appropriate missions and observational strategies when the time comes. The goal of this study program is to establish a strategy for testing the validity of the current models of solar system formation and dynamics. While primitive bodies are a priori the best place to search for the record of origins, to date, no such testing criteria has been identified.

Stated simply, one challenging question lies at the forefront of this study—what is it that can be observed about primitive bodies in order to determine where these objects originated and to what extent they hold the clues to early solar system formation?

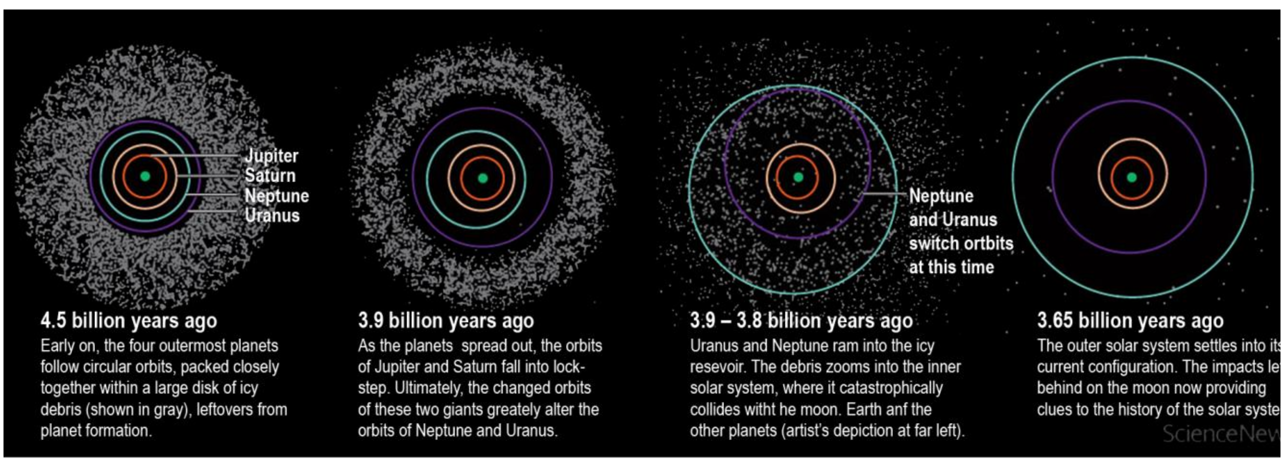

Figure 1. Cartoon showing the large-scale rearrangement of the solar system predicted by the Nice model. Credit: Illustration: Mark A. Gerlick / space-art.co.uk; simulations: adapted from Gomes et al./*Nature* 2005.

3.0 MULTIDISCIPLINARY APPROACH

We started by examining whether current theories of dynamical evolution of the solar system lead to predictions about the chemical and isotopic properties of solar system bodies that are directly related to where and when these bodies formed. The current evidence to support the Nice model comes from measuring dynamical properties of solar system bodies, such as the unusual orbital distribution of the Trojan asteroids and their total mass (Morbidelli et al. 2005). However, these bodies are effectively just point masses from this point of view; something more is needed to connect these arguments to the physical, mineralogical, and chemical properties of these bodies. Independently, telescopic observations of these bodies have provided some (albeit limited) knowledge of their compositions (Emery et al. 2006, 2009, Yang and Jewitt 2011). A rich history of detailed characterization of thermal histories of primitive materials comes from the study of meteorites and returned samples (e.g., Stardust) (Bradley 1999, Scott and Krot 2005, Keller and Messenger 2008, 2011, 2012), though it isn't clear how this understanding can be connected to specific groups of solar system bodies. Our current understanding of the isotope geochemistry of the early solar system implies radial gradients in the distribution of deuterium and hydrogen (D/H) (Remusat et al. 2010, Robert et al. 2000) and the stable oxygen isotopes (^{16}O, ^{17}O, and ^{18}O) (McKeegan et al. 2011, Young 2007). However, no one has yet established a direct connection between dynamical understanding of the early solar system and the compositions of solar system bodies. We concluded that the point of the spear for advancing our models for early solar system evolution is to advance our understanding of the mineralogical and chemical consequences of different dynamical scenarios for the origin and evolution of solar system bodies, and to ask how those signatures of dynamical history might be observed.

