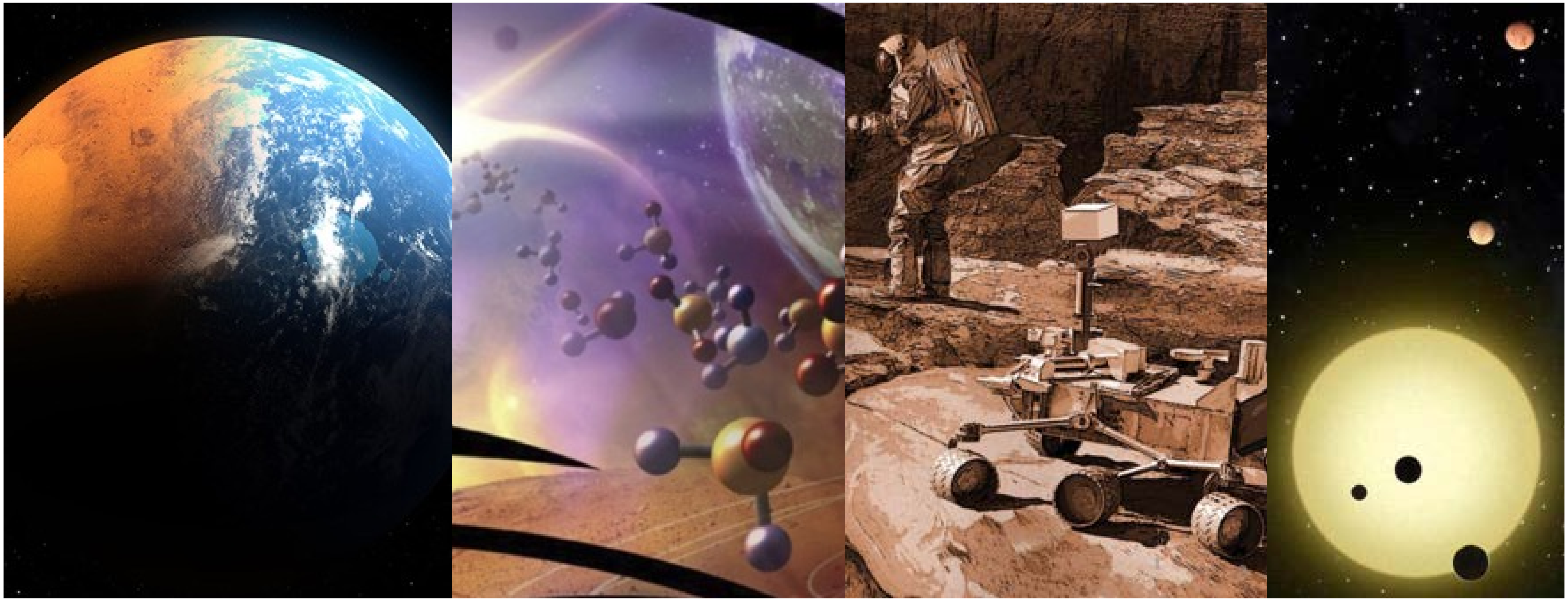
# Mars, The Nearest Habitable World –
## *A Comprehensive Program for Future Mars Exploration*



**Mars Architecture Strategy Working Group (MASWG)**

A Briefing of its Report for Consideration by the

**Planetary Sciences & Astrobiology Decadal Survey Mars Panel**

*Presented by Richard Zurek*
*Jet Propulsion Laboratory, California Institute of Technology*
*17 November 2020*

# MASWG Charter

- In response to the National Academies mid-decadal analysis, the Mars Architecture Strategy Working Group (MASWG) was formed by NASA's Planetary Science Division to:
  - Determine what could and should be done in the scientific exploration of Mars beyond (i.e., in addition to or after) the Mars Sample Return (MSR) campaign.
  - Survey the compelling science addressable by various classes of missions during the period 2020-2035, building on the science goals outlined in *Vision & Voyages* and updated in the *MEPAG Goals Document*.
  - Define mission candidates in various mission classes to guide future MEP planning including, but not necessarily restricted to, missions in the small-spacecraft, Discovery, and New Frontiers categories, which may also be considered by the upcoming Planetary Decadal Survey (2023-2032).
  - Define strategic technologies, infrastructure, and partnerships (international and commercial) that can enable compelling science in the specified time horizon, showing their programmatic linkage.

# MASWG Membership

*MASWG Members*

- Bruce Jakosky*, CU/LASP (chair)
- Rich Zurek, JPL/Caltech (co-chair)
- Shane Byrne, U. Arizona
- Wendy Calvin, U. Nevada Reno
- Shannon Curry, UC Berkeley
- Bethany Ehlmann*, Caltech/JPL
- Jen Eigenbrode, NASA/GSFC
- Tori Hoehler, NASA/Ames
- Briony Horgan, Purdue U.
- Scott Hubbard, Stanford U.
- Tom McCollom, CU/LASP
- Jack Mustard, Brown U.
- Than Putzig, PSI
- Michelle Rucker, NASA/JSC
- Michael Wolff, Space Science Inst.
- Robin Wordsworth*, Harvard U.

