Strategic Investments in Instrumentation and Facilities for Extraterrestrial Sample Curation and Analysis

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NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE

Committee on Extraterrestrial Sample Analysis Facilities

Space Studies Board

Division on Engineering and Physical Sciences

A Consensus Study Report of
The National Academies of
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Preface

Five sets of extraterrestrial samples gathered by missions, both human and robotic, have been returned to Earth: lunar materials from NASA's Apollo program, lunar materials from the USSR Luna program, solar wind particles from the National Aeronautics and Space Administration's (NASA) Genesis mission, cometary dust grains and interstellar particles from NASA's Stardust mission, and asteroid materials from the Japanese Space Agency's (JAXA) Hayabusa mission. In addition, there are more than 50,000 named meteorites recovered from around the world. In the next decade, NASA's OSIRIS-REx and JAXA's Hayabusa2 mission will return samples from two more asteroids, and sample return missions to a comet surface, the Moon, the martian moons, and Mars are being considered. The field of returned sample analysis is active and growing.

As part of preparing for the future influx of samples, NASA's Planetary Science Division asked the National Academies of Sciences, Engineering, and Medicine to assemble a committee to determine what capabilities will be required for curation and analyses of returned samples, where current capabilities exist and if they are accessible, and whether NASA's investment strategy provides the resources to meet the analytical requirements in support of current and future sample return missions. The Committee on Extraterrestrial Sample Analysis was formed and began work on its task (see Appendix A for the full statement of task).

The committee held three in person meetings: November 19-21, 2017, in Irvine, C.A., January 22-24, 2018, in Houston, T.X., and April 3-5, 2018, in Washington, D.C. At the first meeting, the committee heard briefings about the OSIRIS-REx mission, NASA's current plans for a Mars sample return architecture, and overview of the NASA Johnson Space Center's (JSC) Astromaterials Acquisition and Curation Office and Planetary Sample Analysis and Mission Science Laboratory. The committee also was briefed on the current mechanism for sample allocation to external laboratories for study, an overview of the Smithsonian Institution's meteorite collection, two concepts for cometary sample return, the National Science Foundation's Geosciences Instrumentation and Facilities Program, and a European project for returned sample curation (EURO-CARES). At the second meeting, the committee held panel discussions on the curation and analysis of challenging materials, laboratory management and viability, and technological developments and innovation with representatives from university laboratories, NASA, and the U.S. Naval Research Laboratory. The committee was briefed on the CAESAR comet surface sample return mission that had recently been selected for additional study as part of Planetary Science's New Frontiers mission competition. The committee also toured JSC's curation and sample analysis laboratory facilities. The committee's third meeting had a short information-gathering session including briefings on the RELAB facility at Brown University, the Stardust Laboratory at University of California, Berkeley, and the NASA Goddard Astrobiology Analytical Laboratory, as well as additional discussion regarding the challenges of curation for organic and life detection studies, and a detailed update of the JSC Astromaterials Science and Exploration Science (ARES) Facility strategy. The remainder of the meeting was held in closed session for committee discussion and writing. The committee held two additional open teleconference meetings, a discussion with then NASA Planetary Science Division Director James Green on October 31, 2017, before the committee's first in person meeting, and briefings on the sampling system and curation and analysis plans for JAXA's Hayabusa2 mission and the Martian Moons Exploration mission concept on May 10, 2018.

The committee requested information from U.S. and international laboratories and museums on their major instrumentation and facilities, staffing, funding models, and major equipment upkeep. The committee would like to thank the 22 U.S. and 15 international respondents to this request (see Appendix B and C). The committee would also like to thank the many planetary science researchers who discussed their work and opinions on the future of returned sample analysis research with the committee. Special thanks are given to the staff of JSC who graciously spent their first afternoon back in the office following a government shutdown giving tours of their facilities and also to the Lunar and Planetary Institute for hosting the committee's Houston visit.

The report summarizes the history, planned future, and potential future of returned sample analysis missions as well as the current state of relevant laboratory facilities. Sample return from the surface of Mars is not expected until the late 2020s or early 2030s and will require extensive additional planning for special curation and research needs. The committee's recommendations are focused primarily on the near-future needs for analytical and curation capabilities and the longer-term underpinnings for maintaining a vibrant sample analysis research community; thus, this report only briefly discusses the additional complications for curation and analysis of Mars surface samples.

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Peter Buseck, Arizona State University,
Barbara Cohen, NASA Goddard Space Flight Center,
Katherine H. Freeman, NAS,[1] Pennsylvania State University,
Christopher Herd, University of Alberta,
Stephen J. Mackwell, Universities Space Research Association,
Ujjwal Raut, Southwest Research Institute,
Roger Summons, Massachusetts Institute of Technology, and
Stephen Sutton, University of Chicago, Argonne National Laboratory.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Rodney C. Ewing, NAE,[2] Stanford University. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Contents

APPENDIXES

Summary

The United States possesses a treasure-trove of extraterrestrial samples that were returned to Earth via space missions over the past four decades. Starting with the National Aeronautics and Space Administration (NASA) Apollo and Soviet Luna sample return missions to the Moon in the late 1960s and early 1970s, samples of the solar wind (Genesis, 2004), a cometary coma and interstellar dust (Stardust, 2006), and an asteroid (Hayabusa, operated by the Japanese Space Agency, JAXA, 2010) have all been returned to Earth. In addition, there are two missions underway to primitive asteroids (JAXA's Hayabusa2 and NASA's OSIRIS-REx) that are expected to return samples in the 2020s. Plans are in the making to return samples from Mars, the martian moon Phobos, a cometary nucleus, additional samples from the Moon, and, perhaps eventually, ices from comets, lunar polar impact basins, and outer solar system moons. Analyses of previously returned samples have led to major breakthroughs in the understanding of the age, composition, and origin of the solar system. Having the instrumentation, facilities and qualified personnel to undertake analyses of returned samples, especially from missions that take up to a decade or longer from launch to return, is thus of paramount importance if NASA is to capitalize fully on the investment made in these missions, and to achieve the full scientific impact afforded by these extraordinary samples. Planetary science may be entering a new golden era of extraterrestrial sample return; now is the time to assess how prepared the scientific community is to take advantage of these opportunities.

In response to a request from NASA, the National Academies of Sciences, Engineering, and Medicine established the Committee on Extraterrestrial Sample Analysis Facilities to determine the current capabilities within the planetary science community for sample return analyses and curation and where these facilities are located; to assess what capabilities are currently missing that will be needed for future sample return missions, as guided by the Decadal Survey;[1] to evaluate whether current laboratory support infrastructure and NASA's investment strategy is adequate to meet these analytical challenges; and to advise how the community can keep abreast of evolving and new techniques in order to stay at the forefront of extraterrestrial sample analysis.

Readers are directed to the following chapters:

- Introduction to the Background and Committee's Charge and Scope—Chapter 1;
- The History of Sample Return Missions and Other Collections—Chapter 2;
- Current and Future Sample Return Missions and Collections—Chapter 3;
- Current Laboratories and Facilities—Chapter 4;
- Current and Future Instrumentation and Investments—Chapter 5.

The committee concludes that the planetary science analytical community has access to a wide range of instrumentation relevant to sample return missions that are currently flying, and there are no obvious gaps in instrumentation for analysis of rocks, glasses, minerals, and the current inventory of organic materials. However, the committee raises concerns about sample analysis capabilities needed for future missions, including the replacement of aging analytical facilities, the ability for laboratories to innovate and evolve from their current state, and the ability to maintain the technical support to sustain these laboratories. In addition, as many of the current planetary sample scientists will be retired before

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[1] National Research Council. 2011. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13117.

some of these missions fly, laboratory sustainability requires training young scientists in analytical methods and instrumentation and growing the next crop of instrument developers. With the greater challenges of possible future sample return missions that seek to return martian samples, or possibly ices and gases, the committee concludes that developing new partnerships with related communities that analyze terrestrial samples, international collaboration, and finding ways for interdisciplinary discussion and knowledge sharing will be critical.

The above needs are superimposed upon a flat budget for purchasing instrumentation, which, because it does not track inflation, represents declining spending power. Thus, if NASA does not invest new funds into the replacement of current instrumentation and development of new technologies, technical staff support, and training the next generation of analysts, the current capabilities cannot be sustained, and development and adoption of new technologies will be impaired. Under such a scenario, NASA will need to plan for a reduction in the number of laboratories supported by the Planetary Science Division funding program.

ADVICE TO NASA REGARDING FUNDING OF LABORATORIES

As currently formulated, NASA's investment in analytical instrumentation is insufficient to provide for replacement of existing instruments, most of which can be assumed to have an average lifespan of 10 years. This typical timescale for depreciation and obsolescence of analytical instrumentation means a significant fraction of current capabilities will be gone by the time ongoing missions (Hayabusa2 and OSIRIS-REx) return samples to Earth, and most will be gone on the timescale of Mars sample return or other anticipated near-future missions. It follows that the currently robust analytical infrastructure for study of extraterrestrial samples is diminishing. Addition of new technological innovations further stretch the current funding programs. One solution to this dilemma is to leverage NASA funding of laboratory analysis of returned samples with contributions from other funding agencies or institutions, which has long been a key source of support for these efforts. The committee recommends that **NASA Planetary Science Division should continue to engage in and encourage cost-sharing arrangements for laboratory analytical equipment with other funding sources.** (Section 5.2)

Many scientists engaged in analyses of extraterrestrial materials utilize multi-user facilities for sample characterization that are funded through a variety of sources. While multi-user facilities can provide increased access to common instrumentation for many investigators, innovations and breakthroughs have historically occurred at individual principal investigator laboratories. Thus, the committee recommends **NASA Planetary Science Division should continue to invest in both multi-user facilities and individual principal investigator laboratories.** (Section 5.2)

In addition to investing in equipment, having highly qualified technical staff is essential to keep laboratories running efficiently and to develop new methods and instrumentation. Most U.S. laboratories engaged in sample analyses are experiencing increased difficulty finding and retaining good technical support staff because these positions are generally supported by one or more short-term (~1-3 years) research grants (i.e., the "soft money" funding model common in many U.S. institutions). This funding model forces laboratories to distribute their efforts among a variety of tasks and to be accountable to a variety of funding sources, which degrades the specialized skills and sustained advances in capabilities that result from focused study of returned samples and other extraterrestrial materials. NASA's investment in analytical facilities could be enhanced by providing sustained funding for technical support staff, so that the analytical work undertaken by a laboratory remains focused on extraterrestrial sample analyses. The committee recommends that **NASA Planetary Science Division should provide means for longer term (e.g., 5-year) funding of technical staff support.** (Section 5.2.2)

There are currently no missions underway or even planned that entail return of cryogenic materials. However, efforts are underway to undertake missions that could return gases within the next decades (e.g., the Comet Astrobiology Exploration Sample Return—CAESAR mission to sample a comet surface that is currently under consideration) and eventually to return ices from the Moon, comets, or moons of the outer planets. If one or more of these mission concepts is pursued, it could reap tremendous scientific advances. Technology development focused on Cryogenic Comet Sample Return (CCSR), as recommended by the Decadal Survey, is warranted and exploring technologies already available in related communities that analyze terrestrial samples of ices, gases, and organic matter could benefit the extraterrestrial sample analysis community. Given that development of curatorial facilities and instrumentation to handle these challenging materials will likely take decades to complete, the committee recommends that **NASA Planetary Science Division should make appropriate investments in the technological development of novel instrumentation and unconventional analytical techniques, specifically for curation, as well as characterization and analysis of non-traditional samples that are expected to be returned from future missions. These would likely include gases, ices, and organic matter, including volatile organic compounds (VOCs) and related hybrids and complexes.** (Section 5.3.1)

In particular for organic matter, the committee recommends that, **With the rapid developments in related fields such as molecular biology, and concomitant advances in bio-organic analytical methodologies, NASA should consider partnerships with relevant federal agencies (e.g., DOE and NIH) and laboratories (e.g., the National Laboratories). NASA should implement information exchange activities (e.g., joint workshops) to enhance cross-fertilization and cooperative development of analytical instrumentation and methods, specifically to enhance analysis of organic matter (both macromolecular/polymeric and molecular-moderate molecular masses, as well as volatiles-low molecular weight compounds), in the study of extraterrestrial returned samples.** (Section 5.3.1)

Many spacefaring nations have, like the U.S., recognized the scientific potential of extraterrestrial sample return missions and have either executed such missions or are actively planning them. These nations have invested significantly in state-of-the art instrumentation and in developing a highly skilled workforce to carry out analyses of extraterrestrial samples. It would be advantageous for strategic alignment in investments in such facilities by international space agencies to maximize the availability to U.S. researchers. The committee recommends that **NASA Planetary Science Division should continue to engage in strategic relationships with international partners to ensure that the best science possible is extracted from extraterrestrial samples with the limited resources available to all space agencies.** (Section 5.3.1)

The committee further recommends that **NASA Planetary Science Division should consider ways to facilitate the dissemination of information about present and future international, state-of-the-art facilities relevant to sample analysis. This could, for example, include organizing workshops to be held with existing international conferences.** (Section 5.3.1)

Finally, a highly-qualified workforce that is able to perform both routine and state-of-the-art laboratory analyses, as well as develop the instruments of the future, is necessary to fulfill NASA's goals for the characterization and analysis of future returned samples. The committee recommends that **NASA Planetary Science Division should encourage principle investigators to specifically address in their research proposals how the work will contribute towards training future generations of laboratory-based planetary scientists.** (Section 5.3.2)

ADVICE TO NASA ON MAINTAINING WORLD-CLASS CURATION AND DEVELOPING FUTURE CURATORIAL FACILITIES

NASA Johnson Space Center's (JSC) Astromaterials Acquisition and Curation Office is the world leader in curating and tracking returned samples, as well as the types of analyses conducted on those samples. The impact of the JSC curatorial efforts go well beyond their immediate duties of curation, as they have been instrumental in helping to train the next generation of extraterrestrial materials scientists and have helped in the development of curatorial facilities at international partner institutions. It would be desirable to harness the expertise represented by the collective knowledge of the curatorial staff at JSC when future mission principal investigators are planning for sample return missions.

While JSC's current expansion plans will provide adequate curatorial facilities for current (Hayabusa2 and OSIRIS-REx) and possible near-future missions such as martian moons sample return, there is a need to develop additional facilities for any future sample return in the 2030's and beyond. Such facilities will require advanced planning and new technologies for the return of significant organic matter, ices, and gases. To ensure that NASA and the science community continue to be at the forefront of extraterrestrial sample curation and analysis, the committee recommends that **NASA Planetary Science Division should increase support for Johnson Space Center to develop appropriate curatorial and characterization facilities relevant to and necessary for future sample returns of organic matter, ices, and gases.** (Section 5.3.3) In addition, the committee recommends that **NASA Planetary Science Division should accelerate planning for curation of returned martian samples, seeking partnerships with other countries, as appropriate.** (Section 5.3.3)

Finally, there is a need to develop online archives of the analyses undertaken on all return samples, along with metadata (e.g., analytical precision, accuracy, etc.) associated with these analyses.

ADVICE TO NASA REGARDING INVESTMENT STRATEGY

As noted above, NASA's investment in analytical instrumentation is insufficient to provide replacement of existing instruments, as well as develop new instrumentation needed for future missions. Without modest to significant increases in funding by NASA in analytical instrumentation for sample analyses, either a decrease in capacity or a reduction in future capabilities seems inevitable, as well as the inability to support highly-trained technical staff, train the next generation of extraterrestrial sample analysts and laboratory instrument developers, and begin planning for the curation and analyses of challenging new types of samples. The committee recommends that **NASA Planetary Science Division should place high priority on investment in analytical instrumentation (including purchase, maintenance, technical oversight and development) and curation (facilities and protocols) sufficient to provide for both replacement of existing capacity and development of new capabilities. This will maximize the benefit from the significant investment necessary to return samples for laboratory analysis from asteroids, comets, the Moon, and eventually Mars and outer solar system moons.** (Section 5.4)

Lunar samples are excluded from one of the major sources of funding for analytical instrumentation within the Planetary Science Division (the Laboratory Analyses of Returned Samples, LARS, program), and yet fundamental discoveries regarding the origin and nature of the Moon continue to derive from analyses of lunar return samples. Opportunities to propose lunar sample analysis to other research funding programs are limited by the focus of those programs (Solar System Workings and Emerging Worlds, see discussion in Section 5.1). Thus, the committee recommends that **NASA Planetary Science Division should consider opening the Laboratory Analysis of Returned Samples (LARS) grant program to all mission returned extraterrestrial samples.** (Section 5.1)

1
Introduction

1.1 BACKGROUND

To prepare for the analysis of diverse extraterrestrial samples in the coming decades, NASA requires information on the current capabilities of the planetary science community's analytical laboratory facilities, their future requirements, and any associated challenges. Therefore, the National Academies of Sciences, Engineering, and Medicine assembled a committee to determine what capabilities are required for curation and analyses of returned samples, whether such capabilities are currently accessible, and whether NASA's investment strategy provides the resources to meet these requirements and adequately prepares the scientific community to meet the challenges of future extraterrestrial sample analyses.

Sample return missions seek to marshal all of the technological and methodological sophistication of terrestrial laboratories for the study of extraterrestrial materials. Although there have been dramatic advances in, and successes of, remote sensing and robotic systems for sampling and analysis on planetary surfaces, it remains true that the most sophisticated remote and *in situ* observations of other planetary bodies return information that is sparse in its scope and orders of magnitude poorer in sensitivity, precision, accuracy, and spatial scale as compared to what is possible in laboratory studies. And, whereas *in situ* observations are made in a limited time frame using only those techniques that could be anticipated when a mission was designed, returned samples remain available for study by techniques invented years later.

Sample return missions present laboratories with four challenges that each call for unique infrastructure, resources and skills (see more extended descriptions in Section 4.1):

1. *Recovery and initial curation*: Initial curation begins through dialogue between the mission scientists and JSC curatorial staff during the creation of the mission proposal, as all sample return missions are required to have a curation plan. The tasks faced by Earth-bound laboratories begin with the acquisition of the samples and their transit back to Earth by determining whether the samples have been changed in any way. Once the samples are back on Earth, the returned vessel must be located, reached and observed to determine whether it survived intact or was breached. The vessel then must be returned to a controlled laboratory space, potentially contending with severe problems of contamination and planetary protection.
2. *Initial characterization and triaging*: Returned samples must be observed by non- and minimally-destructive techniques to document their number, size and material properties and to prioritize samples for analysis, guided by the science goals of the mission but responsive to any unanticipated discoveries.
3. *Characterization*: After preliminary characterization at the curatorial facility, samples need to be analyzed by cutting-edge methods. Many of such analyses will involve transporting the sample off-site to analytical laboratories globally.
4. *Long-term curation*: All returned samples require long-term curation in specially prepared laboratories that minimize terrestrial contamination while at the same time allowing samples to be accessed by laboratories around the world.

The four tasks outlined above have been faced by one ongoing and five prior programs of extraterrestrial sample return: the cosmic dust collection, the Apollo program, the Luna Program, and the Genesis, Stardust, and Hayabusa missions. However, in the coming decades, sample return missions will have to address three substantial changes brought about by shifting scientific goals and a changing community of stakeholders in sample return missions:

1. *From rocks and minerals to gases, organic materials, and ices*
2. *Planetary protection*
3. *Commercial partners and increased international collaboration*

BOX 1.1 A Few Useful Definitions

Organic materials – An organic material is defined as a molecular substance based predominantly on a carbon-carbon bonded structure. Organic materials exhibit a very large range in molecular weight, spanning small molecules, such as amino acids, to essentially infinite molecular weight organic polymers, both of which are found in primitive meteorites; the latter has been also been found in comets.

Volatile materials – A volatile material or compound has a high vapor pressure at ambient temperatures, i.e., is easily evaporated. For most materials and compounds, vapor pressure increases steeply with increasing temperature. Dry ice (solid CO_2) is a volatile material.

Cryogenic materials[1] – are substances whose chemical, mechanical, and thermal stability are generally strongly dependent on temperature, with most cryogenic materials being stable at lower temperatures. Cryogenic is an adjective referring to the storage, production, and characterization of materials at low temperatures. It is relevant for materials that are volatile or are chemically reactive. Generally, cryogenic refers to temperatures below 93 K, but for the purposes of this report, the term is used to encompass the broad range of temperatures relevant to cold storage on Earth. For example, cores drilled from glacial ice are stored and manipulated at 237 K so the layers of ice remain frozen and distinct.

Hard condensed matter vs. soft condensed matter – These terms relate to how stable a material is in its environment. A "hard" material does not readily change its physical or chemical state when the environment is changed. A "soft" material will easily change its state in response to changes away from standard temperature and pressure. Hard glasses and crystalline solids such as the mineral quartz are examples of hard condensed matter, and foams, gels, and liquid crystals are examples of soft condensed matter. Historically, curation facilities have been accustomed to curating rocks, minerals, glasses and metals. Different techniques are needed for storing, handling, and analyzing soft materials than for hard materials.

1.2 COMMITTEE CHARGE AND SCOPE

According to its charge, the Committee will assess:

- What laboratory analytical capabilities are required to support Planetary Science Division (PSD) (and partner) analysis and curation of existing and future extraterrestrial samples?
- Which of these capabilities currently exist, and where are they located (including international partner facilities)?
- What existing capabilities are not currently accessible that are/will be needed?

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[1] For more information about the field of cryogenic materials, see the Cryogenic Society of America website. https://cryogenicsociety.org/about_csa/

- Whether the current sample laboratory support infrastructure and NASA's investment strategy meets the analytical requirements in support of current and future decadal planetary missions.
- How can NASA ensure that the science community can stay abreast of evolving techniques and to be at the forefront of sample analysis.

Currently, there are two sample return missions flying that will return samples from asteroids (OSIRIS-REx and Hayabusa2), and two mission concepts currently under consideration (Martian Moons Exploration–MMX and Comet Astrobiology Exploration Sample Return–CAESAR) (see descriptions in Chapter 3). There are currently no missions even in the planning stages that propose to return ices. This report therefore focuses especially on the current missions, although it also briefly looks to the future needs for return of gases, organic matter, and ices. Mars sample return is expected but is likely decades into the future, so issues related to martian sample return, such as planetary protection, are only briefly touched on here.

2
Previous Sample Return Missions and Other Collections

This chapter describes materials brought back by previous sample return missions, as well as major meteorite collections, cosmic dust collections, and their curation. Also reviewed is the generation and curation of analog materials, analytical standards, and witness plates.

2.1 SAMPLE RETURN MISSIONS

2.1.1 USA - Apollo

The Manned Spaceflight Center (MSC) was established in 1961 in Houston, Texas, as the home and Mission Control Center for the United States human space flight program. The MSC opened in 1963, with Gemini IV as the first flight controlled there, and continued to grow throughout the Gemini program. In 1961, President John F. Kennedy set the goal of landing men on the Moon and returning them safely within the decade, which led to the beginning of the Apollo missions. In 1973, the MSC was renamed to the Lyndon B. Johnson Space Center (JSC) in honor of the late President and has been the heart of the crewed space flight program ever since.

Six Apollo spacecraft plus 12 astronauts landed on the Moon between 1969 and 1972, each returning lunar samples to Earth (Apollo 11, 12, 14, 15, 16, 17; Table 2.1, Fig. 2.1). Apollo 13 launched to the Moon but did not land because an oxygen tank exploded en route. The Apollo 15-17 missions carried an electric lunar roving vehicle that was used to explore a much wider area. As time on the lunar surface was extended, more areas could be explored, and as the capabilities of the spacecraft were proven; each successive mission brought back more samples than the previous.

TABLE 2.1 Lunar Samples Returned

Apollo crewed landings (USA)					
Year	**Launch Date**	**Name**	**Location**	**Mass Returned (kg)**	**Date Returned**
1969	16 July	Apollo 11	Mare Tranquillitatis	21.6	24 July
1969	14 Nov.	Apollo 12	Oceanus Procellarum	34.3	24 Nov.
1971	31 Jan.	Apollo 14	Fra Mauro	42.3	9 Feb.
1971	26 July	Apollo 15	Hadley Rille	77.3	7 Aug.
1972	16 April	Apollo 16	Descartes Highlands	95.7	27 April
1972	7 Dec.	Apollo 17	Taurus-Littrow	110.5	19 Dec.
Luna robotic sample return (Soviet Union)					
Year	**Launch Date**	**Name**	**Location**	**Mass Returned (kg)**	**Date Returned**
1970	12 Sept.	Luna 16	Mare Fecunditatis	0.10	24 Sept.
1972	14 Feb.	Luna 20	Apollonius Highlands	0.05	25 Feb.
1976	14 Aug.	Luna 24	Mare Crisium	0.17	22 Aug.

A variety of tools were used to collect rock and regolith samples (see Allton, 1989, for a description of all Apollo sampling tools and containers[1]). The six Apollo missions brought back 382

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[1] Allton, J.H., 1989, *Catalog of Apollo Lunar Surface Geologic Sampling Tools and Containers,* JSC-23454, p.97, Johnson Space Center

kilograms (842 pounds) of lunar rocks, core samples, pebbles, sand, and dust from the lunar surface. As part of Apollo preparations in 1964, a small 10-meter square sample receiving laboratory was built so that sample containers could be opened and their contents repackaged under high vacuum for distribution to scientists.

The Lunar Sample Laboratory facility, built in 1979, is now the main repository for the Apollo samples and is located at the JSC complex. It was constructed to provide permanent storage of the lunar samples in a secure and non-contaminating environment. The facility consists of storage vaults for the samples, laboratories for sample curation and study, a vault for sample data and records, and nitrogen-filled cabinets in which the samples are stored and processed (see Section 4.2 of this report, which describes these facilities in more detail). There are two Apollo 15 samples (15012 and 15013) that have had subsamples stored in helium. These were collected in Special Environmental Sample Containers that were sealed on the Moon (15012 achieved a good seal and preserved vacuum, but 15013 did not due to a wire getting caught in the sealing mechanism). They were taken to the University of California Berkeley and opened in a clean room under a helium atmosphere where samples were removed for nitrogen analysis and reserve portions prepared in separate airtight containers for long-term storage under helium at JSC. Since then, the samples have been continuously stored in the returned sample vault in a large container known as the "bean pot" with a constant supply of helium. There are 21 subsamples of 15012 (212 g total) and 16 subsamples of 15013 (198 g total) presently stored in the bean pot. For comparison purposes, portions of both 15012 and 15013 have been stored and processed within a standard Apollo dry nitrogen cabinet.[2]

A second storage facility at the White Sands Test Facility, New Mexico, houses representative samples from each mission. The White Sands facility consists of a ~11 meter square vault and an attached ~12 meter square clean room. Fifty-two kilograms, representing roughly 10-15% of the total Apollo return samples, are stored there as a safeguard should disaster strike the JSC facility.

The list of major scientific results stemming from studies of the Apollo samples are legendary and continue to grow. It is safe to say that the understanding of the Moon, the Earth, and also the solar system, changed profoundly based on these studies. Chief among the most important results is determining the nature of the light-colored crust on the Moon (dominated by a rock called anorthosite which is scarce on Earth), discovery that the Moon had an early magma ocean, placing quantitative constraints on the timing of early impacts, constraining the age of the Moon, revealing that the interior of the Moon contains endogenous volatiles (discovered in 2008), discovery that the Moon and Earth share identical oxygen isotope signatures—which places major constrains on the giant impact hypothesis for generating the moon—and many more. The interested reader is referred to several of the books that have been published on the Moon.[3] [4]

Approximately 1,900 samples are distributed each year for research and teaching projects. These sample requests are handled by the Curation and Analysis Planning Team for Extra Terrestrial Materials (CAPTEM,[5] see Section 4.3).

2.1.2 USSR – Luna

Between 1959 and 1976, the Soviet Union conducted 24 uncrewed Luna missions, including flybys, orbiters, landers, rovers, and sample return missions. Notable among the accomplishments of these missions were Luna 17 and 21, which travelled a total of 47.5 km across the lunar surface over 461

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[2] https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=626457//Specially_Curated_Apollo_Samples_final.pdf

[3] Taylor, S.R., 1975, *Lunar Science: A Post-Apollo View*, Pergamon Press, New York, 390 p..; Ringwood, A.E., 1979, Origin of the Earth and Moon, Springer-Verlag, Berlin, 295 p.

[4] New Views of the Moon (2006) Reviews in Mineralogy and Geochemistry, Volume 60. B.L. Jolliff, M.A. Wieczorek, C.K. Shearer, and C.R. Neal, editors, 720 p. Mineralogical Society of America. ISBN 1529-6466

[5] https://www.lpi.usra.edu/captem/

Earth days, and Luna 16, 20, and 24, which returned a total of ~300 g of lunar regolith samples from the eastern near side of the Moon (Fig. 2.1, Table 2.1). Luna 16 landed in Mare Fecunditatis (returning 101 g) and Luna 24 in Mare Crisium (returning 170 g). Luna 20 landed in a mountainous region between the two basins called Terra Apollonius (returning 50 g). These samples expand the geographical coverage of sampling on the Moon beyond that of the Apollo missions. Samples from the Luna 20 and 24 missions are stored in nitrogen and those from Luna 16 are stored in helium in the Laboratory of Meteoritics at the Vernadsky Institute of Geochemistry and Analytical Chemistry, GEOKhI, of the Russian Academy of Sciences, Moscow, Russia. These samples, along with approximately 1,700 meteorites from the collection of the Russian Academy of Sciences are stored under nitrogen and argon-gas environments.[6] When the samples were returned, initial characterization included magnetic measurements, grain-size distributions, mineralogy and petrology of the samples, as well as stratigraphy of the core. A small fraction of the Luna samples (~11 g total) were provided to JSC in exchange for Apollo samples in the 1970's; approximately 6 g of this material remains in original condition and available for study.[7]

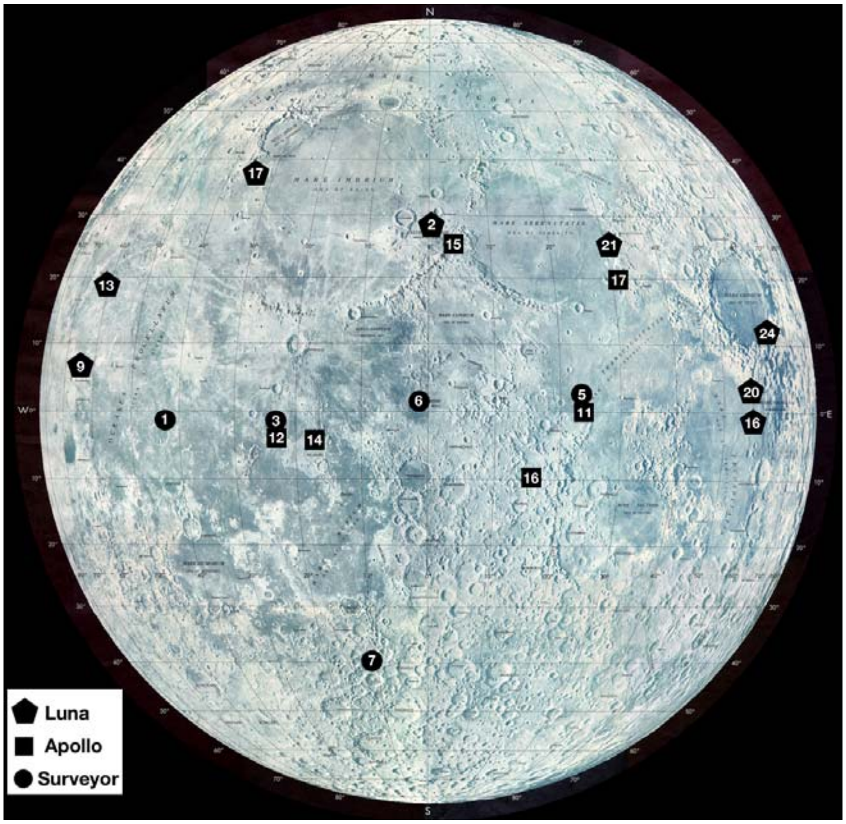

FIGURE 2.1 Lunar nearside map showing the locations of the landed missions during the Soviet Union and USA space race of the 1960s and 1970s. See Table 2.1 for sample masses returned from Apollo and Luna (16, 20, 24) sites. SOURCE: Courtesy of Clive Neal.[8]

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[6] Personal communication, Dmitry Badyukov, Head of the Laboratory of Meteoritics, V.I. Vernadsky Institute, Russia.

[7] https://curator.jsc.nasa.gov/lunar/samplecatalog/sample_results_list.cfm

[8] Modified from C. Neal, 2009, The Moon 35 years after Apollo: What's left to learn? *Chemie der Erde – Geochemistry* 69(1): 3-43.

2.1.3 USA - Genesis (launched August 8, 2001 – returned September 9, 2004)

"All of the objects in our solar system originated from a cloud of interstellar gas, dust and ice, known as the solar nebula. Scientists assume the solar nebula was relatively homogeneous in its chemical and isotopic composition. In contrast, objects currently present in the solar system have a wide variation in composition".[9] To study this evolution, NASA's first sample return since Apollo 17, the Genesis mission, was launched in August 2001 to collect solar wind samples from the Sun-Earth L1 Lagrange point[10] and return them to Earth for study, in order to obtain a better understanding of the origin of the solar system (Fig. 2.2).

The samples were embedded in collector arrays consisting of 15 different ultra-pure, well-characterized materials. Although the craft's parachute failed to deploy on return to Earth, causing the spacecraft to crash-land, sample analysis was still able to be performed on material from the salvaged collectors (Fig. 2.3). Several forms of cutting-edge mass spectrometry and synchrotron-based total reflectance X-ray fluorescence were used to determine elemental and isotopic composition.[11] These included transformational oxygen isotope measurements on an instrument created expressly for this purpose, the MegaSIMS at University of California, Los Angeles (UCLA),[12] which demonstrated the intriguing result that the oxygen isotopic composition of the solar wind (and by inference, the Sun) is very different from inner solar system bodies (Earth, Moon, Mars).[13]

Curation and examination of Genesis samples occurs at the curatorial facilities at JSC. There are two adjacent laboratories for this purpose, both ISO Class 4 cleanrooms.[14] One cleanroom is for cleaning the containers and tools used in handling and cleaning the solar wind samples. The second room is for the long-term storage of samples and for examination and processing of the samples (see Section 4.2 for more details).

