A Consensus Vision for Mars Sample Return

A white paper for the 2009 NRC Planetary Science Decadal Survey

This document reflects the integration of multiple recent community-based strategic planning discussions, including MEPAG science analysis groups, workshops, conferences, and synthesis discussion of these topics at recent full MEPAG meetings. This document was additionally developed in consultation with CAPTEM, which strongly and unreservedly supports MSR.

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Also posted on the MEPAG web site, and may be referenced as follows:

Borg, L., C. Allen, D. Beaty, K. Buxbaum, J. Crisp, D. Des Marais, D. Glavin, M. Grady, K. Herkenhoff, R. Mattingly, S. McLennan, D. Moura, J. Mustard, L. Pratt, S. Symes, and M. Wadhwa (2009). A Consensus Vision for Mars Sample Return, 7p. white paper posted September, 2009 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

Introduction[1]

For the past three decades, the scientific community has repeatedly advocated the return of geological samples from Mars. Summaries of the literature on this topic appear in the extensive writings of the NRC (1978; 1990a, 1990b, 1994; 1996; 2001, 2007), several major recent reports by MEPAG (MacPherson et al., 2001, 2002; ND-SAG, 2008, MRR-SAG, 2009), and a significant recent contribution by the International Mars Exploration Working Group (iMARS, 2008).

The recommendations from the late 1970s and early 1980s envisioned a Mars mission with a reconnaissance purpose, similar to the role played by the Apollo missions and Luna 16, 20, and 24 in advancing lunar science. However, the specific purpose and context of a Mars sample return has changed significantly in the intervening years. To address questions of general planetary geochemistry, petrology, and geochronology, a wide variety of sample types would be sufficient, although the value would be greatly leveraged if the environmental context were known. After all, it has been widely accepted (but not proven) for 15-20 years that we have samples of Mars on Earth in the form of the shergottite, nakhlite, and chassigny (SNC) meteorites. All of these, however, are mafic and ultramafic igneous rocks. This emphasizes the need to return other representative samples, most importantly regolith or breccia (both types played a key role in lunar studies) and, uniquely for Mars, sedimentary rocks.

A further shift in thinking came in 1996 when David McKay and his co-workers (McKay et al., 1996) announced the hypothesis that Mars meteorite ALH84001 contained fossil evidence of martian life. This hypothesis triggered enormous interest from both the scientific community and the public. ALH84001 is a relatively large rock, and it was possible to send subsamples to multiple research laboratories around the world for independent testing and many additional kinds of measurements. One essential lesson from the case of ALH84001 is how involved sample studies can be, sometimes requiring the collective capability of the Earth's research laboratories to evaluate complex questions. In the case of this sample, the evidence for past life was not definitive. Even so, the need of the astrobiology community for samples returned from a well-characterized site became clear as a result of work with this meteorite.

Mars missions, beginning with Mariner 9, have revealed a planet with enormous geologic variety both from place to place and over geologic time. In the last decade, this has included the discovery of a major sedimentary record with facies variations that include playas, deltas, basins, as well as fluvial and aeolian features; a wide range of geomorphic features, some of which are similar to those found on Earth and some of which are not; and systematic changes in the kinds of minerals that were deposited over martian geologic history. Our perspective on the probability that some martian environments could potentially harbor life forms has changed dramatically based on the wide range of past and present environmental conditions we have discovered. The astrobiology sector of the Mars community has recognized that samples currently on Mars would have far better potential to record the evidence of past or present martian life than ALH84001. This recognition is extremely tantalizing to the research community. The sample types needed for astrobiology are more highly selected than for

[1] All acronyms used in this document are defined in "Compiled Bibliographic Citations and Acronym Glossary for the Mars-Related White Papers Submitted to the NRC's Planetary Decadal Survey", which may be accessed at http://mepag.jpl.nasa.gov/decadal/index.html.

mineralogy/petrology reconnaissance, since only certain materials will preserve biosignatures. This requires more carefully selected samples to support a wide range of astrobiology investigations.

This progression in thinking about the role of a potential Mars sample return is a natural consequence of our evolving understanding of both Mars and Earth and the evolving nature of our scientific questions. Importantly, even though the context of this proposed mission(s) has shifted, the overall strength of community support has increased.

The purpose of this white paper is to present a vision of the Mars Sample Return (MSR) mission concept that summarizes the current state of thought regarding the scientific goals that would be best addressed by a sample returned from Mars. The extensive MSR-related discussions by ND-SAG (2008), MRR-SAG (2009), and iMARS (2008) have clarified our vision of a potential MSR. The resulting reports have been widely discussed in conferences and planning meetings over the past year and have led to consensus positions that transcend the interests of individual scientists.

