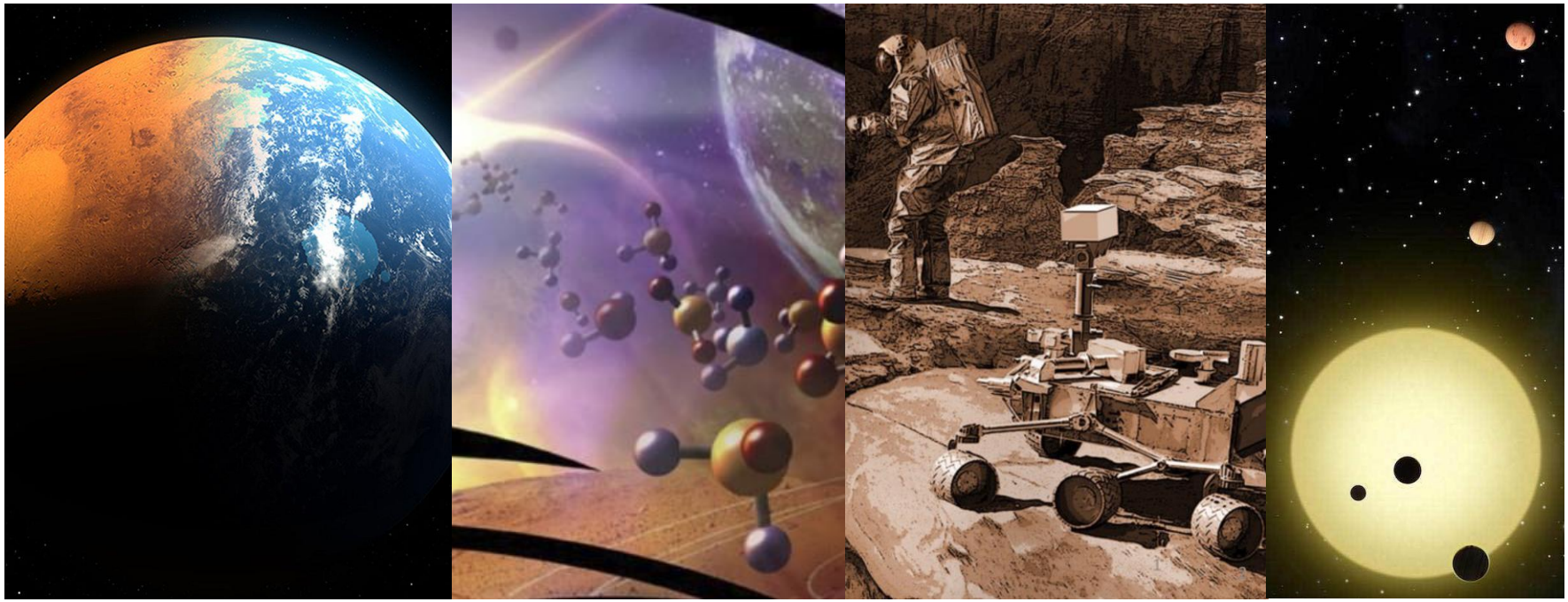
Mars, The Nearest Habitable World –
A Comprehensive Program for Future Mars Exploration



Mars Architecture Strategy Working Group (MASWG)
Preliminary Results
Presentation to MEPAG, 26 June 2020

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Preliminary Findings and Recommendations for Discussion and Feedback

MASWG is requesting input and feedback on the concepts and discussion in this presentation. Please send comments to MASWG-Feedback@jpl.nasa.gov, no later than 10 July.

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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 habitability of a terrestrial planet.
- A distinct and identifiable robotic Mars program, separately funded, is necessary to accomplish this compelling science and to help prepare for human missions. A program provides feed-forward on both science and technology development, coordination across missions to achieve the science objectives, 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 appropriately utilizing missions in all size classes, in addition to MSR. 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 pursue compelling science objectives across a suite of missions over the next fifteen years.

MASWG Origins and Charter

- The NAS Mid-Term Decadal Survey committee (co-chaired by Louise Proctor and Joe Rothenberg) recommended that:

  "NASA should develop a comprehensive Mars Exploration Program (MEP) architecture, strategic plan, management structure, partnerships (including commercial partnerships), and budget that address the science goals for Mars exploration outlined in Visions and Voyages."