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[9] https://www.nasa.gov/mission_pages/genesis/main/

[10] L1 is an equilibrium point between the Earth and Sun's gravitational forces.

[11] Burnett and the Genesis Science Team, 2011, Solar composition from the Genesis Discovery Mission, *Proc. National Academies of Science* 108(48): 19147-19151.

[12] http://megasims.ess.ucla.edu/index.php

[13] K. McKeegan et al., 2011, The oxygen isotopic composition of the Sun inferred from captured solar wind, *Science* 332(6037): 1528-1532.

[14] The International Organization for Standardization (ISO) for clean rooms reflects the concentration of particles of different sizes per volume of air. For example, ISO 4 indicates a concentration of 10 particles of greater than or equal to 0.5 microns per cubic foot of air. The lower the ISO number, the fewer the concentration of particles. https://www.iso.org/standard/53394.html

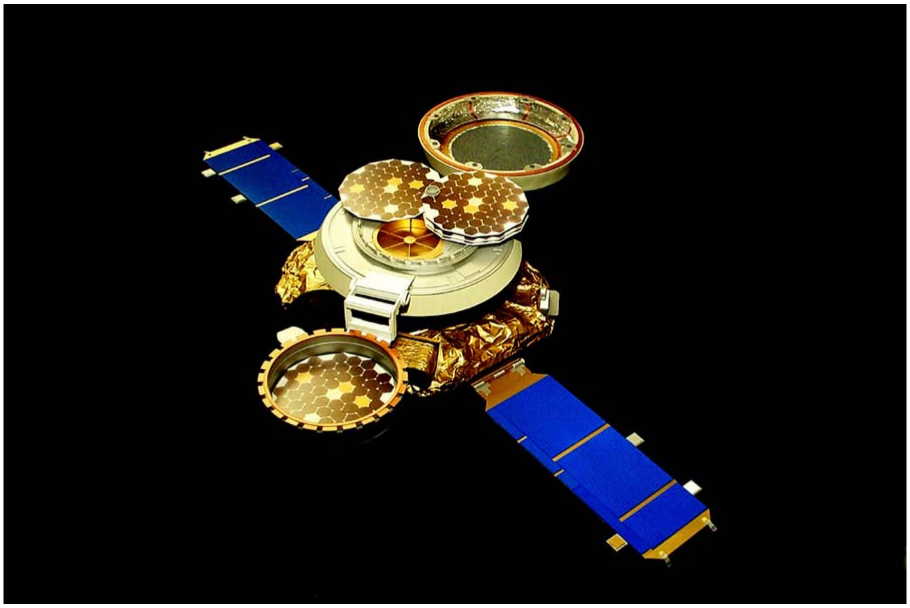

FIGURE 2.2 Artist's rendering of the Genesis spacecraft in collection mode SOURCE: NASA/JPL.[15]

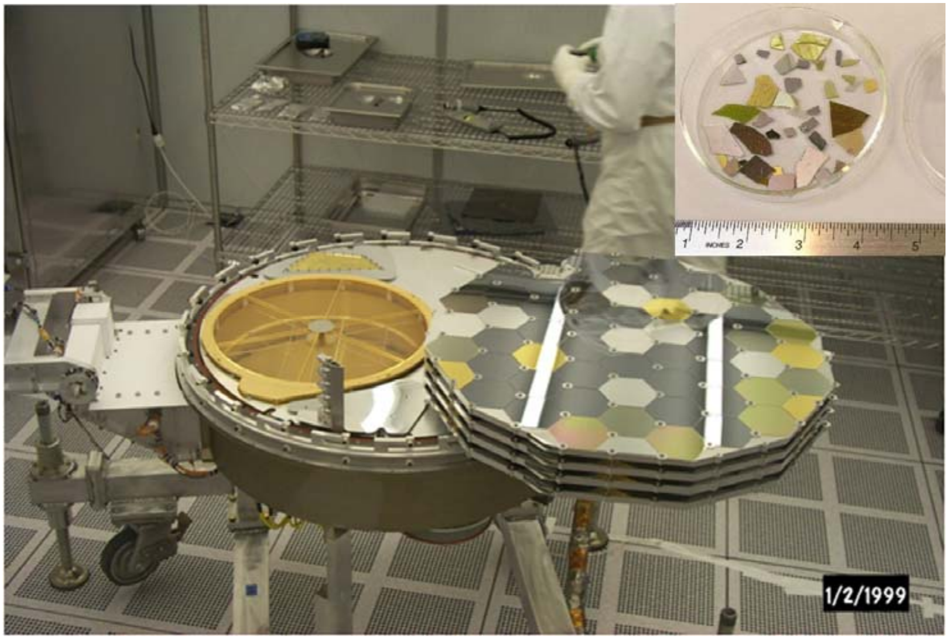

FIGURE 2.3 The Genesis spacecraft prior to launch showing hexagonal polished collectors of pure materials that accumulated solar wind from three regimes over a 28-month time period. (Inset) Pieces of Genesis collector array wafers recovered from the impact site of the sample return capsule. The Genesis curation team was able to recover solar wind samples from these pieces and their analyses by an instrument that was specially built for the mission (MegaSIMS) demonstrated the unexpected finding that terrestrial planets have a distinct oxygen isotopic composition from the solar nebula, as represented by the Sun. SOURCE: NASA-JSC[16]

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[15] https://www.nasa.gov/mission_pages/genesis/main/

[16] https://www.nasa.gov/mission_pages/genesis/main/

2.1.4 USA - Stardust (launched February 7, 1999 – returned January 15, 2006)

NASA's Stardust mission, launched February 7, 1999, was a 390 kilogram robotic space probe that encountered comet Wild 2 and collected thousands of coma dust grains of sizes 100 µm or smaller (Fig. 2.4).[17] The main challenge in collecting the dust grains was successfully slowing the particles from their high velocity with minimal heating and without altering their physical state. Stardust used a substance called aerogel, a silicon-based solid with a porous, sponge-like structure in which 99.8% of the volume is empty space, to collect the coma dust grains. In addition, metallic aluminum alloy foils exposed on the forward, comet-facing surface of the aerogel tray were impacted by the same cometary particle population and were able to record hypervelocity impacts as bowl-shaped craters.

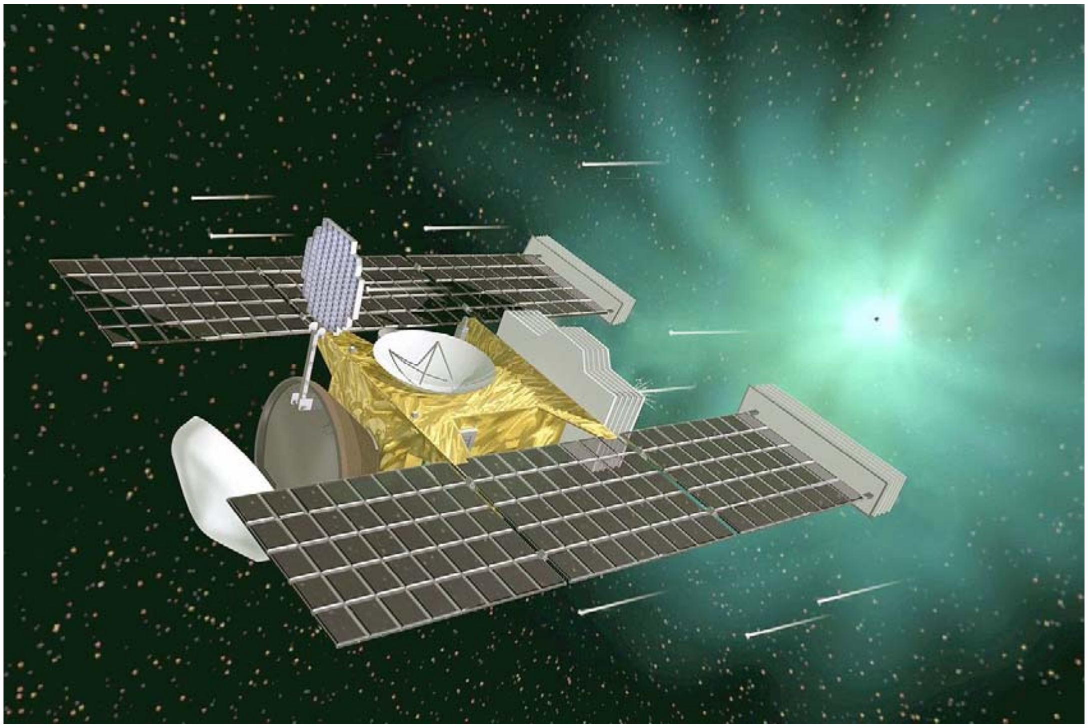

FIGURE 2.4 Artist's rendering of the Stardust spacecraft with the aerogel collector extended. SOURCE: NASA/JPL[18]

On its return to Earth, Stardust exposed an additional aerogel tray with the goal of collecting approximately 100 interstellar dust particles. The sample containers were taken to a clean room, and preliminary estimations suggest that at least a million microscopic specks of dust were embedded in the aerogel collectors (Fig. 2.5). Some of the material, totaling less than 1 mg, has been extracted using various techniques and analyzed. To date, seven dust particles of interstellar origin have been identified.[19] Dust grains are being observed and analyzed by a volunteer team, calling themselves "Dusters," through the distributed computing project, Stardust@Home, a UC Berkeley citizen-science project that proved critical to finding these dust grains. The identification, extraction, analyses, and curation of these particles is on-going.

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[17] Tsou, P., Brownlee, D.E., Sandford, S.A., Horz, F., and Zolensky, M.E., 2003, Wild 2 and interstellar sample collection and Earth return, *Journal of Geophysical Research: Planets* 108(E10)

[18] https://stardust.jpl.nasa.gov/home/index.html

[19] Westphal, A. J., et.al., 2014, Interstellar Dust. Evidence for interstellar origin of seven dust particles collected by the Stardust spacecraft, *Science* 345: 786-91.

Like its predecessor, Genesis, the Stardust mission held big surprises once analyses were made of the returned materials. Foremost among these was the discovery of high temperature, inner solar system materials as the dominant component of the rocky portion of the comet, which had been expected to be dominated by interstellar dust.[20] This finding requires that an effective means of transport existed between the inner and outermost solar system very early on, a process not previously imagined prior to this mission. Another surprise was the discovery that organic solids in Stardust samples are similar to those found in carbonaceous chondrites, interplanetary dust particles, and at least one Kuiper belt object.[21] This is significant because it was previously assumed that organic solids associated with outer solar system bodies, such as comets, were formed from a different process than organic solids found within the inner solar system (e.g., in chondritic meteorites). The Stardust samples demonstrated that the known extraterrestrial organic solids formed from a common process.

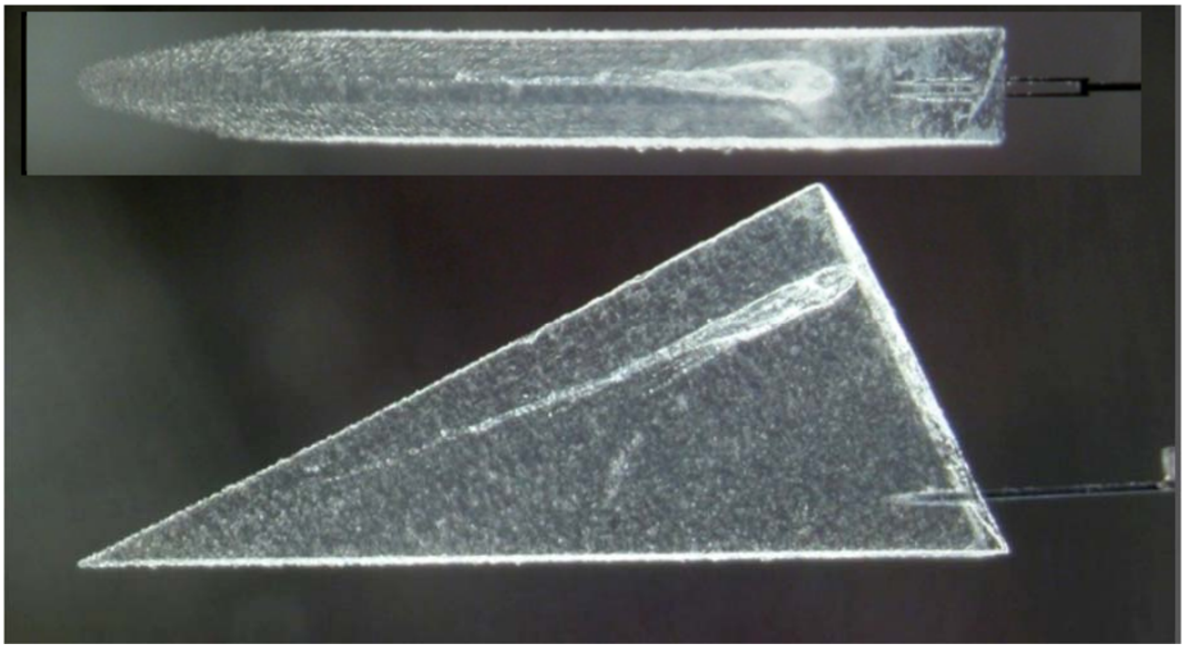

FIGURE 2.5. 1500-µm long track containing material from the coma of comet 81P/Wild 2, extracted from the Stardust cometary aerogel collector in a `keystone' and mounted on a polysilicon “micropicklefork” for synchrotron X-ray microprobe analysis. SOURCE: Andrew Westphal, University of California, Berkeley.

2.1.5 Japan - Hayabusa (launched May 9, 2003 – returned June 13, 2010)

The Hayabusa mission launched in May 9, 2003, with the goal to return samples from the small, near-Earth asteroid 25143 Itokawa (Figure 2.6). It rendezvoused with the asteroid mid-September 2005 where it studied the asteroid’s shape, spin, topography, density, and composition. In November, 2005 the craft’s sample collection technique of firing small projectiles into the asteroid and using a funnel to catch the resulting debris did not work; however, the spacecraft made several touch and go maneuvers on the asteroid. During one of these, Hayabusa inadvertently impacted on the asteroid’s surface after losing

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[20] Ishii, H.A., Bradley, J.P., Dia, Z.R., Chi, M.F., Kearsley, A.T., Burchell, M.J., Browning, N.D. and Molster, F., 2008, Comparison of comet 81P/Wild 2 dust with interplanetary dust from comets, *Science* 319: 447-450.

[21] Cody, G.E., Heying, E., Alexander, C.M.O’D., Nittler, L.R., Kilcoyne, A.L.D., Sandford, S.A., Stroud, R.M., 2011, Establishing a molecular relationship between chondritic and cometary organic solids, *Proceed. Nat. Acad. Sci.* 108: 19171-19176.

communication with Earth, but it was recovered and did collect approximately 5,000 particles in the funnel that were approximately 10 micrometers in size, with a total weight of less than a milligram.[22]

The Japanese Space Agency (JAXA) returned the craft to Earth June 13, 2010, and 10% of the samples, which range in size from 26 µm to 177 µm, were allocated to NASA in exchange for their support of the mission. The samples were recovered by swabbing a Teflon spatula along the collector. Since collection at Itokawa did not go as planned, it is believed that some particles represent contamination.[23]

JAXA's Hayabusa collection is stored at the Extraterrestrial Sample Curation Center (ESCuC) at the Institute of Space and Astronautical Science, Sagamihara City, Japan, which was completed in 2008. The facility is on two floors, with the analytical equipment in the basement and the sample curation facilities on the first floor, taking up approximately 1,000 square meters. The collection is cataloged online and is available for loan.[24] The Astromaterials Science Research Group (ASRG), established in 2015, is continuing the curatorial work for Hayabusa returned samples. As of February 2017, approximately half of NASA's Hayabusa collection is available for study and stored at NASA's Johnson Space Center; the other half is out on loan to academic and other research institutions where detailed chemical, microstructural, and other analyses are being undertaken.

Phase-1 curation (sample description) was completed at the JAXA curation facility. The phase-2 curation of these returned samples will entail thorough analysis and characterization through methods such as X-ray computed tomography/X-ray diffraction (XCT/XRD), transmission electron microscopy/scanning transmission electron microscopy (TEM/S-TEM), electron probe micro analysis (EPMA), secondary ion mass spectrometry (SIMS), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, instrumental neutron activation analysis (INAA), noble-gas-mass spectrometry, time-of-flight SIMS (ToF-SIMS) (see Appendix E for a key to instrument acronyms) in both the JAXA curation facility and in several research institutes outside JAXA led by the JAXA curation facility.

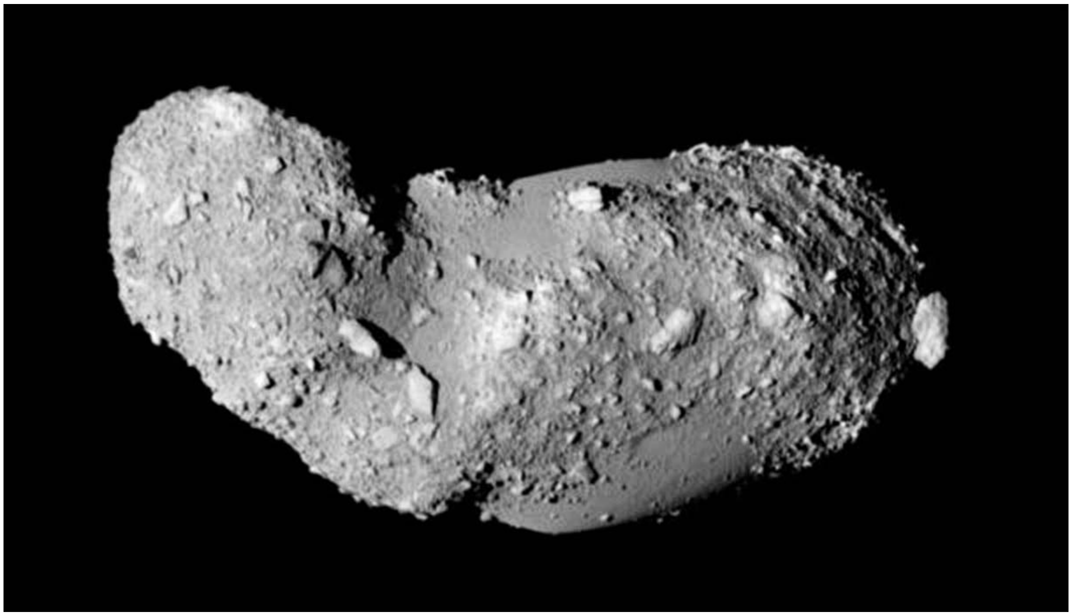

FIGURE 2.6 Image of the asteroid Itokawa, taken by the Hayabusa spacecraft from approximately 8 km away. SOURCE: JAXA/ISAS[25]

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[22] https://repository.exst.jaxa.jp/dspace/handle/a-is/867999

[23] https://www.hou.usra.edu/meetings/metsoc2014/pdf/5239.pdf

[24] https://hayabusaao.isas.jaxa.jp/curation/hayabusa/index.html

[25] https://apod.nasa.gov/apod/ap140209.html

2.2 OTHER COLLECTIONS

2.2.1 Major Meteorite Collections and Their Current Curation

Although meteorites have been recovered and preserved since at least 1492 with the fall of the Ensisheim meteorite in France, scientific collections of meteorites emerged in Europe in the first decade of the 19th century with the recognition that meteorites were objects of extraterrestrial origin. Early studies focused primarily on obtaining bulk chemical compositions. Introduction of the petrographic microscope to the study of meteorites yielded a number of new and interesting minerals. Nonetheless, meteorites remained curiosities through the 19th and first half of the 20th centuries, largely confined to collections of major museums in Europe and the U.S., a few universities and a handful of private collectors. Interest in meteorites – and the associated analytical equipment with which to study them – grew rapidly after World War II and the introduction of chemical and isotopic studies.

Within a few decades, instrumentation for *in situ* mineralogical and mineral chemical analyses, including the scanning electron microscope (SEM) and electron microprobe, were commonplace in universities, museums and research institutes. Chemical analyses of meteorites included both stable and radiogenic isotopes, yielding the first reliable estimates of the age of the Earth and solar system. Meteorite collections grew serendipitously through 1969, with both occasional finds of meteorites that had fallen within the last few thousand years and modern falls, some of which were observed. The introduction of fireball observing networks yielded proof of the asteroidal origin of most meteorites. From the 1960's through the end of the 20th century, analytical techniques were pushed to increasingly precise measurements of ever smaller volumes, driven in part by the recognition that bulk isotopic signatures reflected the inclusion of particles and individual grains formed at or even before the birth of the solar system. At the same time, the availability of meteorites increased dramatically with the recognition that deserts held vast numbers of meteorites. The first recognition of this came from the cold deserts of Antarctica, where discovery by Japanese glaciologists of distinct meteorites concentrated by ice movement would cascade into discovery of tens of thousands of meteorites. Towards the turn of the century, comparably large numbers of meteorites would be recovered from the hot deserts of the world, notably in northern Africa and the Middle East. As of the writing of this report, more than 57,000 named meteorites, with another nearly 8,000 provisionally named, were known to science, representing, by far, the largest share of extraterrestrial material available for study in our analytical laboratories.

There are currently different levels of curation and accessibility to collections in the United States. There is the Johnson Space Center (high-level curation; accessibility through committee review of requests), then major museums and a few universities (mid-level curation; readily accessible through a single curator) and a myriad of other collections (mid- to low-level curation; not widely accessible to the community). A few of the major museums and universities with high-level curation are listed below to illustrate the depth and history of these major meteorite collections that are accessible to the scientific community.

2.2.1.1. Smithsonian Institution (Washington, D.C.)

The meteorite collection at the Smithsonian Institution traces its origin to the collection of James Smithson and has grown to its current size through large donations of personal collections, purchases, and trades. The meteorite collection currently includes 19,596 different meteorites and 56,190 specimens. The Smithsonian also provides initial characterization of the newly collected specimens from the Antarctic Meteorite Program and then permanent storage and distribution to the scientific community. Of the almost 16,000 Antarctic meteorites collected since 1976, over 14,000 meteorites are permanently housed at the Museum Support Center clean room facility at Suitland, Maryland.

2.2.1.2. Field Museum (Chicago, Illinois)

The meteorite collection at the Field Museum is housed within the Robert A. Pritzker Center for Meteoritics and Polar Studies. The collection currently includes 1,593 different meteorites and 12,251 specimens in a newly renovated climate-controlled, secure facility in dust-tight metal cabinets.[26] The Field Museum is part of a three-institution Chicago Center for Cosmochemistry (C^3) together with Argonne National Laboratory and the University of Chicago, whose mandate is to promote education and research in cosmochemistry.

2.2.1.3. American Museum of Natural History (New York, New York)

The meteorite collection of the American Museum of Natural History (AMNH) is housed in the Earth and Planetary Sciences Department on the museum campus, with over 120 samples on display in the Arthur Ross Hall of Meteorites. The collection includes more than 5,500 samples of roughly 1,350 unique meteorites housed in a secure space in metal cabinets, some dust-tight, monitored 24/7 by museum security. The AMNH collection serves the global meteoritics community and acts as a hub for researchers in the New York region.

2.2.1.4. Major University Meteorite Museums

A significant number of universities have acquired meteorite collections that range from small collections primarily used by researchers within that university to major collections that serve as repositories for research materials used by the broader scientific community. Among these are Harvard, Yale, Texas Christian University, Arizona State University, the University of Arizona, the University of New Mexico, and UCLA. Here, two of these collections are highlighted – one started in the early 19th century and the other primarily resulting from collections of the 20th century.

Peabody Museum of Natural History (New Haven, Connecticut)

The Peabody Museum of Natural History is located on the campus of Yale University. The collection started in 1807, which makes it the oldest in the world and has strengths in American meteorites of the 19th century. The meteorite collection currently includes approximately 1,100 different meteorites and approximately 4,000 total specimens. In 2019 there will be a major acquisition which will double the number of meteorites and bring the total number of individual specimens to approximately 5,500.[27]

Arizona State University (Tempe, Arizona)

The Carleton B. Moore meteorite collection is housed in the Center for Meteorite Studies (CMS) at Arizona State University. It is touted as the largest university-based collection, with 2,000 distinct meteorite falls and over 40,000 individual specimens. A ~370 square meter, climate-controlled collection storage vault, including specialized steel specimen cabinets, nitrogen dry-environment cabinets and heavy-duty full-extension shelving cabinets for oversized meteorites was built in 2012. The associated Isotope Cosmochemistry and Geochronology Laboratory contains a wide-range of analytical equipment such as a class 10,000 clean laboratory, a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) with laser ablation system (see Appendix B).

2.2.2 Cosmic Dust

In addition to the other extraterrestrial materials collections located at the JSC curatorial facility, there exists the unique cosmic dust collection.[28] Cosmic dust generally refers to extraterrestrial particles with sizes below 100 µm that float down through Earth's atmosphere. Starting in the early 1980's NASA began a program collecting such particles (also known as Interplanetary Dust Particles, IDPs) in the Earth's stratosphere, largely using ultra high flying piloted planes with accessory collectors. The collectors are stored and curated at the JSC curatorial facility.

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[26] http://meteorites.fieldmuseum.org/node/12

[27] Jay Ague, personal communication.

[28] https://curator.jsc.nasa.gov/dust/

Whereas cosmic dust clearly comes from many different sources, it became clear that certain Earth orbit crossings by specific objects (e.g., comets such as 55P/Temple-Tuttle and 26P/Grigg-Skjellerup) provided an opportunity to sample cosmic dust from these primitive bodies. Most recently, a collection flight designed to capture cosmic dust from the comet 21P/Glacobini-Zinner was flown. The Cosmic Dust Collection Program provides a means of sampling a wide range of primitive objects.

The Cosmic Dust Laboratory resides in a ISO Class 5 laminar flow clean room. The collectors are subject to preliminary investigation using optical microscopy. Identified particles are removed and cleaned of silicone oil and a subset are subsequently characterized using SEM and energy dispersive X-ray (EDX) analysis.

According to Zolensky (2016), the current NASA collection residing at JSC includes over 3,000 particles that are "pre-characterized"—meaning assessed via optical microscopy—but not analyzed further.[29] The analytical techniques developed in terrestrial laboratories and the experience gained through studies of IDPs greatly enhanced analytical capabilities leading to the conception and implementation of the NASA Stardust sample return mission to Comet 81P/Wild 2.

2.2.3 Analog Materials, Analytical Standards, and Witness Plates

A number of ancillary materials are required in order to obtain accurate and precise data for returned samples. These include analog materials such as rocks, minerals, ices, gases, and organic compounds, both naturally occurring and manufactured, that play an important role in connection with the curation and subsequent study of extraterrestrial samples from sample return missions; analytical standards that are required to calibrate instruments and to assess accuracy of data; and witness plates, which are used to assess possible contamination experienced by the sample.

Analog Materials

These are samples with well-characterized physical, chemical, or biological properties that serve as analogs of returned samples for assessing the effects of sample flow from storage and handling in the curation facility, distribution to laboratories outside the curation facility, and handling of these materials in the laboratories. These materials can be used to test and refine the protocols for handling returned samples in the curation facility and in external laboratories, and for transport within and between these facilities.

To the extent that some returned samples will require extreme special handling out of concerns for planetary protection from biological hazards (see Section 3.4.2), analog materials will be especially useful in documenting how such special handling will affect the overall organic and inorganic properties of the samples. The analog materials also allow for studies of how expected changes in environmental conditions between sample collection, transport to and on Earth, storage, and manipulation both in a curatorial facility and at outside laboratories will potentially degrade certain key properties that one would otherwise want to analyze.

Analytical Standards

Analytical standards are materials with well characterized chemical properties that are used for referring analytical measurements to internationally recognized standard values. Another important use of either natural or synthetic standard materials is to document and correct for mass fractionation in mass spectrometers as a function of matrix composition (e.g., a set of olivine standards with known isotopic composition and different iron-magnesium ratios for use in SIMS isotopic analyses). In many cases, correcting for matrix effects is the limiting factor in high-precision microanalytical measurements by laser

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[29] Zolensky M. E. (2016) NASA's Cosmic Dust Program: Collecting Dust Since 1981, *Elements* 12: 159-160.

ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) or by SIMS. Developing and distributing comprehensive sets of samples for quantifying matrix effects across the range of relevant properties of extraterrestrial samples will allow for more precise and realistic interlaboratory comparison of analytical results for these *in situ* methods.

Arguably the most widespread use of analytical standards is to document accuracy of analyses by various analytical methods, where the standards are analyzed as unknowns using the same protocol as the samples. Many organizations (e.g., National Institute of Standards (NIST), United States Geological Survey (USGS), Smithsonian Institution, Geological Survey of Japan, Max-Planck Institute for Chemistry, Mainz, Germany, etc.) have generated analytical standards and most are freely available upon request. A relatively comprehensive compilation of published standard values for trace elements and isotopes is available on the GeoReM website, which is maintained by a group at the Max-Planck Institute for Geochemistry in Mainz, Germany.[30]

Witness Plates

Witness plates are used to document in space and time the environment in which extraterrestrial materials are sampled, stored, manipulated, and analyzed in terms of chemical, organic, and/or biological contamination.[31] Witness plates fly on all current and planned extraterrestrial sample return missions and these are curated at JSC for all NASA missions.

Witness plates are an essential element of any contamination control (CC) and contamination knowledge (CK) plan for a space mission. In particular, contamination knowledge samples are critical for sample return missions, because they represent the baseline from which contamination is established in the returned samples. In all space missions, witness plates are exposed during spacecraft manufacturing, integration, and testing. CC samples serve as the ground truth for effective contamination control and mitigation actions. They are periodically examined and then removed from the spacecraft before launch. CK samples are collected in parallel with the CC samples, but they are archived without examination. Both the CC and CK pre-flight witness plates are archived for resolving questions that might later arise. For sample return missions, returnable witness plates are installed that will document the environment of the spacecraft and the sample collection systems throughout the mission. Exposure of spacecraft to vacuum causes outgassing of various materials, including organic materials from lubricants and combustion products from maneuvering thrusters and propulsion systems. Sample collection systems are often kept sealed until late in the mission to minimize contamination opportunities. For example, an extensive collection of witness plates was employed during spacecraft assembly, testing and launch operations for the OSIRIS-REx mission (see Section 3.1.1).[32]

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[30] Geological and Environmental Reference Materials http://georem.mpch-mainz.gwdg.de/

[31] Witness plates are also known as witness surfaces or witness standards.

[32] Lauretta, et al., 2017, OSIRIS-Rex: Sample Return from Asteroid (101955) Bennu, *Space Science Reviews* 212:1-2, p925-984

3

Current Sample Return Missions, and Near-Future Priorities Outlined in the Planetary Science Decadal Survey

This chapter continues the discussion of sample return missions into the present and the future, with a discussion of the priorities and challenges for the next generation of sample return missions. Section 3.1 discusses the two sample return missions in progress that are scheduled to return with samples in the next five years (Fig. 3.1). Section 3.2 provides an overview of the priorities for sample return missions, as outlined in the current Planetary Science Decadal Survey. Sections 3.3 and 3.4 outline the next phase of sample return missions that are in the planning stages—a NASA New Frontiers-class mission[1] that is currently in competition for funding (i.e., it has been down-selected) to return comet samples (CAESAR), and a JAXA Martian Moon Explorer (MMX) mission, and continues the discussion of potential future sample return missions based on the priorities outlined in the Planetary Science Decadal Survey (Table 3.1). Finally, Section 3.5 summarizes some of the challenges associated with the next stages of sample return missions, including handling thermally unstable samples, planetary protection considerations, and possible modes for lunar sample return, including human spaceflight and commercial missions.

FIGURE 3.1 Dual asteroid explorers: Left: Artist's rendition of Hayabusa2 (JAXA) Right: Artist's rendition of OSIRIS-REx spacecraft performing a 'touch and go' sample acquisition at Bennu. *SOURCE: From the Bruce Murray Space Image Library of the Planetary Society. NASA / Goddard / University of Arizona / JAXA*[2]

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[1] NASA missions currently fall into three categories related to overall cost: large strategic missions (also known as flagships), costing >$1 billion (the Mars 2020 rover is an example), New Frontiers missions, with intermediate costs ($0.5 to $1 billion; OSIRIS-REx is an example), and the relatively low cost Discovery missions, which cost <$0.5 billion (both Genesis and Stardust missions fall within this category).

[2] http://www.planetary.org/multimedia/space-images/spacecraft/dual-asteroid-explorers.html

TABLE 3.1 Sample Return Missions Currently In Progress, Missions in Consideration for Possible Implementation, and Some Potential Future Missions

Mission Name	Lead Agency		Launch Year/ Sample Return Year	Target/Amount of Sample
OSIRIS-REx	NASA	Current	2016/2023	Carbonaceous Asteroid Bennu, 60 g to 2 kg
Hayabusa2	JAXA	Current	2014/2020	Carbonaceous asteroid Ryugu, ≥0.3 g[3]
CAESAR	NASA	Candidate for selection	Estimated 2024/2038	Comet 67P, Churyumov-Gerasimenko, 100 g
MMX Martian Moons Exploration	JAXA	Identified as high priority in Decadal Survey	Estimated 2023/2030	Phobos, ~10 g
Mars Sample Return	NASA/Multiple Agencies	Identified as high priority in Decadal Survey		Mars 2020: Jezero Crater
Lunar Sample Return	NASA	Identified as high priority in Decadal Survey		South Pole-Aitken Basin
Moon Express	Private		Estimated 2019/2021	

3.1 CURRENT SAMPLE RETURN MISSIONS

3.1.1 OSIRIS-REx—NASA

The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx), the NASA-operated New Frontiers 3 mission, was launched on September 8, 2016, and is currently approaching 101 955 Bennu, a primitive carbonaceous asteroid. The mission is being carried out in partnership with the Canadian Space Agency, as described below. The spacecraft is scheduled to arrive at Bennu on December 3, 2018, and begin 505 days of surface mapping to study the asteroid with five suites of instruments for surface imaging and spectroscopy. A sample of Bennu's regolith will be collected by a robotic arm touch-and-go sample acquisition mechanism (TAGSAM). Sample collection by the TAGSAM system blows compressed nitrogen onto the surface regolith of Bennu, and collects the fluidized solid materials into a ring-shaped canister. The system will collect at least 60 g (and up to 2 kg) in up to three sample collection attempts, and is able to collect a variety of sizes and size-frequency-distributions of particles. The spacecraft is expected to return the sample to Earth in September 2023, via a sample return capsule (SRC, Fig. 3.2) that will re-enter Earth's atmosphere after being released from the spacecraft.

