Introduction: Partnerships between science and human exploration have recent heritage for the Moon (Lunar Precursor Robotics Program, LPRP) and near-earth objects (Exploration Precursor Robotics Program, xPRP). Both programs spent appreciable time and effort determining measurements needed or desired before human missions to these destinations. These measurements may be crucial to human health or spacecraft design, or may be desired to better optimize systems designs such as spacesuits or operations. Both LPRP and xPRP recommended measurements from orbit, by landed missions and by sample return.

LPRP conducted the Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) missions, providing high-resolution visible imagery, surface and subsurface temperatures, global topography, mapping of possible water ice deposits, and the biological effects of radiation [1]. LPRP also initiated a landed mission to provide dust and regolith properties, local lighting conditions, assessment of resources, and demonstration of precision landing [2]. This mission was canceled in 2006 due to funding shortfalls. For the Moon, adequate samples of rocks and regolith were returned by the Apollo and Luna programs to conduct needed investigations.

Many near-earth asteroids (NEAs) have been observed from the Earth and several have been more extensively characterized by close-flying missions and landings (NEAR, Hayabusa, Rosetta). The current Joint Robotic Precursor Activity program is considering activities such as partnering with the New Frontiers mission OSIRIS-Rex to visit a NEA and return a sample to the Earth. However, a strong consensus of the NEO User Team within xPRP was that a dedicated mission to the asteroid targeted by humans is required [3], ideally including regolith sample return for more extensive characterization and testing on the Earth.

The Case for Mars Sample Return: Returned samples provide a unique perspective on the planetary environment, based on our ability to manipulate the sample, the capability to analyze the sample at high precision and accuracy, and the ability to modify experiments as logic and technology dictates over time [4]. For example, while the results of the Viking life detection experiments are still regarded by some as ambiguous, the return of samples to terrestrial labs would have enabled a battery of tests that would have left no doubt in interpretation of results.

The Decadal Survey sample-return mission will make significant progress regarding questions related to Mars habitability and past potential for life. It requires extensive surface mobility and capability to examine samples in situ to ensure the right samples are returned. However, a simpler, “groundbreaking” Mars Sample Return (GMSR) mission has been advanced several times as delivering a significant fraction of important Mars science objectives at a reduced cost. Such a mission architecture would do double duty for science and exploration at a price point well within the Mars Next Decade budget.

Science. The scientific value of a simplified sample return includes characterizing the igneous products and interior evolution of Mars, characterizing surface depositional processes and post-depositional histories, tying absolute ages to relative crater histories, and determining how regolith forms and is modified [5-7]. It is to be emphasized that the science community would not be satisfied with this approach if it were the only sample return mission under consideration for a Mars program; but if it is approached as the first in a series, it would enable paradigm-altering science and satisfy many stated science goals for MSR.

Engineering. Mechanical design and testing relies on knowledge and simulation of the surface environment. Lunar simulant has been extensively used for mobility tests, resource production, human health, and dust control technologies. Particle shape and size, composition, and bulk density may be characterized in situ, but more detailed measurements including trace composition, mineralogy relative to size and shape distribution, internal textures and compositions, particle strength, and abrasivity require sample return to create a better testing environment than the current Mars soil simulant JSC Mars-1 [8].

Human health. Recommended measurements needed for human health assessment include the presence of hexavalent chromium, pH and buffer capacity, and abundance of organic carbon [8], which may be done well-planned in situ investigations. However, parallels with the work done by Lunar Airborne Dust Toxicity Advisory Group [9], which includes not just toxicology but also inhalation, dermal and ocular exposure, suggest that a sample of at least 50 g from the surface is greatly desired (J. James, pers. comm).

Programmatic risk. Currently, planetary protection guidelines dictate that returned Mars samples be kept in a CDC-type containment facility until acceptably tested and sterilized to minimize the threat to life on Earth. On the other hand, the Human Exploration program is considering immersing its crew in the Mars environment for up to 500 days after a slate of in situ microbial and toxicity measurements are made. Sample return provides the material to design new tests that cannot yet be imagined but may well become crucial in preventing crew loss at the surface of Mars.
**GMSR Mission Architecture:** The concept of Groundbreaking Mars Sample Return was developed by MEPAG [10, 11] to lower sample return mission cost and complexity. The GMSR architecture does without precision landing, extensive roving, and in situ instrumentation. It consists of a lander, extendable arm, simple sampling devices (scoop, sieve), and a context camera. The mission visits a site previously characterized by other missions to provide context and design envelopes. The collected samples include 500g of soil, dust, rock fragments, and atmosphere.