*Ex Officio*

- Michael Meyer, NASA HQ

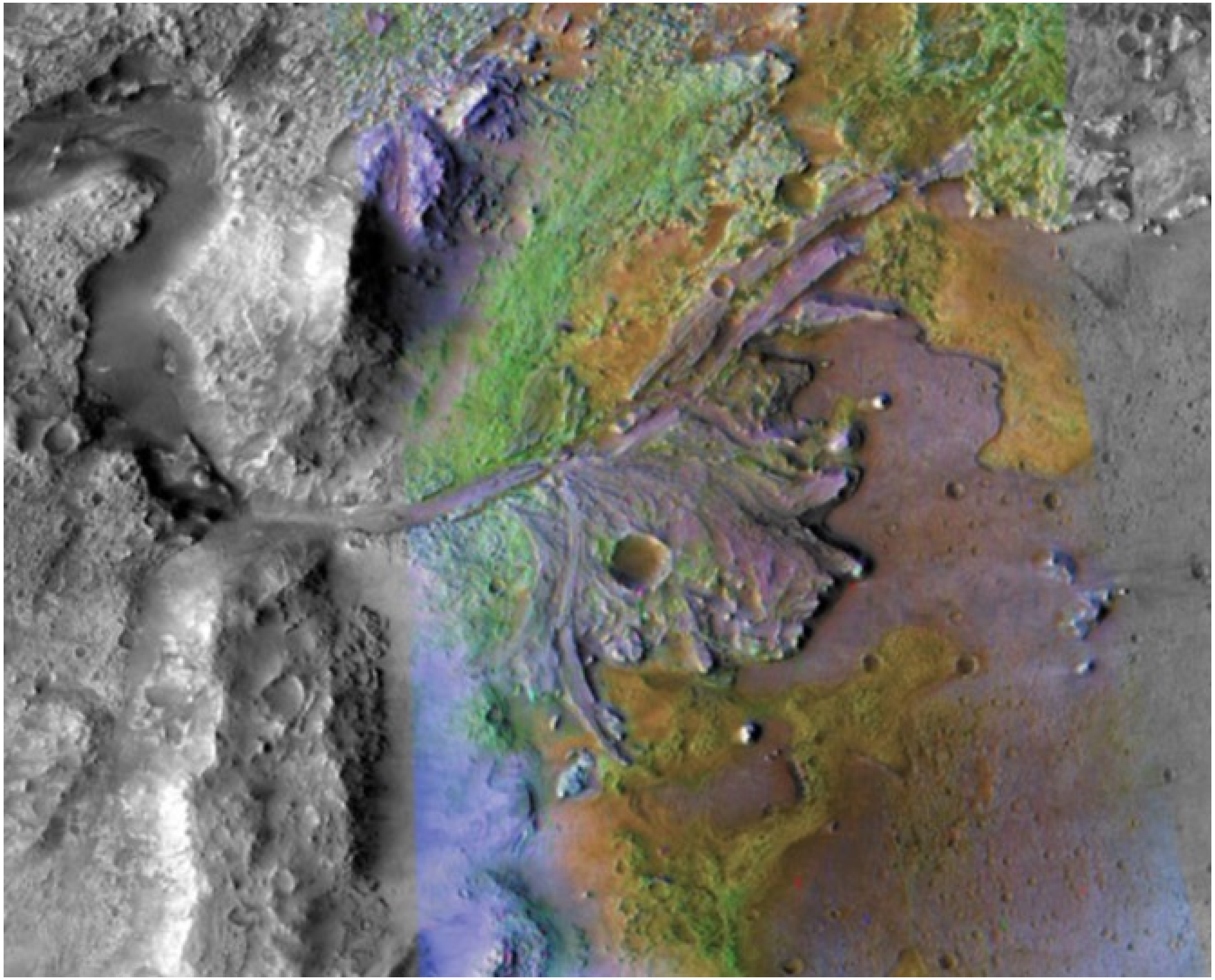
**Also members of the Mars Panel*

All slides presented here are based directly on the full text of the MASWG Report to NASA. That report can be found at:
[https://mepag.jpl.nasa.gov/reports/MASWG NASA Final Report 2020.pdf](https://mepag.jpl.nasa.gov/reports/MASWG NASA Final Report 2020.pdf)

# *Executive Summary*

- Mars has a physical and chemical record of planetary processes spanning more than 4 billion years. It provides an unparalleled opportunity to study the climate, geology, geophysics, and environment of a habitable planet.
- Mars Sample Return is important and should proceed, as it would produce a major step forward in our understanding of Mars, as envisioned by *Visions & Voyages*.
- Measurements/missions beyond MSR are required to address the full range of fundamental science objectives at Mars and to place the MSR results in the broader context of Mars planetary history and comparative planetology.
- A distinct and identifiable robotic Mars program is necessary to accomplish this compelling science and to help prepare for human missions, while complementing the MSR campaign.
    - A program provides feed-forward on both science and technology development, coordination across missions to achieve the science objectives, new coordination with international and corporate partners, and coordination with HEOMD to ensure that objectives necessary to support humans can be attained.
- A Mars program can most effectively address the full range of key science objectives by utilizing missions in all size classes, including the rapidly developing category of small spacecraft. The key is to match the mission class to the science objectives, spanning the range from small spacecraft up through at least New-Frontiers-class missions.
- We've defined four "mission arc" scenarios in different science areas *as examples* to demonstrate how a cost-effective Mars Exploration Program could, in concert with the Mars science community, pursue compelling science objectives across a suite of missions over the next fifteen years.

# Scientific Progress At Mars



# Mars Exploration Beyond Mars Sample Return

**Mars exploration over the last two decades has revealed:**

- A variety of environments that could have been habitable for microbes;
- An early more-Earth-like climate that changed dramatically over time;
- A geologically recent epoch of ice ages; and
- A dynamic planet that still changes today.

**Mars sample return flowed directly out of this program, as a way to address fundamental scientific issues about Mars:**

- The *Perseverance* rover is on its way to Jezero Crater, where it will explore an ancient deltaic environment and collect samples for possible future return.
- NASA and ESA have joined in partnership to develop the follow-on missions needed to bring those samples during the coming decade, as endorsed by *Visions and Voyages*.
- it will result in a *major* step forward for Mars and for planetary science, addressing scientific issues related to potential life, planetary formation and evolution

**MSR alone will not answer all of the fundamental questions about Mars.**

- The history of any one site must be integrated into the global context of a diverse planet
- The processes by which Mars evolved to its present state need to be understood
- Mars can address issues central to terrestrial planets in general and to exoplanets