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[3] Sawada et al., Hayabusa2 Sampler: Collection of Asteroidal Surface Material, Space Sci. Rev. 208, No. 1-4, 81-106 (2017) DOI 10.1007/s11214-017-0338-8

Bennu was selected because it is an easily-accessed near-Earth carbonaceous asteroid, which is expected to contain primitive material, perhaps including organic molecules. In addition, Bennu is relatively large (492 m in diameter) and has a slow-enough rotation speed (4 hours for one rotation) to allow sampling operations. The samples collected will provide information about the composition of materials that built the terrestrial planets during the formation of the solar system, including sources of water and organic molecules, key components for the development of life on Earth.

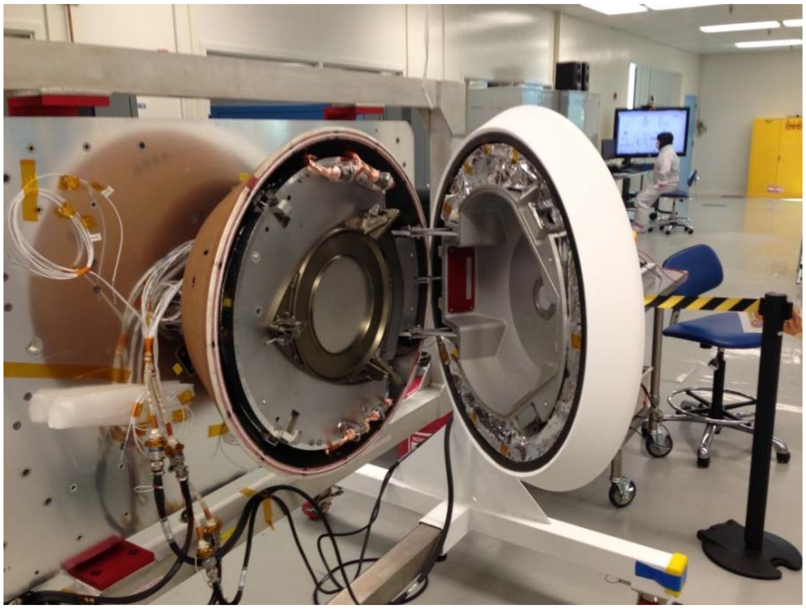

FIGURE 3.2 Sample return capsule (SRC) of OSIRIS-REx undergoing an open spin balance test. This test spins the SRC while it is in the open configuration. The cylindrical structure on the left side is where the sample head will be stored with the sample from Bennu. SOURCE: https://dslauretta.com/2015/07/15/osiris-rex-testing-in-progress/.

Since the target asteroid is predicted to be carbon-rich, all stages of the curation require great care to prevent terrestrial contamination. Part of the early curation involved monitoring all materials that go into the design and construction of the TAGSAM system and the return capsule. The samples will be returned to a contamination-free curation environment at JSC. The sample return, curation, and characterization environments require prohibiting materials in the facilities that would create amino acid-like materials, such as latex, nylon, etc. The Canadian Space Agency (CSA) will receive 4 percent of the returned sample of Bennu in return for their contribution of the Laser Altimeter instrument to the mission. Per international agreement, NASA will provide 0.5 percent of the returned sample of Bennu by mass to JAXA, and JAXA will provide 10 percent of the returned sample mass of Ryugu from the Hayabusa2 mission to NASA (see Section 3.1.2).

The OSIRIS-REx Bennu sample curation laboratory is currently under construction within existing space in Building 31 at JSC (Fig. 3.3). The space will be entirely refurbished, cleaned, and all electrical, mechanical, security and information technology will be upgraded. Adjacent to the OSIRIS-REx cleanroom, a sample preparation room with separate access will be dedicated to cutting, grinding, thin sectioning, and other types of necessary sample preparation. The cleanroom suite's completion date is scheduled for June 2020, allowing time for commissioning, including rehearsals of sample reception, preparation, and handling.

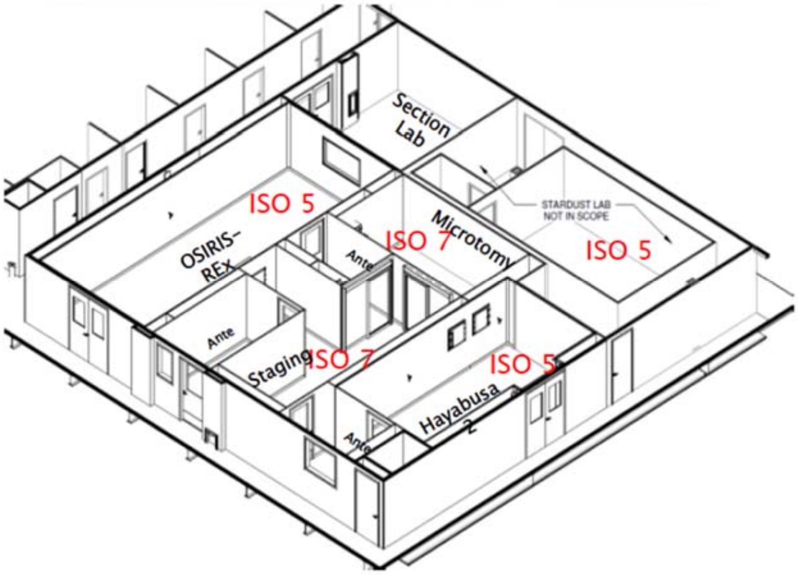

FIGURE 3.3 Drawing of planned new curatorial space at Johnson Space Center designed to handle returned samples from OSIRIS-REx and Hayabusa2. Also shown are existing laboratories for Stardust samples. The air purity of each laboratory is shown in red; the lower the ISO (International Standards Organization) number, the lower the concentration of particulates in a given laboratory. SOURCE: courtesy Lisa Pace, JSC.

3.1.2 Hayabusa2—JAXA

The Japanese Aerospace Exploration Agency (JAXA) spaceship Hayabusa2 was launched on December 3, 2014, and is an asteroid explorer whose target is a C-type asteroid named 162173 Ryugu. Hayabusa2 arrived at Ryugu in late June 2018 (Fig. 3.4 and Fig. 3.5), and will study the asteroid for one and a half years before leaving at the end of 2019 and returning samples to Earth at the end of 2020. Like its predecessor, the Hayabusa mission to the near-Earth asteroid 25143 Itokawa, Hayabusa2 will also use a projectile blast and funnel method to collect samples from the asteroid. However, unlike Hayabusa, Hayabusa2 will release an impactor to generate a crater on Ryugu, in which it will then land and collect samples. The reflectance spectra of C-type asteroids are similar to carbonaceous chondrites; therefore, Ryugu is thought to be a more primordial body than Itokawa and may contain organic matter, water, and hydrated minerals.

Once the samples are received, phase-1 curation (sample description) will be done at the JAXA curation facility. Phase-2 curation, consisting of further analysis, description, and creation of a sample database will be done both at and outside of the JAXA curation facility, all supervised by the JAXA curation staff.

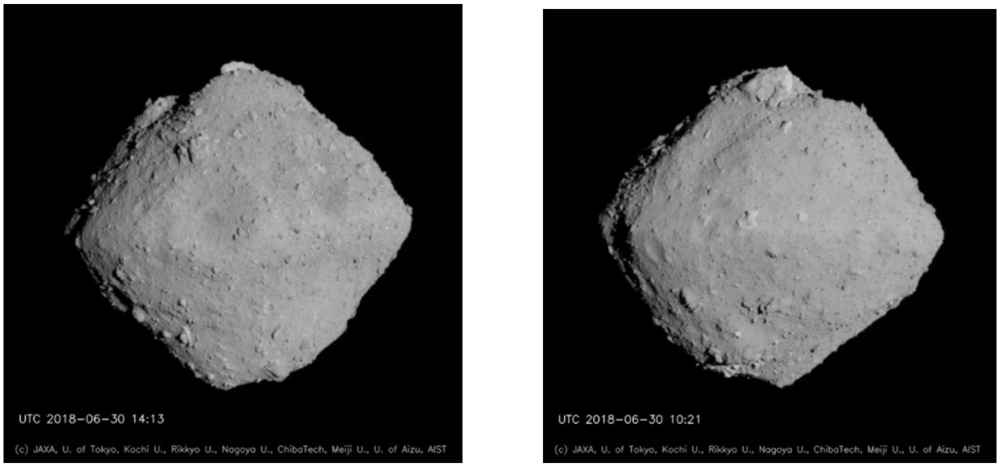

FIGURE 3.4 Left: Asteroid Ryugu photographed by Hayabusa2 from a distance of about 20 km. The image was taken at around 23:13 JST on June 30, 2018. Right: As the asteroid has rotated, this image is almost the reverse side of the figure on the left. SOURCE: JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu and AIST.[4]

FIGURE 3.5: The surface of asteroid Ryugu imaged by the MINERVA-II1B rover on September 23, 2018, one of two rovers deployed from the Hayabusa2 spacecraft. SOURCE: JAXA[5]

A new clean chamber is being built at the JAXA facility in Sagamihira, Kanagawa, Japan for the Hayabusa2 return samples at a cost of 12.5 million U.S. dollars,[6] and is opening in 2018.[7] The new clean chamber includes areas designated for vacuum conditions, as well as other areas intended to be operated in an ultra-pure nitrogen atmosphere. The vacuum area has separate rooms for opening the sample container, for sampling, and for storage. The nitrogen atmosphere area has separate chambers for examining ~micron-sized particles and ~mm-scale particles. The JAXA team is building on the Hayabusa curation expertise[8] and furthering the technical development for handling and cutting the larger particles,

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[4] http://www.isas.ac.jp/en/topics/001724.html

[5] http://www.hayabusa2.jaxa.jp/en/topics/20180927e_MNRV/

[6] *pers. Comm*. Masaki Fujimoto

[7] Abe et al., Curation facility for asteroid sample return missions in Japan. LPSC 2018 LIP Contrib. No 20183.

[8] Yada et al., Meteoritics & Planetary Science 49, Nr 2, 135–153 (2014) doi: 10.1111/maps.12027

which were not necessary for the Hayabusa samples. Preventing and monitoring contamination of the Hayabusa2 samples is a high priority, with additional engineering controls designed for all stages of sample collection, return, sample handling, curation, and characterization.

As noted above, 10% of the Ryugu samples be provided to NASA for curation at JSC. Fig. 3.3 shows the curation facility for Hayabusa2 at JSC, which will be co-located within the curation facilities OSIRIS-REx described in Section 3.1.1.

3.2 PRIORITIES FOR SAMPLE RETURN MISSIONS OUTLINED IN THE 2013-2022 DECADAL SURVEY

The decadal survey *Vision and Voyages for Planetary Science in the Decade 2013-2022*[9] is an extensive ten-year plan for solar system science and mission priorities. It provides an overview of the current state of solar system knowledge, and identifies the next sets of science questions and measurement targets for the period 2013-2022. In addition, the Decadal Survey assesses current solar-system-related research programs and infrastructure, and prioritizes next investments to support missions. Finally, the Decadal Survey identifies mature spacecraft mission concepts, and prioritizes them within their class.

The highest priority large strategic mission named in the decadal survey is the Mars Astrobiology Explorer-Cacher (MAX-C) to begin the task of returning samples from Mars,[10] noting that this will be a multi-decadal and multi-mission effort. In the New Frontiers class ($0.5-$1B), out of five candidate mission targets[11], two sample return missions were specified: a comet surface non-cryogenic sample return mission, and a mission to sample the Lunar South Pole-Aitken basin.

The Decadal Survey also highlights technology development for future sample return missions, from comets, Venus, Mars, and the icy moons of the outer planets (e.g., Enceladus and Europa), and highlights the need for investment to support eventual cryogenic sample return.[12] It also notes that “future sample return missions from Mars and other targets that might potentially harbor life (e.g., Europa and Enceladus) be classified as “Restricted Earth Return” and are subject to quarantine restrictions [under planetary protection], requiring special receiving and curation facilities.”[13] (see Section 3.4.2)

Finally, the Decadal Survey directly addresses sample curation, stating that the initial curation costs associated with the mission need to be a part of the mission budget: "Every sample return mission flown by NASA should explicitly include in the estimate of its cost to the agency the full costs required for appropriate initial sample curation.”[14]

3.3 POTENTIAL FUTURE MISSIONS GUIDED BY THE DECADAL SURVEY

3.3.1 Down-selected: Comet Surface Sample Return *via* CAESAR—NASA

The return of cryogenic comet samples is considered by the Decadal Survey as an essential goal in the study of primitive bodies. However, such missions are logistically challenging and will require extensive technological development. Thus, in preparation for eventual cryogenic comet sample return, the decadal survey recommended a comet surface sample return (CSSR) mission capable of returning a

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[9] National Research Council. 2011. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13117

[10] NRC, 2011, Vision and Voyages, pp157-161

[11] Ocean Worlds (Titan and/or Enceladus) was later added as an addition New Frontiers mission target after the publication of the Decadal Survey.

[12] NRC, 2011. *Vision and Voyages*, p311

[13] NRC, 2011. *Vision and Voyages*, p296

[14] NRC, 2011. *Vision and Voyages*, p296

minimum of 100 g of material. Such a mission was considered the highest priority in studying primitive materials and the origin of the solar system.

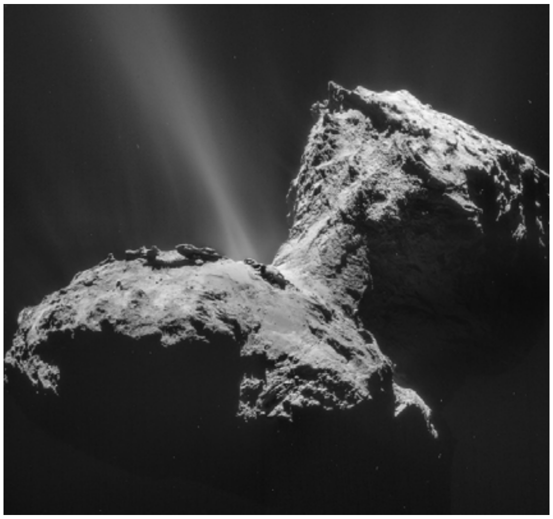

FIGURE 3.6 Comet 67P, Churyumov-Gerasimenko. SOURCE: European Space Agency (ESA)/Rosetta/NAVCAM – CC BY-SA IGO 3.0

Accordingly, in December 2017, the Comet Astrobiology Exploration Sample Return (CAESAR) mission was down-selected as one of two finalists for NASA's New Frontiers program. The objective of CAESAR is to collect material from the surface of comet 67P, Churyumov-Gerasimenko (Fig. 3.6), a Jupiter-family comet that was previously investigated by the ESA's Rosetta mission, which included sending the Philae lander to its surface for in situ analyses of organic molecules. Churyumov-Gerasimenko has spectral characteristics suggesting the presence of non-volatile organic materials at its surface[15] and a suite of 16 organic compounds were detected by Philae.[16] The mission would use a touch-and-go (TAG) robotic arm to collect between 80 to 800 grams of regolith from the surface. The sample target includes the solid components of the particulate matter that comprises the surface of a comet, which will likely include ices and organic material, as well as rocky material.

CAESAR is not a cryogenic sample return mission and will only return solid materials and the associated gas liberated from the sublimation of the ice. The container system collects the sample, then systematically devolatilizes it, sequestering the resulting gas from the solid samples; both are returned in differentially cooled chambers of the return container (Fig. 3.7). The return capsule also preserves the samples, insulating them using phase-change materials that will maintain the samples at subzero (ºC) temperatures until recovery.

If selected as the New Frontiers 4 mission, the projected launch date is August 2024; the craft will arrive at the comet in March 2029 and depart in November 2033. The Earth return is estimated to be November 2038. After retrieval from the spacecraft in the Utah desert, the samples will be transported to JSC for curation and initial characterization. The curation team will leverage JSC's experience with OSIRIS-REx samples, as well as the cold-curation expertise for the Tagish Lake meteorite samples at the University of Alberta.[17]

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[15] Capaccioni et al., The organic-rich surface of comet 67P Churyumov-Gerasimenko as seen by VIRTIS/Rosetta, *Science* (2015) 347(622).

[16] Goesmann et al., Organic compounds on comet 67P/Churyomov-Gerasimenko revealed by COSAC mass spectrometer (2015) *Science* 349(6274).

[17] Herd et al., Cold curation of pristine astromaterials: Insights from the Tagish Lake meteorite, (2016) *Meteoritics and Planetary Science* 51(3): 499-519.

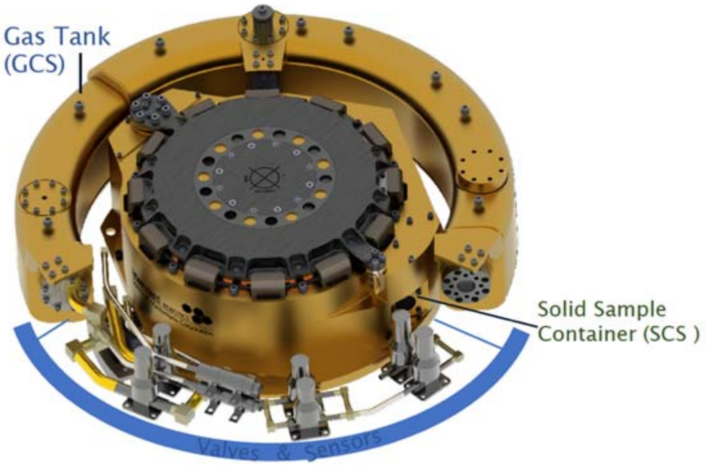

FIGURE 3.7 A rendering of the prototype of proposed sample containment system for the CAESAR comet return mission, which will separate solids from gases sublimated from cometary ice. SOURCE: Steve Squyres, Cornell University.

3.3.2 Martian Moons Exploration (MMX)—JAXA

Martian Moons Exploration (MMX) is a mission concept currently under consideration by ISAS/JAXA to investigate the martian moons Phobos and Deimos, with sample return from Phobos as a major scientific goal. JAXA proposes to fly a Hayabusa-like spacecraft to the martian moons, spend about one year studying these objects, then sample the regolith of one moon and return this sample to Earth. The scientific rationale for the mission centers on whether these moons are captured asteroids or coalesced impact ejecta from a large impact on Mars. A primary test for these models is the overall nature of the material, with captured asteroids expected to sample primitive chondritic material, perhaps akin to CM2 chondrites, while coalesced impact ejecta would be expected to be heavily shocked or impact melted material of primarily igneous origin. The mission, if funded, would launch in the mid-2020's, perhaps in 2023, with a return date in the late 2020's or early 2030's. The stated sample return objective is ~10 g of material.

3.3.3 Mars Sample Return

Mars sample return was identified as the highest priority large strategic mission by the Decadal Survey and will require multiple missions to accomplish, spanning into the next decadal survey.[18] There are also sample return missions to Mars being explored by Russia (Mars-Grunt Mission, mid 2020's), and China (2030).

With the recent publication by Eigenbrode et al.[19] showing evidence for the presence of organic molecules on Mars, the demand for Mars sample return to Earth continues to escalate. Whereas martian meteorites are readily available for study on Earth, they are presumably not fully representative of any plausible martian biosphere or its fossil remnants. By contrast, the Mars Science Laboratory (MSL) rover Curiosity has encountered exclusively sedimentary martian rocks and now has demonstrated that at least

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[18] NRC, 2011. *Vision and Voyages*, p157

[19] Eigenbrode et al., 2018, Organic matter preserved in 3-billion-year-old mudstones at Gale crater, Mars, *Science* 360: 1096-1101.

one of these rocks contained some sedimentary organic matter, released as small volatile organic molecules when heated. On Earth one finds the vestiges of ancient life (kerogen) primarily in shales; so naturally these same lithologies on Mars would be prime targets for future sampling.

One of the primary objectives of the Mars 2020 mission is to identify and collect and cache optimum martian samples of sedimentary rock.[20] The plan will be for a future mission(s) to be sent to retrieve and transport these samples back to Earth. From the perspective of future sample handling, the design of the cache containers and transport canister will dictate the design and operation of the sample handling facility back on Earth. From the standpoint of Planetary Protection standards (Section 3.4.2), it is likely that the technological complexity of the Mars sample return facility will require a significant investment long before the costs of subsequent analysis by the broader community are assessed.

3.3.4 Lunar Sample Return

Several types of lunar sample return missions are currently being explored by NASA, including the South Pole-Aitken (SPA) Basin sample return mission[21], new commercial sample return missions from the Lunar Exploration and Discovery Program, and the potential for using the proposed NASA Gateway (see Section 3.3.4.3) to facilitate sample return. Additional missions to return samples from the Moon may be explored through Discovery class missions. The Decadal Survey highlights potential targets for such sample returns that could explore “the nature of polar volatiles [where cryogenic sample return would be enabling], the significance of recent lunar activity at potential surface vent sites, and the reconstruction of both the thermal-tectonic-magmatic evolution of the Moon and the impact history of the inner solar system through the exploration of better characterized and newly revealed lunar terrains.”[22] A lunar polar volatiles explorer concept is described in Appendices D and G of the Decadal Survey.

3.3.4.1 South Pole-Aitken Basin Sample Return

The SPA basin sample return mission has been identified in the last two decadal surveys as a high priority New Frontiers class mission. The mission would seek to determine whether there was a late heavy bombardment of the inner solar system around 3.9 Ga (as suggested by studies of the Apollo samples) or if there was a gradual decline in impacts over time, by providing high precision dates of impact melts from the basin. The SPA basin is now quite degraded, so it is expected to be older than 3.9 Ga, supporting a gradual decline in inner solar system bombardment. If, however, the age is ~3.9 Ga, a late heavy bombardment is indicated. The results of this mission extend far beyond the Moon, as they will inform us about the evolution of the outer planets and their orbits, and will have implications for the origin of life on Earth.

3.3.4.2 Commercial Lunar Sample Return

On July 12, 2017 the privately-funded company Moon Express[23] unveiled a lunar robotic sample return architecture (Fig. 3.8). With the first mission to land on the Moon (Lunar Scout) by the MX-1E lander approved by the Federal Aviation Administration in 2016, Moon Express plans to launch this inaugural flight in 2019, with plans to return lunar samples to scientists by 2021. There are also plans by another private company, Astrobotic,[24] to offer sample return, but the architecture has not yet been made public.

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[20] Jezero Crater has been selected as the landing site for the Mars 2020 mission.

[21] NRC, 2011, *Vision and Voyages*, p127

[22] NRC, 2011. *Vision and Voyages*, p133

[23] http://www.moonexpress.com/

[24] https://www.astrobotic.com/

FIGURE 3.8 Artist's rendition of the Moon Express sample return architecture launching back to Earth from the Moon. SOURCE: http://www.moonexpress.com/

The Planetary Science Division of NASA's Science Mission Directorate sponsored a workshop January 10-12, 2018, to identify landing sites on the Moon that have high scientific interest.[25] The workshop developed a list of potential landing sites that take advantage of these new commercial capabilities to get to the lunar surface for in situ science, as well as for sample return. As can be seen in Figure 3.9, there are many sites that could address fundamental lunar science questions defined by National Academies documents and Lunar Exploration Analysis Group reports.

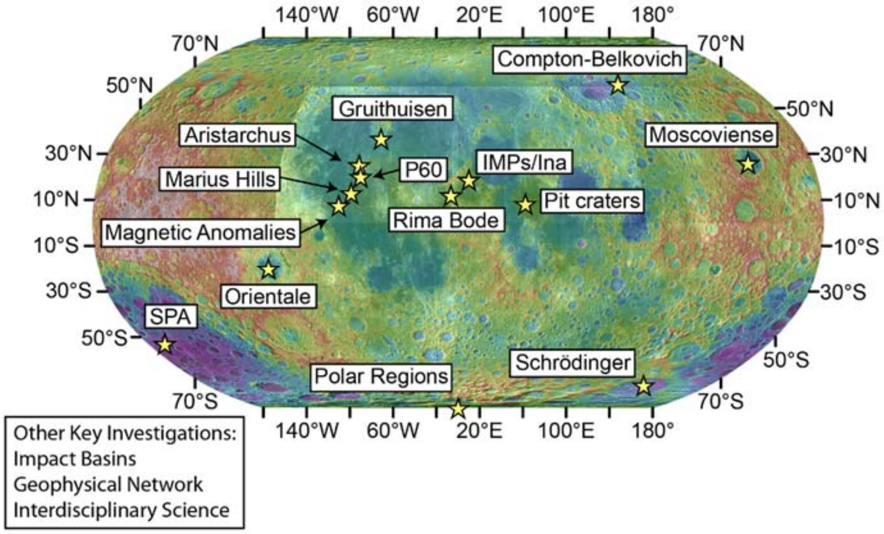

FIGURE 3.9. Potential landing sites (indicated with yellow stars) for lunar science including sample return outlined in the Lunar Science for Landed Missions workshop report.[26]

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[25] See https://lunar-landing.arc.nasa.gov/overview for more details.

[26] https://lunar-landing.arc.nasa.gov

The new Lunar Exploration and Discovery Program is directed to utilize commercial lander and sample return capabilities as public-private partnerships for payloads ≤200 kg at the cadence of ~1 per year for 10 years on the notional architecture. This will be realized through a Commercial Lunar Payload Services (CLPS) call. Initial missions will not involve sample return, but the later ones will. Returned sample caches could be up to 2 kg. This represents a new paradigm for lunar exploration, as NASA will be a customer and will not be responsible for building the lander or sample return capsule. While some private companies have proposed architectures for landing assets on the lunar surface, none have actually demonstrated that capability to date.

3.3.4.3 Human Spaceflight-Related Lunar Sample Return: Gateway

The proposed NASA Gateway[27] that will orbit the Moon could be used to facilitate sample return in a number of ways, all returning sample caches to the Gateway before return to Earth:[28] 1) robotic landers launch from Earth to gather samples on the lunar surface and return the sample cache to the Gateway; 2) a roving robotic asset on the lunar surface could be teleoperated (either from the Gateway or Earth), caching samples from a region before returning them to the Gateway; and 3) humans would descend to the lunar surface from the Gateway and undertake geologic investigations, including sample return. These samples would be brought back with the humans. As the Gateway architecture is still evolving, it is unclear how efficient it will be in facilitating lunar sample return.

3.4 ADDITIONAL CONSIDERATIONS FOR CURRENT AND FUTURE SAMPLE RETURN MISSIONS

3.4.1 Missions Returning Thermally Unstable Samples

The return of cryogenic and atmospheric samples to Earth is essential in order to answer questions about presolar and nebular cosmochemistry, as well as to evaluate potential habitable environments in the solar system. The Decadal Survey, applying the Aerospace Corporation’s cost and technical evaluation (CATE) methodology, did not select cryogenic sample return missions, as they were considered unachievable in the scope of the 2013-2022 Decadal Survey. As discussed in Section 3.3.1, comet surface sample return is part of the current New Frontiers mission competition, but CAESAR is not a cryogenic sample return mission and is designed to return rocky materials and sublimated ices in the form of gases.

Successful return of cryogenic samples requires significant development of sample return technologies, an ability to pay the high costs of sample curation (which would require cryogenic storage and characterization technologies), and adherence to planetary protection principles. There are numerous challenges for cryogenic sample return missions involving sample collection, return, curation, and analysis. Each of these steps needs to be achieved without affecting the original state of the sample by chemical, thermal, or mechanical reactions, while at the same time adhering to planetary protection requirements, which vary according to target body. For example, cryogenic ice return from Mars or Enceladus would require a dual-pressure enclosure (i.e., returned samples cannot be allowed to contaminate the environment, and the environment cannot be allowed to contaminate the samples), whereas cryogenic sample return from a comet or lunar polar ice would not.

Cryogenic sample collection can be performed from the subsurface of an ice-bearing region of a comet, or through the capture of ice and gas plume material, for example on satellites of the outer gas giants, such as the plumes imaged by the Cassini spacecraft on Enceladus (Fig. 3.10). Cold curation

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[27] https://www.chron.com/techburger/article/NASA-Lunar-Gateway-Space-Station-Will-Soon-12850444.php

[28] https://www.nasa.gov/pdf/491544main_orion_book_web.pdf

involves the preservation of samples at or below the ambient temperature of collection, which can be categorized on the basis of our current knowledge of the maximum temperatures such materials would see (Fig. 3.11).

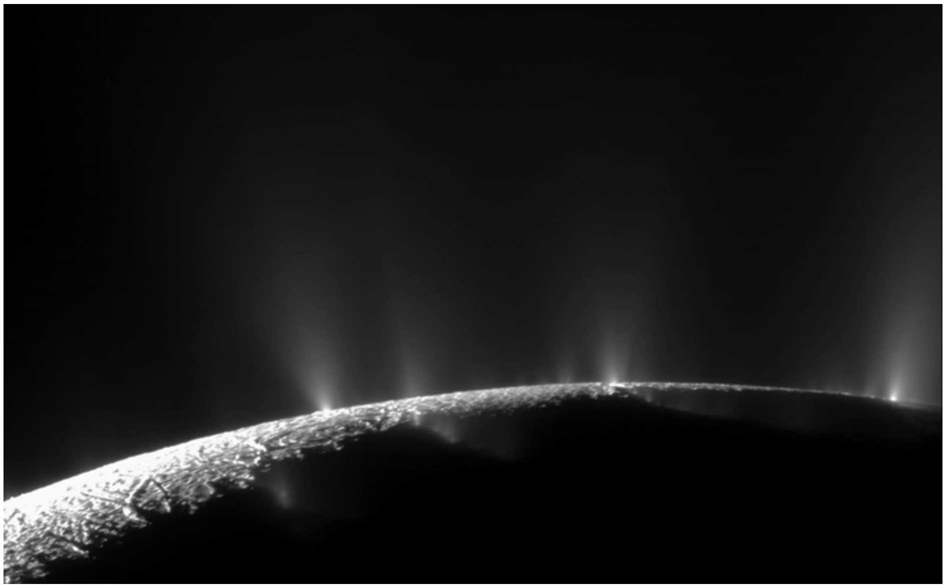

FIGURE 3.10 Image from Cassini shows backlighting from the sun spectacularly illuminating Enceladus' jets of water ice. SOURCE: NASA/JPL-Caltech/SSI

The actual surface temperatures of solar system bodies likely deviate from the calculated equilibrium surface temperature due to contributions from internal heating, the blanketing effects of atmosphere, and details of the orbit and surface morphology. In addition, surface temperatures may show significant variations in time (day versus night; summer versus winter) or geography (equator versus poles; exposed versus permanently shadowed regions). For example, the average temperature of the lunar surface is approximately 200 K, but can be over ~300 K during the long lunar day (~13.5 Earth days) near the equator, and drop to below 100 K in the high latitudes during the lunar night. Surface albedo and geometry also play a role, with temperatures in the permanently-shadowed cratered regions expected to stay below 40 K.[29] Mars, like the Moon, experiences large temporal and spatial variations in temperature, with average surface temperatures also around 200 K. Europa is estimated to have an average surface temperature of about 100 K, and Titan’s surface will likely be somewhat warmer due to its atmosphere. The temperatures of comet nuclei are unknown at this time.

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[29] Williams et al., Icarus 283 (2017) 300–325

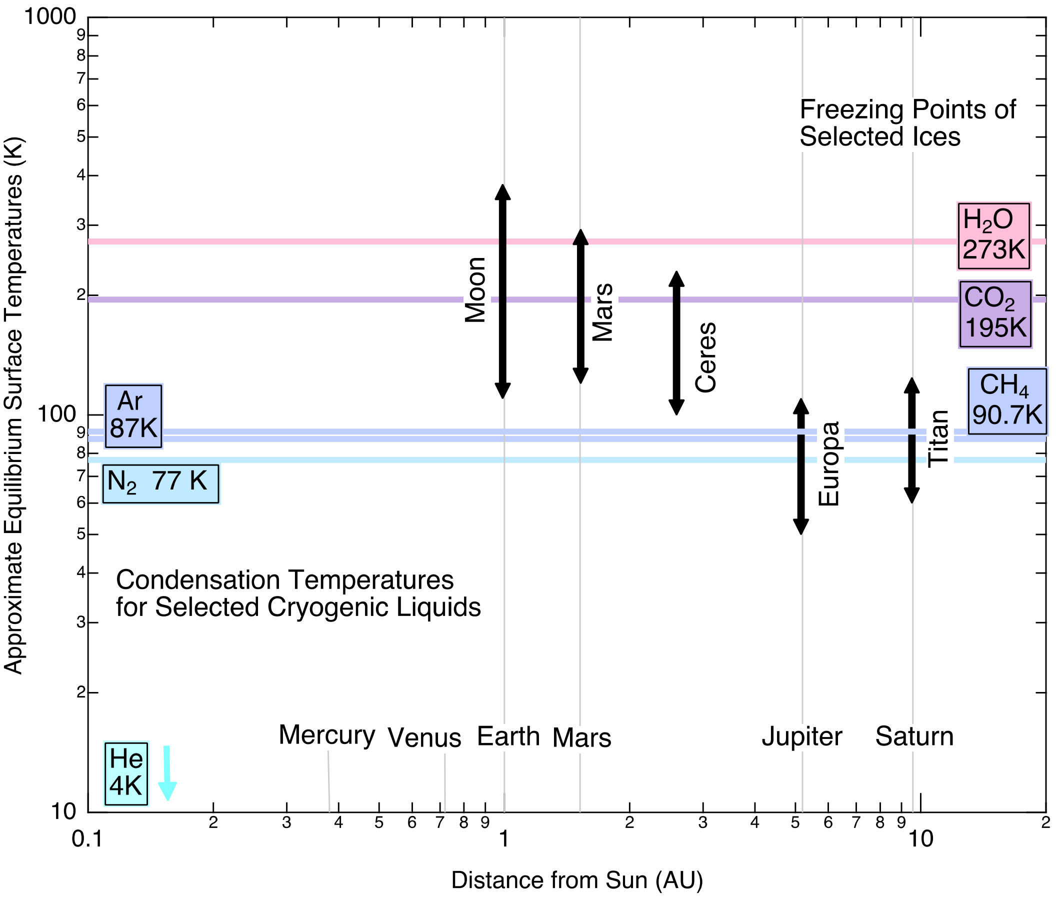

FIGURE 3.11 A schematic diagram of approximate surface temperatures for selected solar system bodies as a function of their distance from the Sun (in astronomical units, AU). Horizontal lines show the 1 atmosphere pressure freezing points or condensation temperatures for selected cryogenic substances. The pressure and temperature conditions vary on planetary surfaces, and also may change significantly within the first few cms- to -meters underneath the surface. These in situ conditions are also likely different from the conditions that may be experienced during storage. The average equilibrium surface temperatures of many solar system bodies of interest lie at or above the condensation temperature for liquid nitrogen (77 K), where storage capabilities are well-established. Source: Committee-generated

Figure 3.11 shows that an estimate of average equilibrium surface temperatures of many solar system bodies of interest lie at or above the condensation temperature for liquid nitrogen. The technology for long-term storage of materials at liquid nitrogen temperatures is well-developed, with many applications in medical and biochemical storage and is less costly than storage at lower temperatures. The test facilities at NASA Glenn Research Center (Cleveland, Ohio) have a -180˚C (93 K) chamber. In addition, freezing points and condensation points are pressure-sensitive, therefore, the pressure of the sample return and curation environment will be an important variable. Cold curation will require strict monitoring of temperatures, pressures, and also sample reactivity.