The second workshop of our study focused on the following question. If dynamics hasn't provided us with specific predictions about properties of bodies that we can go measure, it does make statements about the location and timing of accretion and later rearrangement of solar system bodies, and these statements have implications for thermal histories, which should lead to mineralogical and chemical effects that can be measured. It makes sense to use a multidisciplinary approach to push forward on this problem, one that combines dynamics, cosmochemistry, mineralogy, and engineering of instruments and flight platforms. Our study brings together experts in solar system origin and migration, experts in planetary instruments, and experts in laboratory measurement techniques in order to target the best measurements and planetary bodies.

4.0 CHOICE OF PRIMITIVE BODIES – WHERE SHOULD WE GO?

During our first workshop we spent some time addressing the question of where to go to make measurements. What bodies might have observable properties that inform our understanding of early solar system dynamics? Many ideas were discussed, including Jupiter's Trojan asteroids, Centaurs, main belt asteroids, asteroids families in the outer main belt, Ceres, and irregular satellites (Phoebe, Phobos, and Deimos), and Kuiper belt objects (KBOs). Each workshop participant had the opportunity to advocate for their preferred exploration targets for the purpose of constraining the early history and dynamical evolution of the solar system. The group came to the consensus that we need to focus on the most primitive bodies, and concluded that D-type bodies best satisfy that requirement. These bodies comprise the Jupiter Trojan clouds as well as many irregular satellites and some outer main belt asteroids. The moons of Mars, Phobos and Deimos, have also been associated with the same spectral type, however, whether they share a common origin with other D-type bodies is the subject of much debate. Unfortunately, there is no known D-type material in the meteorite collection and so the ability to study these materials in detail is sorely lacking. Remote compositional information is faint and provides only limited insight into the mineralogy. There are various arguments for visiting each body, but over time, our group built consensus on the high value of choosing Jupiter's Trojans as our target, which reside at the crossroads between the inner and the outer solar system (Figure 2). There is also a line of reasoning that we may be able to use irregular satellites as a proxy for the Trojans, but regardless, the theoretical framework that we would need to search for markers of origins would remain the same.

Different origins have been suggested for Jupiter's Trojan asteroids, including very different scenarios: one theory says they formed *in situ* (e.g., Jupiter's planetesimal reservoir), while another says they were captured during episodes of planetesimal migration at the large scale. The Nice model suggests that Jupiter's Trojans may be KBOs that were scattered inward and captured at their current location. Spectral observations indicate that the Trojan clouds contain a large fraction of D-type objects, which are said to be primitive, as well as C-type and P-type bodies. However, it is not known whether any of these spectral types are tracers of migration from the Kuiper belt. The consensus in our first workshop was that the Trojans should be highly ranked as a target for our study, in part because Jupiter's Lagrange point 4 (L4) and L5 regions (gravity wells) represent key witnesses of large-scale migration in the solar system. This is in line with the fact that it is a priority outlined in *Visions and Voyages* (NRC 2011).

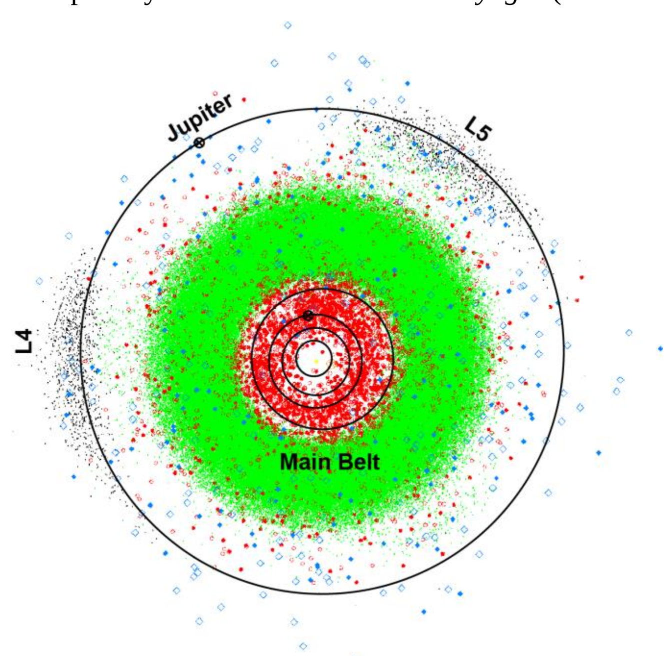

Figure 2. Jupiter's Trojans are shown in the L4 and L5 regions. From Minor Planet Center.