- In response, 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 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)
- Shane Byrne, U. Arizona
- Wendy Calvin, U. Nevada Reno
- Shannon Curry, UC Berkeley
- Bethany Ehlmann, Caltech/JPL
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- Briony Horgan, Purdue U.
- Scott Hubbard, Stanford U.
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- Than Putzig, PSI
- Michelle Rucker, NASA/JSC
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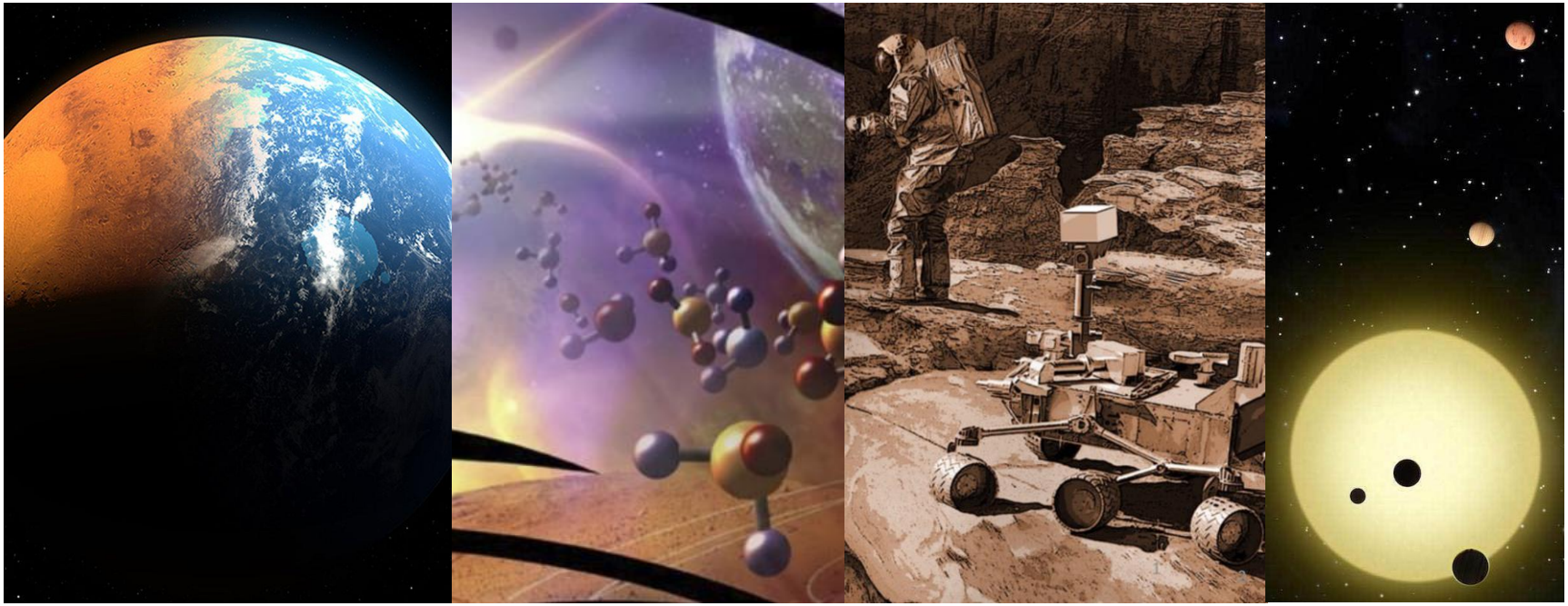
- Robin Wordsworth, Harvard U.

Ex Officio

- Michael Meyer, NASA HQ
- Rich Zurek, Mars Program Office, JPL[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, operated under contract to NASA

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*

Mars Is A Compelling Target For Both Science And Exploration (1 of 2)

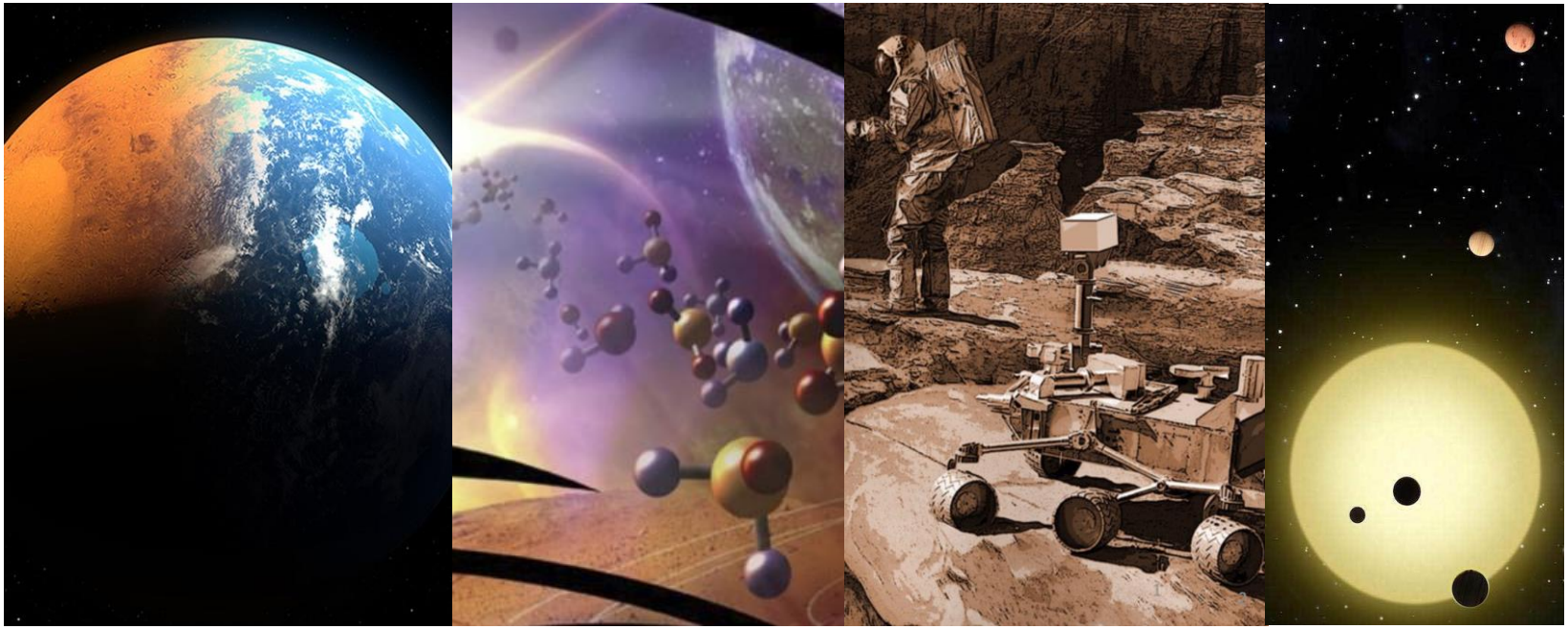
Mars has a uniquely accessible archive of the long-term evolution of a habitable planet. *The well-exposed and preserved 4-billion-year record of physical and chemical planetary processes is unique in the solar system because of its preservation, accessibility, and importance to understanding planetary 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 (2 of 2)