Maintaining the 40 K temperatures of permanently shadowed regions of the Moon and other bodies will be technologically and fiscally challenging, and the temperatures for true preservation will be untenable. Thus, the temperature at which these samples will be transported back to Earth and curated will need to be a compromise between what can be reliably maintained and the available funding. Assuming that this temperature will be higher than ambient, it will be important to quantify what is lost.

For example, at 1 atmosphere, 80 K will preserve ices of CO and CO_2, but above 110 K, CO ice will be lost and water ice will sublime.

3.4.2 Planetary Protection Requirements

Preparations for eventual curation and characterization of extraterrestrial soft matter samples (e.g., volatile, organic, and high surface area samples) have to be done in a way that is mindful of the considerations and constraints of planetary protection guidelines. Planetary protection is defined as "the practice of protecting solar system bodies… from Earth life…and of protecting Earth's inhabitants and environment from harm that could be caused by possible extraterrestrial life forms."[30] This dual-directional requirement, in concert with the potentially high stakes of failure in either direction, makes planetary protection a complicated and costly engineering constraint for both curation and characterization of extraterrestrial materials.

Consideration of issues related to planetary protection for extraterrestrial sample return has, over the years, led to development of extensive NASA and international guidelines regarding the proper handling of returned extraterrestrial samples (see references in the National Academies report cited in the preceding paragraph). It is clear that the degree of stringency regarding planetary protection issues differs with the nature of the object being sampled. Missions like OSIRIS-REx and Hayabusa2 to asteroids and the CAESAR mission to a comet will sample regolith from small primitive bodies that lack any features consistent with the sustenance of "life as we know it", namely liquid water and some type of atmosphere. Furthermore, there has been no credible evidence of life discovered in any meteorite, and meteorites have continuously rained upon Earth over 4.5 billion years of Earth history. In these cases, focus is principally stringent design for sample containment and, ultimately, transfer of a given containment canister into an appropriately designed Earth-based sample handling chamber, as was the case for the Stardust samples, Hayabusa and now (in progress) Hayabusa2 and OSIRIS-REx.

In the future, there may be sample return missions that pose a risk for the capture of non-Terran micro-organisms. For example, any sample return from Mars or from its moons (e.g., MMX sampling Phobos regolith) or even a mission to return high altitude martian dust, could contain a contribution from Mars, and will be subject to planetary protection protocol. In addition, proposed missions to retrieve particles from the plumes of Enceladus (Fig. 3.10) have the possibility for returning extraterrestrial life. These missions will require considerable effort in the development of fail-proof containment. It is assumed that such sample containment facilities will require all of the functionality that current facilities have (e.g., those for Stardust samples, Hayabusa, Hayabusa2 and OSIRIS-REx), but, in addition, operate at the highest level of biohazard protection. The complexity and costs of such facilities are expected to be substantial.[31]

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[30] National Academies of Sciences, Engineering, and Medicine. 2018. *Review and Assessment of Planetary Protection Policy Development Processes.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25172

[31] National Academies of Sciences, Engineering, and Medicine. 2018. *Review and Assessment of Planetary Protection Policy Development Processes.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25172

4

Current Laboratories and Facilities

This chapter focuses on the following questions posed by the charge to the committee:

- What laboratory analytical capabilities are required to support the NASA Planetary Science Division's (and partners') analysis and curation of existing and future extraterrestrial samples?
- Which of these capabilities currently exist, and where are they located (including international partner facilities)?

In order to understand the significance of existing infrastructure for sample curation and analysis, the tasks associated with retrieving the samples from the spacecraft, initial characterization, and curation are first summarized (Figure 4.1).

4.1. RETREIVAL, CURATION, AND CHARACTERIZATION OF RETURNED EXTRATERRESTRIAL SAMPLES

Recovery and initial triaging: Recovery from the field of sample return landing craft and delivery to an appropriate curatorial facility generally calls for procedures and equipment idiosyncratic to each mission and separate from permanent curation and analysis facilities. However, retrieving sample containers from that craft, initial handling and opening of those containers, and initial inspection of their contents will occur within facilities considered by this report. Key capabilities include: environments and handling devices that carry minimal contamination; environments with controlled atmospheres and temperatures; and instruments for non-destructive inspection (e.g., optical microscopes).

Sample description: Recovered samples must be described for their form (e.g., solid or gas), material properties (e.g., rock chips or powders) and size (volume and/or mass), and initial interpretations made regarding their general categorization (e.g., petrologic classification). These activities also commonly take place in a curatorial facility and call for various common, non-destructive or minimally destructive (e.g., thin sections of hard samples) observational or measuring tools (e.g., microscopes, spectroscopes, balances).[1]

General non-destructive analyses: As sample investigation transitions from initial description and categorization to scientific inquiry, the first detailed observations are generally made with a set of non-destructive (or minimally destructive) methods that are sufficiently general that they are likely to be useful for virtually any material or motivating science question. Examples include optical microscopies and spectroscopies, and scanning electron microscopy. Laboratories for such measurements are commonly available at the same institutions that fill a curatorial role, but analyses also may be made in other laboratories, as an initial step to more specialized measurements.

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[1] See Table 4.2 for a listing of various types of instrumentation, and Appendix E for definition of abbreviations used for these instruments.

Sub-sampling and preparation for specialized analysis: While initial triaging of returned samples calls for some level of sample subdivision to facilitate organization and simple descriptions, preparation for specialized, hypothesis-driven measurements often requires more significant modification, and destruction of samples is often required. This might include sorting by physical properties, crushing, grinding, cutting or polishing, exposure to solvents or other reagents, or manipulation by specialized devices such as microtomes or focused ion beam (FIB) mills. This is another activity that is frequently performed at curatorial facilities, but also often performed in analytical laboratories as part of their sample preparation procedures. These procedures have a high potential for sample contamination or destruction and therefore can only be carried out by highly experienced and skilled staff who strictly follow established protocols.

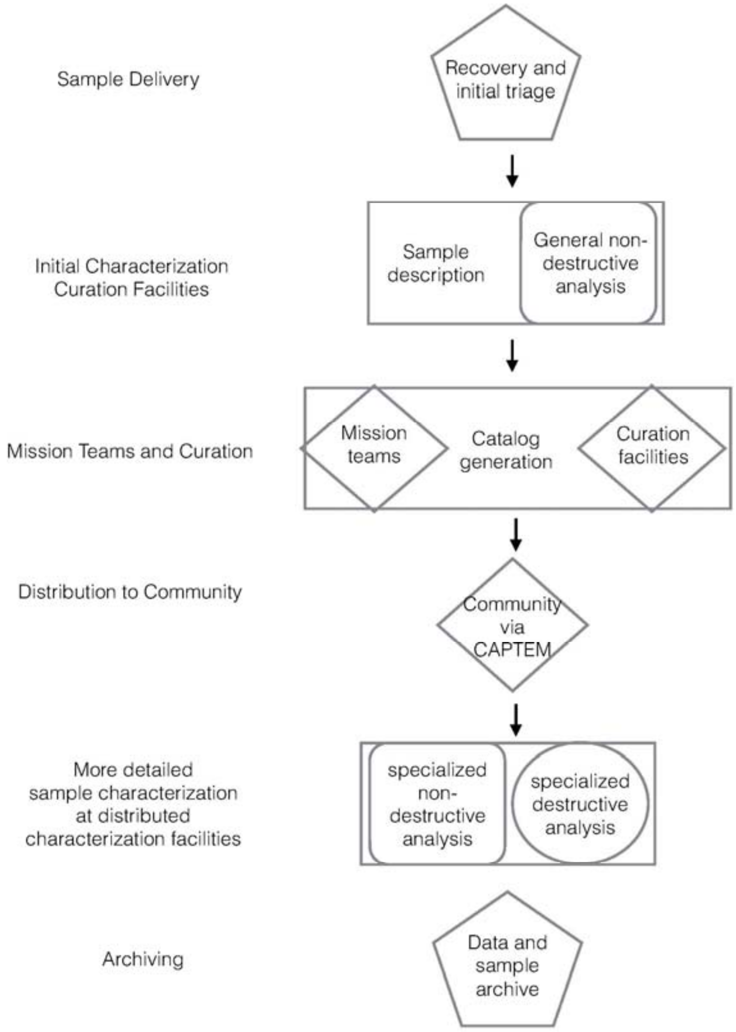

FIGURE 4.1 Returned sample processing flow chart. Source: Committee-generated

Specialized non-destructive or minimally destructive analyses: Detailed studies aimed at addressing mission science questions may call on techniques that are highly specialized but generally non-destructive or minimally destructive to the sample, once the sample is prepared. These techniques include spectroscopic techniques to assess compositional, structural, and physical properties of materials using a variety of probes, such as light sources (from IR to X-ray), and electron, neutron, and ion beams[2]. Most facilities for these specialized studies exist outside of curatorial institutions.

Specialized destructive analyses: Some fraction of returned samples may be sacrificed for destructive analysis, including most methods of mass spectrometric study for molecular identification or isotope ratio determination. Most facilities for these specialized studies exist outside of curatorial institutions. These types of analyses are performed to answer questions related to the age and the origin of extraterrestrial sample materials. Cutting-edge technologies that are currently in use and that will remain necessary in the future include those that are capable of measuring the isotopic composition of various elements (e.g., mass spectrometers). Diverse radiogenic isotope systems can be used for geochronology and source tracing purposes for both terrestrial and extraterrestrial materials (e.g., long-lived Re-Os, Rb-Sr, Sm-Nd, Lu-Hf, Ar-Ar, K-Ar, U-Th-Pb). Because of their short half-life, short-lived radiogenic isotope systems are powerful tools to study early solar system processes and chronology (e.g., Al-Mg, Fe-Ni, Mn-Cr, Pd-Ag, Hf-W, I-Xe, Pu-Xe, Sm-Nd), and some of these systems are exclusively used in extraterrestrial studies. Recently, an increasing number of capabilities are also being developed for the study of non-traditional stable isotope systems (e.g., Si, Zn, Cr, Mg, K, Mo, Nd) in order to detect nucleosynthetic anomalies. This diversity of isotope systems and accompanying analytical capabilities are required to study the range of extraterrestrial materials (metal, silicate, liquid, gas). The challenge for the future is to develop capabilities to adapt to all sample sizes (rocks to dust particles) and materials (e.g., ices, gases).

Archiving: Finally, data products generated during all stages of sample study and any leftover sample material that was not consumed during sub-sampling and destructive analysis are archived. In general, long term archiving of sample materials occurs at a curatorial facility, whereas archiving of observational data is tasked to the laboratories in which those observations were made.

4.2 FACILITIES FOR CURATION, TRIAGING, AND DESCRIPTION OF RETURNED SAMPLES

Curation of returned extraterrestrial samples occurs at several facilities around the world, as described in Chapter 2. Russian Luna samples are mainly curated at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow, Russia. The main portion of the Hayabusa sample return is maintained at the Extraterrestrial Sample Curation Center at the Institute of Space and Astronautical Science, Sagamihara City, Japan. A small fraction (10-15%) of returned samples within the US are stored at the White Sands Test Facility in New Mexico. The vast majority of NASA mission returned samples (Apollo, Genesis, and Stardust), as well as aliquots of Hayabusa and Luna samples are curated by NASA at the Johnson Space Center facility, which is described below.

With nearly 50 years of experience since the return of the Apollo samples, Johnson Space Center has been a world-leader in curatorial management and has developed a range of techniques, materials, and expertise to handle returned samples. The samples curated at JSC are diverse, including lunar samples returned by six crewed Apollo missions, solar wind collectors from the Genesis mission, samples from the coma of comet Wild 2 collected in aerogel by the Stardust mission, a subset of samples collected from the surface of asteroid Itokawa by the Hayabusa mission, cosmic dust collected in the stratosphere, and meteorites collected in Antarctica (which are co-curated with the Smithsonian Institution). Each of these sample types are curated in different facilities that have unique requirements for sample handling and contamination control.

The largest and oldest curatorial facility at JSC is the ~300 square meter Apollo sample suite, which is subdivided into four laboratories. One securely stores pristine Apollo samples that have not

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[2] See Table 4.2 for a listing of various types of instrumentation and Appendix E for definition of abbreviations used for these instruments.

previously been allocated. These are housed in 22 stainless steel nitrogen-purged storage cabinets under International Standards Organization (ISO) Class 6 clean room conditions (Fig. 4.2).[3] A second ISO Class 6 clean laboratory, the largest of the suite at 186 square meters, is used to process previously unallocated samples and includes a specialized band saw and core processing cabinets. A Return Sample Vault (RSV) securely stores previously allocated and returned Apollo samples in either aluminum or stainless steel under ISO Class 7 conditions. Portions of other collections (Cosmic Dust, Genesis, OSIRIS-REx contamination knowledge, Mars2020 contamination knowledge) are stored in the RSV on a semi-permanent basis. If processing is required on samples from these collections, they are returned to their main laboratory for work. Finally, several ISO Class 7 clean rooms are used for secure processing of previously allocated and returned Apollo samples. These are processed either in nitrogen-purged stainless steel cabinets, or within two laminar flow hoods.

FIGURE 4.2 A lunar sample processor prepares to begin work on pristine lunar samples by placing her hands in the gloves attached to a nitrogen-filled glovebox. SOURCE: https://curator.jsc.nasa.gov/lunar/laboratory_tour.cfm

The Genesis sample suite consists of ISO Class 4 clean laboratories (~93 square meter in overall area) that were used to assemble the Genesis Sample return capsule, load the collector arrays and to clean and store the array and concentrator collectors after their return. It consists of three rooms. First, a laboratory where the Genesis collectors are stored in six permanent nitrogen-purged desiccators. This is where the samples are characterized using a spectroscopic ellipsometer, a compound scanning microscope, and a micro-FTIR situated on vibration isolation tables. Three digital cameras are used for imaging on each microscope. A second laboratory houses an ultra-pure water (UPW) cleaning wet bench that is used to clean Genesis samples prior to allocation and study. Sample containers and processing tools are also cleaned here. A liquid particle counter and a total organic carbon (TOC) unit are used to

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[3] ISO Class 6 indicates less than 1,000 particles greater than or equal to 5 microns in size per square foot of air.

verify water quality prior to cleaning procedures. The third and final laboratory of the Genesis suite is an anteroom where a clean flow bench, a compound microscope and a high-efficiency particulate air (HEPA) cabinet are used for return sample processing and storage. A UV ozone cleaner is also used here for thin-film removal from collector surfaces.

A 65 square meter ISO Class 5 clean room is used to store and process the Stardust cometary and Stardust interstellar trays (Fig. 4.3). It consists of an anteroom with a clean flow bench and two micropipette pullers, which are used to create pulled quartz needles that are used to subdivide the aerogel cells for allocation. The sample storage and processing room is used to store the aerogel samples in four custom nitrogen-purged desiccators. The samples are imaged and processed using specialized microscope systems situated on three vibration isolation tables. Three scanning compound microscopes are used to subdivide and document cometary and interstellar track morphology using MATLAB scripts. Four digital cameras are attached to the microscopes for high resolution image capture.

FIGURE 4.3 Scientists examine the Stardust aerogel collector upon its arrival in the curatorial facility at Johnson Space Center. SOURCE: https://curator.jsc.nasa.gov/stardust/index.cfm

Finally, the aliquot of Hayabusa sample returned from the Itokawa asteroid by JAXA and provided to NASA is housed in a small ~18 square meter ISO Class 5 clean laboratory that contains a nitrogen-purged glove box for storage and handling of the samples. A compound scanning microscope with a digital camera is situated on a vibration isolation table with micromanipulators for sample handling.

Other suites within the curatorial facility house Antarctic meteorites, cosmic dust, and the microparticle impact collection (satellites that have recorded microparticle impacts in space). Additional information about curation of lunar, Genesis, and Stardust returned sample is provided in the relevant sections of Chapter 2.

While the present suite of samples curated at JSC are diverse, they share the common feature of being primarily rocky samples composed of materials that are largely stable at ambient pressure and temperature conditions (i.e., hard condensed matter, as defined in Box 1.1). As such, capabilities developed during Apollo (e.g., dry nitrogen storage, class 6-7 clean rooms, etc.) have largely preserved the pristine condition of these samples. More recent sample return missions, such as the cometary dust from Wild 2 captured in aerogel by the Stardust mission, have required corresponding development of new techniques. This development has been facilitated by close partnership between JSC Astromaterials Curation and the mission team. As currently formulated, curation of samples returned by Discovery and New Frontiers class missions will be conducted at JSC, with major development and initial operations costs paid by the respective mission, while long-term curation is supported by NASA through funding of JSC Astromaterials Curation. Planning for potential future sample return missions, such as from Mars, is discussed in Chapter 5 (Section 5.3).

4.3 SAMPLE DISTRIBUTION

Once returned samples are documented and characterized by the mission team, and safely housed in the curatorial facility, aliquots may be sent to laboratories around the world for cutting-edge analyses. As all returned samples are considered national and future heritage resources, strict protocols are in place for requesting, transporting and securing these samples. All requests for samples curated at NASA JSC are vetted first by the relevant curator, and then by the Curation and Analysis Planning Team for Extra Terrestrial Materials (CAPTEM).[4]

Apollo sample requests are made to the Apollo Sample Curator at JSC, who reviews them for content, and those deemed to be suitably mature are sent to CAPTEM for further evaluation.[5] Investigators must provide evidence that their science, including analytical protocols, have passed peer review. This generally requires funding of a science proposal (from NASA, or other foreign or domestic government or nonprofit funding agency) within the past three years to work on the requested samples or submittal of a science proposal to work on the samples, backed up by evidence of peer-reviewed publications that report results using the same methods to be used on the requested samples and thorough documentation of the analytical methodology. CAPTEM then reviews the appropriateness of the sample request and makes a recommendation to the Apollo Sample Curator. Investigators must furthermore adhere to strict protocols for transporting, storing and documenting sample handling and weight.

Similarly, Genesis mission sample requests are made to the Genesis Solar Wind Sample Curator at JSC, who reviews them for content and those deemed to be suitably mature are sent to the Genesis Allocation Subcommittee of CAPTEM for further evaluation.[6] The proposals must define the science objectives and document the sensitivity, precision and accuracy of the analytical methods to be employed in the investigation. The proposals must also document that the method exceeds set precision and accuracy goals, or justify why the science can be accomplished without meeting these goals, as well as providing a plan for surface cleaning of the samples appropriate for the particular analyses being proposed. Finally, because the Genesis samples are small and easily contaminated, the investigator is encouraged to design a shipping container that will safeguard the integrity of the sample, or use a shipping container supplied by the curatorial staff.

Stardust mission sample requests are sent to the Stardust Sample Curator, who evaluates them and then forwards viable proposals to the Stardust Sample Allocation Subcommittee (SSAS) of CAPTEM. This committee evaluates "the scientific content of the proposal, capability of the proposers, availability of requested samples, and the realism of the investigation. SSAS will also weigh the overall merit of the proposal with the required amount of sample and any possible collateral damage to the remainder of the collector."[7] Because of the extremely limited sample size, investigators are encouraged to work in consortia to maximize the science yield from each particle, in particular, coordinating analyses that entail sample destruction.

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[4] https://www.lpi.usra.edu/captem/

[5] https://curator.jsc.nasa.gov/lunar/sampreq/lunarallochndbk-jsc06090_revf_2012.pdf

[6] https://curator.jsc.nasa.gov/genesis/forms/genesisguidebook-jsc63358reva.pdf

[7] https://curator.jsc.nasa.gov/stardust/forms/stardustinvestigatorsguidebook.pdf

The committee has not evaluated CAPTEM's processes in detail, but notes that CAPTEM has been an effective means by which to allocate existing Apollo, Stardust, Genesis, and meteorite samples.

Finding: Allocation of returned samples to laboratories around the world requires careful vetting of requests for samples and special handling during shipment and storage at an analytical facility.

4.4 ANALYTICAL EQUIPMENT

4.4.1 Classifications and Overview of Analytical Instrumentation

The scientific goals of sample return missions are broadly defined. For example, one of the OSIRIS-REx mission's goals is to "return and analyze a pristine carbon rich asteroid sample."[8] These analyses are accomplished using a large range of instruments distributed across dozens of institutions. Additionally, the types of materials being analyzed are changing, from the lunar samples composed primarily of silicates, oxides, glasses, and metals, to the more recent and upcoming samples that contain significant amounts of organic materials. Accordingly, the committee has focused on techniques that have been used to analyze both rocky and organic materials, as well as some methods likely to become more relevant in the near future. To facilitate discussion of this complex topic, the discussion is organized by defining how each technology relates to the following four traits or qualities:

1. *Types and purposes of methods*: Extraterrestrial sample analysis involves diverse technologies and modes of material description and quantification. Tables 4.1 and 4.2 provide a guide to these, which are sub-divided into several broad categories (microscopy, tomography, etc.), each of which are further divided into sub-categories described by brief narrative explanations of their core technologies or procedures and their purposes. See Tables 4.1 and 4.2 for details.
2. *Availability and access*: A very large number of laboratories have contributed to sample return science or could be used as analytical resources for ongoing or near-future sample return missions. The committee has not attempted to create an exhaustive list of all such facilities (and the committee believes this could not be done without omissions). Instead, each technology is categorized according to a 5-tier scheme describing its availability and access. These categories range from commonly available and accessible (category 1), to unique technologies that are available at only one institution and accessible only through a gate-keeping procedure controlled by that institution (category 5). Thus, availability and access generally becomes more restricted as the numbering in this scheme increases. See Table 4.1 for details.

The instruments and methods described as **Common** (category 1) are in widespread use in tier-1 research universities and other relevant research institutions, and typically have few restrictions on their access and use. They can be assumed to be available for current sample return science (and likely will remain so in the future, provided the instruments are replaced once they reach their operational lifetime). Our categories of **Multiple Regional Facilities** (categories 2 and 3) include instruments that provide 'flagship' analytical or experimental capabilities for leading research laboratories; they exist in multiple U.S. and international institutions and are widely recognized in the sample return science community, yet their expense and sophistication is such that only relatively well funded laboratories with highly trained staff can obtain and operate them. For this reason, they may exist as regional centers, used by both members of their home institutions and visitors from other institutions. Finally, the categories of **Unique**

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[8] www.nasa.gov/sites/default/files/atoms/files/osiris_rex_factsheet5-9.pdf

instruments (categories 4 and 5) include experimental or prototype instruments, generally designed to meet specific analytical or experimental goals that cannot be reached by other technologies, and that exist in only one location and generally require highly specialized skills to use.

Both Regional Facilities and Unique instrumentation can present difficulties with respect to access, depending on the policies of the stakeholders who control them; for this reason, they are subdivided into user facilities and non-user facilities. 'User' facilities (categories 3 and 5), are open to external access, usually subject to a peer-reviewed proposal review process. 'Limited access' facilities (categories 2 and 4) are generally used only by their directing scientific staff, and occasionally through collaboration with outside users. The distinction here is that User facilities have routine procedures in place to permit access to any outside user, whereas Limited Access facilities treat outside use on a case-by-case basis.

3. *Relevance to sample return missions and materials*: Investments in analytical infrastructure for sample return missions are guided by the science goals of missions, as defined by a traceability matrix or equivalent statement of concrete goals. However, the long timescales of mission return science and the complexity and unpredictability of returned materials make it difficult to foresee which technologies might be useful for a given set of mission objectives, or what questions future generations might ask about returned samples. Moreover, much of the analytical infrastructure available to the community of scientists concerned with analysis of returned samples is either heritage technology developed for some previous mission having different goals, or was created to meet some different need in the natural or applied sciences. For these reasons, many forms of instrumentation used by the institutions engaged in sample return science have potential value. Nevertheless, limitations to the resources available through the Planetary Science grant programs (Laboratory Analysis of Returned Samples: LARS and Planetary Major Equipment and Facilities: PMEF) mean one must discriminate between investments that advance the goals of sample return science and those that have no recognized use for that purpose. For this reason, Table 4.2 also includes a brief description of the ways in which each listed analytical technology has a recognized relevance to the scientific goals of sample return missions.

One challenge faced in making instrument investment decisions in the coming years is the changing nature of science goals driving sample return missions. Prior to the Genesis mission, extraterrestrial sample analysis science focused exclusively on lunar samples returned as part of the Apollo or Luna programs, cosmic dust, or meteoritic materials. A large fraction of this work focused on characterizing the mineralogy and elemental and isotopic compositions of silicates, oxides, glasses and metals, typically on scales of micrometers or larger. More recent sample return missions, including Stardust, Hayabusa, OSIRIS-REx and Hayabusa2, call for study of the structures and molecular chemistries of organic materials, structurally amorphous organic solids with highly complex molecular structures, and small (sub-micrometer) objects or domains. This means that technologies that used to be considered highly mission relevant may now have lesser relevance to ongoing or near-future missions. The committee's evaluation of this issue considers continued science on materials returned by the Apollo program, but more strongly emphasizes science goals of the Genesis, Stardust, and Hayabusa missions, the ongoing OSIRIS-REx and Hayabusa2 missions, and planned near-future sample return missions (including possible Mars sample return and cometary sample return).

4. *Stakeholders and hosting institutions*: Sections 4.2 through 4.4 — the main body of this chapter — consist of detailed descriptions of the curatorial and analytical facilities relevant to study of returned extraterrestrial materials in the United States and international partners in sample return missions. We organize this material according to the 'stakeholders' in each institution. A stakeholder in a facility or instrument is the party principally responsible for investing the capital costs and paying for related infrastructure, staffing and continuing costs

of operation. Many instruments are initially purchased with multiple stakeholders (e.g., through cost sharing arrangements), so the definition used here considers the full costs of operating an instrument over its useful lifetime.

Stakeholders generally have a high level of access and control over an instrument's uses, condition, staffing, and associated sample holding and preparation facilities. Non-stakeholders may make use of an instrument, and they benefit from lack of responsibility for continuing costs, but in exchange they often must adapt their samples and analytical goals to conform to the lab's practices. In the case of the precious and sensitive (possibly hazardous) materials considered by sample return missions, an entity that controls the samples, but is not an analytical facility, may be forced to make difficult judgements as to whether a given instrument out of its control is maintained and operated in a way that meets scientific and safety standards (which may differ from mission to mission, and over time – see Section 4.3 for a description about how sample allocation is determined for present return samples). These issues are particularly important when considering facilities and instruments that are not 'common' or 'user facilities,' yet have high mission relevance (by the definitions used in Table 4.1). In such cases, it is particularly important that a stakeholder in that capability has direct connections with the science teams and funding agencies of sample return missions. Thus, investment decisions will need to balance availability and mission-relevance of technologies with some understanding of which institutions need to be stakeholders in those technologies in order for them to be used appropriately for sample return mission science.

Specifically, the committee classifies a given facility or instrument as having NASA, or any Other U.S. Institution (such as a university or non-NASA national lab), or any International Institution as the primary stakeholder. Some judgement was required in some such instances; for example, the committee regards the MegaSIMS instrument as having NASA as the stakeholder, because it was funded and operated largely using mission-specific NASA funding, but it is housed at a U.S. University (UCLA) and is therefore listed under U.S. laboratories external to NASA. Finally, there are two types of analytical technologies that raise special issues with regard to investment strategies for sample return missions and associated science: '*Cutting edge*' technologies are instruments and methods that break new ground in fundamental abilities to observe physical and chemical properties of natural materials; recent examples include MegaSIMS (developed for the Genesis mission) and CHILI (built to study samples from Stardust and similarly small, complex, extra-terrestrial materials). Such projects present unique risks (as their outcomes cannot be confidently foreseen), but also unique opportunities, where investment can lead to dramatic advances, creating new ways of observing, describing, and analyzing materials and environments. Highly innovative or inventive technologies may have increased 'return' on investment because of the new opportunities for scientific advancement that they create, and therefore are an important part of any balanced portfolio of investments in instrumentation. *'Non-traditional' technologies* are instruments and methods that may be common in scientific disciplines that have not had significant overlap with the community of researchers performing sample return science, but have potential to impact the study of samples returned by ongoing or near-future missions. Examples include the 'Atom Probe', various forms of advanced molecular mass spectrometry (FTMS, MS-MS), and high sensitivity molecular surface analysis (soft sputtering ion sources).