A direct entry/direct return architecture for MSR has been studied numerous times. A large launch vehicle delivers a payload to the surface of Mars consisting of sample collection and processing capabilities, a sample return capsule, and a Mars Ascent Vehicle (MAV) fueled for an ascent from Mars and flight back to Earth. Upon approach to Earth, the capsule separates from the rest of the vehicle and performs a high-speed re-entry similar to Stardust or Genesis.

Previous studies [12-15] estimate the landed mass of a direct-return mission as 1000-1500 kg (higher estimates include a rover), but find the direct return approach to be prohibitively expensive, because it requires a very large (=costly) large launch vehicle and lander to carry a fully fueled ascent vehicle. However, several advancements in technology encourage a re-examination of the direct return GMSR architecture. We highlight here two relevant developments from MSFC, though others certainly exist.

**Launch Vehicle:** The Space Launch System (SLS) provides around 50,000 kg to TMI (or 30,000 kg for the initial 70 mT configuration) direct from Earth. In an MSR study enabled by the Constellation-era heavy lift vehicle [16], aerocapture of 40 metric tons (mT) and landing of 8 mT were achieved. In this study, three 500 gm sample return capsule were launched from two separate Martian locations with a lander and rover having a mobility of >1 km, subsurface sampling, and additional investigations. This capability far exceeds the GMSR mission needs, opening the possibility of a GMSR mission sharing SLS launch capability and perhaps travelling to Mars after being launched to Earth-Moon L2 in an SLS reference mission.

**DACS Thrusters:** The Robotic Lunar Lander Development Program has invested in high thrust-to-weight thrusters for planetary landers, specifically missile-heritage, miniaturized thruster technologies used for Divert and Attitude Control Systems (DACS). MSFC hot-fire tested 100-lbf and 5-lbf thrusters with MMH/MON-25 under various pulsing durations, power levels, and propellant mixture ratios (Fig. 1). These tests show that DACS thrusters exhibit combustion stability, engine efficiency, and ability to perform pulsed and steady state burns at full power. Such thrusters need to be tested under Mars conditions but hold promise for lowering the mass of the MAV in a GMSR direct return architecture.

**Conclusions:** A simplified approach to the first Mars sample return can return samples of paradigm-changes geologic importance and provide detailed knowledge to aid in planning safe and productive human exploration missions. The elements of such a mission (heavy lift, large landers, and high-speed re-entry) can also be used to provide test data for human systems design. Technological advances such as heavy-lift capability in the SLS, trajectories from Earth-Moon L2, and high thrust-to-weight ratio engines may enable a viable single-launch, direct return mission. A Groundbreaking MSR mission has not been updated or costed for a decade, so we suggest that the MSR Program mission an independent engineering and cost estimate such a mission.

GROUNDBREAKING MARS SAMPLE RETURN FOR SCIENCE AND HUMAN EXPLORATION

Barbara Cohen, NASA MSFC, Barbara.A.Cohen@nasa.gov
With David Draper, Dean Eppler, Allan Treiman

Recommended reading:
MacPherson et al. (2002) GMSR Study for MSR Science Steering Group
Treiman et al. (2010) Decadal survey white paper (15 coauthors & 72 signatories)

LPRP and xPRP: Some Lessons Learned

- Both were precursor robotics programs with input from science, human exploration, and technology
- Missions (LRO, LCROSS) were responsive to science but were not meant to meet Decadal-level goals
- Missions were meant to be part of a series (flybys, orbiters, landers, sample return)
- Sample analysis in terrestrial labs was critical to address Strategic Knowledge Gaps related to geotechnical properties and mobility, mechanical and suit design, and human health assessment

Fun exercise: Revisit the notional xPRP Mars mission plans!
http://www.nasa.gov/pdf/457443main_EEWS_ExplorationsPrecursorRoboticMissions.pdf
Groundbreaking Mars Sample Return

- Is responsive to the astrobiological and chronological science goals of MEPAG, Decadal Survey, and E2E-iSAG
- Addresses the chemical & biochemical nature of the surface to fill “Strategic Knowledge Gaps” for human exploration of Mars
- Avoids the MSR appearance of lower priority MAX-C science coupled with initiation of large long term fiscal and political commitment
- Probably fits within cost constraints (cost bogey ~$1B)