- **The best place in our solar system to study the first billion years of evolution of a terrestrial, habitable planet is Mars.** 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. (See Appendix D.)
- **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.

Findings



High-Level 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. As currently envisioned, MSR would give us an exquisitely detailed understanding of one carefully chosen place on Mars. Many fundamental 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.

* *See Appendix A for full details of findings*

High-Level 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.

Why Does Mars Need A Program?

- *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 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 models and our understanding
- *Programmatic:* Mars is accessible enough to allow multiple missions to explore the different components of the Mars environment and their interactions with each other, including substantial access to the surface
- *Exploration:* Mars is NASA's stated long-term destination for human exploration

The Mars Program Should Be (And Mostly Is) Doing These Things:

- Allows coordination and continuity between missions to achieve science objectives beyond what a single mission or even a series of one-off missions could accomplish
- Provides feed-forward between missions on both science and technology, including use of small spacecraft as proof of concept for innovative approaches or measurements
- Allows development of infrastructure that can serve multiple missions (e.g., comm. relay from orbit, landing-site selection)
- Allows effective negotiation and coordination with international and commercial partners to take advantage of the tremendous interest in exploring Mars
- Allows focused development of required spacecraft and instrument technology in advance of mission selection (e.g., MAV development for MSR)
- Allows coordination with HEOMD to ensure strong connections between the human and robotic programs for Mars

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

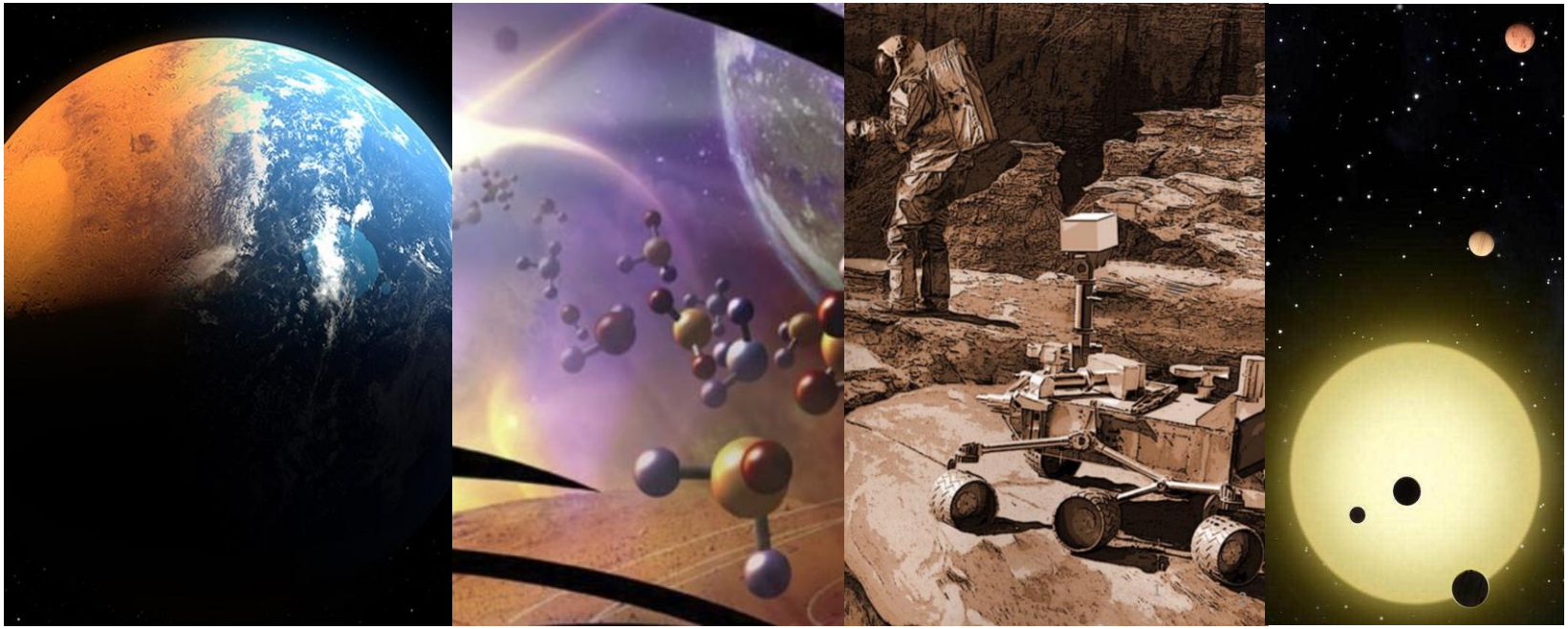
- The term “small spacecraft” encompass a wide range of concepts, depending on the science objectives and observation requirements. The ongoing rapid development of small-spacecraft capabilities has the potential to revolutionize Moon and Mars exploration by providing more affordable and more frequent 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.