TABLE 4.1 Classification of Facilities by Availability and Access (1-5) and by Broad Types of Analysis (A-C)

Types of Analysis **Types of Facilities**	**A. Sample & specimen preparation**	**B. Physical or Structural Analysis**	**C. Chemical or Compositional Analysis**
1. Commonly available at most institutions—broadly accessible	1A e.g., cutting, grinding, thin section preparation	1B E.g., optical microscopy—zoom and petrographic microscopes	1C E.g. general analytical chemistry equipment
2. Multiple regional facilities—limited access*	2A E.g., scanning electron microscope (SEM) equipped with Focused Ion Beam (FIB) technology	2B E.g., X-ray tomography laboratories; M^{3}EGA Laboratory, JSC	2C E.g. many mass spectrometry laboratories Tabletop FTIR and Raman spectroscopy systems
3. Multiple regional facilities—with access open to users**	3A E.g., neutron activation sources	3B E.g., national Center for Electron microscopy	3C E.g. national ion microprobe centers
4. Unique facility—Limited access*	4A E.g., Creek Road Cryogenic Complex, NASA Glenn Research Center	4B E.g. shockwave laboratories, specialized laboratories at national laboratories and related research centers	4C E.g. MegaSIMS (UCLA), CHILI (University of Chicago)
5. Unique Facility—access open to users***	5A E.g., Molecular Foundry, Lawrence Berkeley National Laboratory	5B E.g. synchrotron-and/or neutron- based diffraction and or tomography techniques	5C E.g. synchrotron and/or neutron based spectroscopy techniques

NOTE: Examples of specific facilities are provided when they are notable or unique. Mission relevance classifications are provided below the main table. These classifications are used in Table 4.2. Acronyms are defined in Appendix E.
* Facilities with limited use external to the institution
** open access, often by recharge for regional facilities
***open access, often by peer-reviewed proposal for unique user facilities

Mission Relevance Classifications (Additional mission-specific information is provided in comments in Table 4.2, where applicable)	**MR I** Fundamental tools relevant for all sample return missions.	**MR II** More specialized tools, required for rock and metal samples	**MR III** More specialized tools, required for organic, volatile, and other low temperature materials	**MR IV** Direct mission relevance not established; however, technique may generate unique data relevant to specific missions

TABLE 4.2 Examples of specific instruments, methods, facilities or facility types used in extraterrestrial sample analyses

Method	**Purpose**	**Availability and Access and Mission Relevance (see Table 4.1)**	**Comments on Relevance to Extraterrestrial Materials and Sample Return Missions**
Sampling and Specimen Preparation Methods			
Mechanical perturbations to the sample: Crushing, grinding, cutting, polishing,	Observations of surfaces, internal structure/sub-structure; typically for subsequent scattering, imaging, spectroscopy etc. related measurements.	1A MR I	Available in most laboratories involved with ET material analysis More relevant for hard materials
Chemical polishing, electro-thinning, electro-chemical polishing	Improved surface finish, preparation of thin sections for microscopy/analysis.	1A MR I	Available in most laboratories involved with ET material analysis More relevant for hard materials
Micro-/nano-manipulation, sample positioning, monitoring	Positioning of samples for subsequent sub-sampling and/or analysis	1A MR I	Relevant for both hard and soft materials
Robotic sampling, sample-handling, manipulation/positioning	Minimal human intervention in sampling/sub-sampling, selection, positioning for subsequent sampling and analysis.	2A, 3A MR II	Relevant for both hard and soft materials Robotic and remote sample handling will be especially important for sensitive samples and planetary protection
Laser cutting, lithography, curing, and related photo-induced methods	Sampling, positioning, sectioning and related micromechanical manipulation	2A, 3A MR II	
Ultramicrotomy/wire-saw/sectioning (typically hard-particulates in soft matrices)	Preparation of ultra-thin sections; typically for subsequent microscopy/analysis	2A, 3A MR I	Relevant for both hard and soft materials
Focused ion beam (FIB)	Site- and shape-specific sectioning, lift-off, milling for scanning transmission and transmission electron microscopy (S/TEM) and other analytical methods FIB with cryo-stage is rapidly evolving as a key method for sectioning and preparation of soft (bio/polymer), hybrid (soft-hard interfaces and complexes) and even hard structures which otherwise are fragile and prone to damage.	2A, 3A MR II	More relevant for hard materials Soft materials require cryogenic microscope capabilities

CPD (critical point drying), chemical fixation, related soft/bio-sample preps. (ambient temp. prep methods)	Dehydrate, or chemical fixing of soft/biological structures while retaining structural architecture of soft/biological matter. Typically for subsequent analysis (SEM/TEM etc..)	1A MR III	More relevant for soft materials
Resin embedding, ultramicrotomy, sectioning	Thin/thick sections of soft matter, soft-hard interfaces, soft/hard inclusions. Typically for subsequent analysis	1A, 2A, 3A MR I	Relevant for hard materials. Soft materials require specialized cryogenic techniques
Plunge-freezing and related cryo-preservation techniques. (low temp./cryo-methods)	Thin vitrified ice sections containing soft matter, soft/hard inclusions in soft matrices. Typically for further analysis with electron microscopy	2A, 3A MR III	Relevant for soft materials
Freeze fracture, High-pressure freezing (HPF), ion etching, replica methods	Preparation of hard-soft surfaces, composites; typically for subsequent EM/S-TEM and other analysis.	1A MR IV	Relevant for hard or soft materials; particularly useful for fine-grained mixed materials
Ultramicrotomy/Cryo-Ultramicrotomy	Thin sections of soft/hybrid structures, monolithic slices or particulate composites; for subsequent analysis	2A, 3A MR IV	Relevant for hard or soft materials, particularly fine grained mixed materials
Microscopy, Tomography, and Diffraction Techniques			
Light Microscopy			
Optical microscopy techniques: binocular, optical, reflected, polarized petrographic scopes	Non-invasive imaging, spectroscopy, depth and through-thickness analysis.	1B MR I	
Specialized and unconventional light-optical techniques: e.g., second harmonic generation SHG), waveguide- and near-field techniques	Non-invasive, optical and structural measurements; typically via light-optical response of the materials.	2B, 3B MR IV	
Computed and Computer-Aided Tomography (CT/CAT)	Radiation-based 3D (4D reconstruction) of objects/structures, down to submicrometer resolution.	4B, 5B MR I	Laboratory based X-ray tomography and synchrotron-based X-ray tomography
Electron Microscopy			
Scanning electron microscopy (SEM), including field emission SEM	Imaging the surface of materials at the nano- to micrometer scale; capable of wavelength and energy dispersive spectrometry, cathodoluminescence, and SEM-based Raman; low vacuum and environmental chamber SEMs can be used for unprepared surface observation of non-conductive materials.	1B MR I, MR III	Capable of characterizing both hard and soft materials.
Electron probe microanalysis (EPMA), including field emission EPMA	In situ major and trace element analyses; quantitative microchemical measurements, typically by wavelength-dispersive spectrometry (WDS), but electron-dispersive spectrometry (EDS) also possible, as is concomitant CL spectral acquisition.	1C, 2C MR I	

	Combined WDS-EDS mapping for trace and major element composition at the micro-scale.		
SEM-Electron backscatter diffraction (EBSD)	Characterization of crystalline structure of materials, crystal orientation, orientation mapping	1B MR I, II	Microtextural analysis of hard, crystalline materials
Transmission and Scanning Transmission Electron Microscopy (S/TEM)	Atomic- and nanoscale imaging, diffraction, spectroscopy and spectroscopic imaging of hard, soft or hybrid materials	1B, 2B MR I, MR II	
Cryo/cold stages for SEMs	Imaging soft or volatile materials, frozen materials, EBSD measurements on ice, etc.	2B, 2C MRIII	Often associated with low vacuum and environmental chamber SEM
Cryo-microscopy S/TEMs	Cryo-stage enable improved integrity and stability of structures against radiolysis (beam damage), reduce diffusion at low temperatures etc.; all of which facilitate extended S/TEM observations, for typically atomic and nanoscale imaging and analysis of soft and hybrid (and even hard) structures.	2B, 2C MRIII	
Diffraction techniques			
Laboratory-based X-ray diffraction	X-ray diffraction patterns for mineral identification and characterization	1B, 1C MR I	Essential tool for mineral identification
Synchrotron-based X-ray diffraction	Synchrotron X-ray sources have widely tunable X-ray energies, with high spatial and energy resolution, and development of specialized techniques	5B, 5C MR II	Requires proposal-based access to use facilities. More routinely-available laboratory-based diffractometers can be used also.
Other microscopy methods			
Atomic Force Microscopy (AFM) Scanning Tunneling Microscopy (STM)	Surface structure, surface topography of non-conductive (AFM) and conductive (STM) samples.	2B, 3B MR IV	Surface sensitive technique
Ultrasound imaging/spectroscopy	Non-invasive, sub-surface imaging, analysis (mm scale resolution but large depth access)	1B MR I	Non-destructive characterization of internal structures of hard or soft materials
Piezo-resistive Force Microscopy (PFM), Magnetic-force microscopy (MFM) and related local measurements	Surface and sub-surface imaging, analysis of polarization, magnetization and related near-field measurements.	2B, 3B MR IV	Characterization of surfaces of hard or soft materials
Spectroscopy Techniques			
Light Spectroscopy Techniques			

Laser-based Raman Spectroscopy	Non-destructive method for phase identification and estimates of pressure (for inclusions within minerals)	2B, 2C MR I	First-line characterization for curating most ET materials
Synchrotron-based X-ray Raman Spectroscopy	Non-destructive method for phase identification and estimates of pressure (for inclusions within minerals)	5B, 5C MR IV	Specialized phase identification in fine-grained mixed solids
Laboratory-based Infrared, UV-Vis, multiphoton/related spectroscopy	Vibration, absorption and electronic structure determination of structures, suspensions, gases and hybrids	2B, 2C 3B, 3C MR I	Identification of water and volatiles within small samples
Synchrotron-based Infrared, UV-Vis, multiphoton/related microscopy, spectroscopy	Characterization of absorption features of materials for comparison with remote sensing IR spectra, identification of organic C-H and C-O features. High spatial and energy resolution.	5B, 5C MR II, MR III	Identification of water and volatiles within small samples
Nuclear magnetic resonance (NMR) and related magnetic techniques,	Non-invasive, sub-surface imaging, spectroscopy, and tomography (e.g., MRI imaging).	2B, 3B MR II	Provides a quantitative analysis of functional groups in organic solids. Sensitive detection of hydrogen in inorganic solids.
Mössbauer Spectroscopy	Non-destructive bulk characterization method for local electronic environment of selected isotopes, including ^{57}Fe. Determination of valence, spin state, coordination number, ligand orientation, and magnetic information. Can be performed in bench top laboratory mode using gamma rays as well as synchrotron-based using inelastic X-ray scattering.	4C, 5C MR II	Identification of iron oxidation state and speciation in mineral structures
X-ray & Neutron Based Spectroscopies			
Laboratory-based X-ray fluorescence	Analyses of whole rock major and trace element compositions	2C, 3C MR I	
Synchrotron-based X-ray fluorescence techniques	X-ray diffraction at small scales (µm to nm), determination of oxidation states of minerals, map functional groups in organic phases	5C MR II	Requires proposal-based access to use facilities.
Synchrotron-based scanning transmission X-ray (micro) spectroscopy (STXM)	Non-destructive method of submicron imaging of organic and inorganic compounds and molecular structure using X-ray absorption near edge structure (XANES) spectroscopy of ultra-thin section of solids	3B, 3C 4B, 4C MRII, MR III	Provides functional group level characterization of organic solids as well as element mapping at special scales down to 30 nm.
Neutron scattering	Non-invasive, deep penetrating imaging, spectroscopy/scattering magnetic measurements	5B, 5C MR III	Requires proposal-based access to use facilities. Sensitive to proton position within structures. Helps characterize presence of water and other volatiles.

Misc. techniques: Gamma Ray imaging, terahertz spectroscopy;	Specialized capabilities, analysis of radioactivity,	MR IV	
Mass Spectrometry for Chemical and Isotopic Analysis			
In situ techniques			
Time-of-Flight SIMS (ToF-SIMS)	Elemental, isotopic and molecular in situ analysis at the micron scale, elemental and isotopic mapping	2C, 3C MR I	Analysis of small samples, such as interplanetary and presolar dust grains, and inclusions in meteorites. Molecular and atomic ion species are measured simultaneously. Little sample destruction.
SIMS (large radius – CAMECA 1270, 1280, SHRIMP)	In situ trace element and isotopic analyses at >5 µm. May be fitted with a cryo-stage for analyses of ices.	2C, 3C MR I	Measurements of volatile compounds and trace elements with a high special resolution.
nanoSIMS	In situ trace element and isotopic analyses with <100 nm spatial resolution and high sensitivity	4C, 5C MR II	Identification of small grains (sub-micron), characterization of µm elemental and isotopic compositions in small grains. Studies of presolar grains and organic matter, Stardust and Genesis samples, lunar samples and meteorite geochronology.
megaSIMS	Genesis oxygen isotope analyses	4C MR II, MR III	Specialized measurements of low-abundance components of surfaces and nanograins
Chicago instrument for laser ionization (CHILI)	Isotopic analyses at nanometer scale	4C MR II, MR III	Analysis of small particles with exceptional sensitivity, such as Stardust samples
Resonance ion mass spectrometry (RIMS)	High sensitivity atomic and isotopic analysis	4C MR II	Specialized high sensitivity analysis
He ion microscopy	Imaging of surfaces, electronic structure contrast, topography analysis, orientation imaging	4C MR II, MR III	
Laser ablation ICP-MS, and laser ablation MC-ICP-MS (including split-stream)	In situ trace element and isotopic analyses at >10 µm scale	2C MR II	Spatially resolved trace-element and isotopic analysis of hard solids. Geochronology and source tracing of extraterrestrial materials.

Atom Probe Tomography (APT)	3-D subnanometer mapping, atomic number identification and mass measurement of individual atoms (combined field-ion microscope with ToF MS)	3C MR II, MR III	Atomic and isotopic mapping of exceptionally small domains; suitable for hard materials, or soft materials when equipped with cryogenic sample handling
Bulk chemical and isotopic analysis			
Accelerator Mass Spectrometry (AMS)	Form of mass spectrometry that accelerates ions to ultrahigh kinetic energies before mass analysis. The special attribute of AMS is its ability to separate rare isotope from abundant neighboring mass of another element.	2C MR II	Specialized high sensitivity analysis of rare nuclides; used for cosmic ray exposure dating
Thermal ionization mass spectrometry (TIMS)	Measurements of trace element concentrations through isotope dilution, high precision isotope ratio measurements of isotopes through thermal ionization mass spectrometry. Geochronology and source tracing purposes.	2C MR II	Relevant for high-precision analyses of a variety of isotope systems (both stable and radiogenic). Chronology of extraterrestrial materials.
Multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS)	Measurements of trace element concentrations through isotope dilution, high precision isotope ratio measurements of isotopes through high temperature ionization via an argon plasma.	2C MR II	Relevant for high-precision analyses of a variety of isotope systems (both stable and radiogenic). Chronology of extraterrestrial materials.
Quadrupole or single magnetic sector ICP-MS	Trace element concentration measurements, lower precision isotopic ratio measurements.	2C MR II	Relevant for routine analyses of a variety of isotope systems (both stable and radiogenic)
Gas source mass spectrometry	High precision molecular identification and isotope ratios analysis for organic matter and gases. May use any of several sector, TOF or Fourier Transform mass spectrometers.	1C, 2C, 5C MR III	Molecular characterization and isotope ratio analysis of organic matter and gases
Gas and liquid chromatography mass spectrometry	Chemical separation of complex mixtures of volatile compounds followed by on-line mass spectrometry; for molecular identification and isotope ratio analysis. May use any of several sector, TOF or Fourier Transform mass spectrometers.	1C, 2C, 5C MR III	Molecular characterization and isotope ratio analysis of organic matter and gases
Atomic absorption mass spectrometry	Destructive analytical chemistry technique to determine the concentration of a species within a gas or liquid solution. Can be used to evaluate the concentration of a specific species within a multicomponent solution.	1C, 2C MR III	
Instrumental and radiochemical neutron activation analysis (INAA)	Trace element analyses of whole rock and mineral powders	4A MR II	Used to analyze meteorites but destructive of returned material at the nuclear level.

Thermoanalytic Methods			
Thermal gravimetric analyzers (TGA)	Destructive thermoanalytic technique in which the mass (or density) of a sample is measured as a function of increasing temperature. Can be used to identify phase changes, volatilization, combustion, and other thermal breakdown processes. Can be combined with other chemically-sensitive techniques such as mass spectrometry to get chemical as well as physical information.	1B, 2B, 3B MR I, MR III	For example, M^3EGA Laboratory at JSC (4C) is a TGA and DSC device coupled with additional gas mass spectrometers for chemical analysis.
Differential scanning calorimetry (DSC)	A thermoanalytic technique that measures the heat capacity of a material with respect to a reference. This technique is especially sensitive for detecting phase transitions in polymers and other organics.	1B, 2B MR III	

NOTE: Acronyms are defined in Appendix E.

A few examples of how to interpret Table 4.2, referencing Table 4.1: Scanning electron microscopy is classified as 1B, 1C in availability and access, i.e., used for physical analysis and commonly available and accessible. SEM is classified as MR I and MR II in mission relevance, i.e., relevant to the fundamental analysis of all returned samples, as well as some SEM techniques having more specialized applications. On the other hand, synchrotron-based X-ray Raman spectroscopy is classified as 5B and 5C in availability and access, i.e., used for structural and chemical analysis and available at unique facilities with user access. It is classified as MR IV in mission relevance, i.e., not commonly used for analysis of returned samples but could provide unique data and become more relevant to future missions. Helium ion microscopy (4C, MR II) is used for high spatial-resolution imaging and compositional analysis and is available at unique facilities with only limited access. It is a specialized tool currently relevant for rock and metal samples, but is rapidly developing for organic and hybrid structures (i.e., materials that are a mixture of hard and soft condensed matter).

The following sections discuss laboratory instrumentation available at the institutions involved in sample return science, organized according to the dominant 'stakeholder'.

4.4.2 NASA Center Analytical Laboratories and Facilities

4.4.2.1 Johnson Space Center (JSC)

JSC has over 200 active research and operational scientists, analysts, and technicians who support the missions of NASA, and of these, ~75 are involved in analyses of extraterrestrial materials. JSC is involved in developing planetary science mission concepts and providing Earth imagery to the Earth science community. There is a wide range of equipment in the Astromaterials Research and Exploration Science (ARES) section that is used for the analysis and classification of terrestrial, planetary, and solar materials and space-exposed hardware. See Appendix B for a listing of the analytical equipment available at JSC.

4.4.2.2 Goddard Space Flight Center

The Astrobiology Analytical Laboratory at NASA Goddard occupies 167 square meters of newly renovated laboratory space. Staffed with nine principal scientists and technical staff, it provides state-of-the-art analytical capabilities for studies of organic molecules in terrestrial analogs and extraterrestrial materials. The analytical instrumentation primarily focuses on chromatographic systems for molecular separation that employ either gas chromatographs or liquid chromatographs. These include multiple instruments. Molecular detection is afforded via optical detectors (e.g., linear diode array detectors and fluorescence detectors) and mass spectrometry (e.g., quadrupole mass analyzers, dual quad mass analyzers, ion cyclotron resonance mass spectrometry, time-of-flight mass analyzers, and isotope ratio mass spectrometric analyzers- post combustion interface oxidation). In addition to this major analytical instrumentation, the Astrobiology Analytical Laboratory is equipped with a wide range of sample preparation facilities including HEPA filtered benches, furnaces for off-line pyrolysis, ball mill for sample pulverization, balances, fume hoods, etc.

4.4.2.3. Jet Propulsion Laboratory (JPL)

JPL maintains three research groups concerned with cosmochemistry and astrobiology, two of which focus primarily on chemical analysis relevant to sample return science (the third is a group focused on geobiology and astrobiology, but having no history of study of returned extraterrestrial materials; therefore, it is not included in this review). The Planetary Chemistry and Astrobiology division at JPL includes a laboratory for the analysis of trace metals and their isotopes in extraterrestrial samples, including ultra-clean laboratories for sample handling, digestion and chemical separation, and analytical instrumentation for characterizing metal abundances (by ICP-MS) and isotope ratios (by TIMS). The primary research focus of this group has been early solar system chronology, based on the study of meteorites and samples returned by the Apollo program. This group is being restructured at present, in response to the impending retirement of its long-time director. The analytical capabilities will be merged with the laboratories for geochemistry and cosmochemistry at Caltech. A second laboratory at JPL uses TOF-SIMS techniques to study trace contamination of surfaces of space flight instruments and platforms, with the aim of characterizing and improving planetary protection threats and contamination hazards to sample return missions.

4.4.3 Keck/NASA Reflectance Experiment Laboratory (RELAB)

The Keck/NASA Reflectance Experiment Laboratory (RELAB) is housed at Brown University but supported by NASA as a multi-user spectroscopy facility. Laboratory time is available at no charge to investigators who are in funded NASA research programs. Users can visit the laboratory or send samples to be analyzed. RELAB maintains the Spectral Database, a reference for spectral reflectance data returned by planetary missions. The facility has two operational spectrometers available to NASA-funded scientists:

- A near-ultraviolet, visible, and near-infrared bidirectional spectrometer;
- A near- and mid- infrared FT-IR spectrometer.

These spectrometers are being used to expand the Spectral Database, which is a freely-accessible on-line archive.[9] The database is becoming the principal reference for remotely sensed spectral reflectance data for planetary science. The RELAB policy is that all data are publicly archived within three years of acquisition.

The RELAB has two technical staff positions that aid in the maintenance of the laboratory, the spectrometers, and the spectral database. The technicians also assist users who visit the facility and analyze samples sent for analysis. Technical support is directly funded by NASA as is instrument upkeep

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[9] http://www.planetary.brown.edu/relabdocs/relab_disclaimer.htm

and modernization. User fee models are considered unsustainable and will add volatility to retaining technical staff, as corporate memory and experience is highly valued.

Conclusion: RELAB has been a community resource in producing and compiling spectral databases of rocks, asteroids, and planets. In light of flat or decreased budgets, this type of multi-user facility may be an appropriate future model for other common types of instrumentation used for extraterrestrial analyses.

4.4.4 U.S. Laboratories External to NASA or Other Government-Supported Facilities

The committee requested information from a number of U.S.-based laboratories currently undertaking analyses of extraterrestrial materials (see Appendix B for data compilation) to ascertain the array of analytical capabilities and staffing. These are mainly university-based laboratories, but also include museums (Smithsonian, American Museum of Natural History) and private institutions (Carnegie Institution of Washington). This synopsis does not include large, multi-user facilities such as synchrotrons, or laboratories supported by government agencies other than NASA, which are described separately in following sections. However, the committee recognizes that these demarcations of how facilities are supported are not necessarily clearly defined. Many user facilities benefit from leveraged support amongst different agencies, including NASA. For example, the upgrade of the X-ray beamline at the GSECARS user facility at the Advanced Photon Source was cost-shared by NASA, NSF, and DOE.

A wide variety of analytical equipment is currently in use in non-NASA U.S. laboratories to characterize and study extraterrestrial samples. This instrumentation covers every major category of technology and analytical target that can be addressed by existing technologies, including common, commercially available instruments (i.e., non-prototype versions of microscopes (SEM, TEM, EPMA), spectroscopies (FTIR/Raman), commercially available common and more specialized mass spectrometry instrumentation (e.g., (MC)-ICPMS, TIMS, SIMS, IRMS, and RIMS), as well as specialized sample preparation equipment (e.g., FIB).[10] It also includes two unique instruments designed for high resolution sampling and high precision *in situ* isotopic measurements: the CHILI instrument at the University of Chicago, and the MegaSIMS at UCLA. Collectively, these data suggest that, at present, U.S. laboratories are generally well instrumented to carry out extraterrestrial sample analyses.

The data provided by NASA detailing funding of analytical instrumentation through the LARS and PMEF programs over the past 10 years shows that NASA funding generally falls well below the cost of instrument purchases from commercial vendors (see Section 5.2.1).[11] Thus, it can be inferred that much of the instrumentation currently used for extraterrestrial sample analysis is funded entirely by or via cost-share arrangement with other funding agencies (e.g., NSF), foundations (e.g., Keck), institutions, or other sources, and is likely also used for analyses of terrestrial samples.

Appendix B shows that staffing of analytical laboratories varies greatly from one institution to another, and from one type of institution to another. Most laboratories undertaking extraterrestrial sample analyses employ one or more highly-trained technical staff, as well as post-docs and graduate students. Generally, institutional-based funding for technical staff is more readily available at NASA centers, museums, or private research institutions compared to university-based laboratories. This reflects the fact that universities have significantly reduced funding for technical support staff over the past three decades, which has implications for the sustainability of such laboratories, as addressed in Chapter 5.

Finally, most sample return analyses to date have focused on rocks, minerals, glasses and metals (hard condensed matter). Future missions, as detailed by the Decadal Survey, may seek to return gases, ices, and associated organic materials. Whereas the handling and analysis of extraterrestrial organic molecules, both low and high molecular weight (e.g., amino acids to polymeric organic matter) in primitive meteorites and comet samples (comet 81P/Wild 2 via the Stardust Mission) is now very mature in many laboratories (e.g., NASA, university, and private institutions), the handling and transfer of more

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[10] See Appendix E for abbreviations and Table 4.2 for a more detailed enumeration of capabilities

[11] Jeffrey Grossman, NASA, personal communication

fragile samples such as ices and gases presents a new set of challenges for both NASA and sample recipients.

4.4.5 Other U.S. Government-Funded Facilities

The United States is the world leader in materials characterization, not only with a breadth of state-of-the-art characterization techniques, but also a broad portfolio of laboratory governance modalities (single-principal investigator [PI] laboratories, regional multi-PI laboratories, to larger multi-user facilities) and funding modes (governmental, non-governmental/non-profit, and commercial entities, as sole-funding entities or part of a consortium). As a result, a healthy ecosystem of non-NASA facilities across the nation can provide standard, routine or specialized materials handling, characterization, measurements and related capabilities for extraterrestrial materials and their analysis.

The materials characterization enterprise of the United States consists of a diverse portfolio of laboratories at all scales (from tabletop experiment to multi-experiment particle accelerators) with a variety of scopes (serving specific scientific and or technical niches, or covering a range of science and/or techniques), with a diversity of paths to access (from access based on personal relationship with PI, to merit-reviewed proposal-based open access), and funded by a variety of organizations or a combination of organizations (including government, non-governmental non-profit organizations, and commercial).

While an exhaustive summary and review of all of the United States' capabilities in materials characterization is beyond the scope of this report, in this section a synopsis is provided of the (mostly governmental) organizations that provide a large part of the funding for materials research centers, with particular focus on examples of multi-user facilities that are most pertinent to present and likely future extraterrestrial sample return.

4.4.5.1 U.S. Department of Energy (DOE) Major User Facilities

U.S. DOE is known for historical stewardship of diverse user facilities for high-energy and radiation-based tools, techniques, and measurements. These facilities and associated infrastructure have been developed and nurtured by specific DOE divisions, programs, and initiatives, but they are typically broadly accessible to users (including international users). The access to these DOE facilities often requires a relatively straightforward proposal process and the facilities provide technical support (staff, data gathering/analysis, etc.) before, during and after the experiments, together with computational analysis.

Specifically, DOE has significantly invested in and manages synchrotron X-ray scattering, neutron scattering, and electron-beam based facilities. DOE also operates nanoscale science research centers (NSRCs), which provide user access to synthesis and fabrication of nanoscale structures and systems that will likely be relevant to the sampling/concentrators, characterization, and measurements of extraterrestrial materials analysis.

Some noteworthy and globally unique user facility examples include: the synchrotron radiation source and associated capabilities at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL); the National Synchrotron Light Source-II (NSLS-II) at Brookhaven National Laboratory (BNL); the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory; the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory; among several others partly supported or managed by DOE.

The DOE Office of Science is a useful resource and acts as "one-stop-shop" for all information related to facilities and infrastructure for instrumentation related to fabrication, characterization and measurements.[12]

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[12] https://science.energy.gov/user-facilities/

4.4.5.2 *U.S. National Science Foundation (NSF) Facilities & Infrastructure Programs*

NSF has invested in the development of state-of-the-art tools for advanced materials research, with direct or indirect applications to extraterrestrial materials characterization through a variety of programs, including within the directorate of Geoscience, the Division of Materials Research, and in cross-cutting programs from the Office of Integrated Activities. These include multi-user distributed instrumentation networks and arrays, accelerators, research vessels, aircraft, telescopes, and simulators, among others. In addition, NSF has also invested in internet-based and distributed user facilities; some of which may be relevant to extraterrestrial materials analysis, archiving, and data analytics.[13]

In some cases, NSF-supported programs manage major facilities and infrastructure programs for extended duration (e.g., Laser Interferometer Gravitational Wave Observatory — LIGO). In other cases, NSF partially or fully manages infrastructure programs and initiatives, such as the National High Magnetic Field Laboratory (NHMFL)[14] at Florida State University that can be used to make high-performance nuclear magnetic resonance measurements to characterize organic molecular structures, and the National Superconducting Cyclotron Laboratory (NSCL)[15] that can be used to generate tracers for tomographic imaging and related radioactive decay measurements. NHMFL and NSCL are unique, unusual, and potentially useful tools and techniques for analysis of returned extraterrestrial samples.

The Directorate of Geoscience (GEO) has several programs and initiatives that support specialized facilities and analytical instrumentation with overlaps with the sample return community. Dr. David Lambert, Program Director of Instrumentation & Facilities of the GEO directorate provided an overview of these programs to the committee, which include funding of a single PI for instruments costing up to $500K through the regular program (e.g., SEMs, quadrupole ICP-MS), or, for more expensive instrumentation (e.g., electron microprobes, large radius SIMS instruments), through the Major Research Instrumentation program, which provides funding in the range of $100K to $4M. Very expensive instrumentation and facilities costing more than $100M (e.g., telescopes) can be funded through the Major Research Equipment and Facilities Construction (MREFC) program. NSF-funded user facilities within the GEO directorate include COMPRES, which funds mineral physics research in the Earth Sciences, and GSECARS, which provides support for the synchrotron X-ray user facility for the Earth sciences at APS. Many of the instruments currently employed for extraterrestrial sample analyses have been partially funded by NSF.[16]

Other notable NSF programs and facilities relevant to extraterrestrial materials analysis include the National Nanotechnology Coordinated Infrastructure (NNCI) program,[17] which provides regional nodes of excellence in fabrication, and characterization facilities that are accessible to local/regional, national and international institutions, as well as corporations. These are geographically widely distributed and each one has some unique or integrated capabilities often needed to solve a particular materials analysis challenge.

4.4.5.3 National Institute for Standards and Technology (NIST) Facilities

As part of the Department of Commerce, NIST traditionally provides measurements and standards expertise to the scientific, technical and corporate communities. As extraterrestrial materials handling, analysis, data archiving and dissemination become more pervasive and globally accessible, NIST may offer unique opportunities for the community to standardize various experimental and computational parameters for more consistent and cross-correlative undertakings.

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[13] https://www.nsf.gov/about/budget/fy2018/pdf/36_fy2018.pdf

[14] https://nationalmaglab.org

[15] https://www.nscl.msu.edu/index.php

[16] Lambert, D., Kelz, R., and Johnson, K., Instrumentation & Facilities (IF) Program: Division of Earth Sciences, Directorate for Geosciences. Presentation to the committee November 20, 2017.

[17] www.nnci/net

NIST runs a number of laboratories and operates two key facilities—the NIST Center for Neutron Research (NCNR) and the Center for Nanoscale Science and Technology (CNST).[18] Several NIST facilities and expertise are available to the broader analytical community and users. For example, the materials and measurement laboratory (MML) serves "as the national reference laboratory for measurements in the chemical, biological and materials sciences,”[19] especially related to the certified reference materials, critically evaluated data and analysis, and other programs to ensure and assure the quality of measurements (see Section 2.2.3). MML coordinates the NIST-wide Standard Reference Material and Standard Reference Data programs.

The Precision Measurement Laboratory (PML) is involved in the science of “measurement” of diverse kinds. It sets the definitive U.S. standards for nearly every kind of measurement employed in commerce and research, provides NIST-traceable calibrations, and disseminates standards and best practices.

4.4.5.4 US Department of Defense (DOD) Programs & Facilities

The DOD science and technology enterprise provides basic and applied research support and operates directly or indirectly several facilities and infrastructure programs related to materials synthesis, characterization, behavior, and system- or device-level considerations. The end of this section contains relevant web portals that provide broad overview and key-word searchable items for facilities/equipment for research at DOD science and technology enterprise and related capabilities relevant to extraterrestrial materials analysis.

Some of the DOD laboratories are well known for their unique capabilities for materials and analysis that have been developed for many decades. Some notable examples include: the Naval Research Laboratory (NRL), Wright-Patterson Air Force Base (WPAFB), and Edgewood Chemical Biological Center (ECBC), which offer advanced technical capabilities and in-house expertise that may be relevant to handling and analysis of future extraterrestrial materials. The NRL has been involved in analyses of Stardust return samples.[20] Other major or unique capabilities include materials, structures, phenomena, systems and their behavior in the context of high velocity impact, energetic materials and other military-related specialized capabilities and facilities.

The DOD laboratories and facilities are typically accessible through collaborative programs or through contact with individual division and section heads, per local protocol and access constraints driven by DOD considerations.[21]

4.4.5.5 National Institutes of Health (NIH) Infrastructure and Facilities

NIH offers major instrumentation access and capabilities through its intra-mural program and support to external institutions and consortia. Some of these are called “Cores”, which provide centralized and coordinated capabilities for specific biomedical research and development needs. Unlike agencies such as DOE or DOD, NIH does not have or has not invested in widespread physical presence or facilities and infrastructure. However, the Cores and facilities affiliated with universities or institutions (at least partly supported by NIH) are spread widely throughout the U.S. (and outside) and have several modes of

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[18] https://www.nist.gov/labs-major-programs/user-facilities; https://www.nist.gov/nist-center-neutron-research

[19] https://www.nist.gov/mml

[20] DiGreorgio et al., 2017, Evidence for Reduced, Carbon-rich Regions in the Solar Nebula from an Unusual Cometary Dust Particle, *Astrophys. J.* 848(2), DOI: 10.3847/1538-4357/aa8c07

[21] Detailed list of DOD laboratories: www.defenseinnovationmarketplace.mil/laboratories.html DOD science and technology listing: https://www.acq.osd.mil/chieftechnologist/, https://www.defense.gov/News/Special-Reports/0715_science-tech/, Searchable facilities/labs. doing basic Research at DOD: http://basicresearch.defense.gov/

user access per constraints of the specific programs or NIH division or institute support. The Association of Biomolecular Resource Facilities (ABRF) provide a searchable database of various "cores" and associated tools, techniques and capabilities for researchers. Some of these programs, initiatives and core facilities will likely have directly relevant experience for extraterrestrial materials and their analysis, especially as future incoming sample return materials will likely include organic or volatile substances, and thus be susceptible to damage during handling and examination.

In addition to primary NIH support, some of the core facilities and specialized instrumentation infrastructure for biomedical research across the U.S. are partly or wholly supported by foundations such as the Howard Hughes Medical Institute (HHMI) or the Gates Foundation, among many others. Extraterrestrial materials handling and analysis will likely benefit from the aforementioned capabilities, though these are geographically distributed and often invested for specific NIH institute support (thus specific mandates and goals).

NIH is now considering infrastructure investment similar to NSF and DOE programs (e.g., regional facilities model of the NNCI program) in large projects such as Cryo-EM centers, Magnetic Resonance Imaging (MRI), and related imaging initiatives. These facilities will likely operate analogous to DOE facilities and be accessible to communities and researchers for extraterrestrial materials analysis.

There are also many national biomedical and clinical research centers with extensive facilities and instrumentation infrastructure. In fact, each of the 28 institutes supports centers with research facilities. In particular, the National Institute of Biomedical Imaging and Bioengineering (NIBIB) may be a useful resource for extraterrestrial materials handling and characterization as it also supports, nurtures and (at least partly) manages research facilities.[22] Other facilities include the NIH Core Facilities Support Portal[23] and the Association of Biomolecular Resources Facilities (ABRF) portal.[24]

4.4.5.6 Miscellaneous Government Funded Facilities/Infrastructure

There was a widespread recognition in policy circles in the U.S. after World War II that "science won the war." This recognition was further reinforced during the cold war and led to several public-private partnerships for research and development on behalf of the U.S. government. These are typically administered through the U.S. Code of Federal Regulations (Title 48, Part 35, Section: 35.017) by universities and corporations.

These Federally Funded Research and Development Centers (FFRDCs) in many cases have unique and useful resources for scientific and technical communities. FFRDCs also and often include major facilities, capabilities, and intellectual resources for materials handling, synthesis, characterization, measurements and systems; quite possibly relevant for extraterrestrial materials analysis. For example, FFRDCs include the Center for Nuclear Waste Regulatory Analysis, operated by the Southwest Research Institute (SwRI) on behalf of the Nuclear Regulatory Commission (NRC), which may become an important resource should there be radioactive extraterrestrial materials returned in future missions. Other such niche examples can be found on FFDRCs web portal.[25]

4.5 OVERVIEW OF INTERNATIONAL FACILITIES

The scientific study of extraterrestrial materials, including meteorites, cosmic dust, and returned samples, is a well-established field in more than a dozen countries, with noteworthy centers of excellence in Canada, Denmark, France, Germany, Japan, the United Kingdom (UK), and Switzerland. Space

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[22] https://www.nibib.nih.gov/research-funding/featured-programs/biomedical-technology-resource-centers/supported-centers

[23] https://grants.nih.gov/grants/policy/core_facilities_faqs.htm#3626

[24] https://www.faseb.org/Portals/2/PDFs/opa/2016/Instrumentation;%20Federal%20Grants%20and%20Programs%20for%20the%20Life%20Sciences.pdf

[25] https://www.nsf.gov/statistics/ffrdclist/

missions aimed at solar system exploration, including sample return, are increasingly structured as international collaborations (e.g., Hayabusa2, OSIRIS-REx), with explicit plans for sharing returned materials between nations and dividing laboratory work to meet mission science goals. For these reasons, it will be advantageous to consider existing and likely future capabilities of prospective international partners when defining future investment in U.S. infrastructure for sample return science.