Groundbreaking Mars Sample Return

- Most of the basic concepts about the Moon (and the basis of our understanding for all terrestrial planets) arose from compositions present just at Apollo 11 site, a “grab and go”
- For a similar Mars mission, sampling diversity can be achieved via a “locality sample” consisting of lithic fragments, soil, dust, and atmosphere at a single landing site
- Such a sample
  - Addresses a large fraction of Mars science objectives for sample return – including astrobiologic investigations
  - Provides significant risk mitigation for human exploration
  - Naturally enables several important technology advances
Mars Science Uniquely Addressed by GMSR

- Sample return uniquely benefits goals that rely on trace element analysis, isotopic analysis, independently reproduced results, experimental work, and fine-scale structures or minerals
- **Search for life**
  - Trace organics, biogenic elements & their isotopic compositions, biomarkers
- **Following the water**
  - Alteration rinds, hydrous minerals/veinlets, stable isotope fractionation
- **Surface processes**
  - Extent of regolith gardening, nature and thickness of coatings, exposure ages
- **Basic planetology**
  - Ages and compositions of materials set in geologic context, isotopic tracers of source regions and reservoirs
- **Ground truth / experience** for complementary missions
  - Enormous context for orbital missions
  - Feed-forward to later, more highly targeted MSR missions

<table>
<thead>
<tr>
<th>Group B. Humans to the Martian Surface</th>
<th>Orbital</th>
<th>Lander / In Situ</th>
<th>Sample Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Contamination to Earth.</td>
<td>None</td>
<td>Limited</td>
<td>Full</td>
</tr>
<tr>
<td>Dust Effects.</td>
<td></td>
<td>Limited</td>
<td>Full</td>
</tr>
<tr>
<td>Atmospheric ISRU.</td>
<td>Limited</td>
<td>Most</td>
<td>Full</td>
</tr>
<tr>
<td>Forward Contamination to Mars.</td>
<td>Limited</td>
<td>Limited</td>
<td>Full</td>
</tr>
<tr>
<td>Landing Site and Hazards.</td>
<td>Limited</td>
<td>Most</td>
<td>Full</td>
</tr>
<tr>
<td>Technology: Mars Surface.</td>
<td>Limited</td>
<td>Limited</td>
<td>Full</td>
</tr>
</tbody>
</table>
GMSR Architecture

- Many GMSR studies and architectures exist already (see references in our abstract and others in this session)
- GMSR architecture consists of a lander, extendable arm, simple sampling devices (scoop, sieve), and a context camera
- GMSR does without precision landing, extensive roving, and in situ instrumentation
- GMSR visits a site previously characterized by other missions to provide geologic context and design envelopes
- GMSR naturally incorporates technology desires in EDL, Mars ascent, and sample handling

Proof-of-Concept: Gusev Plains (iSAG ref site)

- Impacts strew basaltic rocks from Hesperian lava flow from at least 10 m depth
- Drifts of soil with particle sizes <2 mm formed from local rocks
- Rocks and dunes coated in bright dust with constant (global) composition
New Technologies Enabling GMSR

- Space Launch System (SLS)
  - Provides ~50 MT to TMI direct from Earth
  - This capability far exceeds the GMSR mission needs; possibility of sharing SLS launch capability and perhaps travelling to Mars after being launched to Earth-Moon L2 in an SLS reference mission
  - Alternatively, can use extra delivery mass to enable fully-powered descent
- Sky Crane
  - Enables 900 kg landed mass
- Miniaturized ascent thrusters
  - Missile-heritage thruster technologies Divert and Attitude Control Systems (DACS) tested at MSFC for lunar case, show promise for MAV (and maybe descent) stages (others later this session)
- SEP and/or solar sails
  - Enables lower-mass return-to-Earth stages (see N. Strange, L. Johnson abstracts)

GMSR: Worth Another Look

- GMSR achieves a significant overlap between fundamental Mars science, human exploration, and technology desires
  - Programmatic risks are bought down across all directorates
  - Meets political cadence and avoids multimission commitment
- New technology development (launch vehicles, landing technology, etc.) enables GMSR
- GMSR hasn't been seriously studied or costed for more than a decade