# Mars Is A Compelling Target For Both Science And Exploration In Addition To Sample Return (1 of 2)

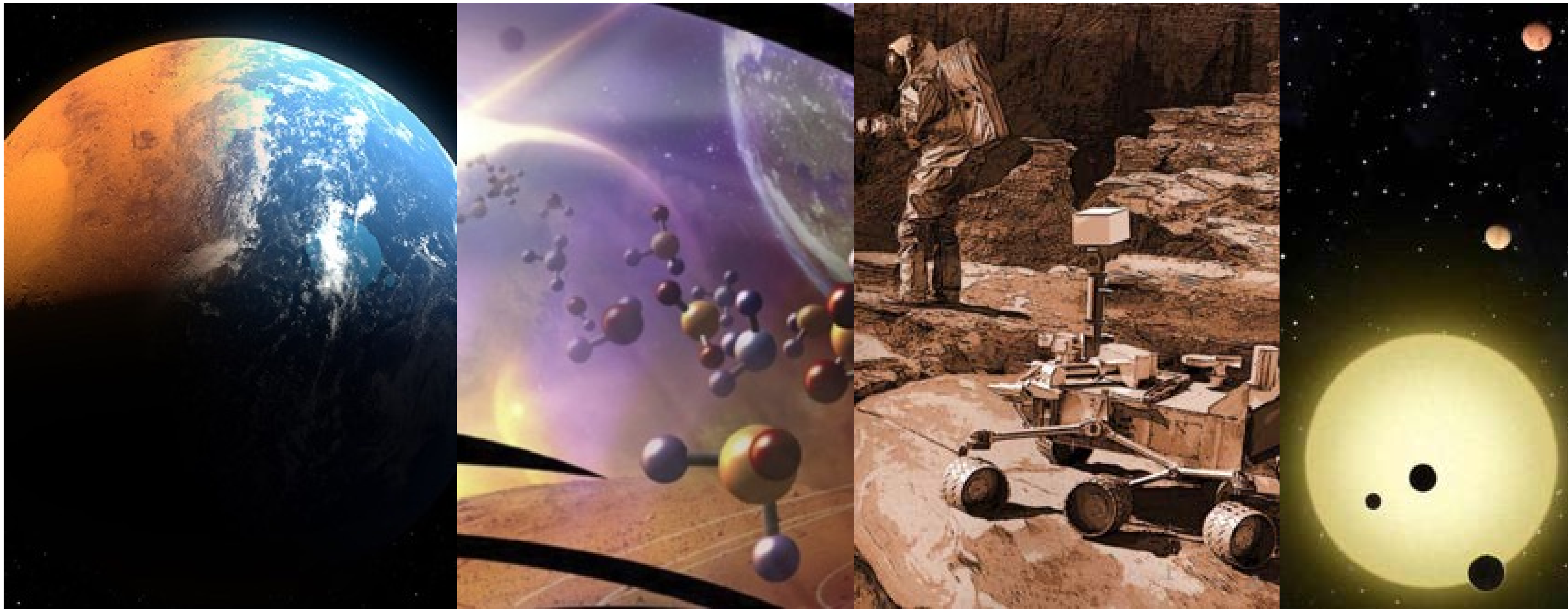
***Mars has a uniquely accessible archive of the long-term evolution of a habitable planet.*** *The well-exposed and preserved 4-billion-year record of physical and chemical planetary processes is unique in the solar system because of its preservation, accessibility, and importance to understanding planetary habitability. This record includes planetary formation, impact bombardment, interior and crustal processes, atmospheric and climate evolution, and potentially the origin and evolution of life on another planet.*

- **Mars presents outstanding access to environments fundamental to the search for past and/or present signs of life.** The prebiotic chemical evolution that led to the origins of life, and evidence of life's origins has been erased from Earth but terrain from this era is preserved and accessible on Mars. Whether life exists or not on Mars will inform our understanding of the origin(s) of life on Earth and beyond.
- **Mars offers an unparalleled opportunity to study climate and habitability as an evolving, system-level phenomenon.** The Martian climate has evolved dramatically through time, from one with abundant liquid water to today's cold and dry surface; habitability is a *time-dependent* phenomenon governed by interacting processes that occur over a range of spatial and temporal scales. The longevity and accessibility of Mars' rock and volatile record allows us to study the interacting interior, atmospheric, and impact drivers of climate and habitability, and their evolving nature. The present climate is observable directly. The record of past climate is stored in the volatile deposits of the polar caps, the crustal rock record, and today's atmosphere; this ancient record has been largely lost on the Earth.

# Mars Is A Compelling Target For Both Science And Exploration In Addition To Sample Return (2 of 2)

- **The best place in our solar system to study the first billion years of evolution of a terrestrial, habitable planet.** Access to pristine terrains that record the end of planetary formation, the coupled early geophysical and geological history, the early evolution of an atmosphere, and the potential for an origin of life is outstanding. These processes are not accessible on the Earth or Venus due to the paucity of unaltered ancient materials nor on the Moon and Mercury due to lack of coupling with atmospheric evolution and habitability.
- **Outstanding opportunities for elucidating the climate, prebiotic and possible biological history of Mars informs our understanding of the evolution of exoplanets.** Processes operating at Mars have operated, and may be operating currently on many planets around other stars. Mars is the only place with that record that we can study in detail. These fundamental problems of planetary evolution brings together our understanding of Earth, the terrestrial planets of our solar system, and beyond.
- **A compelling destination for human exploration and science-exploration synergism.** After the Moon, Mars is the next-most accessible destination for humans. Future human exploration and science investigations at Mars are complementary activities that can leverage advancements from each other. New science investigations (such as understanding the dust cycle and the formation of low-latitude ice deposits) support planning of human exploration activities. In turn, the arrival of humans at Mars will dramatically enhance our ability to achieve big-picture science objectives.

# Mars, The Nearest Habitable World – *Defining An Exploration Program*



*Reading the Martian record:*

- *Potential for life*
- *Mars' habitability and changing climate*
- *The first billion years of planetary evolution*
- *Using Mars to understand exoplanet evolution*
- *Mars as a destination for human exploration*

# Path Forward For Exploring Mars

MASWG conducted a detailed analysis of the science and mission needs for exploring Mars, and surveyed the emerging capabilities in order to provide a new vision of what the Mars Exploration Program, working alongside the MSR campaign, should be.

A focused Mars Exploration Program should:

- Prioritize the most important science, utilizing a range of mission size classes and science objectives that build on one another to meet the program objectives
- Leverage the development of new technical capabilities, including rapidly evolving small spacecraft that could enable measurements that address many key science objectives at Mars
- Work with different NASA directorates and international and commercial partners in new—and possibly radically different—ways
  - A successful Mars-focused CLPS-like program (perhaps Commercial Mars Payload Services [CoMPS]) could serve as a programmatic vehicle to allow development of technologies for future exploration as well as delivery of science payloads.
  - NASA and the Mars community should continue to explore, negotiate, and support international collaborations as a means of leveraging flight opportunities to achieve compelling science.

# MASWG High-Level Recommendations

1. Mars Sample Return should proceed as currently planned, as it would produce a major step forward in our understanding of Mars, as envisioned by *Visions & Voyages*.
2. NASA should support missions that address fundamental science objectives at Mars in addition to MSR, using the full range of technically viable mission classes. During the MSR era, the emphasis should be on achieving other high-priority science objectives, while developing the needed technologies for going forward.
3. For this next phase of Mars exploration, NASA should retain a programmatically distinct Mars Exploration Program. NASA should institute mission or budget lines that can allow Mars-specific missions, from small spacecraft through New-Frontiers-class missions, to be strategically integrated into a program, with missions chosen and implemented as appropriate for the science to be achieved.
4. To the extent possible, missions and instruments should be openly competed; where specific investigations are desired, objectives can be defined and then opened to competition.
5. A robust Mars exploration program will require affordable access to multiple places on the Martian surface and affordable long-lived orbiters. NASA should invest early to expedite the rapidly evolving small spacecraft technologies and procedures to achieve these capabilities at lower costs than past missions.

