ASTROMATERIALS RESEARCH IN NASA'S REORGANIZED PLANETARY R&A PROGRAM

A white paper by the
Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM)

Executive Summary

CAPTEM is concerned that apparent prioritizations in NASA's reorganized R&A programs may have deleterious effects on NASA's capabilities for laboratory investigations of astromaterials, and thus hamper goals identified in the Planetary Decadal Survey. CAPTEM finds that the recent R&A reorganization has decreased funding for astromaterials research, which will affect mission-critical laboratory infrastructure and expertise. Here we review how astromaterials research enables NASA to achieve its planetary exploration and science goals, and we assess the analytical capabilities that will be needed in the coming decade. CAPTEM recommends that the Science Directorate reassess prioritization in its planetary R&A programs and ensure that competitive astromaterials laboratory investigations can be sustained at levels consistent with science goals and mission requirements. We also emphasize that astromaterials support is critical for educating the next generation of scientists required for mission design and operations, and that general-use facilities are not substitutes for the laboratories of individual investigators, where most technological innovations take place.

The Issue

The NRC's 2010 report, *An Enabling Foundation for NASA's Earth and Space Science Missions*, concludes that "NASA must fly critical Solar System missions with focused scientific objectives, balanced with a portfolio of mission enabling activities." This portfolio of foundational activities includes development of:

(1) A knowledge base that allows NASA and the scientific community to explore new frontiers in research and to identify, define, and design cost-effective space and Earth science missions,
(2) A wide range of technologies that enable NASA and the scientific community to equip and conduct spaceflight missions,
(3) A robust, experienced technical workforce to plan, develop, conduct, and utilize the scientific missions.

In response to this report, the Science Mission Directorate reorganized its R&A programs to match more closely the R&A programs to its strategic goals. CAPTEM is concerned that the planetary R&A reorganization may have a negative impact on all three of these long-term foundational activities, and could therefore compromise the science return from future missions and the ability to achieve stated objectives.

Specifically, as a result of the reorganization, the former Cosmochemistry Program, representing most of the investigations of extraterrestrial materials (henceforth astromaterials), was mapped into the new Emerging Worlds (EW) and Solar System Workings (SSW) Programs. Results from the first year of the reorganizaiton indicate a significant decrease in selection of astromaterials proposals (by our counts from the ROSES website, ~17 in EW and ~11 in SSW, down from an historical average of ~38-40 astromaterials-focused grants per year funded by the former Cosmochemistry and Origins Programs). This indicates a disproportionate impact on NASA-supported astromaterials research, which if continued into the second and third years, would result in an approximately one-third decrease in the number of laboratories available to support NASA's scientific objectives.

In this white paper we reiterate how astromaterials investigations directly address the enabling activities defined above, and identify critical needs for future missions and other NASA objectives. More importantly, we suggest some possible corrective actions that could prevent further programmatic imbalance such as that which appeared in the first year as a consequence of the reorganization.

Astromaterials Research as Enabling Activities

(1) The NRC 2012 Decadal Survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, states that "While planetary missions get the lion's share of the public's attention, they are supported by an infrastructure and research program that is vital for mission success. These research activities also generate much of the planetary program's science value on their own." Astromaterials include samples returned to Earth by spacecraft missions and those that arrive here naturally (meteorites and interplanetary dust particles). Research on these samples creates the knowledge base needed to explore new frontiers by answering questions that no other avenue of research can, and in so doing advances new hypotheses for ongoing exploration. A few specific examples of significant scientific advances, from the many we could cite, made possible by astromaterials research, are:

- Determining the timing of formation of solar-system bodies through measurements of the absolute ages of samples using long-lived radioactive isotopes as clocks can generally be accomplished only in the laboratory; although one pioneering measurement by remote sensing on Mars was recently made using instruments on the Curiosity rover, this was made possible only by developments in the laboratory.
- Analysis of interplanetary dust particles (IDPs) collected by NASA in the stratosphere enables interpretation of laboratory analyses of comet Wild 2 samples returned by the Stardust spacecraft to be extrapolated to other comets.

- The discovery of oxygen isotope anomalies in primitive meteorites made 40 years ago provided the motivation for the Genesis Discovery mission. The resulting analyses of a returned sample of the Sun fundamentally altered our view of the chemical processing of volatile elements in the solar nebula: it is the Earth and the rocky bodies of the inner solar system that are isotopically anomalous, not refractory inclusions in meteorites.