5.0 THE SEARCH FOR CHEMICAL MARKERS OF ORIGINS

The search for chemical markers (compositional, mineralogical, and isotopic) offers the most promise for addressing origin science, because of the significant well of knowledge that has been built up from meteoritic studies and returned samples. In addition, small body colors and spectral properties obtained from telescopic observations are in large part determined by surface chemistry (superimposed with some physical effects such as surface structure and porosity). Hence, getting a better understanding of the information contained in these features is the most promising pathway to finding markers of origins for small and primitive bodies.

Through the course of the study, we did consider whether it is possible to use physical characteristics alone to constrain origins (e.g., size-frequency distribution of bodies, crater counting, rotational properties). However, these physical features are too specific to each reservoir of small bodies and it was not clear how characterizing these features would contribute to understanding the relationships between these reservoirs.

We therefore explore three approaches to searching for "markers of origins": 1) use of chemical composition, 2) mineralogy, and 3) petrology and isotopic composition. These are inevitably linked because it is often necessary to have mineralogy and petrology in order to interpret isotope measurements (e.g., to understand whether the sample being measured has undergone some thermal processing that would lead to isotopic fractionation). We present these two pathways in the sections below.

From an experimental perspective, the analysis of primitive meteorites has placed constraints on the thermal history of silicates in the solar nebula. Through the study of chondrites, which are the most primitive solar system materials we have at our disposal, we attain a level of knowledge about thermal histories of the primitive bodies from which they came. If we had this level of knowledge about the thermal histories of large numbers of primitive bodies in the solar system, we expect that we could potentially map out their origins. In order to do this properly, we need three pieces of the puzzle: petrology, phase information, and isotope information. This suggests three possible pathways to obtain the needed information.

1. Obtain enough data remotely to tie each body of interest to the meteorite collection (e.g., Vesta and howardite, eucrite, and diogenite [HED] meteorites)
2. Return samples from each body of interest
3. Go there and measure on the surface (or subsurface)

It is almost certain that we require a combination of all three of these pathways in order to form a more complete picture of solar system evolution. The goal of our study was focused on the third pathway, and more specifically, we aimed to identify the key measurements to make once on the surface. In a broader sense, the identification of markers of origins would be important in achieving all three pathways.

6.0 THERMAL HISTORIES THROUGH CHEMICAL COMPOSITION, MINERALOGY, AND PETROLOGY

Chondrites are the meteorites that provide us with the most detailed clues to the composition and origin of the solar system. They contain a complex mix of phases, such as chondrules and refractory inclusions, that provide links to thermal histories (Figure 3).

Through the study of meteorites in the lab, we have built up an understanding of their formation conditions and histories. This leads to a set of requirements identified for mineralogy and petrology measurements that could potentially be mapped to *in situ* measurements on the surfaces of primitive bodies. Both surface imaging (macroscopic and microscopic) and mineral phase mapping to specific grains in microscopic images are required. Many mineral phases identified in meteorites exist in very small grains and would be missed by bulk analysis (Figure 4). Cometary samples (e.g., Stardust) have been found to be very fine-grained (sub-micron) and their characterization has been done using the most advanced laboratory instruments including nanoSIMS (nano secondary ion mass spectrometry) and other microprobe techniques. There was a lot of discussion about how we could accomplish such an analysis *in situ* and whether sample return might be necessary. While we did not have a definite answer to this question, there was consensus that if we were to advocate for *in situ* measurements, we had better identify a small suite of very targeted measurements that could answer important questions of origins within the context of a small mission.

As part of the second workshop, we had an "instrument fair", where each participant had the chance to present the instrument that they thought would be most promising for *in situ* missions to small bodies. Many techniques were discussed such as Infrared (IR) Spectroscopy, Raman, Laser Induced Breakdown Spectroscopy (LIBS), Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray Diffraction (EDX), Tunable Laser Spectroscopy (TLS), Mass Spectroscopy (Mass Spec), SIMS, and sampling using penetrator deployment. There seemed to be consensus in the group forming around Raman and IR Spectroscopy for mineralogy measurements and TLS and Mass Spec for isotope measurements. Instruments to perform these techniques will be a central part of the focus of any future follow-on work proposed by our group.