# MASWG Detailed Recommendations For A Successful Future Mars Exploration Program (1 of 2)

**6. The guiding principles required to drive the program should include:**

- **Be responsive to discoveries by ongoing and new missions;**
- **Address science priorities as defined by the Decadal Survey and by MEPAG;**
- **Have missions build on each other both scientifically and technologically;**
- **Compete missions or payload elements to the extent possible within strategic direction;**
- **Inject a sufficient number of flight opportunities to sustain technical capability and to achieve steady progress on key goals; frequent missions may be essential to attracting the commercial sector and international partners;**
- **The choice of mission class should be determined by the specific science objectives.**

7. Program should be sustained at a steady funding level, with commensurate results. The size and scope of the program — and therefore the progress that it can make — will depend upon the resources provided.

**8. Utilize a line of PI-led small spacecraft, Discovery and New-Frontiers-class missions, competed in a separate program line while addressing strategic goals.**

9. The Program should have a protected, adequately funded, and competed technology development program to advance instrumentation and developments in key areas (e.g., as has been done for the Mars Ascent Vehicle). The technology invested should be focused and leveraged within NASA and with other agency and commercial entities.

**10. With regard to technology development, a critical need for Mars exploration is that NASA develop low-cost approaches for entry vehicles at all size classes, including entry, descent, and landing.**

# MASWG Detailed Recommendations For A Successful Future Mars Exploration Program (2 of 2)

11. NASA should develop low-cost approaches for long-lived orbiting small spacecraft and for aerial vehicles, landers, and rovers to provide access and mobility after landing.

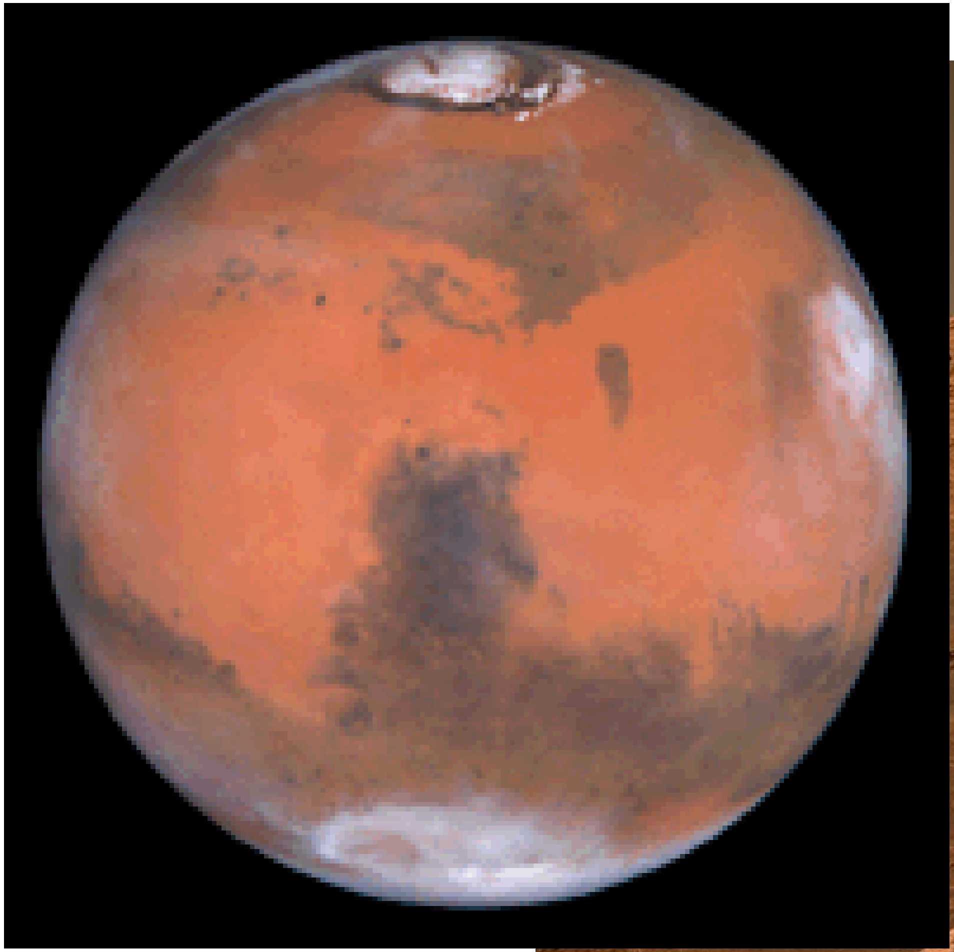
**12. NASA and the Mars community should study the feasibility of adapting the CLPS program to Mars.**