Recommendations



MASWG High-Level Recommendations

1. Mars Sample Return should proceed as currently planned, as it will 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. 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.
4. 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.*
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.

The following charts describe what MASWG believes are the necessary attributes of this Mars Exploration Program.

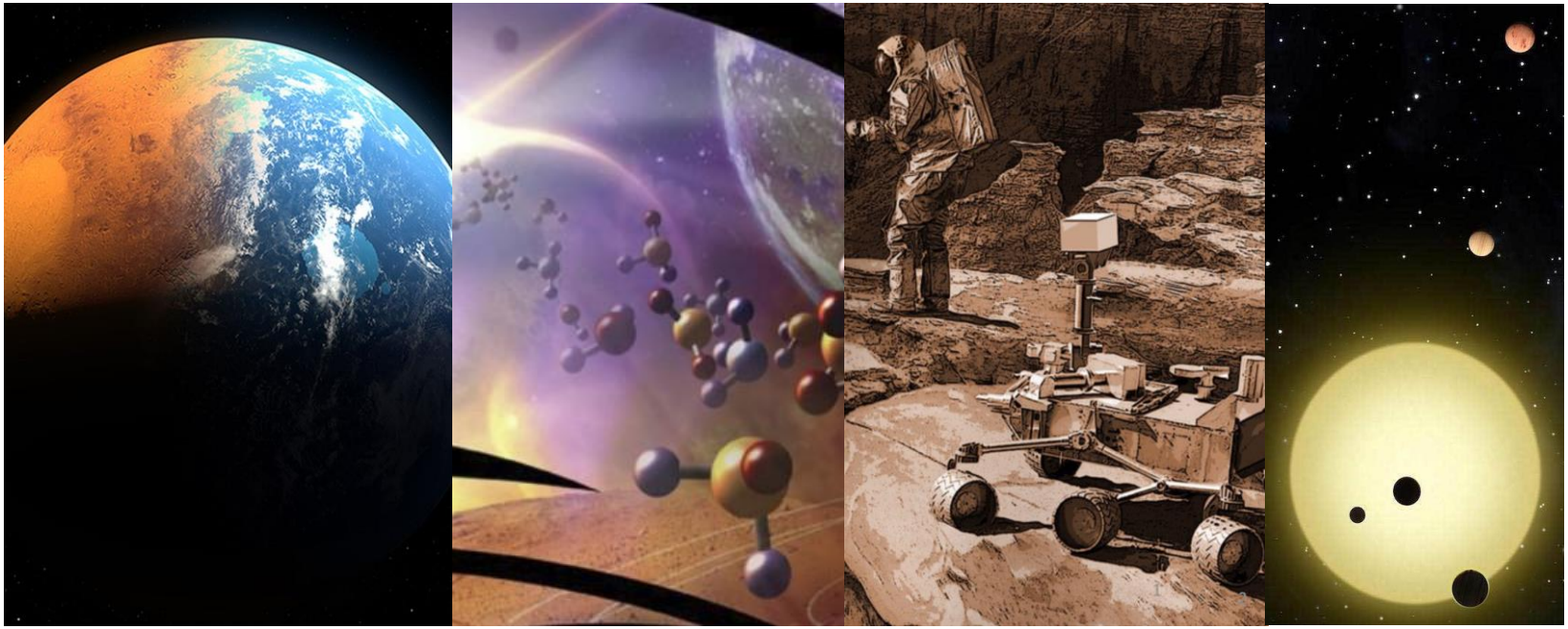
MASWG Recommendations for a Successful Future Mars Exploration Program (1 of 2)