Appendix C summarizes technical data for more than two dozen international facilities that perform analytical science in support of previous, ongoing, or planned near-future sample return missions. The following paragraphs summarize the committee's findings from review of these data.

Instrumentation and technology strengths: The collective analytical instrumentation of the international facilities considered relevant to this study covers every major category of technology and analytical target that can be addressed by existing technologies, including common, commercially available instruments (i.e., non-prototype versions of microscopes (SEM, TEM, EPMA), spectroscopies (FTIR/Raman)), commercially available common and more specialized mass spectrometry instrumentation (e.g., MC-ICPMS, TIMS, SIMS, IRMS[26]), large-scale user facilities based at national-scale synchrotron X-ray or neutron beam sources, and unique instrumentation specially built for returned sample analyses (e.g., the RELAX instrument at University of Manchester).

The breadth and depth of the analytical capabilities of international facilities are impressive. Most of these laboratories duplicate widely available capabilities present in U.S. laboratories. However, if gaps emerge in U.S. capabilities in the general category of common, commercially available instruments (e.g., through decommissioning or nonrenewal of existing laboratories), it is notable that similar facilities exist in top laboratories doing return sample analyses elsewhere in the world. More importantly, several of the international facilities possess unique or prototype analytical or experimental equipment that cannot be found in U.S. institutions. Examples include the 'Argus' collision cell in the MC-ICPMS laboratory at Bristol, UK; the RELAX resonance ionization noble gas isotope instrument in Manchester, UK; the high-velocity particle impact laboratory in Heidelberg, Germany, and the breadboard Orbitrap flight instrument (dubbed the Cosmorbitrap) in Université d'Orléans, France. Each of these capabilities represents years to decades of investment and would be expensive to duplicate or supersede.

Instrumentation and technology weaknesses: The primary weaknesses of international facilities, as compared to their U.S. peers, from the perspective of this report's charge, are the relatively small number and brief history of technology development projects directly inspired by and connected to the aims of returned sample science. There are several examples of ambitious, impactful instrument development projects conducted in the U.S. that grew directly out of sample return mission goals (in some cases even directly funded by sample return missions; e.g., Mega-SIMS and CHILI), and these are just the most recent examples of a long history of engagement between sample return missions and analytical laboratory developments (e.g., the 'Lunatic' class of TIMS instruments in the 1970's). The lack of similar long-term engagement in international institutions puts international partners at a significant disadvantage, at least in the near term, when it comes to organizing and executing programs of technical development in support of sample return missions.

Staffing Strengths: The committee's review of international facilities revealed two significant strategic strengths in personnel management: (1) several narrow but scientifically important areas of technical and scientific leadership, particularly in the noble gas geochemistry of extraterrestrial materials (Nancy, France, and Manchester, UK). The decades of excellence demonstrated by these groups could not be readily duplicated elsewhere and are a valuable resource to support collective goals. (2) It is common (though not universal) for international institutions to provide salaried, permanent staff positions to support the construction, maintenance, and use of analytical instruments. This support is strongest in

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[26] See Appendix E for abbreviations and Table 4.2 for a more detailed enumeration of capabilities.

France, Germany, Canada, and Switzerland, where it is common for laboratories to be staffed by highly qualified technical staff whose salaries are paid by the university or government. For example, the CNRS in France hired 332 new technical support staff in 2016.[27] The stability of funding for these positions means these facilities can develop and maintain well trained and experienced staff and are able to translate their skills from one generation to the next. This level of continuity is important for maintaining the highest levels of technical readiness, particularly for projects such as sample return missions where the time span from mission conception to sample analysis can be ten or more years. This model of staff support has largely disappeared in U.S. institutions over the last ~20 years, in response to changing financial models for academic institutions and funding goals and models from federal agencies. International partners provide clear examples of the benefits of their vision for the connection between support for technology and support for long-term development of the staff who make that technology work.

Staffing Weaknesses: While each individual laboratory and facility has its unique sets of strengths and weaknesses with regard to human resources, two trends are typical to foreign laboratories' staffing strategies in conjunction with sample return missions and represent weaknesses in these programs. First, compared with the U.S., international laboratories have a relatively short heritage of close connection between the research groups spearheading the sample return missions and the research groups involved in the primary characterization of the returned samples. A second issue is that many European and Japanese academic organizations are strongly hierarchical, with fewer opportunities for promotions. This is an important issue for technical support staff who might also be early career academics. The culture makes it difficult for junior scientists to advance in their careers over the time scale of a given mission. This serves as a disincentive for early-career scientists to take on the role of scientifically-trained technical support staff.

4.6 LABORATORY AND FACILITY CONCLUSIONS

This chapter describes broad classes and thematic categories of analytical instrumentation and capabilities that are used in curation and analysis of existing returned samples and which may be used for future sample returns. This chapter also discusses various national and international facilities and their locations around the world. Specific examples of laboratories in the US and abroad that house these capabilities are provided in Appendix Tables B and C, respectively. Researchers use these instruments and facilities to characterize the physical properties and chemical composition of returned samples. In many cases, the functional behavior or properties associated with the samples can also be determined using complementary analytical techniques, or by using the same instrument in a different manner. For example, the atomic force microscope is often used for "metrology" (i.e., determining the sample size, shape, and related physical measurements). Yet, the same instrument can be used for magnetic force microscopy to map magnetic domain formation in the material, or to help reveal the distribution of magnetic phases across the field of view.

Infrastructure, instrumentation, and facilities are well developed for characterization and analysis of hard sample returns (i.e., minerals, glasses, metals, and rocks). The committee did not identify any techniques or instruments that are highly relevant to current returned samples or missions in flight that are missing or entirely unavailable to U.S. researchers. In some cases, such as synchrotrons with broad mission relevance, facilities are few, but they are generally available to users via peer-reviewed proposals. However, given finite lifespans, instrumentation and facilities require continual upkeep and renewal to assure that the latest technologies and methods are available for characterization and analysis of returned samples.

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[27] 2016 A Year at CNRS, Excerpts from the 2016 Annual Report which can be viewed at: www.cnrs.fr

Samples of soft condensed matter, including organic materials, as well as gas- and ice-based materials, are becoming increasingly important to returned sample analysis. For example, organic materials are important targets for both missions currently in flight to sample primitive asteroids (Hayabusa2 and OSIRIS-REx). In addition, future missions may aim to return ices and gases. Thus, more increased capabilities for the collection, transport, curation, and analysis of such fragile and damage-prone materials and structures will be needed in the future, as outlined in the conclusions, below.

Conclusion: The committee's analysis of analytical equipment available at U.S. laboratories indicates that there is a wide range of instrumentation that is currently accessible for returned sample analyses. There are no obvious gaps in instrumentation for analysis of returned rocks, glasses, minerals, and the current inventory of organic materials.

Conclusion: Missions in flight will not return samples for at least five years, therefore, some of the current analytical capabilities will be decommissioned before the samples are available.

Conclusion: Future sample return missions are focused on returning and analyzing more challenging materials (e.g., gases, ices, organic compounds, see Chapter 3) and will require investment in technologies that are not currently widely utilized by the sample return community.

5

Current and Future Instrumentation and Investments for Extraterrestrial Sample Analysis

In this section we first review current NASA funding programs and then assess what capabilities or opportunities are or will be needed for analyses of returned samples. This encompasses curation facilities, sample distribution, funding of instrumentation, training and support of personnel, developing new methods for handling and analyzing challenging samples, and leveraging other U.S. facilities and international collaborations.

5.1 OVERVIEW OF NASA FUNDING PROGRAMS RELEVANT TO RETURNED SAMPLE ANALYSIS

Currently, instrumentation for analyses of extraterrestrial materials is funded through two NASA programs: Laboratory Analysis of Returned Samples (LARS) and Planetary Major Equipment and Facilities (PMEF).

A primary goal of the LARS program is to maximize the science derived from planetary sample return missions. This is encompassed by two categories: "1) development of laboratory instrumentation and/or advanced techniques required for the analysis of returned samples; (2) direct analysis of samples already returned to Earth."[1] However, LARS specifically excludes analysis of lunar samples returned by the Apollo and Luna programs, terrestrial collections (meteorites, cosmic dust), and space-exposed hardware. It also does not support development of instruments to fly on planetary missions; these are normally funded through the mission proposals and/or specific programs for spacecraft instrumentation (PICASSO and MatISSE). Finally, LARS does not support service contracts for established instruments, or technical support to run and maintain them. In 2018, the LARS program expected to fund ~10 awards with a total of ~$2.6M.

The scope of the Planetary Major Equipment and Facilities (PMEF) program[2] allows proposals for the purchase or development of new or upgraded non-flight analytical, computational, telescopic, and other instrumentation with hardware costs over $50,000 to be used in investigations in Planetary Science Division (PSD) research programs. Two types of PMEF instruments can be proposed: 1) Investigator Instruments (instruments "acquired or developed by the proposer to support the PI's research, where the PI has full authority for its exclusive use, and where there are no commitments to make the instrument available to other investigators"),[3] and 2) Facility Instruments (a significant fraction of instrument time will be made available to other researchers in planetary science). The individual investigator instruments can be proposed as an addendum to research proposals, whereas the facility instruments are only stand-alone proposals to the PMEF program. This program does not support repairs of existing instrumentation, funding for technical support staff, or service contracts. In 2018, the annual expected budget for the PMEF is ~$2M with the expected number of awards being between 5 and 9. Cost sharing with other federal agencies is encouraged.

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[1] ROSES 2018, C.18-1

[2] ROSES 2018, C.17-1. Note: Until March 2018, PMEF allowed a third category of proposals, Regional Facility Instruments—like an investigator facility, but the instrument was of considerable cost or was limited to a particular location by virtue of its use in a specific facility.

[3] ROSES 2018, C.17-2

Additional grant programs that may support analysis of extraterrestrial samples are Emerging Worlds (EW) and Solar System Workings (SSW) and to a lesser degree, Exobiology.[4] These programs provide the only NASA-funded opportunities to propose the analysis of meteorites and lunar samples. Emerging Worlds aims to explore the formation of the solar system and its early evolution. Major interdisciplinary efforts to solve key questions are particularly valued. Solar System Workings is a broad program that "supports research into atmospheric, climatological, dynamical, geologic, geophysical, and geochemical processes occurring on planetary bodies, satellites, and other minor bodies (including rings) in the Solar System. This call seeks proposals to address the physical and chemical processes that affect the surfaces, interiors, atmospheres, exospheres, and magnetospheres of planetary bodies."[5] The goal of the Exobiology program "is to understand the origin, evolution, distribution, and future of life in the Universe. Research is centered on the origin and early evolution of life, the potential of life to adapt to different environments, and the implications for life elsewhere."[6]

The Lunar Data Analysis Program supports scientific investigations of the Moon using publicly available (released) mission data from orbital lunar missions, both U.S. and non-U.S. While this program does not preclude sample analyses, these are discouraged unless they enhance the analysis and understanding of the data from more recent (i.e., Lunar Prospector or younger) missions. For example, analysis of samples to understand reflectance spectra can be proposed, but detailed geochemical studies focused only on samples cannot.

When founded, the precursors to the LARS program were funded by the Discovery Program to support analyses of soon-to-be-returned Genesis and Stardust samples. As such, lunar samples, despite being returned by missions, were not included. As LARS has evolved, its focus on Discovery missions has diminished and older sample sets are supplanted in priority for funding by newer samples. Nonetheless, lunar samples make up the majority of the current collection of returned extraterrestrial samples. Further, new studies have revealed records of volatile abundances in the lunar interior that have challenged long-held paradigms about a dry Moon. While these efforts have been funded by NASA's core programs, the exclusion of lunar samples from LARS limits the ability to develop laboratory instruments specifically to address these new hypotheses. At the time of the Apollo program, there was explosive growth in laboratory instrumentation that was then state-of-the-art (e.g., electron microprobes, thermal ionization mass spectrometers), but now the only program that funds the development of laboratory instrumentation specifically for lunar samples is the PMEF, in competition with all other non-flight instrumentation for planetary science. In addition, the most recent Decadal Survey prioritizes a lunar sample return program (see Section 3.3.4). The recent change in the United States Space Policy that directs NASA to return humans to the Moon[7] has resulted in a new lunar emphasis in the Science Mission Directorate (e.g., the Lunar Exploration and Discovery Program) and the PSD research programs (e.g., the Development and Advancement of Lunar Instrumentation (DALI) program). In 2018, PSD issued a special call for proposals for the Apollo Next Generation Sample Analysis Program (ANGSA) that focused on specially curated lunar samples (unopened vacuum-sealed, frozen, or stored in helium). This solicitation funded sample analysis research, but instrumentation funding is only available via the PMEF.[8] Although originally considered as a one-time solicitation, it may be competed again in the future to look at novel ways to investigate the current Apollo samples (e.g., new analyses of large regolith samples, new clasts in breccias identified through CT scans). Note that this would not be a general call for the analysis of Apollo samples. Therefore, the current exclusion of lunar

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[4] NASA Planetary Science research programs were reorganized in 2013, and the new programs were first funded in 2015. Previous relevant programs include Cosmochemistry and Planetary Geology & Geophysics.

[5] ROSES 2018, C.3-1

[6] ROSES 2018, C.5-1

[7] Presidential Memorandum on Reinvigorating America's Human Space Exploration Program, issued December 11, 2017. https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/

[8] ROSES 2018, C.24-4

samples from LARS is inconsistent with NASA's objective of maximizing scientific return from returned samples, irrespective of when those samples were returned. However, if LARS is opened to lunar sample analyses and funding remains constant, the resources available for analyses of other types of returned samples will be diminished.

Conclusion: The very broad nature of the SSW program, the very specific requirements of the EW program, and the exclusion of lunar sample analyses from the LARS program place limitations on sample-based research, particularly from the Moon and the terrestrial meteorite collections.

Recommendation: NASA Planetary Science Division should consider opening the Laboratory Analysis of Returned Samples (LARS) grant program to all mission returned extraterrestrial samples.

5.2 CURRENT NASA PLANETARY SCIENCE INVESTMENTS

This section lays out the current NASA Planetary Science Division investment strategy for instrumentation, workforce development, and curation. The next section, Section 5.3, discusses future needs in these three areas.

5.2.1 Instrumentation

The capability to purchase or build new instrumentation and to repair, upgrade and replace existing instrumentation (which may, in some cases, necessitate service contracts from equipment manufacturers) is central to maintaining the laboratories needed to analyze returned sample. The current investment strategy of NASA has been to support purchases and upgrades of equipment by individual investigators through the LARS or PMEF programs, as described in Section 5.1. A significant proportion of the equipment purchased appears to be cost-shared with other funding agencies (e.g., NSF) or institutions (e.g., universities or private foundations), thus leveraging NASA funding.

There is an overall downward trend in the success rate of PMEF proposals funded by NASA (see Figure 5.1); success rates hovered around 30% prior to 2011 (with the exception of 2010, which had an anomalously low success rate of about 16%, because a smaller number of more expensive proposals were funded), and has decreased to less than 20% since 2014. This is over a period when the total awards for the program averaged around \$2 million per year, not adjusted for inflation, which means that absolute funding decreased. From these data one can surmise that the demand for funding of major equipment has increased over the past 10 years. By contrast, the total amount spent on major equipment in LARS and PMEF, as well as the subset spent on equipment specifically for sample analysis, while variable from year to year, decreased significantly since 2008 (Figure 5.2, also not adjusted for inflation). Collectively, these data suggest that there is an increasingly greater demand for purchase and upgrading of analytical equipment used for extraterrestrial sample analysis than can be met by current funding levels. In addition, the number of available extraterrestrial samples is increasing. New meteorites are returned each year through NASA-funded fieldwork in Antarctica (as well as new meteorites from other locations becoming available), two sample return missions are currently in flight, new sample return missions are either in early stages of approval or are being studied, and there has been renewed interest in the Apollo and Luna samples since the change in national space policy through Space Policy Directive 1.[9]

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[9] Presidential Memorandum on Reinvigorating America's Human Space Exploration Program, issued December 11, 2017. https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/

Further, laboratory instrumentation has a limited functional lifetime (typical university depreciation rates have an average lifespan of 10 years), with an even shorter period to obsolescence for state-of-the-art technology. Common instrumentation such as a field emission electron microprobe currently costs ~$1.5-1.7 million, while the PMEF program has had annual expenditures in the range of ~$1-3 million over the last decade. Even assuming a generous 50% cost share from a source outside NASA, the current budget allows for replacement of only 1-4 instruments annually. With an average functional lifetime of ~15-20 years for most instrumentation (i.e., longer than average depreciation lifetimes), this budget would replace ~50 instruments in two decades. These estimates are consistent with NASA's investment through LARS and PMEF totaling ~$17 million in the period 2011-2018. This limited replacement schedule is exacerbated by the fact that even for existing technology, the analytical instrumentation available in laboratories today will not be the instruments that analyze samples of currently proposed or considered sample return missions.

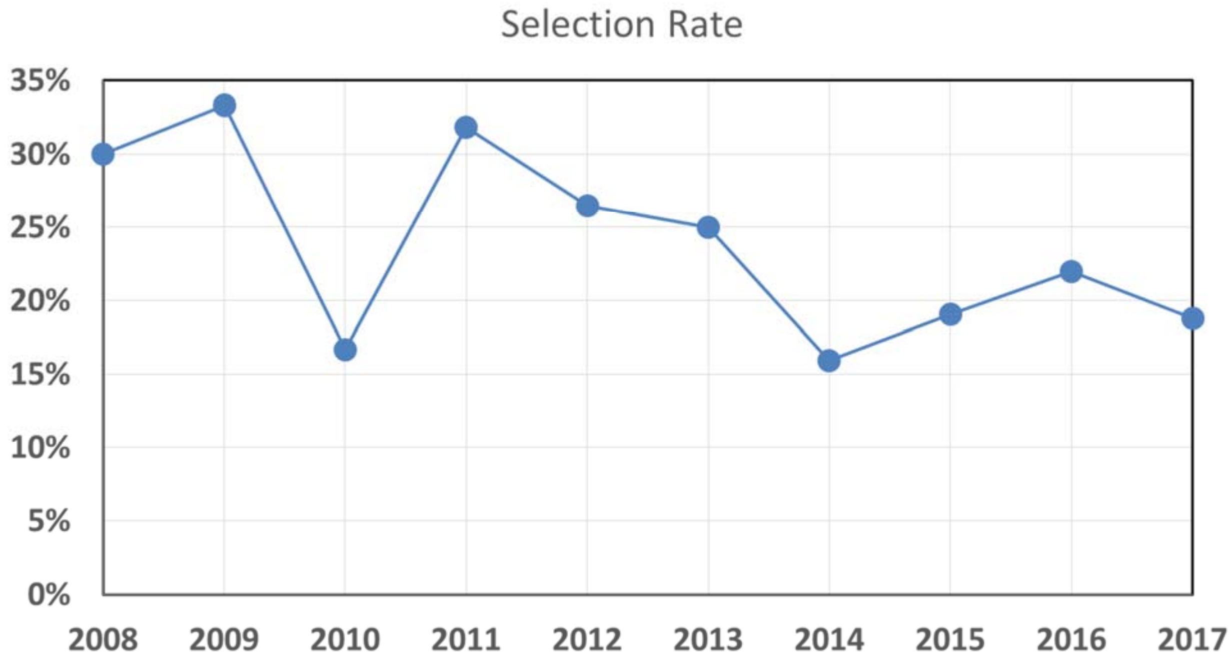

FIGURE 5.1: Planetary Major Equipment and Facilities proposals selection rate, 2008-2017, excluding Laboratory Analysis of Returned Samples proposals with integrated equipment. The 2017 numbers are incomplete. SOURCE: Jeffrey Grossman, NASA, personal communication.

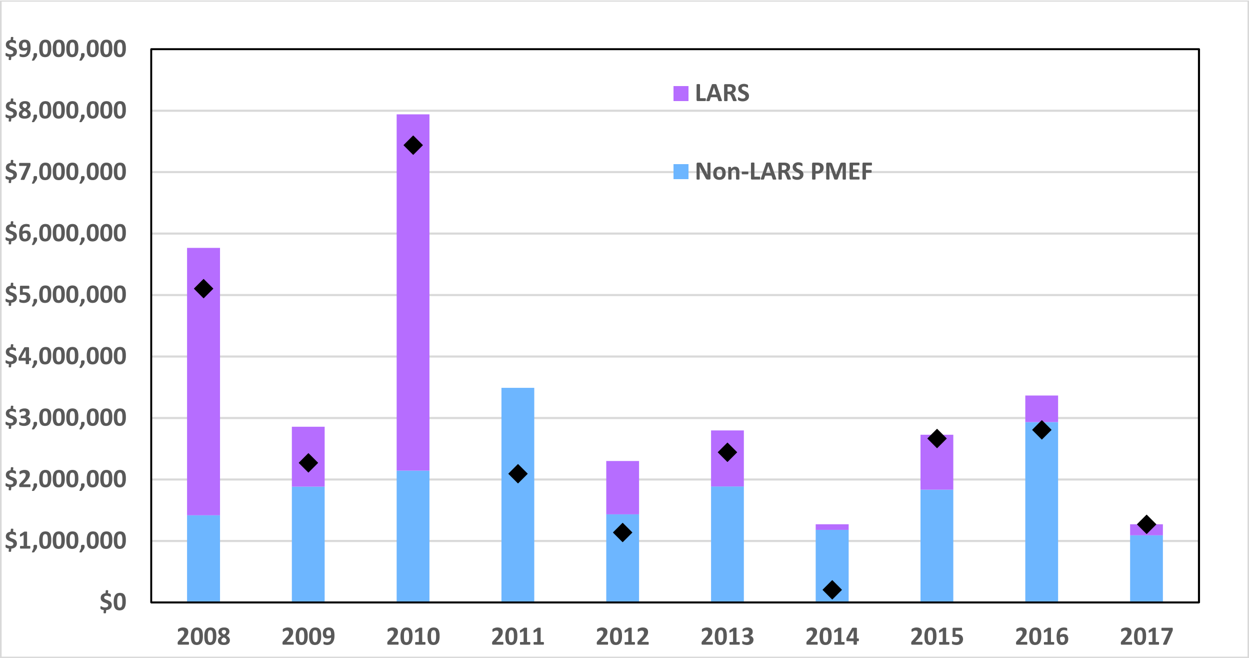

FIGURE 5.2: Major Equipment Investments per year from Planetary Major Equipment and Facilities (PMEF) and Laboratory Analysis of Returned Samples (LARS) Programs, as well as the subset of the investments spent on equipment for sample analysis, 2008-2017. The 2017 numbers are incomplete. SOURCE: Jeffrey Grossman, NASA, personal communication.

Recognizing that future funding for analytical instrumentation is uncertain, the committee considered the impact of flat or decreased funding (the current situation), a modest funding increase, and large increased funding. Each of these scenarios is described below.

If funding for instrumentation continues to remain flat or decreases, as is currently the case, it will not be possible to fund both replacement of existing capacity and development of new capabilities. This will necessitate a reduction in the overall number of analytical laboratories supported by NASA, particularly through the PMEF and LARS programs. The reduction in capacity of existing instrumentation could be mitigated by preferentially funding regional or national facilities that commit a portion of available time to outside users, such as through an open call judged by a panel of internal and external experts. While this requirement could be levied on future proposals, it could also be applied to existing facilities, including NASA centers that receive ongoing support for analytical instrumentation for sample analyses. However, the committee notes that the record of major breakthroughs developing novel analytical instrumentation, advances in using existing instrumentation, and major discoveries derived from using these instruments is strongly biased toward principal investigator-led research in university settings, or in privately funded research laboratories.[10] Purchase of analytical instrumentation via leveraging with other funding agencies (e.g., NSF, DOE), private foundations, or via matching funds from the hosting institution could also be favored, as these matching funds leverage NASA's investment.

If modest increased funding is implemented, the choice between reducing current capacity and not developing new capabilities would be mitigated to some extent. Implementation of some shared facilities and continued encouragement of leveraged purchases would still be warranted. Further, analyses of reactive and cryogenic materials (e.g., ices, gases, and certain organic compounds) might still prove

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[10] Historical examples include Claire Patterson's determination at Caltech of the age of meteorites and Earth at 4.55 Ga; discovery of pre-solar grains by Edward Anders at Univ. Chicago; discovery of the evidence for extinct radionuclides of xenon by John Reynolds at UC Berkeley and of aluminum in Gerald Wasserburg's laboratory at Caltech.

challenging without significant influx of new funds on an as-needed basis corresponding to specific sample return missions.

Significant funding increases not only provide for replacement of existing capacity and development of new capabilities, but also would spur innovation, provide stability for both instrument purchase and technical support, and provide funding for long-term planning for both curation and analytical instrumentation for new types of samples. Note that having multiple laboratories analyze the same sample is important for evaluating the credibility of the data produced. With return of soft condensed matter samples (e.g., organic-rich materials, ices, gases), this could be challenging, but now is the time to be establishing such analytical protocols.

Finding: A funding strategy for instrumentation for returned sample analysis will need to consider several competing demands, including: maintaining and replacing existing capabilities, specifically those required for science goals of ongoing missions; advancing innovative and inventive technologies that will maximize science returns from mission-returned samples; curatorial facilities tailored to mission needs; technologies used in study of the products of past sample return missions and relevant meteoritic, terrestrial, and experimental materials; and continuity of support for personnel with mission-critical curatorial and analytical skills.

Finding: As currently formulated, NASA’s investment in analytical instrumentation is inadequate to provide for replacement of existing instruments, so the analytical base for extraterrestrial samples is diminishing. Addition of new technological innovations further stretch the current funding programs.

Finding: Many scientists engaged in analyses of extraterrestrial materials utilize multi-user facilities for sample characterization that are funded through a variety of sources.

Conclusion: The ability to analyze extraterrestrial materials has benefited tremendously from leveraging of NASA funds with contributions from other funding agencies or institutions.

Conclusion: While multi-user facilities can provide increased access to common instrumentation for many investigators, innovations and breakthroughs have historically occurred at individual principal investigator laboratories.

Conclusion: In the event of flat or decreased funding, there will be significant challenges in developing new analytical instrumentation, particularly as the number and types of returned samples (e.g., gases, ices, organic materials) increase with new missions.

Conclusion: If future instrument funding decisions must be made under the constraint of flat or decreasing overall funding levels, then the several competing demands of sample return science will likely exceed available resources, necessitating a focus on a few highest priority needs.

Recommendation: NASA Planetary Science Division should continue to engage in and encourage cost-sharing arrangements for laboratory analytical equipment with other funding sources.

Recommendation: NASA Planetary Science Division should continue to invest in both multi-user facilities and individual principal investigator laboratories.

5.2.2 Technical Staff

Developing, maintaining and operating high-tech instrumentation requires highly skilled technical staff. The staff of a laboratory frequently includes the principal investigator for the laboratory instruments, graduate students and postdoctoral researchers, and, in some instances, technical support staff. PIs who are full or part time faculty are generally paid a salary from their institution, but others may be entirely supported by research grants, termed "soft money." Graduate students and postdocs may be fully or partially supported by research grants. Technical support staff who operate and maintain instrumentation also may develop new techniques and instruments, or may be involved with training users and students.

The current community of highly trained scientists undertaking analyses of extraterrestrial samples are employed in diverse settings. Of the 85 individual PIs who received NASA funding via the PMEF and LARS programs to purchase equipment for extraterrestrial sample analyses over the past ten years, 54 (64%) are at educational institutions (Universities, Community Colleges), 18 (21%) are at government agencies or laboratories (e.g., NASA centers, National Laboratories, USGS, etc.), 11 (13%) are at non-profit research institutes (e.g., Carnegie Institution of Washington), and 2 (2%) are at museums.[11] Most PIs have some percentage of their salaries paid by their home institutions. University faculty typically receive 9 months of salary and are encouraged to raise the remaining three months of salary through funded research proposals.

Until recently, under full cost accounting, employees of NASA centers were required to raise their salaries through competitive research proposals. However, research funding for civil servants might also come, in part, from the SMD internal scientist funding model (ISFM), a three-year pilot program that provides some direct funding to scientists at NASA centers.

Highly trained scientists or engineers who can provide technical support are essential for laboratory sustainability. Technical staff exist in some, but not all laboratories that have been funded for analytical equipment by PMEF and LARS. At Johnson Space Center and Goddard Space Flight Center, technical support staff in laboratories doing extraterrestrial analyses now typically receive about 50 to 66% of their salaries via the ISFM program. The remainder of their salaries is raised through grants or recharge work for outside users. Currently, NASA Planetary Science Division does not fund technical support staff or service contracts on instrumentation purchased through LARS or PMEF, though PIs may request partial salaries for staff as part of research and analysis grant proposals. These research and analysis grants are typically three years or less in duration. Thus, many laboratories operate without trained technical staff, or they must find other avenues to fund such staff.

The funding models for technical support at universities are varied. In one unique laboratory, the RELAB spectroscopy laboratory at Brown, NASA funds permanent technical support (see Section 4.4.3). A few university laboratories have institutional funding for their technical staff. Generally, this is partial funding (see data in Appendix B). Many more university technical staff are funded entirely by soft money, which is generally a combination of three-year grants and recharge for service work. Feedback from a NASA survey of funded PIs taken in 2016 indicates that many laboratories are finding it difficult to fund and retain skilled technical staff.[12] Another consequence of using soft money to fund technical positions is that the most qualified people for these positions may be discouraged due to the lack of job security and advancement.

The difficulty in paying for and retaining technical support staff means that NASA-funded equipment may be under-utilized for returned sample analysis, may be busy running unrelated samples to ensure sufficient funds are available to run the facility, or the facility is operated inefficiently while waiting for repairs or for someone available to operate the instruments. Funding technical staff through recharge accounts means sample throughput must be maintained in order to generate funds, which limits

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[11] Jeffrey Grossman, NASA, "List of funded PMEs and LARS equipment," personal communication. January 11, 2018.

[12] https://www.lpi.usra.edu/psd-facilities/LaboratorySupportSurvey.pdf

the time available to undertake analyses of extraterrestrial samples and to develop new and cutting-edge analytical techniques and instrumentation.

In contrast to the U.S., institutional funding of technical support staff in Europe is common, and is becoming increasingly common in Asia (see Appendix C). For example, in France, the Centre National de la Recherche Scientifique (CNRS) has an annual competition to recruit engineers and technicians. Engineers define technical characteristics of scientific projects, develop new methods and techniques, and build and maintain or repair instruments. Technicians provide support to research scientists and engineers. Both engineers and technicians are hired in permanent positions and support researchers in their scientific activities (see Section 4.5).

There is a need for increased technical support within the U.S. sample return community. Currently, researchers are allowed to request partial salaries for technical staff in their science proposals, but there is not a mechanism to request funding specifically for technical support. In order to function efficiently and at the cutting edge, laboratories require staff with deep expertise, which is typically gained over decades of experience. Support of such highly-skilled staff will benefit development of new methodologies for sample return analyses and allow laboratories to operate on firmer financial footing. Funding specifically for technical staff would differ from the current PSD opportunities; however, such funding would still need to be tied to the science that is to be undertaken by the laboratory.

Finding: U.S. extraterrestrial sample analysis laboratories are experiencing increased difficulty finding and retaining good technical support staff because of the soft money funding model.

Conclusion: Having laboratories dependent on recharge to pay technical support staff and maintain instruments suggests that NASA’s investment in analytical facilities is not being maximized.

Conclusion: NASA’s investment in analytical facilities could be enhanced by providing sustained funding for technical support staff, so that the analytical work undertaken by a laboratory remains focused on extraterrestrial sample analyses.

Recommendation: NASA Planetary Science Division should provide means for longer term (e.g., 5-year) technical staff support for analytical instrumentation.

5.2.3 Sample Curation

Sample curation begins with mission planning and the acquisition of the samples; sample return missions are required to include costs of initial curation within their budgets, including preliminary examination and cataloging of the samples and ancillary materials (e.g., contact pads, witness plates). However, curation costs are a long-term investment, and will always exceed budgeted costs for curation associated with the mission, as samples need to be archived in clean, controlled environments and accessed as needed for analyses for decades following their return to Earth. Moreover, preliminary examination may exceed the two-year post-mission window, depending on the nature of the materials. For example, preliminary examination is ongoing for the Stardust mission, more than a decade after the samples were returned. The costs of long-term curation of returned samples at JSC, including paying the salaries of the JSC curatorial staff and construction and maintenance of the curatorial facilities on the JSC campus and White Sands Test Facility site are currently paid directly by NASA.

Sample curation and access requires long-term support of highly trained personnel and building of clean-laboratory facilities to house and process the samples. Furthermore, while curation is often viewed as activities within the Astromaterials Acquisition and Curation Office at JSC and associated analytical facilities, curation does not end once the sample reaches the door, mailroom, or loading dock of that facility. There are significant challenges in distributing samples and coordinating movement of samples, as described in Sections 4.1 and 4.2.

All of the tasks described above are ably performed by the curatorial staff at JSC. Construction is underway for curatorial facilities to handle sample returns from Hayabusa2 and OSIRIS-REx, as described in Chapter 4. The JSC curatorial staff provide expertise on sample handling, curation and distribution to international partners who are preparing for their own sample returns (e.g., JAXA, ESA). The staff also help to train young scientists in the handling and characterization of returned samples.

Finding: Johnson Space Center's Astromaterials Acquisition and Curation Office is the world leader in curating and tracking returned samples, as well as the types of analyses conducted on those samples.

Finding: The impact of the JSC curatorial efforts go well beyond their immediate duties of curation, as they have been instrumental in helping to train the next generation of extraterrestrial materials scientists and have helped in the development of curatorial facilities at international partner institutions.

5.3 FUTURE NASA PLANETARY SCIENCE INVESTMENTS

5.3.1 Instrumentation

While the current suite of instrumentation that is available for extraterrestrial sample analyses is adequate for the task at hand (see Chapter 4), there will be a need to access and develop different types of instruments and facilities if return of ices, gases, and additional organic matter becomes a reality. Moreover, collaboration with other nations offers a way to economize on instrumentation in order to maximize investment in return sample analyses.