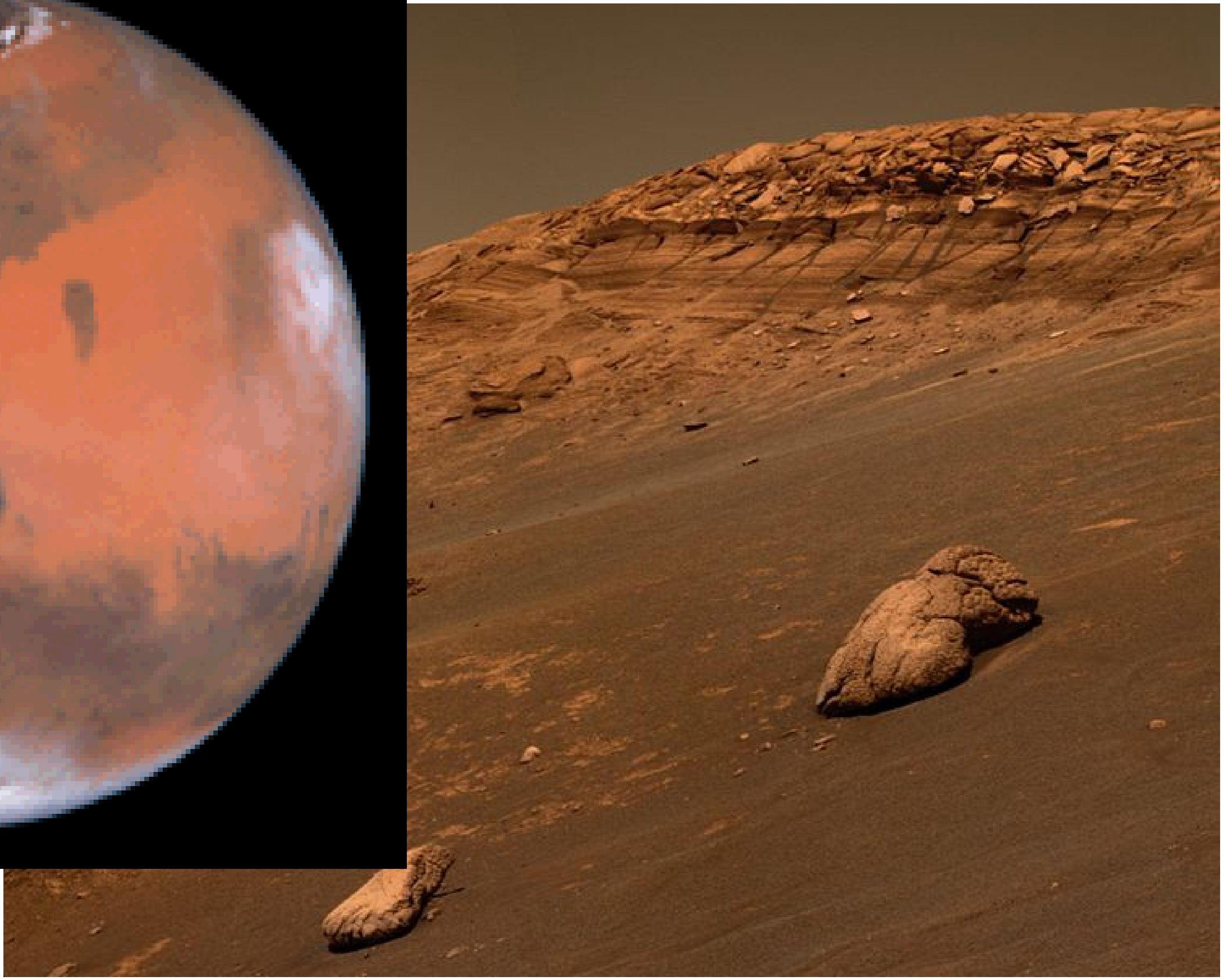
13. NASA and the Mars community should continue to explore, negotiate, and support international collaborations as a means of leveraging flight opportunities to achieve compelling science.
    - Involve the respective scientific communities in the definition and execution of joint missions
    - To the extent possible, missions & instruments should be competed openly to get the best science
    - Financially support the mission participants adequately to achieve their mission objectives (Instrument Teams, Science Team members, Participating Scientists, Interdisciplinary Scientists).

14. Adequately fund the analysis of returned mission data so results can be achieved in timely fashion; support extended missions as long as they make solid scientific progress.

**15. Enhance interactions between the revitalized Mars Exploration Program and the Human Exploration & Operations Mission Directorate (HEOMD) to define needs and the opportunities to address them. Coordination would ensure that:**
    - **Adequate, accurate, and appropriate Mars knowledge and experience is provided in support of human missions**
    - **Scientific progress will be sustained and advanced by missions with humans when they do fly.**

# Program Architecture: Mission Arcs and Scope





# Example Mars Exploration Program: Definition of Mission Arcs

- To demonstrate how a Mars Exploration Program could pursue compelling science objectives while utilizing a suite of missions, we have defined four “mission arcs” or scenarios; these are examples and do not encompass the entire range of compelling options.
- *There are other potential “arcs”.* The ones cited here are meant to demonstrate that such strategically linked, compelling arcs exist.
- In most cases there is a progression from building on what is known today (e.g., diverse environments) to more-capable missions. The increased capability is typically driven by the payload as more-complex measurements are needed to follow up earlier discoveries or more-challenging science objectives.
- While individual missions in a mission arc could be achieved through the Discovery/New Frontiers competitive process, inclusion in a strategic program line would ensure a consistent approach with missions building on one another and being synergistic with each other. *New Frontiers should not be closed to Mars missions if missions of that class were prohibited by inadequate funding of the Mars program.*

# Mission Arc Brief Descriptions

- Diverse Ancient Environments & Habitability
  - Explore diversity of ancient Mars, following up on the thousands of possible sites, to understand early planetary evolution and the nature, timing and geochemistry of environments, habitability, and/or biological potential of Mars.
  - *Would greatly benefit from lower cost /smaller mission access to the surface.*
- Subsurface Structure, Composition & Possible Life
  - The subsurface of Mars is largely unexplored and yet its structure and composition holds many clues to the early evolution of Mars. Further, it could be the refuge of an early Martian biosphere.
  - *There are smaller mission concepts that could take the first steps, but this is new—and exciting--territory*
- Ice: Geologically Recent Climate Change
  - Understand Martian ice ages in terms of the distribution and stratification of ice as it was emplaced/removed over the last hundred million years, both in the polar regions and at lower latitudes.
  - *The real first steps here are probably discovery class missions, building on what we know. Strong intersection between science and resource utilization.*
- Atmospheric Processes and Climate Variability
  - Record variability of the current climate from hours to decades and the processes of transport and photochemistry, Sun-Mars interactions, exchange of water, dust, $CO_2$ and trace gases.
  - *We know how to make progress here with smaller spacecraft, permitting an early start on filling strategic gaps in our time-space coverage for both science and design of human missions.*

# Mission Arc Detailed Example — Ice: Geologically Recent Climate Change

<u>Compelling Science</u>: Understand Martian ice ages in terms of the distribution and stratification of ice as it was emplaced/removed over the last hundred million years, both in the polar regions and in lower latitudes.

<u>Goals</u>: *Climate Change*: Exploit the detailed record preserved in ice deposits, understand processes, quantify relation to orbital cycles. *Biochemistry*: Seek evidence of past or extant life preserved in ice. *Resources*: Are there deposits suitable for supporting human activities on Mars?

<u>Mission Arc</u>:

- Phase 1: Determine extent and stratification of near-surface ice across the planet from orbit.
  - **SSc**: Polar energy balance mission: Are the caps seen today growing or shrinking?
  - **DSc**: Synthetic aperture radar and radar sounding. Synergistic with subsurface Mission Arcs #1-2; or
  - **NFc**: Would combine radar and high-resolution stereo imaging, potentially with spectrometers for ice discrimination and thermal inertia (depth to ice); aids characterization of diverse sites (Arc #1).
- Phase 2: Quantify drivers of ice emplacement /removal.
  - **DSc**: Landed imaging, shallow drilling /trenching, meteorology on polar cap and/or layered terrains. Complementary to low-latitude field work (#4).
- Phase 3: Observe and analyze detailed ice stratigraphy.
  - **NFc/FLG**: Landed imaging, deeper drilling and meteorology on polar cap ice even in the polar night.

# Prototypical Mission Arcs: Surface & Subsurface

*Possible Examples of Linked Missions Achieving Compelling Science*

**1. Diverse Ancient Environments & Habitability**

Compelling Science: Explore diversity of ancient Mars, following up on the thousands of possible sites, to understand early planetary evolution and the nature, timing and geochemistry of environments, habitability, and/or biological potential of Mars.