1. 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.
2. 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.
3. Develop a line of PI-led small spacecraft, Discovery and New Frontiers-class missions, competed in a separate program line while addressing strategic goals.
4. The Program should have a protected, adequately funded, and competed technology development program to advance instrumentation and developments in key areas (e.g., as is being done for the Mars Ascent Vehicle). The technology invested should be focused and leveraged within NASA and with other agency and commercial entities.
5. NASA should develop low-cost approaches for entry vehicles at all size classes, including entry, descent, and landing; for long-lived orbiting spacecraft; and for aerial vehicles, landers, and rovers to provide access and mobility after landing.

MASWG Recommendations for a Successful Future Mars Exploration Program (2 of 2)

6. NASA and the Mars community should study the feasibility of adapting the CLPS program to Mars. A successful Mars-focused Commercial Mars Payload Services (CoMPS) could serve as a programmatic vehicle to allow, at reduced cost, development of technologies for future exploration as well as delivery of science payloads.
7. 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, compete missions and instruments to get the best science
   - Financially support the mission participants adequately to achieve the mission objectives (Instrument Teams, Science Team members, Participating Scientists, Interdisciplinary Scientists).
8. 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.
9. 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. This group would ensure that:
   - Adequate, accurate, and appropriate information and experience is provided in support of human missions
   - Scientific progress is sustained and advanced by missions with humans

Program Architecture: Mission Arcs and Scope



Mission Arcs (1 of 2): Definition And Description

- To demonstrate how a Mars Exploration Program could pursue compelling science objectives while utilizing a suite of missions, four “mission arcs” or scenarios have been defined; these are examples and do not encompass the entire range of compelling options.
- Each example identifies an area of compelling science, with a brief statement of goals, and then a progression or choice of missions that could be strategically linked to achieve the goals.
- *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.
    - An exception to this might be the long-term observations of the current climate where a succession of small satellites with a standardized payload, modestly upgraded over time, could achieve much of that goal.
- 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. New Frontiers should not be closed to Mars missions if missions of that class were prohibited by inadequate funding of the Mars program.