While it can be anticipated that future missions will seek to return ices from comets or other bodies (e.g., from the polar regions of the Moon, Mars, etc.), the Decadal Survey did not select any cryogenic sample return missions.[13] Applying the Aerospace Corporation's cost and technical evaluation (CATE) methodology, such missions were considered unachievable because the technology needed for their success is not yet developed. Rather, the survey suggested initiating a technology development program focused on Cryogenic Comet Sample Return (CCSR).[14] Such a program has not yet been initiated, but the CAESAR mission, a non-cryogenic comet surface sample return mission, is currently in competition as part of the latest New Frontiers program.

The return of organic matter in samples retrieved from on-going missions to asteroids (Hayabusa2 and OSIRIS-REx) is anticipated. Furthermore, proposed missions such as the MMX mission to Phobos also seeks to return samples that may contain organic matter from either chondrites or Mars. The ability to analyze extraterrestrial organic matter has continued to improve along with advances in all aspects of analytical instrumentation: mass spectrometers have greater sensitivity and resolution, synchrotron light sources continue to evolve with brighter X-ray sources, enhanced beam control, and new types of analyses, as well as sample preparation (e.g., Focused Ion Beam milling) continue to emerge. Many of these advances occurred in response to the challenges of new sample availability, for example the increased availability of meteorites (Section 2.2.1), the collection of interplanetary dust particles (Section 2.2.2), and in sample return from the Stardust mission (Section 2.1.4) and Hayabusa (Section 2.1.5). In the future it is expected that, in all areas of analytical instrumentation, there will continue to be advances in sensitivity and resolution. For example, all current X-ray synchrotron light sources anticipate major upgrades in performance on frequencies of approximately 20 years; with such

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[13] National Research Council. 2011. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13117.

[14] Ibid. p 101.

upgrades come opportunities for significantly better instruments and analytical capabilities. In the case of the analysis of extraterrestrial organic matter, it is expected that there will be major advances in analytical instrumentation.

International space agencies such as NASA, JAXA, ESA, CSA, Roscosmos (the Russian state corporation for space activities), and others have a long history of collaboration in space exploration missions (for example the ISS). Participation by supplying elements of the mission in exchange for access to samples is commonplace. As we enter into an era with more space agencies conducting sample return missions, it is prudent to continue to extend such cooperation to the instruments required to analyze the returned samples. Maximizing the scientific value of the returned samples requires both standard laboratory equipment, large specialized laboratories, and facilities. These facilities can be quite expensive and are sometimes very specialized for extraterrestrial samples. These instruments can, in some case, be as large as sports arenas and can have the cost to match. It is costly to keep these laboratories funded, to retain the staff required to run them effectively and efficiently, to continue pushing the capabilities of the instruments, and to develop new capabilities. Duplication of highly specialized (and expensive) equipment by multiple agencies or countries is not always desirable or affordable. Appendix C provides data on some international laboratories and facilities that undertake extraterrestrial sample analyses and illustrates the broad range of equipment available, and the significant investment that these laboratories embody.

Individual scientists often collaborate across international boundaries to bring advanced instrumentation to bear on extremely rare and precious extraterrestrial samples. An example of this is the nitrogen isotope analyses carried out by SIMS at the University of Nancy, France, on samples from the Genesis mission. Such collaborations are presently encouraged and are expected to continue. This, however, does not address the more strategic challenge of making sure international resources are better optimized, and ensuring the availability of robust state-of-the-art instrumentation for extraterrestrial sample analysis. NASA has experience in developing international collaborations for space missions, and this can be applied to the complex, state-of-the-art instruments necessary for sample return missions. Care will need to be taken to structure the agreement in ways that fully take into consideration hidden complexities such as export controls and restrictions on foreign nationals.

Finding: There are currently no missions underway or even planned that entail return of cryogenic materials. The potential return of gases is being considered (e.g., the CAESAR mission).

Finding: Many spacefaring nations have, like the U.S., recognized the scientific potential of extraterrestrial sample return missions and have either executed such missions, or are actively planning such.

Finding: These nations have invested significantly in state-of-the art instrumentation and in developing a highly skilled workforce to carry out analyses of extraterrestrial samples.

Conclusion: It would be advantageous for strategic alignment of investments in such facilities by international space agencies to maximize the availability of such facilities and, thus, the science of the returned samples.

Conclusion: Technology development focused on Cryogenic Comet Sample Return (CCSR), as recommended by the Decadal Survey, is warranted.

Conclusion: Exploring technologies already available in related communities for analyses of ices, gases, and organic matter could benefit the extraterrestrial sample analysis community.

Recommendation: NASA Planetary Science Division should make appropriate investments in the technological development of novel instrumentation and unconventional analytical techniques,

specifically for curation, as well as characterization and analysis of non-traditional samples that are expected to be returned from future missions. These would likely include gases, ices, and organic matter, including volatile organic compounds (VOCs) and related hybrids and complexes.

Recommendation: With the rapid developments in related fields such as molecular biology, and concomitant advances in bio-organic analytical methodologies, NASA should consider partnerships with relevant federal agencies (e.g., DOE and NIH) and laboratories (e.g., the National Laboratories). NASA should implement information exchange activities (e.g., joint workshops) to enhance cross-fertilization and cooperative development of analytical instrumentation and methods, specifically to enhance analysis of organic matter (both macromolecular/polymeric and molecular-moderate molecular masses, as well as volatiles-low molecular weight compounds), in the study of extraterrestrial returned samples.

Recommendation: NASA Planetary Science Division should continue to engage in strategic relationships with international partners to ensure that the best science possible is extracted from extraterrestrial samples with the limited resources available to all space agencies.

Recommendation: NASA Planetary Science Division should consider ways to facilitate the dissemination of information about present and future international, state-of-the-art facilities relevant to sample analysis. This could, for example, include organizing workshops to be held with existing international conferences.

5.3.2 Staffing Required for Future Sample Return Analysis

Given that most of the current generation of planetary scientists will be retired by the time extraterrestrial samples are returned from future missions, a crucial aspect of laboratory sustainability is that young scientists are adequately trained in analytical methods and instrumentation. Graduate students and early career scientists need to develop skills sets that will allow them to stay at the forefront of analytical techniques, and be able to trouble-shoot, maintain, and potentially design and build the instruments of the future.

In 2010, one quarter of NASA’s Science Mission Directorate (SMD) budget was identified as mission-enabling.[15] Recruiting and training the next generation of planetary scientists was part of NASA’s Planetary Science Division mission enabling activities[16]. This was implemented through the following opportunities: 1) education and public outreach supplements (which has since been curtailed), 2) fellowships for early career researchers, 3) NASA Earth and Space Science Fellowships (NESSF) and 4) NASA’s postdoctoral program (NPP).

Education and public outreach supplemental awards were accessed by funded investigators to cover expenses related to outreach activities and education related to the PI’s research. The Early Career Researchers fellowships allowed the integration of new Planetary Science Division researchers into established research programs and provided tools and experience useful when searching for more advanced (i.e., tenure-track, civil servant, or equivalent) positions. The NESSF were created to ensure continued training of a highly-qualified workforce in disciplines needed to achieve NASA’s scientific goals. These fellowships are training grants provided to the respective universities, with the advisor serving as the principal investigator. The NPP, administered by Universities Space Research Association

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[15] National Research Council. 2010. *An Enabling Foundation for NASA's Earth and Space Science Missions*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12822.

[16] Planetary Sciences Subcommittee, Assessment of the NASA Planetary Science Division’s Mission-Enabling Activities, 2011.

(USRA), offers research opportunities to highly talented national and international individuals to engage in ongoing NASA research programs at NASA Centers, NASA Headquarters, or NASA-affiliated research institutions. In addition, one of the missions of the now defunct NASA Lunar Science Institute was to advance lunar science through training the next generation of lunar scientists and encouraging education and public outreach.

Mission-enabling activities were part of the Research and Analysis Program. This program was recognized by the Decadal Survey as being of high priority: "For stability and scientific productivity, long-term core NASA research and analysis (R&A) programs are needed that sustain the science community and train the next generations of scientists." In fact, in this survey, several scientific programs classified as "robust" were the ones providing opportunities for the training and development of the next generation of planetary scientists.

The Research and Analysis programs were re-organized in 2015. The NESSF, NPP, and the Early Career Fellowships continued unchanged. The Undergraduate Student Research Program (USRP) was transformed into a new NASA internship program that is administered by USRA. Funding for the Planetary Biology Internship in Exobiology is uncertain. Besides the need for stable funding that will allow these programs to continue, current PIs could be motivated to train the future generation of laboratory scientists by including criteria within the current evaluation for NASA Planetary Science proposals that addresses the needs for training the future generation of laboratory/planetary scientists, similar to the NSF system. Especially needed is the encouragement of future analytical instrument developers.

Conclusion: A highly-qualified workforce that is able to perform both routine, and state-of-the-art laboratory analyses, as well as develop the instruments of the future, is necessary to fulfill NASA's goals for the characterization and analysis of future returned samples.

Recommendation: NASA Planetary Science Division should encourage principle investigators to specifically address in their research proposals how the work will contribute towards training future generations of laboratory-based planetary scientists.

5.3.3 Future NASA Planetary Science Investments for Sample Curation

One of the paramount needs in curation is adequate space in clean laboratories to handle, store, and process current and future returned samples. While JSC is the center of such activities in the United States, the center footprint is constrained. However, JSC has developed a plan for expansion of the extraterrestrial sample curation facilities to accommodate samples from the asteroid return missions Hayabusa2 and OSIRIS-REx, and anticipated future missions such as the Phobos sample return mission MMX (see Section 3.1). For this, JSC will add an annex to building 31 to allow for renovation of current curatorial space in building 31. Plans are also being made to renovate another existing building to consolidate astromaterials research laboratories. While there will be no attempt to isolate organic materials that may be contained within the sample returns from asteroids, there has been significant investment to limit organic contamination on the spacecraft and collectors and, especially, to document the amount of contamination through the extensive use of witness plates and materials coupons, which are curated at the JSC facility.[17]

The first step in NASA's Mars sample return, the Mars 2020 rover, is now being built and is expected to launch in July 2020. JSC curatorial staff are also beginning to formulate plans for handling of more challenging samples such as martian returned samples, which might include ices, gases, and a variety of organic compounds. Planning of the missions to return these challenging samples would benefit

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[17] Dworkin, J.P., Adelman, L.A., Ajluni,T., et al., OSIRIS-REx contamination control strategy and implementation, *Space Science Reviews* 214(1)

from input from the curatorial staff, given the depth of knowledge accrued from decades of curation, in addition to the knowledge gained as they ramp up for new types of samples. Finally, while JSC does not currently have the curatorial or analytical capabilities for the curation and examination of ice, gas, or challenging samples such as volatile organic compounds, these capabilities currently exist in companies that have developed multi-instrument configurations for analyses of such materials using different techniques.[18]

Another growing need, separate from curatorial needs but of great importance, is archiving the diverse array of information garnered from returned extraterrestrial samples (informatics). Informatics is currently under the purview of CAPTEM. An online archive of lunar sample analyses is currently being constructed,[19] but online archives for other returned sample suites do not exist. Sample data archiving requires careful coordination between analysts and data managers to develop online databases capable of capturing the complex range of information associated with extraterrestrial sample analyses, and make the data readily available to the community.

Conclusion: It will be desirable to harness the expertise represented by the collective knowledge of the curatorial staff at JSC when future mission principal investigators are planning for sample return missions.

Conclusion: While JSC's current expansion plans will provide adequate curatorial facilities for current (Hayabusa2 and OSIRIS-REx). and possible near-future missions such as martian moons sample return (MMX), there is a need to develop additional facilities for any future sample return in the 2030's and beyond. Such facilities will require advanced planning and new technologies for the return of diverse organic matter, ices, and gases.

Conclusion: There is a need to develop online archives of the analyses undertaken on all returned samples, along with metadata (e.g., analytical precision, accuracy, etc.) associated with these analyses.

Recommendation: NASA Planetary Science Division should increase support for Johnson Space Center to develop appropriate curatorial and characterization facilities relevant to and necessary for future sample returns of organic matter, ices, and gases.

Recommendation: NASA Planetary Science Division should accelerate planning for curation of returned martian samples, seeking partnerships with other countries, as appropriate.

5.4 SUSTAINING A SYSTEM OF PLANETARY SCIENCE LABORATORIES

In the next decade, the OSIRIS-REx and Hayabusa2 missions will return samples of primitive, organic-rich asteroids. The following decades hold the promise of sample return from our Moon, the moons of Mars, comets, and the surface of Mars. Collectively, these missions promise to revolutionize our understanding of the origin and evolution of the solar system. These samples, returned at considerable cost to the taxpayer, will only yield scientific insights if properly curated, distributed, and analyzed. Numerous challenges exist to optimize this scientific return. While new missions will return unprecedented samples, existing samples continue to yield new clues to the solar system's origin. Curatorial facilities utilizing existing technology will need expansion, while entirely new types of curation for gases, ices, and organic compounds will have to be developed. These facilities will require highly-trained staffing, along with the physical and data infrastructure to maintain the integrity of the

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[18] e.g., the European company Tescan, https://www.tescan.com/en-us/technology

[19] http://www.moondb.org/

samples. Analytical laboratories will require continual replacement of obsolete equipment. While current capacity and capability is maintained, new analytical instrumentation will increase capability. These instruments require highly-trained professionals afforded the stability to develop and operate these instruments. Collectively, the above needs present significant challenges for NASA to maintain and improve upon capabilities and capacities for analysis of returned sample, and for the community to benefit scientifically from the extraordinary financial commitment required to return these samples to Earth.

Finding: As currently formulated, NASA's investment in analytical instrumentation is insufficient to provide replacement of existing instruments. Addition of new technological innovations further tax the current funding programs.

Conclusion: Without modest to significant increases in funding by NASA in analytical instrumentation for sample analyses, either a decrease in capacity or a reduction in future capabilities seems inevitable, as well as the inability to support highly-trained technical staff, train the next generation of extraterrestrial sample analysts and laboratory instrument developers, and begin planning for the curation and analyses of challenging new types of samples.

Recommendation: NASA Planetary Science Division should place high priority on investment in analytical instrumentation (including purchase, maintenance, technical oversight, and development) and curation (facilities and protocols) sufficient to provide for both replacement of existing capacity and development of new capabilities. This will maximize the benefit from the significant investment necessary to return samples for laboratory analysis from asteroids, comets, the Moon, and eventually Mars and outer solar system moons.

Appendixes

A
Statement of Task

To prepare for the analysis of diverse extraterrestrial samples in the coming decade, NASA requires information on the current capabilities of the planetary science community's analytical laboratory facilities, their future requirements, and any associated challenges. Therefore, the National Academies of Sciences, Engineering, and Medicine will assemble a committee to perform a study addressing the following questions:

- What laboratory analytical capabilities are required to support the NASA Planetary Science Division's (and partners') analysis and curation of existing and future extraterrestrial samples?
    - Which of these capabilities currently exist, and where are they located (including international partner facilities)?
    - What existing capabilities are not currently accessible that are/will be needed?
- Whether the current sample laboratory support infrastructure and NASA's investment strategy meets the analytical requirements in support of current and future decadal planetary missions.
- How can NASA ensure that the science community can stay abreast of evolving techniques and be at the forefront of extraterrestrial sample analysis?

B

A Sampling of United States Laboratories Engaged in Extraterrestrial Sample Analysis

The data in the table below were gathered by individual committee members who sought information from scientists at the institutions represented in the table. This is not meant to be (nor could possibly be) a comprehensive listing of all laboratories in the US where analyses of extraterrestrial samples are carried out. Laboratories in the table were selected based on information provided by NASA on the history of laboratory equipment funding,[1] as well as discussion amongst the committee members. Acronyms are defined in Appendix E.

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
American Museum of Natural History	High-resolution 3D imaging and non-destructive Raman spectroscopy of tracks and particles embedded in aerogel from the Stardust mission. Analyses of meteorites and cometary samples for chemical composition, mineralogy, and 3D structure.	1 electron microprobe, 1 field emission SEM, 1 SEM with EBSD & EDS capabilities, 1 laser scanning confocal microscope with attached imaging Raman spectrograph, 1 X-ray computed tomography (CT) scanner, 1 FTIR, 1 XRD	Service contracts are maintained for the confocal microscope, electron microprobe, CT scanner, and SEM	1 curator, 2 museum specialists, 2 technical staff, 1 graduate student	3 FTE (1 specialist, 2 technical staff) Remaining positions are funded through grants	~12	The FTIR and FE-SEM are reaching their shelf life and will soon need to be replaced; the electron probe is underperforming (currently awaiting NSF decision on funding for a replacement). Staff also use the Advanced Photon Source for 1) tomography of meteorite specimens, and 2) X-ray fluorescence mapping of comet sample tracks in aerogel. Inside users support the facilities with grant funds in lieu of hourly fees. Outside user fees remit to the general fund of the Museum directly, and return as institutional support for facilities.

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[1] Jeffrey Grossman, NASA, personal communication

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
Arizona State University	The Center for Meteorite Studies is home to the world's largest university-based meteorite collection. The **Eyring Material Center (EMC)** examines the structures and compositions of a wide range of natural and synthetic materials under a range of experimental conditions, including samples under cryogenic conditions. The nanoSIMS laboratory is primarily designed to handle and analyze micron-sized particles of stardust (presolar grains), cosmic dust (interplanetary dust particles), and samples returned by missions (e.g., Hayabusa). The SIMS laboratory undertakes microanalyses (typically 4-30 μm lateral resolution, sub-micron depth resolution) for trace elements (from H to U) and isotope ratio analyses for selected species (H, Li, B, Mg, Si, and others, depending on the precision needed). The noble gas laboratory undertakes geochronology and thermochronology of Apollo lunar samples and a variety of meteorites, and is also used for reconnaissance U/Pb geochronology of extraterrestrial zircons, and, recently, high spatial-resolution analyses of noble gas (Xe, Kr, Ar, Ne, He) geochemistry of	1 Cameca NanoSIMS 50L, 1 Cameca ims 6f SIMS, 1 electron microprobe, a gas-source magnetic sector mass spectrometer, two gas-source mass spectrometers, 1 quadrupole ICP-MS, two excimer laser ablation systems, MC-ICP-MS with laser ablation capabilities, microtome, The EMC has 10 TEM/STEMs: 3 aberration-corrected instruments for imaging, EDS, & EELS; 1 for cryo-electron microscopy; and 6 standard TEMs, each with added special capabilities; 4 SEMs; a dual-beam FIB with EELs, and a cryo-FIB is on order.	Service contract on the nano-SIMS; service contracts on 5 TEMs and 3 SEMs within the EMC.	Other than EMC: 5 faculty members, 5 technical staff, 2 post-docs, 7 graduate students. The EMC has 9.25 FTE, 4.25 non-doctorate staff, 4 professional staff PhD, and 1 research faculty staff.	2 FTE Remaining technical positions are funded through grants and recharge.	~ 50/year across all laboratories outside of the EMC. For the EMC: 318 ASU users (~ 200 students and 50 post docs) and 52 non-ASU users	Postdocs and graduate students are funded by a combination of the university, NASA, and NSF grants.

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
	carbonaceous chondrites by laser ablation microprobe.						
Brown University	Major and trace element analyses of lunar glasses, elemental mapping.	1 MC-ICP-MS, 1 quadrupole ICP-MS with laser ablation capabilities, 1 electron microprobe	No service contracts	2 faculty, 2 technical staff, 5 graduate students and postdocs, on average.	1.2 FTE Remaining partial salaries are funded through grants and recharge.	~10 in 2017-2018 period	
California Institute of Technology	Ion microprobe facility: study of element and isotopic abundances in Genesis and Apollo lunar samples. Electron microscopy and microprobe facilities and the ion microprobe facilities: study meteoritic samples. The stable isotope facility: properties of meteorites and Apollo lunar samples and home to an experiment funded by the LARS program, aimed at developing Fourier transform mass spectrometric methods for isotopic analysis of organic compounds that will be returned as part of the OSIRIS-REx.	Three Fourier-transform mass spectrometers, three high-resolution gas source isotope ratio mass spectrometers, five low resolution gas source isotope ratio mass spectrometers, high resolution noble gas mass spectrometer, three Neptune MC-ICPMS, benchtop GC quadrupole MS, GC/FID, Thermal ionization mass spectrometry, nanoSIMS ion microprobe, ims-7f geo ion microprobe, automated electron microprobe, field emission SEM; shock-wave, piston cylinder, multi-anvil, diamond-anvil, and gas-mixing furnace experimental laboratories.	The nanoSIMS ion microprobe are under full service contracts, paid for from institutional funds	Three faculty members, five staff scientists, and typically approximately 5 graduate students and/or postdoctoral scholars working on problems relevant to extraterrestrial materials.	The five staff positions contributing to research on extra terrestrial materials are funded through a combination of sponsored research funding and laboratory charges, supplemented by an institutional matching program. All faculty positions are fully funded by institute funds (typically relieved 10-15 % by sponsored research).		Each staff position receives about 1/4 funding from the institute provided that person's salary primarily comes from external overhead-bearing sponsored research funding.

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
Carnegie Institution of Washington, Geophysical Laboratory and Department of Terrestrial Magnetism	Characterization of all aspects of the studies of extraterrestrial materials	1 field emission electron microprobe, 1 field emission SEM, FIB Mill-SEM, 1 scanning Raman microscope and spectrometer, 1 nanoSIMS, 1 6F SIMS, 1 TIMS, 2 MC-ICP-MS, 1 quadrupole ICP-MS, 1 ArF laser ablation system, 3 gas chromatograph MS, 1 ultra-performance liquid chromatograph tandem MS spectrometer, solid state nuclear magnetic resonance spectrometer	The electron beam and SIMS instruments are under service contracts, paid through the annual budget of the institution. There are no service contracts for the mass spectrometers	7 staff scientists, 5 full-time support technical staff	All technical staff are paid for by the institution (FTE)	20-30 each year	
Florida State University	Inorganic elemental and isotopic studies. Nucleosynthetic isotope anomalies and cosmogenic neutron capture isotope effects in highly siderophile elements. Distribution of inorganic elements phases at spatially resolved scales, particularly siderophile elements.	1 MC-ICP-MS, 1 quadrupole ICP-MS with laser ablation capabilities		1 faculty, 2 postdoc, 2 graduate students	0	27 in 2017-2018 period	
Harvard University	Isotopic analyses of extraterrestrial materials including lunar and martian samples.	1 TIMS, 2 MC-ICP-MS, 1 quadrupole ICP-MS, 1 electron microprobe with SEM	A service contract for the electron microprobe is paid for by research grants. No service contracts exist for mass spectrometers, repairs performed in-house.	1 faculty, 2 technical staff, 7 post-docs and/or graduate students	0	0	

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
Lamont Doherty Earth Observatory, Columbia University[2]	Isotopic analyses of lunar and meteoritic materials.	1 SEM, 1 FTIR, 1 quadrupole ICP-MS, 1 magnetic sector single collector ICP-MS, 3 MC-ICP-MS, 3 TIMS	No service contracts	3 faculty, 4 post-docs or research scientists (to be hired in 2019)	0		Expecting to hire a technical support person in near future. All technical staff will be supported on soft-money, mingled grant and institutional funds for fixed terms. Repairs are performed by non-permanent technical staff, and paying for service from vendors or third party service companies.
Smithsonian Institution	Curation support of the US National Meteorite Collection and classification of the US Antarctic Meteorite Program, as well as research on meteorites and returned samples (e.g., OSIRIS-REx)	FE-EPMA, FE-SEM, experimental laboratories	Service contracts on the SEM and EPMA	3 full-time laboratory staff (2 federal civil servants, 1 permanent trust funded scientist) 1-3 postdocs at any time	All full-time laboratory staff funded as federal civil servants	1-3 / month	
University of Arizona	Chemical analysis and characterization of extraterrestrial materials of all types, lead on OSIRIS-REx.	1 TEM, 2 electron microprobes, 2 SEMs (one with W filament and variable pressure + Raman; another with cold FEG and Si(Li) EDS system), 1 FIB-SEM, and a range of optical instruments that support development and testing of spectroscopic and imaging instruments for use on ground and space-based platforms	Yes, on all instruments	3 faculty, 3 technical staff, 2 postdocs and 5 graduate students	1	10/year	
University of California Davis	Isotope measurements for nuclear anomalies, long and short-lived isotope dating methods, major, minor, and	1 MC-ICP-MS, 1 TIMS, 1 HR-single collector ICP-MS, 1 quadrupole ICP-MS with laser	No service contracts	2 faculty, 2 assistant project scientists, 1	0	~ 10-15 per year	

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[2] Much of the instrumentation is in the process of being acquired following the arrival of Dr. Alex Halliday in 2018.

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
	trace elements analyses of meteorites. Shock experiments on meteorites.	ablation capabilities, MC noble gas mass spectrometer		staff research associate, 3 postdocs, 3 graduate students			
University of California, Los Angeles	Research in support of missions Genesis, Stardust, Apollo. Early solar system chronology, lunar chronology, stable isotope anomalies in primitive solar system materials. Isotopic composition of the Sun. Isotope ratios in Moon, Vesta, asteroids.	2 SIMS (Cameca 1270 and 1290), 1 MegaSIMS, 1 MC-ICP-MS, 1 high-mass-resolution (Panorama) gas-source mass spectrometer, 2 gas-source IRMS	No service contracts	3 faculty, 4 staff, 3 postdocs, 3 graduate students.	0.83 FTE	~15-20 per year	
University of California San Diego	Isotope measurements of Mars and lunar samples for studies of the origin and evolution of the solar system, Mars atmospheric evolution, and lunar history, including water and solar wind. Formation and evolution of planetary bodies by analysis of rocks and minerals, including meteorites and Apollo samples. Tracing and chronology, focused on early silicate-metal differentiation, late accretion and planetary volatile inventories.	3 gas source IRMS,1 optical nanoscope to detect IR radiation, 1 TIMS (Triton),1 magnetic sector ICP-MS (Element2), 2 quadrupole ICP-MS with laser ablation capabilities, high-pressure washer		2 faculty, 2 postdocs, 9 graduate students, 2 technical staff	0	30-50 external users over the last 1-2 years, including several for NASA-related projects.	At present, no extraterrestrial measurements are made because after the re-organization of NASA when the funds for extraterrestrial analysis were folded in with astrobiology we have not been able to acquire funds for sample analysis. Some extraterrestrial measurements are still done but at a reduced level.
University of Chicago	Analyses of meteorites and samples returned to Earth by spacecraft to study early solar system chronology, early planetary evolution, stellar nucleosynthesis.	The Chicago Instrument for Laser Ionization (CHILI), a custom-built resonance ionization mass spectrometer; 1 focused ion beam/field emission scanning electron microscope (FIB/FESEM); 1 MC-ICP-MS with laser ablation capabilities and a pneumatic chromatographic sample introduction system; 1 gas source mass spectrometer		3 faculty, 1 research professor, 1 part-time faculty, 1 half-time technical staff, 3 postdocs, and 6-8 graduate students,	One full-time laboratory manager funded by the Museum/University. Funding for 0.5 FTE technical support for the MC-ICP-MS laboratory.	CHILI is currently used by 3-4 outside users per year. One visitor per year for the Field Museum laboratory. The MC-	Graduate students funded largely by NASA and NSF grants.

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
		for noble gases; 1 Raman microanalysis system; 1 SEM; 1 quadrupole ICP-MS with laser ablation capabilities				ICP-MS laboratory hosts 2-3 visitors per year.	
University of Hawaii	Research on NASA returned samples and meteorites. Active research programs in measuring Genesis and Stardust samples, Hayabusa samples, research motivated by Astrobiology, basic research to understand the origin and evolution of the solar system and its constituent bodies. Intention to participate in analysis of samples returned by Hayabusa2 and OSIRIS-REx.	1 modified Cameca IMS 1280 ion microprobe and supporting SEM		1 full time faculty at 1 FTE state funding, 1 full time faculty at 0.5 FTE state funding and 0.5 FTE revolving fund and sponsored research, 2 graduate students funded on sponsored research, 2 post docs funded on sponsored research, 1 additional faculty does a lot of measurements in the laboratory 1 FTE state funding.	0.5 FTE of state funding for technical support for the Cameca IMS 1280 laboratory.	~10 last year	Other technical positions are paid for by external grants (NASA) and our revolving fund.
University of Houston	Radiogenic isotope measurements of bulk meteorites and their components to examine variation in their nucleosynthetic components and to determine isotopic variation in different parent bodies, obtain crystallization ages and trace their origins resulting from planetary differentiation. Petrologic	2 TIMS, 1 MC-ICP-MS, 2 quadrupole ICP-MS, 1 ICP-OES, laser ablation capabilities	No service contracts	3 faculty, 2 postdoc, 12 graduate students, 8 research staff	1 FTE	~ 15/year	

Institution	**Primary use of facility**	**Major instrumentation**	**Service contracts**	**People employed by institution***	**Institutionally-funded technical support (full-time equivalent, FTE)**	**Outside users**	**Comments**
	analyses and major, minor, and trace element analyses of materials (bulk or *in situ*).						
University of Maryland	Measurements of isotopic ratios to characterize meteorites, meteorite components, and lunar samples, assess cosmic ray exposure effects, and date metal-silicate segregation. Isotope-dilution measurements of siderophile elements and Re-Os isotopic measurements, and laser ablation analysis of phases for siderophile trace elements. Major, minor and trace element composition of extraterrestrial samples, inventory of refractory organics hosted in these materials. Studies of oxidized S compounds in martian meteorites, studies of achondrites to document similarities and differences in the materials that are diagnostic of their origin. Sulfur isotope variation studies to document consistency or alternatively disprove links between iron meteorite groups achondrite groups, to study core formation and loss (volatilization) of sulfur for asteroids from which these achondrites come. We study primitive meteorites to understand how evidence for gas-phase (photochemical) effects were produced.	2 TIMS, 1 MC-ICP-MS, 2 ICP-MS with laser ablation capabilities, gas source IRMS, HPLC	No service contracts	3 faculty, 3 research scientists who also serve in a technical roll, 2 postdocs, 5 graduate students.	2.16 FTE	~5 per year	

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
University of Wisconsin	Chemical and isotopic analyses of meteorites, Apollo lunar samples, and comet samples from NASA and JAXA missions.	Geoscience: 1 TIMS, 1 MC-ICP-MS with femtosecond laser ablation, 1 Cameca IMS-1280 SIMS with RF-plasma (Hyperion-II) source, 2 gas-source IRMS for with two laser systems for stable isotopes, 1 FE-EPMA, 1 SEM, 1 XRD, access to Cameca atom-probe factory UW- Materials Analysis Center: TEMs, atom probe, FIB, FE-SEMs	Service contracts for SIMS, EPMA, SEM	2 faculty, 8 technical staff (including research scientists). Last 10 years: 9 post-docs, 2 grad students.	3.95 FTE	~2 per year	WiscSIMS is funded by NSF-EAR-IF as a National Facility
Washington University	Determination of mineral major- and minor-element compositions, mineral proportions, compositional x-ray imaging, radiogenic and stable isotopes of planetary materials, including lunar and martian samples, chondrite and achondrite meteorites, analyses of returned samples (Hayabusa, Stardust, Genesis), interplanetary dust particles, primitive and presolar grains in meteorites and terrestrial analog materials.	1 electron microprobe, 1 micro XRF spectrometer, 1 XRD, 2 laser Raman microprobes, 1 LIBS, 1 gamma-ray spectrometer for INAA, 1 MC-ICP-MS, 1 quadrupole ICP-MS, 4 noble gas mass spectrometers, 1 MC noble gas mass spectrometer, 1 Cameca nanoSIMS with Hyperion plasma source, 1 TESCAN MIRA3 FEG-SEM, 1 FEI Focused Ion Beam instrument, 1 JEOL 840A SEM, 1 Phi Auger nanoprobe, 1 7F Cameca SIMS	Service contract for MC-ICP-MS, 7F SIMS, and EPMA	7 faculty, 4 research faculty, 7 technical staff, 6 post-docs, 12 graduate students	3 FTE	~ 80/year	
Federal Centers							

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
Jet Propulsion Laboratory (JPL)	Measurements of lunar samples and primitive meteorites; studies of surface contamination for the purposes of planetary protection and purity of returned samples	Clean rooms for metal and heavy-element isotope analysis; ICP-MS, TIMS (to be housed at Caltech fall of 2018)	No service contracts	1 senior research scientist, 2 permanent senior researchers (sponsored research), 2 Caltech postdocs (Caltech sponsored research), 1 graduate student (UCLA sponsored research), the occasional Caltech or JPL electronics engineer.	0		
Goddard Spaceflight Center (GSFC)	The study of the small soluble organic compounds (e.g., amino acids) in extraterrestrial samples, principally meteorites. Focus is on the isotopic, structural, and enantiomeric distribution of compounds across a range of materials to gain insight into astrobiology and astrochemistry.	Waters Xevo G2 QTof, Waters ACQUITY UHPLC (2), Thermo Finnigan hybrid GC-MS/IRMS instrument with auxiliary TC/EA and EA inlets, Waters Micromass LCT Premier, Thermo Finnigan Trace 1310-TSQ8000 GC-triple quadrupole MS system, Thermo Finnigan Trace DSQ GC-QMS system, Waters Quattro Micro API, Waters 2695XE HPLC, Thermo LTQ Orbitrap XL, Waters nanoAcquity UHPLC, LECO GCxGC-HRMS	Instruments are generally covered by service contracts. The prorated cost of the service contract for the relevant instrument is built into budget requests. Funds for gaps are sometimes available from the Goddard Technical Equipment program.	7 NASA employees, 1 laboratory manager	0	7 in past year (received by mail)	

Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support (full-time equivalent, FTE)	Outside users	Comments
Johnson Space Center (JSC)	Analysis and classification of terrestrial, planetary, and solar materials and space-exposed hardware. Terrestrial and planetary remotely sensed data analysis and visualization. High-pressure materials fabrication and analysis. Field surveys and data collection: planning, performance, and testing of field equipment. Hypervelocity impact and materials testing.	1 SEM, 2 TEM, 1 FIB, 1 EPMA, LIBS, XRD, atomic absorption, ion chromatography, 1 MC-ICP-MS, 1 single collector magnetic sector ICP-MS with 193 nm laser ablation capabilities, 1 nanoSIMS 50L, 1 TIMS, 1 dual laser ToF mass spectrometer (L2MS), high resolution x-ray computed tomography (CT) laboratory, TEGA, FTIR spectroscopy, and optical microscopy. Piston cylinder and multi-anvil presses, 5–300 kbar, and up to 2500 °C capability. Visible through shortwave Infrared (IR) and thermal IR spectrometers, handheld X-ray fluorescence (XRF), and forward-Looking IR (FLIR) cameras	Service contracts for most instruments	25 civil service scientists, ~30 research scientists employed through contractors, ~20 technical support staff			

*Counts those involved with extraterrestrial analyses only; does not include undergraduate research assistants, "faculty" are ladder faculty, not research scientists, who may be considered faculty in some institutions.