Goals: Quantify relative timing of major climatic / geologic / biochemical events and transitions, in order to understand planetary evolution and biotic/pre-biotic change.

Mission Arc:

- Phase 1: High-spatial resolution mineralogy (≤ 6 m/pixel) from orbit to find best sites.
  - **SSc**: Mineral mapping by orbital spectroscopy
  - **DSc**: Spectral and visual imaging from orbit. Synergistic with Arc #3.
- Phase 2: Surface exploration of a subset of these environments with small landers.
  - **SSc**: Investigation of multiple sites using pin-point landing, mobility (air, ground).
  - ***Tech enabler*: *Affordable access to dozens of sites in the small spacecraft class.***
- Phase 3: In-depth characterization of most promising sites in terms of geochemistry, mineralogy and biosignatures.
  - **NFc**: Detailed in situ imaging and spectroscopy, biogeochemical sampling and analysis, age dating.
  - **FLG**: Life / biosignature analysis; 2$^{nd}$ MSR?

**2. Subsurface Structure, Composition & possible Life**

Compelling Science: The subsurface of Mars is largely unexplored and yet its structure and composition holds many clues to the early evolution of Mars. Further, it could be the refuge of an early Martian biosphere.

Goal: Explore the subsurface of Mars for water, chemical gradients and signs of extant life.

Mission Arc:

- Phase 1: Orbiter missions to: 1) improve surface magnetism and gravity maps and 2) map ice structures and geomorphology beneath dust-covered terrains.
  - **SSC**: Low-altitude magnetic survey & gravity mapping
  - **DSc/NFc**: Orbiter with radar imager & sounder. Synergistic with Ice science Arc #3.
- Phase 2: Land electromagnetic sounders and active-source-seismic devices at key surface locations from which to remotely probe subsurface structure, conductivity, geochemical gradients.
  - **SSc/DSc**: Dedicated to landed remote EM sounding and active-source seismic devices; trace gas fluxes. ***Tech enabler: Affordable access to multiple sites.***
- Phase 3: At most-promising sites, drill/investigate to great depths, with in situ biogeochemical analysis.
  - **NFc/FLG**: Probe deeper at the most promising sites revealed in Phase 2.
  - ***Tech enabler: More advanced instrumentation, active devices & drilling techniques*. Access to subsurface portals (e.g., caves, vents, cliffs, canyons)**
  - **NFc**: Prove out potential resources for ISRU by humans

# Prototypical Mission Arcs: Climate and Climate Change

*Possible Examples of Linked Missions Achieving Compelling Science*

**3. Ice: Geologically Recent Climate Change**

Compelling Science: Understand Martian ice ages in terms of the distribution and stratification of ice as it was emplaced/removed over the last hundred million years, both in the polar regions and in lower latitudes.

Goals: *Climate Change*: Exploit the detailed record preserved in ice deposits, understand processes, quantify relation to orbital cycles. *Biochemistry*: Seek evidence of past or extant life preserved in ice. *Resources*: Are there deposits suitable for supporting human activities on Mars?

Mission Arc:

- Phase 1: Determine extent and stratification of near-surface ice across the planet from orbit.
  - **SSc**: Polar energy balance mission
  - **DSc**: Synthetic aperture radar and radar sounding. Synergistic with subsurface Mission Arcs #1-2; OR
  - **NFc**: Would combine radar and high-resolution stereo imaging, potentially with spectrometers for ice discrimination and thermal inertia (depth to ice); aids characterization of diverse sites (Arc #1).
- Phase 2: Quantify drivers of ice emplacement /removal.
  - **DSc**: Landed imaging, shallow drilling /trenching, meteorology on polar cap and/or layered terrains. Complementary to low-latitude field work (#4).
- Phase 3: Observe and analyze detailed ice stratigraphy.
  - **NFc/FLG**: Landed imaging, deeper drilling and meteorology on polar cap ice even in the polar night.

**4. Atmospheric Processes and Climate Variability**

Compelling Science: Record variability of the current climate from hours to decades and the processes of transport and photochemistry, Sun-Mars interactions, exchange of water, dust, $CO_2$ and trace gases.

Goals: *Climate*: Understand processes of climate evolution, including validation and improvement of models used to understand climate change over time. *Strategic Knowledge*: Provide environmental data for design and implementation of robotic and human missions.

Mission Arc:

- Phase 1: Climate Variability & Strategic Knowledge
  - **SSc**: Multiple, long-lived SSc to achieve global and local time coverage (e.g., areostationary), and long-term records of : Temperature/pressure, winds, and aerosols & water (columns and profiles). ***Tech enabler*: *Long-lived small spacecraft.***
  - **DSc**: Multiple measurements on one spacecraft, including active sensors (e.g., lidar for winds, aerosols). Support for SSc constellation.
- Phase 2: Improve understanding of climate processes (non-polar ice); complement ice landed missions (Arc #3).
  - **DSc**: Intensive 1-2 non-polar field campaigns to understand dust storm onset, water vapor and momentum exchange, and trace gas transfer.
- Phase 3: Understand boundary layer/surface exchange
  - **NFc**: Network of landed stations to profile boundary layer fields and measure near-surface fluxes across Mars. (Measurements should be simultaneous with fields measured by small satellites.)

# Rough Costs Of Potential Program

*Table VI-5 from the MASWG Report to NASA.*

*Mission numbers and estimated costs for the four mission arcs. Costs were roughly estimated assuming full life-cycle cost (including launch) of $200M for SSc, $750M for DSc and $1250M for NFc mission classes. The programmatic support line is specific to these mission arcs; it does not include current R&A, extension of current missions (including Perseverance), or costs associated with handling and analysis of samples returned by the MSR campaign.*