Like all good science, astromaterials research not only provides answers, but also generates new questions that challenge our understanding of planetary origins, thus generating further impetus for exploration.

Investigations of astromaterials also affect other areas of NASA's research portfolio that are not driven by missions. For example,

- Measurement of the abundances of nuclides in presolar grains obtained from meteorites directly constraints theoretical calculations of stellar nucleosynthesis in the Astrophysics Program.
- The geologic processes understood from sample research will potentially provide a crucial context for interpreting the nature of exoplanets, if enough information on them can be gained.

Astromaterials research also plays a critical role in identifying, defining, and designing spacecraft missions – most obviously, but not exclusively, sample return missions. To quote the Decadal Survey, "The most important instruments for any sample return mission are the ones in the laboratories on Earth." Several specific examples are:

- The Genesis and Stardust Discovery missions returned samples of the solar wind and samples of a comet, respectively. The Principle Investigators and Science Teams on these missions were scientists from the astromaterials research community, and the collection devices on them were designed based on studies of IDPs and implanted solar wind in lunar samples. These tiny samples are difficult to analyze, but major advances in micro-analytical instruments have allowed the elemental and isotopic composition of the Sun to be determined and the petrologic and isotopic complexity of the constituents of comets to be recognized.
- OSIRIS-REx will return samples of an asteroid; the target body was selected based on knowledge of what asteroid samples may not be in our meteorite collections, and the collection technology and sample curation plans depend on studies of meteorite breccias that represent regolith samples.

Missions that do not return samples also depend on information gained from astromaterials research.

- Comparison of the compositions of geologically young Martian meteorites with *in situ* analyses of ancient rocks by Mars rovers have allowed the recognition of magmatic evolution on Mars over time.

- Studies of HED meteorites from Vesta have been fundamental to the success of Dawn's exploration of that asteroid. The critical questions that motivated the mission all derived from decades of research on HED meteorites, and those meteorites were also used for instrument calibration and formed the basis for interpretations of vestan data.
- Data from lunar missions, beginning with Clementine and Lunar Prospector in the 1990s and continuing through the Lunar Reconnaissance Orbiter and GRAIL, have been interpreted in the context of Apollo sample analyses, and the models for lunar formation and differentiation were derived from those laboratory data. The analysis of lunar samples constitutes one of the major intellectual advances of 20th century science and contributed significantly to USA's leadership in planetary exploration. The Apollo samples provide essential ground truth for specific locations on the Moon to help calibrate remote sensing data and lunar surface ages estimated from crater counts.

(2) The Planetary Decadal Survey declares that "It is crucial for NASA to maintain technical and instrumental capability in the sample science community. The development of new laboratory instrumentation is just as important for sample return missions as is development of new spacecraft instruments for other planetary missions." It is acknowledged by NASA management that continuity of technical capability in engineering is a strategic imperative, and so too is continuity of technical capability in scientific laboratories. Replacing technical expertise and rebuilding instrumental capability from scratch every time it is needed is not an effective operational model. In many cases, loss of analytical capability may become permanent as discouraged investigators leave the field. Moreover, the development of analytical techniques takes a long time, often requiring decades of incremental advances. The long-term support provided by the former Cosmochemistry Program for the most competitive laboratories, as judged by proposal quality and science impact, enabled significant improvements in analytical techniques.

Historically, laboratories supported by NASA's Cosmochemistry Program have been at the forefront of instrument development and innovation. These efforts have helped ensure American competitiveness by securing leadership in analytical technology. In addition to its economic effects, the new technologies have found application in spacecraft missions. Some recent examples of instruments and techniques developed by astromaterials investigators include:

- The Genesis mission returned samples of the solar wind to Earth. The analysis of isotopes in solar wind, i.e. the determination of the isotopic composition of the Sun, required the development of an especially-designed mass spectrometer at UCLA. This development built on decades of experience in high-sensitivity mass spectrometry supported by the Cosmochemistry Program for the study of meteorites and lunar samples.
- The NanoSIMS instrument was developed primarily to investigate presolar grains, i.e., small rock samples formed in the outflows of dying stars and sequestered, in small concentrations, in primitive meteorites. The CHILI

instrument at the University of Chicago was developed specifically for astromaterials research, focusing mostly but not exclusively on presolar grains. The instrument was funded by the Genesis mission, but the lion's share of the costs were borne by years of development in Argonne National Laboratory funded by DOE, illustrating how NASA funds for instrument development can be leveraged via collaboration with other agencies.