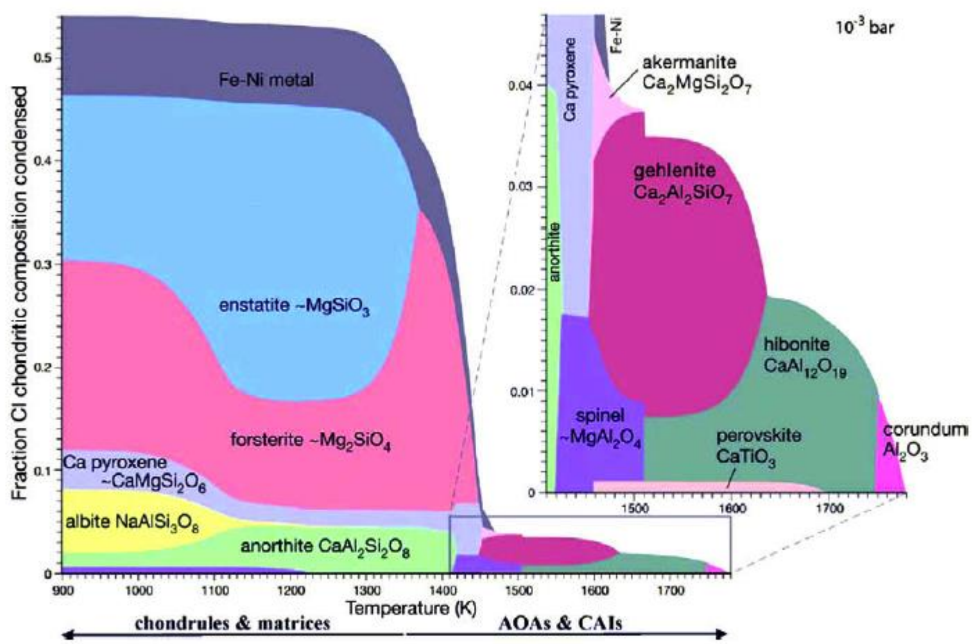

Figure 3. Equilibrium mineral stability diagram for the solar nebula. From Davis and Richter 2003; Krot et al. 2009.

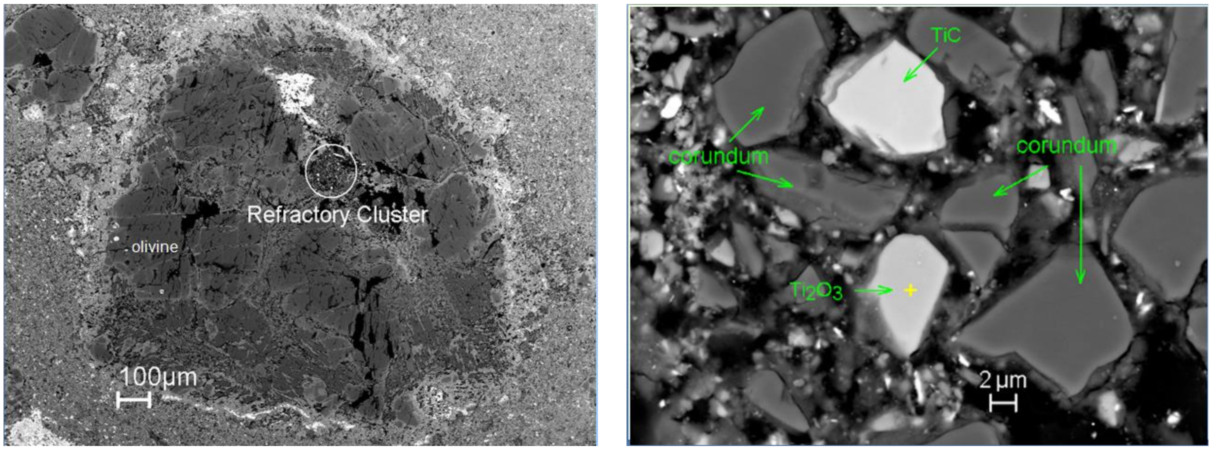

Figure 4. Small refractory clusters in the Allende meteorite including the identification of phases that do not occur naturally on Earth such as Tistarite - Ti2O3. From Ma and Rossman 2009.