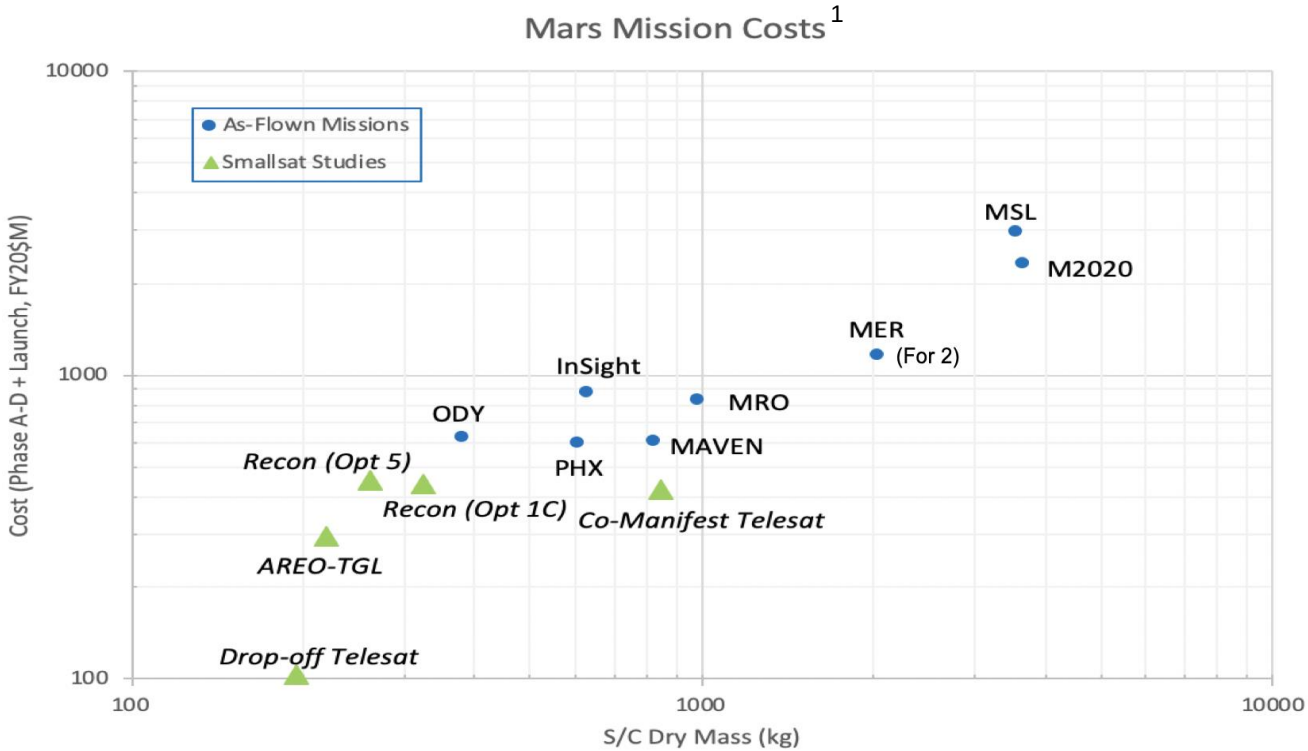
Mission Arcs (2 of 2): Mission Classes

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.
  - 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.
  - It seemed prudent to use a conservative upper-bound cost until the first such missions to Mars have been successful.
  - 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.
  - 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 of a budgetary and planning nature and are intended for informational purposes only. They do not constitute a commitment by NASA.*

Small- To Large-Mission Cost Estimates



- Estimated actual cost of past Mars missions and of small-mission concepts. Includes Launch Vehicle cost and 2-year launch delay for NSYT and MSL, excludes Phase E or extended missions.
- Small-mission cost estimates are for specific candidate missions examined by JPL Team-X and are not necessarily representative of the full range of possibilities.
- Simplex cost cap of $55M is likely to be too compromising for a Mars mission cost; a more-pragmatic lower limit life cycle cost is thought to be nearer to $100M.

[1] *This mission cost analysis was provided as part of a budgetary and planning activity and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.*

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), in situ age dating. ***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.
  - **FLG**: Life / biosignature analysis; 2nd sample return?

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 below several meters and eventually to depths of several km.

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; best done at 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*.**
  - **NFc**: Prove out potential resources for ISRU by humans
- Access to portals to the subsurface (e.g., caves, vents, cliffs, canyons) would require continued technology development.

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.
  - **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 or by active sensors (e.g., lidar for winds, aerosols).
- 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.)

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

▒ possible or partial priority science at this class ■ achieves priority science at this class

Rough Costs Of Potential Program[1]

Mission Arc	2021-2030	2031-2035	Key Tech
Arc 1: Diverse Habitable Envs.	4 SSc	1 NFc*, 1 SSc	Small Landers
Arc 2: Subsurface	1 SSc, 1 DSc	1 NFc*	Drilling/Analysis
Arc 3: Ice Science	1 SSc, 1 DSc	1 NFc*	Ice Landers
Arc 4: Climate Variability and Processes	2 SSc	1 SSc, 1 DSc	Network Landers, Long-lived SSc
Assuming Progress on all Arcs	~$300M / yr (8 SSC, 2 DSc)	~$500M / yr (2 SSc, 1 DSc, *just 1 NFc)	
Assuming Progress in ~ 2 Arcs	~$150M / yr (3-4 SSc, 1 DSc)	~$300M / yr (SSc+ NFc or DSc+3 SSc)	
Technology /Extended Missions / Instruments / Infrastructure**	$100M / yr (added to above)	$150M / yr (added to above)	Key: Affordable access to surface

**Everything else the current MEP provides (funding beyond 1st extended mission, relay hardware/integration, program office, etc.) plus new technology developments.

Key Assumptions:

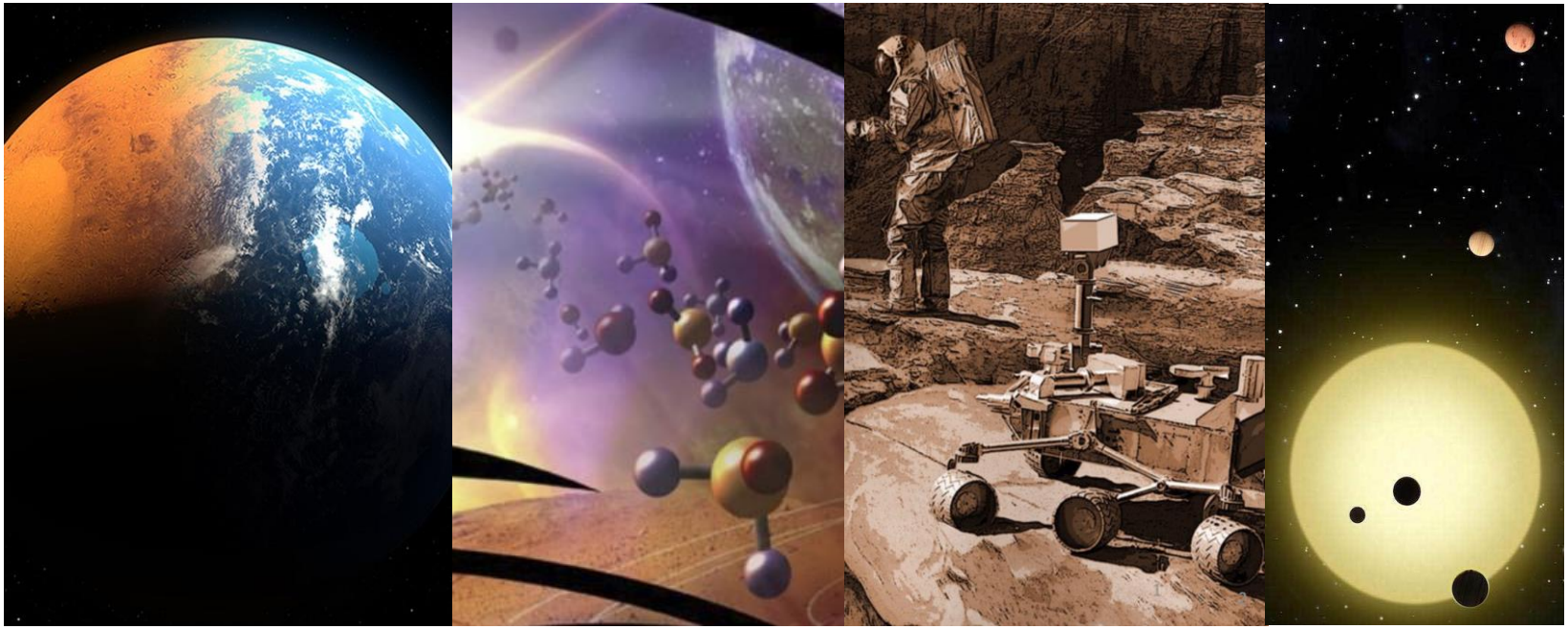
- No prioritization between mission arcs; elements from at least 2 should be pursued.
- No year-by-year cost profiles attempted.
- ***Life Cycle Averages (FY20 dollars)***: SSc = $200M, DSc = $750M, NFc = $1250; Fly 1 NFc in 2031-2035 while planning NFc/FLG for later. Competed NFc provides possible additional outlet in 2023-32.
- Costs do not reflect possible international contributions or commercial partnerships.
- Lower costs before 2031 reflect accommodation of Mars Sample Return while building to post 2031 flights.
- Flagship-class mission options to launch after MSR are likely to emerge, based on compelling science objectives or fundamental new discoveries.