- The aberration-corrected Super TEM is a unique configuration, motivated by the specific requirements of cosmochemical samples such as presolar grains.

While these and NASA investments in many other instrumental developments not listed here will continue to pay scientific dividends for years to come, it should also be recognized that our European, Japanese, and (soon) Chinese collaborators and competitors are rapidly advancing due to significant investments in laboratory infrastructure in support of planetary science. It is not hard to imagine that their efforts could eclipse American leadership in the analysis of solar system materials in the near future; as one example, significant aspects of the "science floor" of the Genesis mission (nitrogen and noble gas isotopes) were accomplished in the laboratories of European colleagues.

(3) A technical workforce knowledgeable about planetary materials is critical in planning, developing, and conducting missions, many of which acquire mineralogical and geochemical data. Just as important, astromaterials investigators are heavily involved in the interpretation of spacecraft data. To quote the Decadal Survey, "Planetary spacecraft return data, but these data only have value when they are interpreted." Many astromaterials researchers interpret data as valued members of mission science teams, such as MESSENGER, Dawn, NEAR, etc.

Astromaterials research has produced a steady stream of highly qualified scientists eager to participate in planetary exploration. Funding interruptions translate into a lost generation that cannot be replaced simply by turning on the funding when astromaterials expertise is required.

Critical Astromaterials Needs for Future Missions and Other NASA Objectives

If NASA is able to follow the mission recommendations of the Planetary Decadal Survey, it will fly a Flagship mission to Mars to analyze and cache samples for a future sample-return mission (Mars2020), fly the OSIRIS-REx mission to return samples of an asteroid, select and possibly launch one or two New Frontiers missions from a predetermined set, and select and possibly fly Discovery missions on a two- to three-year cadence focused on targets that are unknown at the present time. All of these mission opportunities offer the possibility of sample return, and even if samples are not returned, astromaterials research is critically needed to inform mission design, instrument selection, and remote sensing data interpretation. Moreover, other NASA objectives require the capability to characterize astromaterials.

Future Missions

Mars landed missions following Mars2020 should return cached martian samples to Earth. State-of-the-art analytical instruments for the complete petrologic, geochemical, isotopic, and organic characterization of these samples will be required; more importantly, experience in the analysis and geologic interpretation of martian samples (meteorites) will be necessary to extract the maximum amount of science from them. Spacecraft exploration has revealed that Mars is more petrologically complex than previously appreciated and the geochemical literature on martian meteorites is extensive. Terrestrial geologists with no hands-on experience with the igneous and sedimentary rocks of Mars cannot easily step in and fill this need.

The New Frontiers OSIRIS-REx mission will return samples of an unusual B-class asteroid, Bennu, with spectral affinities to carbonaceous chondrites. Analytical experience with chondritic meteorites and the thermal, shock, and aqueous alteration processes they have experienced will be critical for the characterization and interpretation of these samples. Organic and isotopic geochemistry and electron microscopic identification of fine-grained minerals are special requirements for mission success.

The New Frontiers target missions include comet sample return, a Venus lander, and several lunar mission concepts. The closest analogs for cometary materials are carbonaceous chondrites and IDPs. Returned samples of the Stardust mission indicate a complex mixture of chondritic components including refractory inclusions, chondrules, and interstellar grains among cometary dust. Experience with chondritic meteorites, IDPs, and presolar grains will all be required. The proven ability to make measurements on very tiny particles will be critically important. Although the Venus and lunar landed missions may not return samples, the interpretation of their analyses of their surfaces will rely on mineralogic, petrologic, and geochemical experience gained from studies of extraterrestrial materials.

We cannot predict what Discovery class missions might be selected, but it is quite likely that sample return concepts will be proposed. Prior experience also demonstrates that meteorite research can be an essential component of the calibration of flight instruments and the interpretation of remote-sensing data, as clearly demonstrated by the role played by HED meteorites in Dawn's exploration of asteroid Vesta.

Any asteroid samples returned to Earth by astronauts during HEO's Asteroid Retrieval Mission (ARM) will of course be thoroughly characterized, requiring the full panoply of petrologic and geochemical techniques. The assessment of mineralogy and physical properties will be needed to predict geotechnical properties for future human exploration activities on asteroids. This knowledge base also has foundational significance for asteroid hazard assessment and mitigation.