7.0 DYNAMICAL HISTORIES THROUGH ISOTOPIC MEASUREMENTS

Isotopic measurements present a great technical hurdle for solar system exploration because there is no obvious way to combine them with remote sensing surveys (i.e., they are inherently tools of *in situ* or sample return science), and the technologies of *in situ* observation are challenging (though evolving rapidly). On the other hand, it is possible for isotopic properties of solar system bodies to see through many confounding processes, preserving information about origins (i.e., because isotopic diversity in the early solar system exceeds the fractionations and other effects of parent body evolution). The systems we best understand are oxygen and hydrogen isotopes of major reservoirs—CO, H_2O and silicates in the circumsolar disk. Studies of meteorites and previous space missions (e.g., Genesis and Stardust) have led to well-developed models regarding the compositions of the initial "feed stocks" of primitive solar system bodies. In addition, the processes that appear to have created isotopic diversity—photochemical "self shielding", oxidation of pre-solar organics, formation of H_2O and condensation of H_2O ice—are recognized to have varied strongly with heliocentric distance and time. This understanding has led to predictions regarding the variation in D/H ratio of water ice as a function of heliocentric distance, at least across the inner ~5 astronomical unit (AU) of the circumstellar disk. However, no one has put these ideas together into explicit predictions regarding the differences in isotopic composition between primitive outer solar system bodies that formed at different heliocentric distances. In particular, current understanding makes it seem likely that objects that accreted near the current orbit of Jupiter and those that accreted in the vicinity of the Kuiper belt must differ in H and O isotope composition, but no one has examined this problem through detailed, quantitative models. A key next step in our understanding of the isotopic structure of the early solar system must include testable predictions of this kind.

8.0 FUTURE DIRECTIONS

Our second workshop reached several conclusions regarding the near future of the study of primitive solar system bodies:

- The dynamical reorganization of the early solar system as one of the essential problems in planetary science; it is essential that current hypotheses be subjected to rigorous tests.
- Our understanding of this problem is currently disconnected from the origins and evolutionary histories of specific bodies and makes few predictions regarding the properties of solar system bodies. A key step forward will be to turn essentially dynamical models into more integrated theories that predict the mineralogies and chemical and isotopic compositions of primitive bodies.
- Our current understanding of the distributions and isotopic compositions of ices and other solids in the early solar system suggests they could well exhibit the sort of predictable, structured variability that would serve as a forensic “tag” for the heliocentric distances at which solar system bodies accreted. It would greatly advance the study of the early solar system if we could establish whether or not this is true.
- The best path forward will be collaborative study of a single focused problem that can be attacked from many complementary angles, including dynamical hypotheses, models of solar system chemistry, telescopic observations, experimental studies of mineralogical and isotopic compositions, and study of possible technologies for *in situ* analyses.

At the end of our second workshop, the Trojan asteroids were identified as priority targets in group discussions and individual breakout groups. The possibility of the Trojan asteroids originating from the KBOs struck us as a particularly exciting and tractable problem, and we discussed the possibility of testing the hypothesis that Trojans migrated in from the outer solar system.

Discussions focused on studies we might conduct to identify possible markers of the heliocentric distance of accretion of primitive bodies that are specifically relevant to the Trojan asteroids, including properties that could be observed remotely (e.g., IR spectra) and properties that could be measured *in situ* (mineralogy, chemistry, isotopic composition). We concluded that there are ample opportunities for future missions to these bodies, but any such missions will have to be rooted in new fundamental research on underlying principles, experimental studies, and studies of relevant analytical technologies.

One theory with a lot of appeal was the methanol evaporation line. If KBOs came from two reservoirs (one inside the evaporation line and one outside), then that could explain their color bifurcation into “red” and “ultra-red” objects. This led to the concept that these two colors could have been processed by heat and space weathering as they migrated to the current location of the Trojan cloud. Through this evolutionary process, they could have changed into the also-bifurcated colors of the Trojan population. This theory in its simplicity was very appealing, but we realized that to explore it properly, we must perform a rigorous analysis of the starting compositions, included methanol and other ices, silicates, and organics. To do this properly, we would have to make these simulants in the lab and measure their properties. Only then could we find the distinctive minerals produced by these hypothesized histories, understand the isotope geochemistry of these materials, recognize the relationships of these materials to spectroscopic properties, and identify instrumentation most appropriate to study them.