We recommend that the Mars Program commission a study of groundbreaking MSR as a mid-term mission, aiming for $1-1.2B class mission
<table>
<thead>
<tr>
<th>MEPAG Goal</th>
<th>Objective</th>
<th>Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOAL I.: DETERMINE IF LIFE EVER AROSE ON MARS</td>
<td>Objective A: Characterize past habitability and search for evidence of ancient life</td>
<td>Characterize major processes that degrade or preserve complex organic compounds, focusing particularly on characterizing oxidative effects in surface and near-surface environments (including determination of the “burial depth” in regolith or soils that may shield from such effects), the prevalence, extent, and type of exobiology, and potential mechanisms and rates for observing isotopic or biomarker information. Characterize organic chemistry, including stable isotopic composition and astrophysical information. Characterize co-occurring concentrations of possible biomarkers. Constrain the chronology of processes that degrade or preserve complex organic compounds. Determine the major processes that degrade or preserve complex organic compounds, focusing particularly on characterizing oxidative effects in surface and near-surface environments (including determination of the “burial depth” in regolith or soils that may shield from such effects), the prevalence, extent, and type of exobiology, and potential mechanisms and rates for observing isotopic or biomarker information. Characterize organic chemistry, including stable isotopic composition and astrophysical information. Characterize co-occurring concentrations of possible biomarkers. Constrain the chronology of processes that degrade or preserve complex organic compounds.</td>
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<tr>
<td></td>
<td>Objective B: Characterize present habitability and search for evidence of extant life</td>
<td>Evaluate the physicochemical conditions of actual surface regolith or rock environments, in terms of the potential for degradation or preserving biosignatures, and the effects of these processes on specific types of potential biosignatures. Seek evidence of ongoing metabolism in the form of rapid catalysis of for extant life, stable isotope fractionations within ongoing metabolic processes.</td>
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<td></td>
<td>Objective C: Determine how the long-term evolution of Mars affected the physical and chemical environment critical to habitability and the possible emergence of life</td>
<td>Constrain evolution in the geological, geophysical, and geochemical processes that control atmospheric, surface, and subsurface fluid chemistry, particularly as it affects on the preservation of isotopic or biomarker information. Characterize the nature and concentration of potential energy sources as a function of changing water availability, geophysical and geochemical evolution, and evolving atmospheric and surface conditions.</td>
</tr>
<tr>
<td>GOAL II: CLIATE ON MARS</td>
<td>Objective A.: Characterize Mars Atmosphere, Present Climate, and Climate Processes Under Current Orbital Configuration</td>
<td>Determine the chronology, including absolute ages, of compositional variability, and determine the record of recent climate change that are expressed in stratigraphy.</td>
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<tr>
<td></td>
<td>Objective B.: Characterize Mars Recent Climate and Climate Processes Under Different Orbital Configurations</td>
<td>Determine the chronology, including absolute ages, of compositional variability, and determine the record of recent climate change that are expressed in stratigraphy.</td>
</tr>
<tr>
<td></td>
<td>Objective C.: Characterize Mars Ancient Climate and Climate Processes</td>
<td>Determine the chronology, including absolute ages, of compositional variability, and determine the record of recent climate change that are expressed in stratigraphy.</td>
</tr>
<tr>
<td>GOAL III: DETERMINE THE EVOLUTION OF THE SURFACE AND INTERIOR OF MARS</td>
<td>Objective A.: Determine the nature and evolution of the geologic processes that have created and modified the Martian crust</td>
<td>Determine the formation and modification processes of the major geologic units and surface-regolith as observed in their primary and alteration mineralogy. Determine the formation and modification processes of the major geologic units and surface-regolith as observed in their primary and alteration mineralogy. Constrain the absolute ages of major Martian crustal processes, including sedimentation, diagenesis, alteration, and the dating rate. Constrain the absolute ages of major Martian crustal processes, including sedimentation, diagenesis, alteration, and the dating rate. Constrain the absolute ages of major Martian crustal processes, including sedimentation, diagenesis, alteration, and the dating rate.</td>
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<tr>
<td></td>
<td>Objective B.: Characterize the structure, composition, dynamics, and evolution of Mars’ interior</td>
<td>Determine the nature of crustal magnetization and its origin.</td>
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<tr>
<td></td>
<td>Objective C.: Understand the origin, evolution, composition and structure of Phobos and Deimos</td>
<td>Determine the chemical and thermal evolution of the planet, using mineralogy, geochemistry, and isotopic analysis of variouls in volcanic and plutonic rocks.</td>
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</tbody>
</table>