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A Sampling of International Laboratories Engaged in Extraterrestrial Sample Analysis

The data in the table below were gathered by individual committee members who sought information from scientists at the institutions represented in the table. This is not meant (nor could possibly be) a comprehensive listing of all laboratories in outside the US where analyses of extraterrestrial samples are carried out. Laboratories in the table were selected based on discussion amongst the committee members.

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
Japan	Pheasant Memorial Laboratory, Institute for Planetary Materials, Okayama University at Misasa	Chemical and isotopic analyses of extraterrestrial materials including meteorites and return samples from Hayabussa. The laboratory is designated a Phase2 Curation System that will undertake comprehensive initial analysis for the samples to be returned by Hayabusa2	1 gas source IRMS for stable isotope analsyes (H, C, N, O), 1 multichannel gas chromatograph, 2 gas source mass spectrometers for noble gas analyses and K-Ar dating, 1 TEM, 1 FIB, 2 SEM, 1 electron microprobe, 1 Cameca 1280HR SIMS, 1 Cameca ims-5f SIMS, 1 FTIR, 1 micro-Raman microscope, 1 XRF, 1 quadrupole ICP-MS, 1 triple-quadrupole ICP-MS, 1 magnetic sector single collector ICP-MS, 1 MC-ICP-MS, 1 193 nm ArF laser, 3 TIMS, 1 orbitrap MS, 1 single quadrupole GC-MS, 1 scanning system of desportpoino-electro-spray-ionization	Equipment is not covered by service contracts. Repairs are covered by the maintenance fee charged to the machine allowed through annual budget in the institute.	5 faculty members, 3 super-technicians, 2 postdoctoral fellows, 3 technical staff	All technical staff are supported by the government through Okayama University and IPM	
	JAXA	Characterization of asteroid samples	1 SEM, 1 FE SEM with EDS-EBSD, 1 XRD, 1 FTIR, 1 micro-FTIR, 1 micro-Raman spectrometer, 1 TEM, 1 EPMA	Equipment is not covered by service contracts. Repairs are covered by the maintenance fee charged to the machine allowed through annual budget in the institute.	4 faculty, 2 technical staff	All technical staff are paid by the Institute	
	Tokyo Institute of Technology	Trace element and high precision isotope analyses of meteorites and their components	1 TIMS, 1 quadrupole ICP-MS with laser ablation capabilities, SEM-EDS	No service contracts	2 professors, 3 post-docs, 6 graduate students	0	

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
	Natural History Sciences Isotope Imaging Laboratory, Hokkaido University	*In situ* analyses of extraterrestrial materials.	Two multi-collector SIMS (Cameca ims-1270+SCAPS, Cameca ims-1280HR+SCAPS), 1 SIMS (Cameca ims-6f), 1 isotope nanoscope (homemade laser ionization SNMS (sputtered neutral mass spectrometer)), 1 FE-SEM with EDS-EBSD, 1 micro-Laser Raman spectrometer, 1 micro-IR spectrometer	Spot service payed by soft money grants obtained by the professors, e.g. from Kakenhi grants and Program to Support the Establishment of a Shared Platform.	3 professors, no technical staff	0	
China	University of Science and Technology, Hefei	Chemical and isotopic analyses of meteorites, particularly non-traditional stable isotopes and the daughter products of short-lived radionuclide	1 MC-ICP-MS, 1 quadrupole ICP-MS, 1 TIMS, several piston cylinders	Service contract for the MC-ICP-MS.	2 faculty, 1 technical staff, 1 post-doc	0	
Australia	Research School of Earth Sciences, The Australian National University	Isotopic and chemical analyses of extraterrestrial materials, collaborating on Hayabusa, OSIRIS-REx, and Hayabusa2	Three SHRIMPs, 2 TIMS, 1 FTIR spectrometer, 1 XRD	All maintenance done by professional staff, repairs covered by cost recovery and user fees. There are no service contracts.	3 professors, 6 full time professional staff, 1 postdoctoral fellow, 3 graduate students	2.5 FTE	University is stepping back its support of facilities including workshops.
Canada	University of Alberta	Meteorite curation laboratory undertakes cold and ambient curation of extraterrestrial materials	2 EPMA, 2 SEM, 1 TIMS, 1 ICP-MS, 1 LA-ICP-MS, 1 LA-MC-ICP-MS, 1 SIMS, 1 TIMS are used in analyses of extraterrestrial samples	Service contract for both EPMAs, both SEMS and SIMS.	1 faculty, 8 technical staff (associated with the various instruments), 3 graduate students	~6 FTE based funded.	
	University of Saskatchewan - User facility for the Canadian Light Source (CLS)	This university hosts the Canadian Light Source, which is the national synchrotron light source facility	Synchrotron facility, which generates intense beams of Far-IR to Hard X-Ray for analytical purposes. Measurements on minerals, geological samples, as well as other materials. Techniques for analysis of extra-terrestrial materials, such as high resolution imaging and tomography, X-ray spectroscopy for elemental analysis, and x-ray scattering/diffraction for crystal structure analysis and phase identification	Some of the equipment is covered by service contracts. The synchrotron and beamlines are highly customized infrastructure, which are mainly serviced by CLS staffs. The service charges are covered by the operational fund. CLS has a technique services department to support the operation of the whole facility.	CLS has over 20 beamlines, each specialized on several techniques and particular length scale. Each beamline has 2 or 3 scientists for the operation and maintenance of the beamline.	Technical staff of the CLS is funded by several Canadian funding agencies including Canadian Foundation for Innovation (CFI), National Sciences and Engineering Research Council (NSERC), NRC, CIHR, and provincial governments, etc.	
	University of Ottawa	In addition to analysis capabilities for the "standard" AMS isotopes (14C, 3H, 10Be, 26Al, 36Cl, 129I, and the actinides), the	André E. Lalonde Accelerator mass spectrometry (AMS) laboratory	No service contracts.	1 Director, 2 research scientists, 8 technical staff,	1 staff position funded by the university, remaining 7 staff positions are funded 40% from the Canadian	Funds for instrument repairs are included in the CFI-MSI

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
		Lalonde AMS has specialized equipment for noble gas analyses (He, Ne, Ar, Kr, Xe) for a wide range of geological samples. Currently, they do not undertake analyses of extraterrestrial materials, but this facility could be used for such analyses in the future.				Foundation for Innovation (CFI)I Major Science Initiatives (MSI) Program and 60% by user fees.	budget and recharge.
	University of Toronto and the Royal Ontario Museum	Analyses of mineralogy, micro-structure, physical properties, element and isotopic compositions of meteorites. Remote sensing of lunar impact craters	The University of Toronto hosts the Jack Satterly Geochronology Laboratory which was the birthplace of modern ID-TIMS (isotope dilution-thermal ionization mass spectrometry method) and several mass spectrometers. Stable isotope laboratory with a gas source mass spectrometer and a gas chromatograph. Several mass spectrometers such as a LA-ICP-MS, SIMS, EPMA, SEM and X-ray fluorescence spectrometers. The Royal Ontario Museum has capabilities for Raman spectroscopy and single-crystal and powder diffraction, as well as advanced meteorite curation facilities	University of Toronto: Government (NSERC, CFI) and services. Royal Ontario Museum private donations and government (NSERC).	University of Toronto: 4 faculty members, four technicians, five postdoctoral fellows; ROM: 1 curator, three technicians, one postdoctoral fellow	Staff funded by the university and the museum. Postdoctoral fellows funded by government funding, university funding and ROM: private donations	
	University of Western Ontario	Analyses of mineralogy, micro-structure, physical properties, element and isotopic compositions of lunar samples and meteorites, as well as the meteorite fall recovered in Canada (e.g. Tagish Lake, Grimsby). (add X-ray micro-CT scan for equipment)	1 ICP-MS, 1 XRF, a field-emission SEM (Nanomapper) with EBSD and CL, 1 x-ray micro CT scanner, 1 micro-XRD, Raman spectroscopy, a paleomagnetism laboratory and laboratories for the study of physical properties of meteorites	Government (NSERC, CFI)	5 faculty members, 1 technician	Technical staff funded by university.	
	McMaster University	Astrobiology of carbonaceous chondrites and micro-structural analyses of martian and lunar meteorites	The Canadian Centre of Electron Microscopy (CCEM) is located in this university and consists in a TEM, SEM, and an Atom Probe. McMaster University also has an ICP-MS and an astrobiology laboratory and the Origins Institute	Government (NSERC, CFI)	2 faculty members, two technicians		

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
	York University	The Centre for Research in Earth and Space Science (CRESS) focuses on planetary exploration and instrumentation	LIDAR, LIBS, Raman spectroscopy and a custom made variable Mars chamber	Government (NSERC, CFI)	2 faculty members, 1 technician, 1 postdoctoral fellows	Technician funded by university.	
Germany	Bayerisches Geoinstitut, University of Bayreuth	Researchers in the institute have analyzed material returned by Apollo sample return missions and meteorites for their mineralogy, impact processes. The institute is currently setting ultra-clean laboratory and mass spectrometry facilities for meteorite and future sample return mission analyses	Mossbauer spectroscopy, micro-beam FIB, SEM-EBSD, EPMA, TEM, Raman, XRD, micro-XRD, XRF, FTIR analyses and laser ablation ICPMS analyses, (soon) MC-ICPMS	Paid for by the government	2 faculty members, 4 technicians/researchers	Technical staff supported by institution.	
	University of Münster	Isotopic and trace element analyses of lunar samples and meteorites	1 MC-ICP-MS, 1 TIMS and 1 quadrupole ICP-MS	There are no service contracts. Facilities repairs are performed by permanent staff, as long as they can solve the issues. Occasionally, engineers are hired from the manufacturing company, but this has so far only happened twice. Cost for consumables and exchange parts are to some extent covered by the annual budget received from the university. The amount of this budget depends on various parameters, but mostly on how much external funding the PIs have. In reality, PIs try to pay all the repairs out of external funds, basically through a lump rate of 350€/day instrument time, which PIs charge to the individual projects. If PIs have enough funded projects, this works out	1 professor, 1 laboratory manager and 1 laboratory technician. Other technicians work part time in the group, including a secretary, a sample preparer and an IT specialist	All positions are permanent positions from the university	The laboratory manager is a permanent FTE. In addition there is a fixed-term research associate position, in which more experienced people can be hired for up to 6 years. This position is refilled by a different person when the previous person has to leave after the 6 years are over. The research associate contributes to the maintenance of the laboratory.

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
				quite well and PI actually save some money. But even if their funding drops, PI would still have university money to keep the laboratory running, at least for a while.			

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
France	The Centre de Recherches Petrographiques et Geochimiques (CRPG), Nancy	The laboratory has analyzed all material returned by dedicated sample return missions (Apollo, Luna, Genesis, Stardust, and Hayabusa), and is collaborating on OSIRIS-REx and Hayabusa2	Two Cameca large sector SIMS, 4 noble gas mass spectrometers, 5 extraction lines, 1 automated U-He and cosmogenic 3He line, 2 excimer lasers, 2 TIMS, 1 MC-ICP-MS	SIMS and SARM instruments are covered by service contracts, paid by the national facility funds from CNRS. Other facilities are not. For facilities repairs, other than SIMS and SARM, costs are covered by grants from the European Research Council, the national funding agency (Agence Nationale de la Recherche - ANR) and current support from CNRS. Once a group at CRPG is officially involved in a space mission, the national space agency, CNES, supports related research. For instance, CNES supported the development of a dedicated facility to analyze nitrogen isotopes in target material from Genesis.	SIMS: 2 researchers, 4 technicians/engineers Noble gas lab: 5 researchers, 3 technicians/engineers TIMS/ICP: 3 researchers, 3 technicians/engineers Stable isotope lab: 2 researchers, 1 technician/engineer SARM: 10 technicians/engineers	All are full time government employees, paid by CNRS and Université de Lorraine	The SIMS laboratory is a CNRS national facility. CRPG also hosts the CNRS analytical facility called Service d'Analyse des Roches et Minéraux (SARM).
	Laboratoire Magmas et Volcans (LMV), Clermont-Ferrand	Study of meteorites and lunar samples for their mineral, trace elements and isotopic composition	1 electron microprobe, 1 SEM, 1 quadrupole ICP-MS with laser ablation capabilities, 1 MC-ICPMS, 2 TIMS	Equipment is covered by the payment of the analyses. Repairs are performed by permanent staff (engineers) for older instruments, or paid by contracts or the department.	For every instrument there is an engineer with a permanent position, so there are 6 technical support (engineers) working for the laboratory.	They are all funded through hard money via CNRS or the university (University of Clermont Auvergne).	
	Institute Physique du Globe Paris (IPGP)	Chemical and isotopic analyses of lunar and meteoritic materials	2 MC ICP-MS, 1 TIMS, 1 quadrupole ICPMS, laser ablation capabilities	No service contracts.	1 engineer (PhD) on the ICPMS and 1 technician (full time salaried, civil servants). 2 technicians for the clean laboratories (full time civil servants)	They are civil servants and paid for by the institution	

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
United Kingdom	Manchester University	Elemental and isotopic analyses of meteorites, interplanetary dust particles, and return samples from the Genesis and Stardust missions	1 MC-ICP-MS, 2 ToF-SIMS with laser post ionization for analyzing micron to sub-micron samples such as pre-solar grains, cometary dust and material brought back by the Stardust mission (IDLE: Interstellar Dust Laser Explorer), 1 conventional noble gas MS, 2 MC-noble gas mass spectrometers, RELAX: Refrigerator Enhanced Laser Analyser for Xenon is a unique resonance ionization ToF MS, RIMSKI: Resonance Ionisation Mass Spectrometer for Krypton Isotopes, 1 EPMA, 1 ESEM, 1 FTIR, 1 laser Raman, 1 CL, 1 nanoSIMS	EPMA and nanoSIMS covered by service contracts	3 professors, 2 readers, 1 senior lecturer, 2 research fellows, 2 technical staff, 4 post-docs, 5-8 graduate students, within the school there are a further 2 two technical staff, and within material science an additional technician for the nanoSIMS	All technical staff paid for by university, with buy-back from grant income.	Technical support funding model means that technical staff's employment is facilitated by research income, but their jobs are secured during fluctuating research cycles. Service contracts on nanoSIMS and EPMA instruments recover income from charging daily rates on budgeted research grants, teaching projects, and raising new income from commercial payments.
	Natural History Museum, London	Chemical and isotopic analyses of meteorites	2 quadrupole ICP-MS, 1 ion chromatograph, 1 CT scanner, 1 FE SEM, 2 variable pressure SEM, 1 TEM, 1 XRD		1 staff scientist, 6 technical staff		
	Open University	Purpose-built laboratories for handling, processing and studying extra-terrestrial materials, including samples from Apollo, Luna, Stardust, IDPs, and meteorites	Laser-fluorination assisted 3 oxygen isotopes analysis on gas source IRMS, 1 nanoSIMS, 1 custom-built Finesse mass spectrometry system for simultaneous measurements of C, N and noble gases (abundance and isotopes) using a step-combustion technique, a miniature version of which has flown on Beagle2 and Rosetta spacecraft with the next version slated to fly on Russian Luna-27 lander mission. 1 MC-ICP-MS, 1 LA- quadrupole ICP-	All major equipment are covered by service contracts. They are underwritten by the university, although in the past several years, a greater emphasis has been paid towards raising sufficient external grant income to cover some of the service costs.	12 professors, 10 technical staff, 9 post-docs, 12 graduate students	Technical staff supported mainly by the internal funds of the university	There is an ever-increasing expectation that funding for technical staff should be raised through external funding as much as possible which is also reflected in an increase in

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
			MS, 1 GC-IRMS, 1 FIB-SEM, 1 electron microprobe				fixed-term appointments for technical staff tied to specific externally funded project(s). Currently, there is a balance of staff on permanent and fixed-term contracts allowing us to maintain our research activities but there are growing concerns about the future possibility of not being able to replace lost expertise (i.e., retiring staff) with new longer-term appointments in a timely manner.
	Oxford University	Isotopic and trace element analyses of meteorites and lunar samples	Three MC-ICP-MS, 1 TIMS, 1 ICP-MS	Formerly had a Finnigan service contract for a while, paid from a PI start-up (14 years ago). Some instrument repairs are performed by PIs (e.g., simple electronics), some are done by the manufacturer. Machine shop can fabricate new devices for chemistry or mass spectrometry. Components are also fabricated externally (including a novel robotic chemistry system).	4 technical staff	Staffing covered through hard money (full time university salary) partially reimbursed from charges for machine use or as direct salary costs on grants	

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
				Funding for these things comes from PI grants.			
	University of Bristol	High precision measurements of isotope ratios of bulk meteorites and meteoritic components (for all elements other than the standardly gaseous elements- C,O,H,N & noble gases), *in situ* isotope ratio analyses by laser ablation	Proto-type collision cell MC-ICPMS (Proteus), 2 MC-ICP-MS, 1 quadrupole ICP-MS, 1 TIMS, 2 excimer laser ablation systems that can be coupled to the plasma mass-spectrometers	There are no service contracts. The laboratory manager maintains and repairs all our mass-spectrometers. Spare parts are paid for from grants.	1 professor, 1 full time permanent "academic related" member of staff (laboratory manager) who maintains the instruments, trouble shoots applications and helps train users. One part-time (3 days/week), soft-money technician, who helps keep the clean laboratories running, assists and trains others users.	The laboratory manager is core funded by the department/university. The part time technician is funded by grant income of the 4 PIs who use the laboratory.	
Switzerland	ETH, Zurich	High precision elemental and isotope analyses of noble gases (He, Ne, Ar, Kr, Xe) and metals and their isotopes (Ti, Cr, Zr, Pd, Ag, Sr, Cd, Sn, Te, Pt) in extraterrestrial materials	1 HR IRMS, 1 magnetic sector single collector ICP-MS, 3 MC-ICP-MS, 1 TIMS	No service contracts	1 professor, 1.5 senior scientists, 2.5 technical staff, 5 postdocs, 8 PhD students	Technical staff supported by university.	Additional support staff through sharing of part of the lab-infrastructure. Funding for repairs from ETH laboratory & institutional funding, limited external funds: Swiss SNF, ERC etc. New instrumentatio

	Institution	Primary use of facility	Major instrumentation	Service contracts	People employed by institution*	Institutionally-funded technical support	Comments
							n funded from ETH professorial (startup)/ institute support, Swiss SNF “R’equip”, ERC etc. grants.
	Institut für Geologie + Center for Space and Habitability Universität Bern	Isotopic and trace element analyses of meteorites and lunar samples.	1 TIMS, 1 MC-ICP-MS, 1 Cameca 1280 SIIMS (housed at Univ. Lausanne)	Service contracts paid via user-fees and contribution from the department. Repairs paid through university.	3 full time research staff, 1.5 full time technical staff	Technical staff supported by university	
Denmark	Center for Star and Planet Formation, Natural History Museum of Denmark	Destructive analysis of extraterrestrial material to elucidate the timing of processes in the early solar system. Absolute age dating based on the U-Pb and Pb-Pb systems, various short-lived radioisotope systems (i.e., Al-Mg, Mn-Cr, Fe-Ni, Hf-W), nucleosynthetic tracers (i.e. 54Cr, 48Ca, 50Ti) as well as noble gases and trace-element analyses	1 TIMS, 2 MC ICP-MS, 1 triple quad ICP-MS, 2 gas source mass spectrometers for noble gas analyses	Most instruments covered by service contracts paid through research grants.	3 Professors, 2 technical staff, 5 post-docs, 8 graduate students	0	

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Biographies of Committee Members and Staff

ROBERTA L. RUDNICK, NAS, is a professor of geology at University of California, Santa Barbara (UCSB) in the Department of Earth Science. Previously, Dr. Rudnick was on the faculty of the University of Maryland in the Department of Geology where she was a Distinguished University Professor, and at Harvard University in the Department of Earth and Planetary Sciences. At UCSB, Dr. Rudnick uses geochemical and geophysical data to understand the origin and evolution of the continents, including the continental lithospheric mantle. She is a recipient of the Dana Medal from the Mineralogical Society of America, the Bowen Award from the Volcanology, Geochemistry, and Petrology division of the American Geophysical Union (AGU) and the Hess Medal from the AGU. She is a fellow of the American Academy of Arts and Sciences, a member of the American Association for the Advancement of Science, and the National Academy of Sciences, and is a foreign associate of the Chinese Academy of Sciences. She received her Ph.D. in geochemistry from the Australian National University. She previously served on the National Academies Committee on Grand Research Questions in Earth Science.

GEORGE D. CODY is a senior scientist of the Geophysical Laboratory of the Carnegie Institution of Washington. His research interests include the chemical history of the early solar system as recorded in the molecular structure of extraterrestrial organic matter from chondritic meteorites, interplanetary dust particles, and comets. He also studies biochemistry of ancient organic fossils. He is the principal investigator for the W.M. Keck Solid State Nuclear Magnetic Resonance Facility and the Molecular Organic Analysis Laboratory at the Geophysical Laboratory. Dr. Cody recently served as acting director for the Geophysical Laboratory for five years and currently is a member of the working group for the World Premier International Research Center Initiative, Earth Life Science Institute, Tokyo Institute of Technology. Dr. Cody earned his Ph.D. in geosciences from The Pennsylvania State University. He previously served on the National Academies Committee on the Limits of Organic Life in Planetary Sciences and the Committee on Exploring Organic Environments in the Solar System.

JAMES H. CROCKER, NAE, is vice president and general manager, retired, of Lockheed Martin Space Systems Company. The focus of his career has been the design, construction, and management of very large, complex systems and instruments for astrophysics and space exploration both in the U.S. and internationally. These include space missions both human and robotic such as Apollo 17, Skylab, Orion; missions to Mars, Jupiter, Saturn, asteroids, the moon, comets, the Hubble Space Telescope, the Spitzer Space Telescope and the James Webb Space Telescope. In ground-based astronomy, he was program manager for the Sloan Digital Sky Survey and head of the Program Office for the European VLT, an array of optically phased 8-meter telescope in the Atacama Desert in Chile. He serves on the board of the Denver Museum of Nature and Science and as a past member of the Universities Space Research Association. He is a member of the National Academy of Engineering. Mr. Crocker earned a M.S. in management from The Johns Hopkins University and a M.S. in engineering from University of Alabama in Huntsville. Mr. Crocker has not previously served on an Academies committee.

VINAYAK P. DRAVID is the Abraham Harris Chaired Professor and the founding director of the NUANCE Center at Northwestern University. The NUANCE Center is a major instrumentation and characterization facility. He also serves as the director of SHyNE (Soft- and Hybrid Nanotechnology

Experimental) Resource - an NSF-NNCI center of excellence in facility infrastructure program. Dr. Dravid's scholarly interests revolve around statics and dynamics of "microstructure"; at the intersection of materials science with physics, chemistry, biology and engineering. He is an expert on characterization and analysis of materials, structures and systems by diverse tools/techniques such as: radiation sources (electron, ion and light/photon microscopy/analysis), scanned probe microscopy (SPM) and correlative multimodal techniques. In the recent decade, he has expanded his characterization expertise to soft, hybrid (soft-hard), dynamic phenomena under external stimuli; and non-invasive characterization based on ultrasound holography, MRI contrast enhancement and related techniques. He is a recipient of several awards/honors; IBM and NSF young career awards, Burton medal of Microscopy Society of America (MSA), Coble and Fulrath Awards from the American Ceramic Society (ACerS). He is an elected fellow of numerous professional societies including: MSA (inauguration class), Materials Research Society (MRS), American Physical Society (APS), ACerS, AAAS, among others. Dr. Dravid is an honorary life-time member of MRS India (MRSI), and the Hsuen Lee Fellow of the Chinese Academy of Science. He earned his Ph.D. in materials science and engineering from Lehigh University.

JOHN M. EILER, NAS, is the Robert P. Sharp Professor of Geology and Geochemistry at the California Institute of Technology and director of the Caltech Microanalysis Center. His research interests include the isotope geochemistry of light elements (H, C, N, O and S), as applied to: the origin and evolution of igneous rocks; the origin and evolution of meteorites; planetary atmospheres; atmospheric and environmental chemistry; paleoclimate; and paleontology. He is a recipient of the James B. Macelwane Medal of the American Geophysical Union and the Day Medal of the Geological Society of America, and is a member of the National Academy of Sciences. He earned his Ph.D. in geology from the University of Wisconsin-Madison. Dr. Eiler has not previously served on an Academies' committee.

ABBY KAVNER is a professor at the University of California, Los Angeles in the Department of Earth, Planetary, and Space Sciences. Her research interests encompass the behavior of Earth and planetary materials under extreme physical and chemical conditions—especially at high pressures and temperatures--to better understand whole-planet thermal and chemical evolution. Dr. Kavner is chair of the Executive Committee of COMPRES, the Consortium for Materials Physics Research in the Earth Sciences. COMPRES is an NSF-funded consortium to help cultivate and support shared user facilities and infrastructure for mineral physics. She is a fellow of the Mineralogical Society of America and serves on the board of reviewing editors for Science magazine. Dr. Kavner earned her Ph.D. in geophysics from University of California, Berkeley. Dr. Kavner has not previously served with the Academies.

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JONATHAN LUTZ is in his senior year at the University of Colorado Boulder (CU Boulder) in the astrophysics program and worked as a student associate at the Laboratory for Atmospheric and Space Physics. He was the Lloyd V. Berkner Space Policy Intern at the National Academies of Sciences, Engineering and Medicine in autumn 2018. He was a member of a student-led BalloonSat research team that launched a scintillator gamma-ray detector on a small payload to the stratosphere. Previously, he worked as a freelance graphic designer and has a background in data science. He is on the dean's list at CU Boulder.

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Acronyms and Glossary

Instrumentation Acronyms

AFM—atomic force microscopy
AMS—accelerator mass spectrometry
APS—Advanced Photon Source
APT—atom probe tomography
CAMECA—*Compagnie des Applications Mécaniques et Electroniques au Cinéma et à l'Atomistique*
CAT—computer-aided tomography
CL—cathodoluminescence
CNRS—*Centre National de la Recherche Scientifique*
CPD—critical point drying
CT—computed tomography
EBSD—electron backscatter diffraction
ECBC—Edgewood Chemical Biological Center
EDS—energy dispersive X-ray spectroscopy
EDX—energy dispersive x-ray analysis
EM—electron microscopy
EPMA—electron probe microanalysis
FE—field emission
FE-EPMA—field emission electron probe microanalyzer
FE-SEM—field emission scanning electron microscope
FEG—field emission gun
FIB—focused ion beam
FISH—fluorescent *in situ* hybridization
FTIR—Fourier Transform infrared spectroscopy
FTMS—Fourier transform mass spectrometry
GC-MS—gas chromatography mass spectrometry
HEPA—high-efficiency particulate air
HPF—high-pressure freezing
HR—high resolution
ICP-MS—inductively coupled plasma mass spectrometer
ICP-OES—inductively-coupled plasma optical emission spectrometry
ID-TIMS—isotope dilution-thermal ionization mass spectrometry
IMS—ion mass spectrometer
INAA—instrumental neutron activation analysis
IR—infrared
IRMS—isotope ratio mass spectrometry
LA-ICP-MS—laser ablation inductively coupled plasma mass spectrometry

LA-MC-ICPMS—laser ablation multi-collector inductively coupled plasma mass spectrometry
LIBS—laser-induced breakdown spectroscopy
LIDAR—light detection and ranging
MC-ICP-MS—multi-collector inductively coupled plasma mass spectrometer
MFM—magnetic-force microscopy
MR—magnetic resonance
MRI—(technique) magnetic resonance imaging
MS—mass spectrometry
MS-MS—tandem mass spectrometry
NAA—neutron activation analysis
NMR—nuclear magnetic resonance
NSCL—National Superconducting Cyclotron Laboratory
NSLS—National Synchrotron Light Source
PMF—piezo-resistive force microscopy
RELAX—refrigerator enhanced laser analyzer for xenon
RIMSKI—resonance ionisation mass spectrometer for krypton isotopes.
RIMS—resonance ion mass spectrometry
SEM—scanning electron microscope
SHRIMP—sensitive high-resolution ion microprobe
SIMS—secondary ion mass spectrometry
SNMS—sputtered neutron mass spectrometer
SNS—spallation neutron source
S-TEM—scanning transmission electron microscopy
STM—scanning tunneling microscope
STXM—scanning transmission x-ray microscopy
TEM—transmission electron microscopy
TIMS—thermal ionization mass spectrometry
ToF-SIMS—Time-of-Flight Secondary Ion Mass Spectrometry
UV-Vis—ultraviolet-visible spectroscopy
UV/Vis—ultraviolet-visible spectrophotometry
XCT—X-ray computed tomography
XRD—X-ray diffraction
XRF—X-ray fluorescence

Other Acronyms

ABRF—Association of Biomolecular Resource Facilities
AMNH—American Museum for Natural History
ANL—Argonne National Laboratory
ARES—Astromaterials Research and Exploration Science
ASRG—Astromaterials Science Research Group
BGS—British Geological Survey
BNL—Brookhaven National Laboratory
C^3—Chicago Center for Cosmochemistry
CAESAR—Comet Astrobiology Exploration Sample Return
CAGE—Cosmochemistry, Astrophysics, and Experimental Geophysics

CAPTEM—Curation and Analysis Planning Team for Extra Terrestrial Materials
CATE—Cost and technical evaluation
CC—Contamination control
CCIM—Canadian Centre for Isotopic Microanalysis
CCSR—Cryogenic Comet Sample Return
CEPSAR—Centre for Earth, Planetary, Space and Astronomical Research
CFI—Canadian Foundation for Innovation
CHILI—Chicago Instrument for Laser Ionization
CK—Contamination knowledge
CMS—Center for Meteorite Studies
CLPS—Commercial Lunar Payload Services
CNST—Center for Nanoscale Science and Technology
COMPRES—Consortium for Mineral Physics Research in the Earth Sciences
CRESS—Centre for Research in Earth and Space Science
CRPG—*Centre de Recherches Pétrographiques et Géochimiques*
CSA—Canadian Space Agency
DAE—Department of Atomic Energy of India
DOD—Department of Defense
DOE—United States Department of Energy
EAR—Division of Earth Sciences (NSF)
EBSD—electron backscatter diffraction
ECBC—Edgewood Chemical Biological Center
ESA—European Space Agency
ESCuC—Extraterrestrial Sample Curation Center
ET—extraterrestrial
EW—Emerging Worlds
FEI—Field Electron and Ion Company
FFRDCs—Federally Funded Research and Development Centers
GEO—Geoscience
GEOKhI—Vernadsky Institute of Geochemistry and Analytical Chemistry
GeoREM—Geological and Environmental Reference Materials
GSECARS—GeoSoilEnviroCARS
HEPA—High efficiency particulate air
HHMI—Howard Hughes Medical Institute
I&F—Instrumentation and Facilities
IDPs—Interplanetary Dust Particles
IPGP—*Institute Physique du Globe Paris*
IRIS—Incorporated Research for Seismology
IRMS—isotope ratio mass spectrometry
ISAS—Institute of Space and Astronautical Science
ISFM—Internal Scientist Funding Model
ISO—International Standards Organization
JAXA—Japanese Space Agency
JSC—Lyndon B. Johnson Space Center
LARS—Laboratory Analysis of Returned Samples
LIGO—Laser Interferometer Gravitational Wave Observatory

MatISSE—Maturation of Instruments for Solar System Exploration
MML—Materials and Measurement Laboratory
MMX—Martian Moons Explorer
MREFC—Major Research Equipment Facilities Construction
MRI (program)—Major Research Instrumentation
MSC—Manned Spaceflight Center
MSL—Mars Science Laboratory
NASA—National Aeronautics and Space Administration
NESSF—NASA Earth and Space Science Fellowships
NIBIB—National Institute of Biomedical Imaging and Bioengineering
NCNR—NIST Center for Neutron Research
NHMFL—National High Magnetic Field Laboratory
NIH—National Institutes of Health
NIST—National Institute for Standards and Technology
NNCI—National Nanotechnology Coordinated Infrastructure
NPP—NASA postdoctoral program
NRC—Nuclear Regulatory Commission
NRL—Naval Research Laboratory
NSF—National Science Foundation
NSERC—National Science and Engineering Research Council
NSRC—nanoscale science research center
OSIRIS-REx—Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
PARI—*plateau d'analyse haute résolution*
PICASSO—Planetary Instrument Concepts for the Advancement of Solar System Observations
PME(F)—Planetary Major Equipment (Facilities)
PML—Precision Measurement Laboratory
PRL—Physical Research Laboratory
PSD—NASA Planetary Science Division
RELAB—Reflectance Experiment Laboratory
RELAX—Refrigerator Enhanced Laser Analyzer for Xenon
RIMSKI—Resonance Ionisation Mass Spectrometer for Krypton Isotopes.
RMA—Rapid Mission Architecture
RSV—Return Sample Vault
S&T—Science and Technology
SPA—South Pole-Aitken
SRC—sample return capsule
SRI—Southwest Research Institute
SSAS—Stardust Sample Allocation Subcommittee
SSW—Solar System Workings
SUERC—Scottish Universities Environmental Research Centre
SWaP—size, weight, and power
SwRI—Southwest Research Institute
TAGSAM—Touch-And-Go Sample Acquisition Mechanism
TOC—total organic carbon
TIMS—thermal ionization mass spectrometry

UCLA—University of California, Los Angeles
UPW—Ultra pure water
USGS—United States Geological Survey
USSR—Union of Soviet Socialist Republics
WPAFB—Wright-Patterson Air Force Base