We also noted that previous simulations of small body surface evolution through thermal processing and irradiation have focused on the volatile components of these bodies. Research on the silicate component is in its infancy but is an important component of the problem, considering that objects migrated and captured close to the Sun are likely depleted in volatiles (i.e., dominated in silicates, near their surface). The potential interaction of silicates with volatiles (including organics) during the early history of planetesimals may play a major role in defining the surface properties of these bodies, a problem that needs to be approached through experimental research.

Throughout our discussions, the concept of distinct isotopic markers that could remain independent of mineralogy was considered. Is it possible that in some cases the stable oxygen isotope composition of some bodies may have retained its original signature, independent of evolution? We were also intrigued by suggestion that much of the oxygen isotope diversity of the solar system appears to be driven by a "heavy water" component, which is hypothesized to be abundant in the outer solar system but has never been directly observed. Wouldn't it be amazing if we could find this source? This discussion further crystallized the great impact that isotope measurements could have on constraining origins.

We decided that we would pursue funding to perform the end-to-end analysis needed to begin to answer the questions that we started with. We would propose modeling of starting materials, we would make these simulants in the lab, and then we would measure them with all of the most promising instrument that could be developed for future missions. We also determined that more telescopic observations of the Trojan asteroids would be beneficial as well. Several members of our group were inspired and submitted proposals for telescope time. Overall, our study group generated many stimulating discussions, and we forged collaborations that will most certainly last as we move forward.

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10.0 APPENDIX A: WORKSHOP AGENDAS

FIRST WORKSHOP

Keck Institute for Space Studies Workshop

April 30–May 3, 2012

In Situ Science and Instrumentation for Primitive Bodies

The Goals for Our First 4-Day Workshop:

- Identify a set of measurements that are the most promising for testing models of solar system formation and dynamics.
- Prioritize target bodies for these measurements.

Day 1 (Monday, April 30): Focus: Getting everyone on the same page		
Short Course – Primitive Bodies: Unlocking the Secrets of Solar System Origins Salvatori Seminar Room – 365 S. Mudd – Third Floor		
8:00–8:30	Coffee and Refreshments	
8:30–9:00	Introduction	
9:00–9:40	New Dynamics of Solar System Formation and Migration	Hal Levison
9:40–10:20	Missions to Primitive Bodies: Past, Present, and Future	Torrence Johnson
10:20–10:40	Break	
10:40–11:20	Surface Geology and Geologic Processes on Primitive Bodies	Jim Bell
11:20–12:00	Current State of Knowledge about Origins from Remote, In Situ, and Return Sample Exploration	Julie Castillo-Rogez
12:00–12:45	On-site, informal pizza lunch provided by KISS for all short course attendees	
Workshop		
12:45–1:15	Workshop participants walk back to Keck Institute and check in at Keith Spalding Bldg., 3rd floor, rm 367	
1:15–1:45	Introduction to the Institute and to KISS	
1:45–2:15	Participant Introductions and Goal Setting	
2:15–3:45	Ground-based &LEO / Remote Observations Primer	Mike Brown / Scott Murchie
3:45–4:15	Break	
4:15–5:45	On-Surface Measurements Primer	Jordana Blacksberg / Chris Webster
5:45–6:00	Walk to Athenaeum	
6:00–9:00	KISS sinner at the Athenaeum's Rathskeller	
Discussion Topics to Consider: • What dynamical and spectroscopic evidence supports the current model of Solar System Dynamics? • What do we know from remote/ ground based measurements and what more can we learn with new observational strategies (e.g., JWST)? • What do we absolutely need to measure on-surface? • What are the capabilities of the state of the art?		