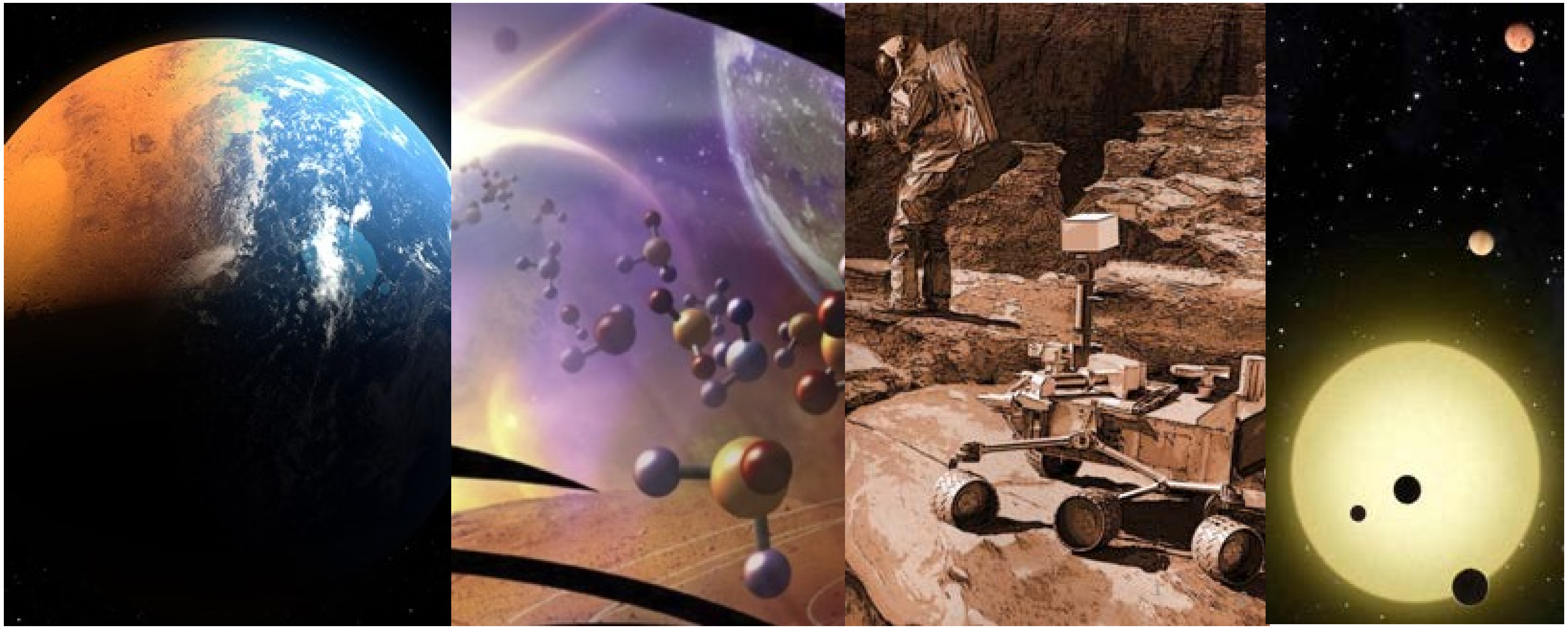
| TABLE VI-5: Mission Arcs & Program Scope | | | |
|---|---|---|---|
| Mission Arc | 2021-2030 | 2031-2035 | Key Technology |
| Arc 1: Diverse Environments | 4 SSC, 1 DSc | 1 NFc, 1 SSc | Small Landers |
| Arc 2: Subsurface Habitability | 1 SSC, 1 DSc | 1 DSc, 1 NFc | Drilling, In Situ Analysis |
| Arc 3: Ice Science | 1 SSC, 1 DSc | 1 DSc, 1 NFc | Ice Landers |
| Arc 4: Climate Variability and Processes | 4 SSC, 1 DSc | 1 SSc, 1 NFc | Long-lived SSc, Network Landers |
| Assuming Progress on several Arcs | ~$300M / yr (8 SSc, 2 DSc) | $500M / yr (2 SSc, DSc, NFc) | |
| Assuming Progress ~2 Arcs | ~$150M / yr (4 SSc, 1 DSc) | $300M / yr (SSC + NFc or 3 SSC + DFc ) | |
| Programmatic Support: Technology, Extended Missions, Instruments, Data Analysis | $150M / yr (additional) | $150M / yr (additional) | Key: Affordable access to the Mars surface |

*Note: Mission cost assumptions in this document are of a budgetary and planning nature and are intended for informational purposes only. They do not constitute a commitment by NASA.*

# A Program for the Exploration of Mars—the Nearest Habitable World

- ***Scientific:*** Mars provides the best opportunity to explore the full range of processes and properties on terrestrial planets under different boundary conditions from Earth, including interactions between geological, geophysical, climate/atmosphere, space weather, and potential biological processes
  - Mars' entire history is preserved in an accessible rock record that includes, almost uniquely amongst solar system planets, the first billion years
  - Mars has key similarities with the Earth to allow us to understand the processes that operated, with enough differences to truly test our understanding
  - Complete MSR which will provide a major step forward in our understanding of Mars; however, it alone cannot answer the many fundamental questions that remain.
  - We need additional flight missions to make further progress on the compelling science—missions that build on and are synergistic with each other. Small spacecraft offer enticing opportunities to make progress more affordably.
- ***Programmatic:*** Mars is accessible enough to allow multiple missions necessary to explore the different components of the Mars environment and their interactions with each other, including substantial access to the surface and subsurface
  - Allows substantial progress to be made on major scientific questions
  - Frequency of opportunities may be essential to attracting the commercial sector and international participation
- ***Exploration:*** Mars is NASA's stated long-term destination for human exploration; NASA needs the right information to do that safely and efficiently and to plan the best science to be conducted once humans are on the planet

# Back-Up



# Summary Of Findings (1 of 2)

1. Many of the most compelling scientific objectives needed to address planetary (including exoplanet) questions can be most effectively achieved at Mars, and a coherent Mars program is required to make the best progress on those objectives.
2. Two decades of exploring Mars from orbit and on the surface have revealed a currently dynamic planet with a diversity of ancient environments, many with the necessary conditions for habitability and clues to their evolutionary history.
3. For both science and exploration by humans, Mars has the compelling advantages of being the most easily accessible planet by both robotic and human missions and retaining a record of its geological, climate, and perhaps biological history throughout time.
4. Mars Sample Return represents a major step forward, is the key flagship mission for Mars, and should be completed. However, the currently envisioned MSR would give us an exquisitely detailed understanding of one carefully chosen place on Mars. Many important science objectives exist that go well beyond what can be accomplished with MSR, providing a systematic look at a dynamic planet.
5. A Mars program can most effectively address the full range of key science objectives by appropriately utilizing missions in all size classes, in addition to MSR. The key is to match the mission class to the science objective.

# Summary Of Findings (2 of 2)

6. Rapidly evolving small-spacecraft technologies and procedures could address many key science objectives. This class of missions could revolutionize robotic exploration of Mars. The most critical need is for affordable access to multiple places on the Martian surface with adequate payload/mobility.
7. Purely commercial or commercial-government partnerships for exploring or supporting the exploration of Mars, where the private entity bears a reasonable fraction of the investment risk are in their formative stages but do not currently exist for Mars. A Mars-focused CLPS-like program could allow technology development for future exploration as well as delivery of science payloads.
8. There is tremendous value in developing collaborations between the many different governments and entities interested in Mars exploration.
9. The scientific and the human explorations of Mars are inextricably intertwined. Addressing science objectives will be an integral part of upcoming human exploration, and preparing for future human exploration provides one of the rationales behind having a vigorous robotic Mars scientific exploration program today.