Why Return Samples from Mars?

Three special attributes make Mars a uniquely compelling target in planetary exploration (as summarized in iMARS, 2008):

- Mars may provide a view into the early history of Earth. While the Archean rock record is not well preserved in the Earth's geologic record, this early history is preserved on Mars. Because life on Earth began during this early period, much of the critical information about its origins and early evolution has been lost due to extensive plate tectonic activity—critical information is missing on our home planet. Mars could provide clues about the early evolution of water-rich terrestrial planets and the evolution of habitable environments.
- Of the various places of interest for evaluating whether or not life exists or has existed elsewhere in the universe, the martian surface is by far the most accessible. We can afford to send a regular series of missions, progressively enhancing exploration capabilities and responding to the discoveries of previous missions. This accessibility allows us to address the life question in a systematic fashion that is essential to achieve success.
- Mars is a potential target for eventual human exploration. Of our nearest planetary neighbors, Mars is the most compatible with crewed missions, and the scientific questions at Mars would most benefit from the attention of human explorers. The return and subsequent analysis of samples from Mars would also reduce the risks to future human exploration.

The unique value of returned samples has been described and defended in many arenas over the years. Because of the high cost of sample return, scientists have had to consider whether their objectives could alternatively be achieved either by *in situ* investigations or by study of the martian meteorites. Notwithstanding the price tag, the clear conclusion has consistently been that there is unique and compelling value to bringing Mars samples back to Earth for study.

MEPAG (2008) identified 58 important future science investigations related to the exploration of Mars. These investigations would depend on measurements from various spacecraft platforms using a variety of instruments, some of which do not yet exist for flight. The ND-SAG (2008) concluded that about half of the 58 MEPAG investigations could be addressed to one degree or another by MSR. In fact, they concluded that the return of carefully selected samples from a potentially habitable site would make the most progress towards the entire list. Moreover, given the scope of what is realistically achievable via *in situ* exploration technology, many of these investigations cannot be meaningfully advanced without returned samples.

Several of the high-priority investigations would involve sample preparation procedures that would be too complicated and impractical for *in situ* robotic missions. In addition, it is difficult to foresee flight instruments that could match the adaptability, array of sample preparation procedures, and microanalytical capability of Earth-based laboratories (Gooding et al., 1989). For example, analyses conducted at the submicron scale were crucial for investigating the ALH84001 meteorite, and they are essential for elucidating many of the complex geological and potential biological processes that have occurred on Mars. Furthermore, spacecraft instrumentation simply cannot perform certain critical measurements, such as precise radiometric age dating, sophisticated stable isotopic analyses, and comprehensive life-detection experiments that are central to current scientific questions regarding Mars. If returned samples yield unexpected findings, subsequent laboratory-based investigations could be adapted accordingly. Adaptations based on new inputs (discoveries) would be much more difficult, if not impossible, for landed or orbital missions. Moreover, portions of returned samples could be archived for study by future generations of investigators using ever more powerful instrumentation. Thus, returned Mars samples would have the great potential to significantly expand our knowledge of the planet and potentially answer some of our most fundamental questions.

The current collection of martian meteorites is very useful for some, but not all, scientific questions. All of the approximately 40 known meteorites that were blasted off the surface of Mars are relatively fresh igneous rocks derived from either basalt flows or subvolcanic intrusive rock. None of these samples are sedimentary, hydrothermally altered rocks, or evolved igneous rocks, which we know to exist on Mars and consequently are not suitable to address several important scientific questions, including whether or not an ancient record of martian life exists. In addition, without ground-truth knowledge of the geological context from which they derive, the scientific value of these martian meteorites is further reduced.

The most recent scientific observations from Mars have further strengthened the rationale for the return of Mars samples. Observations of possibly recent flows of water in gullies and active release of plumes of methane into the atmosphere provide strong new evidence for the presence of life-sustaining resources on Mars. However, detections of discrete plumes are difficult to reconcile with our current understanding of the oxidizing capacity of an atmosphere bathed in UV radiation and charged with fine dust particles. This underscores the fact that there are fundamental aspects of the carbon cycle on Mars even today that we have yet to understand with orbital remote sensing or landed scientific instruments, thus adding to the rationale for returning samples of Mars to highly flexible and adaptable Earth-based laboratories.

Science Objectives for MSR

Eleven candidate scientific objectives for MSR were recently identified by MEPAG ND-SAG (2008) and subsequently incorporated into the iMARS analysis and report (2008).