Day 2 (Tuesday, May 1): Keith Spalding Building – Third Floor Focus: Observations and Measurements		
8:00–8:30	Coffee and Refreshments	
8:30–9:00	Goal Setting	
9:30–10:30	Geochemical tracers of origins	John Eiler
10:30–11:00	Break	
11:00–11:45	D/H and Volatiles	Geoff Blake

11:45–12:15	Mineralogy	George Rossman
12:15–1:45	Buffet lunch at the Athenaeum provided by KISS	
1:45–2:00	Breakout assignment	
2:00–4:00	Breakout by discipline: each group identifies what are the most important measurements in their particular field that link to origins. • Group 1: Geochemistry & Cosmochemistry • Group 2: Dynamics • Group 3: Geology / Geophysics	
4:00–4:30	Break	
4:30–5:30	Reconvene and report	
6:00–8:00	No host dinner in Pasadena (KISS to pay for postdocs and grad students)	
Discussion Topics to Consider: • What do we know and what can we learn from geochemical tracers, e.g., isotope geochemistry? • What are its limitations? • Where do we need mineralogical information for interpretation?		

Day 3 (Wednesday, May 2): Keith Spalding Building – Third Floor Focus: Target bodies		
8:30–9:00	Coffee and Refreshments	
9:00–9:30	Goal Setting	
9:30–12:00	Small Bodies Fair (Roundtable) (with Break from 10:30–11:00) * Everyone come prepared with 1–2 slides on your favorite object or class of objects showing how its study can be used to test models of solar system formation and dynamics: • Comets • NEOs • Trojans • Phobos and Deimos • Irregular Satellites • KBOs • Asteroids • Centaurs • Interplanetary Dust	
12:00–1:30	Lunch on your own	
1:30–1:45	Goals for Breakout Groups	
1:45–3:45	Breakout Groups: • Group 1: Prioritize target bodies • Group 2: Come up with a set of remote measurements and link to target bodies • Group 3: Come up with a set of in situ measurements and link to target bodies	
3:45–4:00	Break	
4:00–5:00	Reconvene and Report	
5:00–6:00	Late Afternoon Poster Session: Postdocs and Graduate Students (wine & beer provided by KISS)	
6:00–8:00	Dinner provided by KISS at the Athenaeum (spouse / guest invited)	
8:00–9:30	Public Lecture: “Exploring Protoplanets Through the Dawn Mission”	Carol Raymond
Discussion Topics to Consider: • How can we use current dynamical evidence to guide where and how we make on-surface measurements? • Strategies for maximum science return (e.g. many small missions to many bodies vs. large and more complex mission to a single or few bodies).		

Day 4 (Thursday, May 3): Keith Spalding Building – Third Floor Focus: Bringing it all together		
8:30–9:00	Coffee and Refreshments	
9:00–9:30	Goal Setting	
9:30–10:30	NASA Small Bodies Exploration Roadmap	John Dankanich
10:30–11:00	Break	
11:00–12:00	Pushing the boundaries of our current knowledge: Comet Exploration through Rosetta	Andy Morse (lander) / Sam Gulkis (orbiter)
12:00–1:30	Buffet lunch at the Athenaeum provided by KISS	
1:30–3:30	Free discussion on the next important steps (to do during the study period)	
3:30–4:00	Break	
4:00–4:30	Closing summary & plan for moving forward	
Discussion Topics to Consider: • Can we answer the important questions without sample return? • What do we want to accomplish during study period? • Build consensus on the measurements and target bodies to focus on during the study period.		

SECOND WORKSHOP

Keck Institute for Space Studies Workshop

February 19–21, 2013

In Situ Science and Instrumentation for Primitive Bodies

The Goals for Our Second Workshop:

- Build consensus on a minimum set of measurements and requirements to inform on primitive body origins and determine how this translates into instrument definition.
- Define an instrument package to meet these requirements with realistic goals for the next generation of landers (perhaps 1 to 10 kg payload)
- Identify one or two instruments that offer the most promising prospects for miniaturization through the KISS/JPL technology development program