# Small Spacecraft For Mars: A Programmatic Opportunity (1 of 2)

- The term "small spacecraft" encompass a wide range of concepts, depending on the science objectives and observation requirements. The ongoing rapid development of small-spacecraft capabilities has the potential to revolutionize Moon and Mars exploration by providing more affordable and more frequent flight of payloads for scientific exploration and for support of human exploration needs.
  - Many science objectives will need to be addressed by the more capable Discovery- and New-Frontiers-class missions, as demonstrated by past missions and as needed in the pursuit of the most challenging objectives (e.g., sample return).
  - Even so, extensive use of small spacecraft at Mars is particularly appealing during an otherwise MSR-focused decade because such use could facilitate a complementary Mars exploration program that achieves high-priority science with frequent launches at an affordable cost, while opening the way for commercial participation.
  - In order to develop small-spacecraft Mars missions that have their scientific results integrate into a compelling whole (as opposed to having unconnected missions), small spacecraft have to be planned and implemented through a distinct Mars program.
- Key to reducing costs is strategic investment in propulsion and communications systems to enable deep-space small spacecraft, the ongoing reduction in mass and cost of capable instruments and subsystems, elimination of dual-string systems, and appropriate relaxation of oversight requirements.
  - Earlier Mars missions have had both success (e.g., Mars Pathfinder, Mars Odyssey, MARCO) and failure (Mars Climate Orbiter, Mars Polar Lander, Deep Space 2) with this approach
  - The Commercial Lunar Payload Services program is pioneering an approach of private companies proposing their own designs to provide services at lower costs; an equivalent Commercial Mars Payload Services might be able to operate in a similar fashion
- However, the ability to sustain a flight program of multiple missions funded by taxpayer dollars requires that an appropriate risk posture (with adequate funding) be used to ensure a reasonable probability of success.

# Small Spacecraft For Mars: A Programmatic Opportunity (2 of 2)

- In that vein, the cost/requirements/performance relationships for small spacecraft have not yet been demonstrated in deep space.
  - First round of planetary SIMPLEx missions are still in development, and other concepts have not yet flown
  - Viability of class D or single-string missions for planetary (including cost trade-offs) needs to be determined for specific objectives; e.g., longer-lived smallsats or a cadence of smallsats would be needed to capture climate variability over multiple Mars years
  - Significant tailoring of requirements from 7120.5 may be needed
  - Planetary protection issues and costs for small spacecraft will have to be addressed (see Appendix C).

- The Mars program needs to develop this potential by matching spacecraft class and capabilities to the mission objectives within a reasonable risk/cost profile. This would be done programmatically by:
  - Choosing missions in the appropriate size class while integrating them into coherent program lines that can achieve major science objectives
  - Set the requirements early and realistically on spacecraft size, capability and longevity
  - Match the level of oversight to the mission complexity and the skill and experience of the team and partners
  - Develop and/or leverage key technical capabilities (e.g., smaller landers, long-lived small orbiters, instrumentation)
  - Assist the process for transit to Mars, including early identification of rideshare opportunities, and maintain the communications infrastructure needed to support data return; otherwise these can be drivers to mission class.

# A Mars Program Could Achieve Key Science Goals Utilizing Missions at Different Cost Levels

- High-priority science goals can be accomplished using a range of classes from Small Spacecraft (SSc) to Flagship (FLG). The goals are linked to mission classes and mission arcs (M-Arc) below.
- Recent developments in miniaturized instruments and small spacecraft may enable some objectives traditionally satisfied with many-instrument, New-Frontiers-class (NFc) missions to instead be distributed to multiple craft, each making 1-2 measurement at a lower price point. *The creativity of the community should not be underestimated!*
- It is necessary to match the mission class to the science objective in a strategically planned program.

| Science Goal Mission Element | M-Arc | SSc | DSc | NFc | FLG |
|---|---|---|---|---|---|
| Orbit-based characterization of atmospheric circulation, transport processes | 3,4 | achieves | achieves | | |
| Transport of dust/aerosols and their relationship to atmospheric escape and climate | 4 | achieves | achieves | | |
| Low-altitude global magnetic field survey, gravity mapping | 2 | possible | achieves | | |
| Environmental transitions in the ancient record by high resolution orbital imaging spectroscopy | 1 | possible | achieves | | |
| **In-situ** geophysics (subsurface ice/water w/ resistivity, GPR; seismo., magnetism) | 2 | possible | achieves | achieves | |
| **In situ** surface-atmosphere boundary layer interactions (trace gas measurements) | 4 | possible | achieves | achieves | |
| **In situ, mobile** geological explorers for characterizing ancient habitable environments, environmental change, organics detection | 1 | possible | possible | achieves | achieves |
| Global orbital radar mapping of ice reservoirs | 3 | | possible | achieves | achieves |
| **In situ** mid-latitude ice sampling for characterization | 3 | | possible | achieves | achieves |
| **In situ** polar layer deposit climate record determination | 3 | | | possible | achieves |
| **In situ** geochronology for Martian and solar system chronology | 1,2,3 | | | possible | achieves |
| **In situ** life/organics detection in Martian ice, deep subsurface | 1,2,3 | | | possible | achieves |

possible or partial priority science at this class | achieves priority science at this class

# Mission Arcs: Mission Classes

The mission classes envisioned here are defined by:

- **SSc** denotes Small Spacecraft class. The life-cycle costs (including launch vehicle and Phase E ops/science) are taken to be in the range of $100-300M[1]. There was considerable debate about this cost range.
  - o The SIMPLeX cost cap was viewed by many as being too restrictive to achieve compelling science. That cap is ~$55M, not including Phase E or launch costs, which are included here.
  - o It seemed prudent to use a conservative upper-bound cost until the first such missions to Mars have been successful.
  - o All agreed that some of the needed missions could be in the lower half of the range, but some objectives (e.g., the need for long-lived climate observers) may require the upper part of the range.
  - o If the cost of successful small spacecraft missions is in the lower half of the cost range, more small spacecraft can be flown, which would boost several of the missions arcs (especially #1 and #4) envisioned here.
- **DSc** and **NFc** describe missions having objectives and requiring resources similar to the Discovery and New Frontiers classes, respectively.
- **FLG** describes a flagship-class mission.

[1] *Mission cost assumptions in this document are from the MASWG report to NASA. They are of a budgetary and planning nature and are intended for informational purposes only. They do not constitute a commitment by NASA.*