1. Determine the chemical, mineralogical, and isotopic composition of the crustal reservoirs of carbon, nitrogen, sulfur, and other elements with which they have interacted, and characterize carbon-, nitrogen-, and sulfur-bearing phases down to submicron spatial

scales, in order to document processes that could sustain habitable environments on Mars, both today and in the past.

2. Assess the evidence for prebiotic processes, past life, and/or extant life on Mars by characterizing the signatures of these phenomena in the form of structure/morphology, biominerals, organic molecular and isotopic compositions, and other evidence within their geologic contexts.
3. Interpret the conditions of martian water-rock interactions through the study of their mineral products.
4. Constrain the absolute ages of major martian crustal geologic processes, including sedimentation, diagenesis, volcanism/plutonism, regolith formation, hydrothermal alteration, weathering, and cratering.
5. Understand paleo-environments and the history of near-surface water on Mars by characterizing the clastic and chemical components, depositional processes, and post-depositional histories of sedimentary sequences.
6. Constrain the mechanism and timing of planetary accretion, differentiation, and the subsequent evolution of the martian crust, mantle, and core.
7. Determine how the martian regolith was formed and modified, and how and why it differs from place to place.
8. Characterize the risks to future human explorers in the areas of biohazards, material toxicity, and dust/granular materials and contribute to the assessment of potential *in situ* resources to aid in establishing a human presence on Mars.
9. For the present-day martian surface and accessible shallow subsurface environments, determine the preservation potential for the chemical signatures of extant life and prebiotic chemistry by evaluating the state of oxidation as a function of depth, permeability, and other factors.
10. Interpret the initial composition of the martian atmosphere, the rates and processes of atmospheric loss/gain over geologic time, and the rates and processes of atmospheric exchange with surface condensed species.
11. For martian climate-modulated polar deposits, determine their age, geochemistry, conditions of formation, and evolution through the detailed examination of the composition of water, CO_2, and dust constituents, isotopic ratios, and detailed stratigraphy of the upper layers of the surface.

Members of ND-SAG discussed at length the different kinds of samples that would be needed to address the different objectives and the fact that there is no single landing site on Mars where it would be possible to collect the necessary samples to achieve all eleven objectives. They concluded that the assignment of scientific objectives to a potential sample return mission would need to be worked as part of the landing site selection process, i.e., these two aspects would be inseparable. Taking this further, MRR-SAG (2009) concluded that a potential sample return mission, given the amount of resources required, would need to address both life-related and geochemical objectives.

It is important to note that in Appendix II of ND-SAG (2008), a complete analysis of the potential to achieve many other scientific objectives is presented. An example is interpretation of the paleomagnetic history of the martian surface. Whether this or other scientific objectives could be achieved would depend both on the configuration of the flight mission(s) and the kinds of rock samples the rover could collect.

The collection of Mars samples would be most useful if they were organized into sample suites chosen to represent the diverse products of various planetary processes. This is a key strategy used by Earth scientists to resolve the many factors that collectively created the heterogeneity of Earth's rocks. Addressing the above scientific objectives for MSR would take multiple sample suites. Candidates sample suites include: sedimentary rocks, hydrothermal deposited rocks, low temperature altered rocks, igneous rocks, a depth resolved sample suite, regolith samples, dust, ice, and atmosphere (ND-SAG, 2008).

There is a strong connection between the highest priority science objectives, the range of lithologies that would have to be sampled—sedimentary, hydrothermal, and igneous—and landing site selection. The coupling of the objectives to the diverse lithologies arises from the variety of significant processes that played key roles in the formation of the martian crust and atmosphere. Each process creates materials that differ in significant ways and that collectively could be used to interpret geological events. The extent of what could be achieved at a single landing site would depend on such things as the rover's mobility, its ability to do scientific sample selection, and context documentation. Fortunately, remote sensing and *in situ* investigations have revealed many diverse sites where materials would be accessible in a single mobile mission. The landing site selection process would, therefore, be an essential part of the scientific planning for sample return. Based on analysis of representative mission sequence timelines, suites of about five samples represent a reasonable compromise between scientific needs and mission constraints for MSR samples. Any decision concerning mission design should consider the number and priority of scientific objectives that could be met with a particular single set of samples or sample suites. Clearly, the types of samples collected must be further refined in light of specific mission objectives for specific sites. But a single mission, returning a collection of carefully selected samples, would greatly facilitate our understanding of the planet, even though it could not address all of the key scientific questions.