Day 1 (Tuesday, February 19): Keith Spalding Building – Third Floor		
8:00–8:30	Coffee and refreshments	
8:30–9:00	Introduction to the Institute and to KISS	
9:00–9:30	Participant Introductions and Goal Setting	
9:30–10:00	The next phase: How to move forward from our KISS Study to a Technical Development Program	John Eiler
10:00–10:30	Break	
10:30–11:20	Review & Summary of First Workshop	Jordana Blacksberg / John Eiler
11:20–12:00	Discussions – building consensus toward our measurement goals	All
12:00–1:30	Buffet lunch at the Athenaeum Provided by KISS	
1:30–3:30	Panel Discussion: Sample Return vs. In Situ Specific Questions for the Panel: 1) What do you view as the most important measurements to make on returned samples, and can we extrapolate these to in situ measurements? 2) What would be a minimum set of either in situ or returned sample measurements needed to answer the question of origins? 3) How would you prioritize the three most important in situ measurements and what are their requirements? 3) Is in situ a good approach instead of sample return?	Lindsay Keller, George Rossman, Bethany Ehlmann, and TBD
3:30–4:00	Summarize results	
4:00–5:00	Group Review: Overview of Measurement Techniques and Instruments	TBD
5:00–6:00	Free discussion and walk to Athenaeum	
6:00–9:00	KISS dinner at the Athenaeum's Rathskeller	

Day 2 (Wednesday, February 20): Keith Spalding Building – Third Floor		
8:30–9:00	Coffee and refreshments	
9:00–9:30	Goal Setting (reflect on previous afternoon)	
9:30–10:15	Instruments Fair – pitch your instrument and measurement in 2 slides (one with the summary technique and previous measurement/mission examples, and second devoted to primitive bodies and expectations) Some ideas generated in the first workshop (we are not limited to these!): • TLS • Mass Spec • Raman • XRD • FTIR	All
10:15–10:45	Break	
10:45–12:15	Instruments Fair continued – pitch your instrument	
12:15–1:45	Buffet lunch at the Athenaeum provided by KISS	
1:45–2:45	Breakout Groups to come up with a prioritized list of measurements • Group 1: Geochemistry & Cosmochemistry • Group 2: Geology and Mineralogy	
2:45–3:45	Converge on instrument package	All
3:45–4:15	Break	
4:15–5:30	Matching instrument packages to specific bodies	All
6:00–8:00	Dinner provided by KISS at the Athenaeum (spouse / guest invited)	
8:00–9:30	Public Lecture: “Exploring Mars, the Moon, Asteroids, and Comets with Rovers and Landers”	Jim Bell

Day 3 (Thursday, February 21): Keith Spalding Building – Third Floor		
8:30–9:00	Coffee and refreshments	
9:00–9:30	Goal Setting	
9:30–10:30	Continue matching to target bodies	All
10:30–11:00	Break	
11:00–12:30	Lab visits	John Eiler, George Rossman
12:30–1:30	Informal lunch at the Institute	
1:30–3:30	Outline Final Report and make assignments	
3:30–4:00	Break	All
4:00–5:00	Closing discussion and handout assignments	

11.0 APPENDIX B: ON SURFACE MEASUREMENTS PRIMER

Available online only via Online link or website http://kiss.caltech.edu/study/primitive-bodies/ (Blacksberg and Webster).

12.0 APPENDIX C: SHORT COURSE PRESENTATIONS

Available online only via study website http://kiss.caltech.edu/study/primitive-bodies/ or links below:

- New Dynamics of Solar System Formation and Migration – Hal Levison (SWRI) Online link
- Missions to Primitive Bodies: Past, Present, and Future – Torrence Johnson (JPL) Online link
- Surface Geology and Geologic Processes on Primitive Bodies – Jim Bell (ASU) Online link
- System Science and Origins – Julie Castillo (JPL) Online link

13.0 APPENDIX D: WORKSHOP PRESENTATIONS

Available online only via study website http://kiss.caltech.edu/study/primitive-bodies/ or links below:

- A Primer – Remote Observations of Primitive Bodies from Spacecraft – Scott Murchie (APL) Online link
- Telescopic Observations Primer – Mike Brown (Caltech) Online link
- On-Surface Measurements Primer Part 1 – Jordana Blacksberg (JPL) Online link
- On-Surface Measurements Primer Part 2 – Chris Webster (JPL) Online link
- The Geochemistry of Primitive Solar System Bodies - John Eiler (Caltech) Online link
- D/H and Volatiles in Primitive Bodies – Geoff Blake (Caltech) Online link
- Mineralogy - The Basic Building Blocks – George Rossman (Caltech) Online link
- Technology Capabilities and Gaps – John Dankanich (AeroDank, Inc.) Online link
- ESA's Comet Lander Mission – Andrew Morse (Open University, UK) Online link