Getting the Most out of Past Missions

The rocks and soils returned by the Apollo missions are still providing new understanding of the Moon's origin and geologic evolution, many decades later. The ability to apply new technologies that did not exist when the samples were returned proves the value of curation and continued petrologic and geochemical analysis. The planned application of X-ray tomography to Apollo samples is likely to reveal unusual components of breccias that are not currently exposed on cut surfaces, and should need to new discoveries about the Moon.

Other curated collections from past missions include the comet dust collection from the Stardust mission and the solar wind from the Genesis mission. These missions, in particular, demonstrate the remarkable evolution in micro-analytical instrumentation and sample handling that was not available at the time of sample recovery. These new techniques have revolutionized our understanding of the compositions of comets and the Sun, and unexpected discoveries continue. The asteroid samples returned by the Japanese Hayabusa mission, and to be returned by Hayabusa2, and shared with American scientists have also demonstrated the value of micro-analytical techniques developed by NASA-funded investigators but not generally available to the broader geologic community.

Interplanetary dust particles collected by high-altitude aircraft also constitute materials returned to Earth by NASA missions, albeit not spacecraft. These tiny grains are derived from asteroids and comets, and some collections are timed to sample specific comets as the Earth passes through the trails of dust they leave behind. This curated collection continues to grow, and the analyses of IDPs provide new insights into the solar system's composition.

Meeting Other NASA Objectives

The Antarctic Search for Meteorites (ANSMET), funded for 35 years by NASA, NSF, and the Smithsonian Institution, has so far provided 20,700 meteorites that represent samples of the Moon and Mars, plus as many as 80 parent asteroids. This is NASA's cheapest planetary exploration mission! The characterization of this treasure trove of extraterrestrial materials, along with meteorite falls and finds from other locations, has literally revolutionized our understanding of solar system bodies. It is no exaggeration to state that the present Mars exploration program with its strong focus on the search for life owes its inception to an Antarctic meteorite, ALH84001. Studies of this collection also provide a critical means of educating the next generation of astromaterials experts for future missions.

Technology development is among NASA's primary objectives. Advances in spacecraft analytical instruments, particularly those on landed missions, as well as sampling devices and sample storage containers, are informed by astromaterials research. In fact, astromaterials researchers are often valued advisors to the design engineering teams. For example, cosmochemistry researchers on the OSIRIS-REx mission defined the materials requirements for the spacecraft and sample return mechanisms.

Observations and Recommendations

In the interest of making the reorganized R&A structure as successful as it can be in terms of providing an enabling foundation for NASA missions and science, we offer the following observations and recommendations:

- Observation: Because many of the missions in the next decade are not yet defined, we can only offer a generalized list of astromaterials needs for NASA missions. These needs include expertise and instrumentation (especially micro-analytical techniques) for mineralogical and petrological characterization, geochemical (elemental) analysis, radiogenic and stable isotope measurements, and organic compound analysis. Other techniques, such as magnetic measurements, will also likely be required.
- ➢ Recommendation: Identify (and update, as missions are selected) specific needs for analytical measurements and ensure that a sufficient number of highly capable laboratories are supported to meet projected mission requirements.

- Observation: R&A reorganization during the first funding year has resulted in a significant decrease in astromaterials research capabilities.
- ➢ Recommendation: Examine how reorganization has resulted in redistribution of effort, whether this change in the diversity of core components of planetary exploration is desired or accidental, and whether the scores of astromaterials proposals are systematically different from those in other areas.

- Observation: Astromaterials research programs cannot be turned off and on annually, because of the investments needed for instrument acquisition and development and of the personnel training required for effective operation and technical innovation.
- ➢ Recommendation: Provide a mechanism to take into account the requirement for sustained funding for high-performing laboratory facilities that are critical for missions and other NASA goals.

- Observation: Real innovation in astromaterials instrumentation comes from individual Principal Investigators. Facilities instruments provide valuable opportunities for many investigators, but NASA history indicates that such facilities do not generally develop innovative instruments and applications.

- <u>Recommendation</u>: In setting funding priorities, general-use facilities should not be viewed as replacements for the laboratories of individual investigators who develop innovative analytical technologies.

- <u>Observation</u>: A ~20% selection rate across the various R&A programs was imposed by management during the first year of the reorganized structure. We do not agree that proposal pressure should be the driving force behind research conducted for a strategic, mission-oriented agency like NASA.
- <u>Recommendation</u>: All stated programmatic goals are not necessarily equal, or even achievable by equal percentage funding rates across programs. PSD should prioritize its critical needs and not necessarily be tied to equal selection rates for the various defined programs.

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