The members of the science community interested in Mars hold a range of viewpoints regarding the mission implementation needed to achieve the return of samples from Mars. Based on multiple discussions over the past two years within large, open community gatherings such as MEPAG meetings and professional conferences; deliberations of CAPTEM; reports of committees working on Mars planning questions; and formal advice to NASA by the NRC and PSS, it is clear that a majority of the Mars science community believes that MSR is essential to the forward exploration of Mars and should be one of NASA's highest priority goals. However, within the context of widespread support for sample return, there are differences in perception of the way the mission should be implemented. The mission described in this report would entail a sampling rover with enough instruments to do scientific sample selection. However, an alternate way to implement MSR would be to use a fixed lander with a very much more limited array of capabilities (scoop, sieve, drill and/or small fetch rover). A significant fraction of the sample science community believes that the benefits of mission simplification, including the potential to reduce cost and engineering risk, would outweigh the loss in scientific return. An even simpler implementation would be to return only an atmospheric and dust sample by means of an aerobraking-like pass through the atmosphere. This version of MSR would be less expensive, but would contribute a small fraction of the scientific value of a surface sample return mission.

Although the return of samples from the surface of Mars would have tremendous scientific potential, it would be an expensive enterprise requiring that difficult choices be made to balance scientific yield and cost. Within this context, the issues that must be balanced include: sample size, number of samples, sample encapsulation, diversity of the returned collection, *in situ* measurements for sample selection and documentation of field context, surface operations, sample acquisition system, sample temperature, planetary protection, and contamination control.

Planetary Protection (PP) and Sample Purity

A central task of PP is the protection of the Earth's biosphere from potentially harmful contamination. Other relevant PP challenges are described in Hayati et al., 2009, but protection of Earth is the highest priority and most complex. If a sample were to be returned from Mars, any Mars material including the sample would need to be reliably contained until completion of a comprehensive test protocol to assess sample safety. This would require construction of a specially designed sample receiving facility (SRF).

The need to preserve sample purity while maintaining containment would continue throughout the sample assessment phase in support of PP and to assure maximum scientific value of the returned samples for decades of work to be performed in Earth laboratories. Design teams should analyze these challenges early in formulation of any flight missions that would acquire and return the samples, and through development of the SRF, because organic and inorganic contamination control measures would be needed from the time of spacecraft construction through the years of sample collection, curation, and study.

Mission Implementation

MSR as envisioned would require at least 1) a lander with a rover to acquire samples and deliver them to Mars orbit via a Mars ascent vehicle (MAV) and 2) an orbiter to capture that sample container, return to Earth, and deliver the sample to the surface via an Earth entry vehicle (EEV). The MRR-SAG (2009) concluded that MSR should be thought of as a campaign, and recommended that the 2-element approach should be separated further into three elements: a rover with the sampling system, a lander with the MAV, and the orbiter. This approach would spread programmatic resources and risk, mission risk, and technology challenges over three separate launch opportunities. Separation of the sampling rover from the lander/MAV (now with a smaller fetch rover) would enable both missions to fit comfortably within capabilities of the Mars Science Laboratory (MSL) delivery system, which would be used to navigate to Mars and perform a direct entry and soft-landing. Specifically, the MRR-SAG recommended that a rover called MAX-C (proposed launch in 2018) [Pratt et al, 2009] perform the sample acquisition and caching for MSR in conjunction with broader *in situ* investigation, thus enhancing the scientific value of the samples, and incorporate MSR considerations (e.g., site selection) since it would now be the first leg of a MSR campaign. An additional significant element of a sample return campaign would be the Mars Returned Sample Handling (MRSH) element, which would include Earth landing site operations, surface transportation, a sample receiving facility (SRF), and curation.

The proposed mission architecture would be compatible with foreign collaboration, as confirmed by a recent international study (iMARS 2008). While building on the last decade of heritage and advancement, several challenges remain (e.g., sample acquisition and caching, the MAV, etc). Technology needs for a potential MSR are described in a separate white paper [Hayati et al, 2009]. Technology development would need to start at least eight years before the launch of each mission element.

In summary,

- There is recognition that the return of well-chosen samples from a well-characterized site is likely to make the greatest advance in our understanding of Mars, particularly with regard to the question of whether Mars has ever been an abode of life.
- We have acquired or can acquire with current assets the information needed to select a sample return site that would address both geological and astrobiological high-priority science objectives.
- A multi-element, step-by-step sample return campaign would reduce scientific, technical and cost risks. It builds on technologies developed over the last decade of Mars exploration, though major technical challenges remain and should be addressed in a technology development effort that would be part of the proposed sample return campaign.

This major milestone could be achieved if the necessary steps are taken this decade. It would be a major advance, not just for Mars science, but also for planetary science and could provide critical insights into fundamental questions about Earth including the most basic: Are we alone in the Solar System?

References

The references cited in this white paper are compiled in a separate document at the following web site: http://mepag.jpl.nasa.gov/decadal/index.html.