[1] *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.*

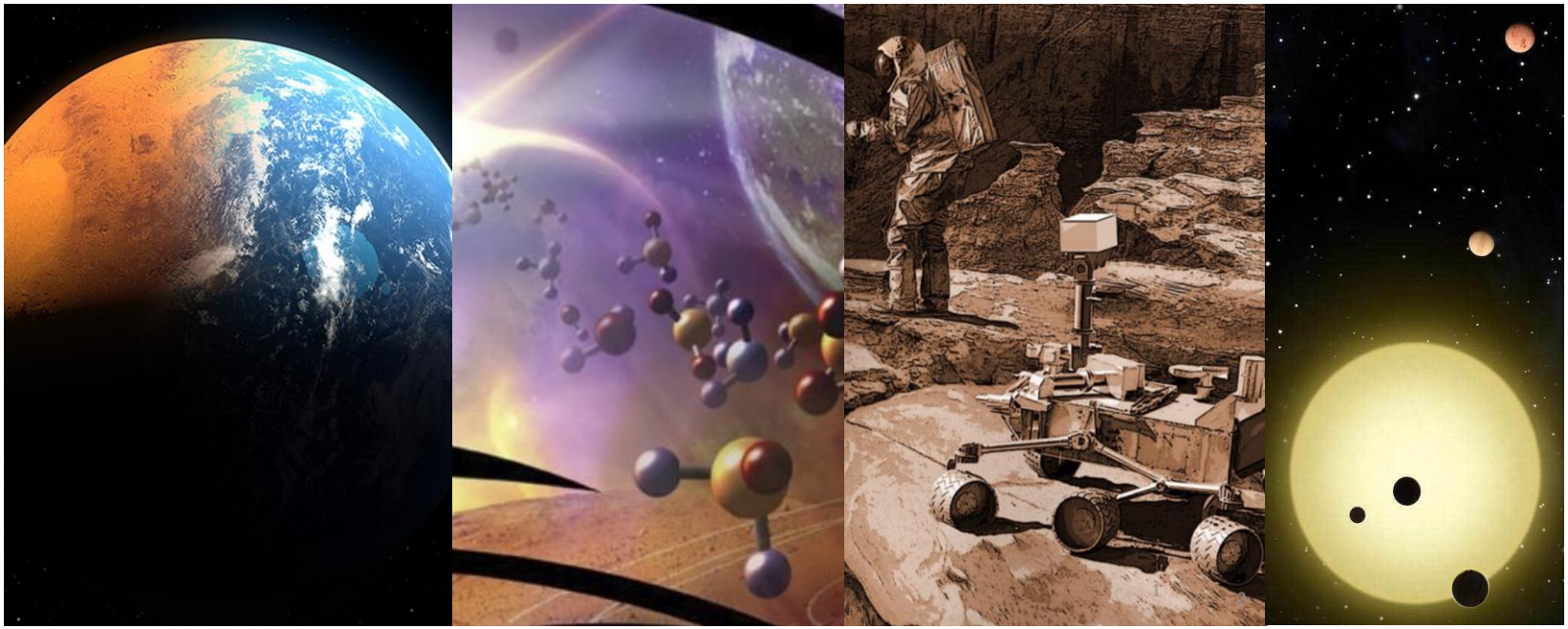
Implementing a Mars Exploration Program

- Compelling scientific, programmatic, and technology arguments exist for NASA to support a vigorous and robust Mars program that operates in addition to and in parallel with the Mars Sample Return program.
- A Mars exploration program would take place most effectively and efficiently if it continued to operate separately and independently within the Planetary Sciences Division.
- Opportunities should be sought for both international and commercial collaborations that can enhance the Mars program, while utilizing competition for missions, payloads and instruments wherever possible.
- Small spacecraft have great potential for carrying out significant Mars science, with the added excitement of being able to have a launch at nearly every opportunity every two years.
  - Rapid development in small spacecraft capabilities for Mars may lead to lower costs than estimated here.
  - A critical development is to land capable small spacecraft on Mars at an affordable cost.
- More-capable missions (Discovery, New Frontiers, Flagships after MSR) will be needed to address the most challenging objectives and discoveries. All will benefit from lower-cost access to the surface.
- We presented several example mission arcs involving a variety of mission types that could make substantial scientific return in a Mars program; ultimately, the rate and extent of progress depends on the available funds.

Appendices



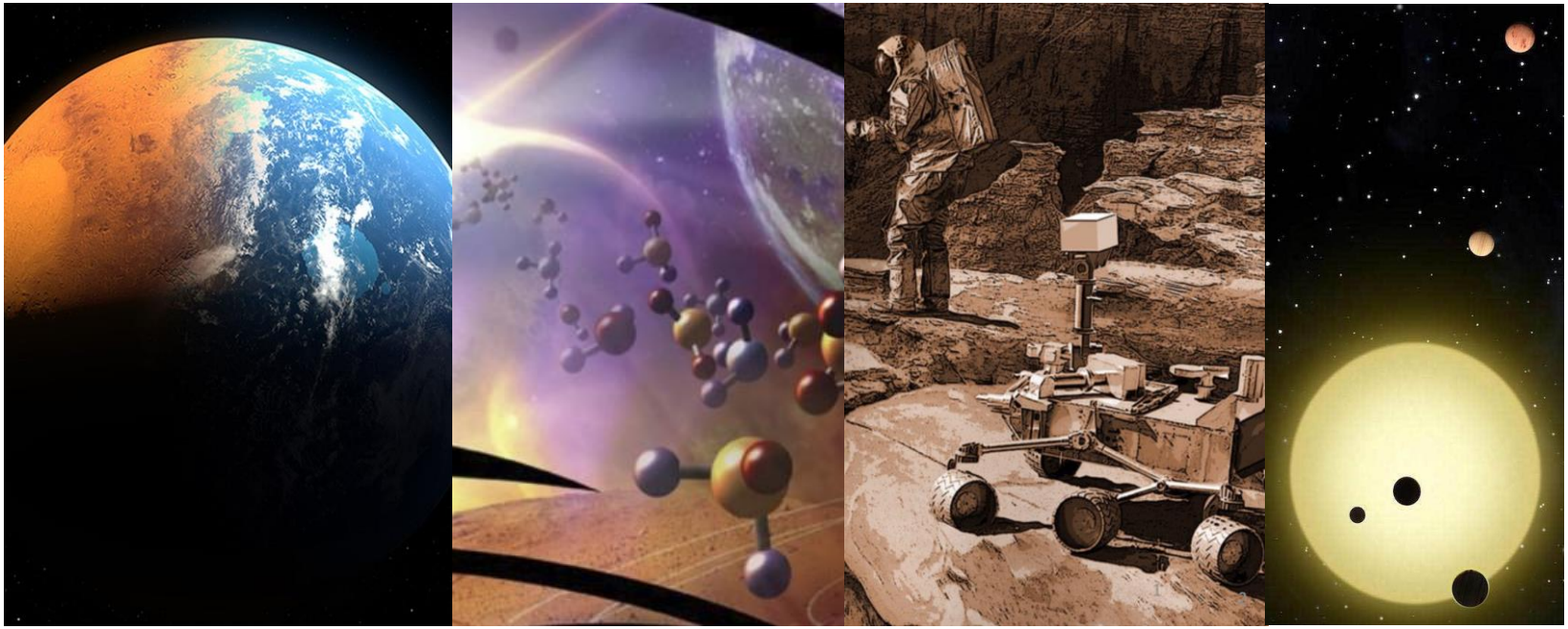
Appendix A: MASWG Meetings And Activities



MASWG Meetings And Activities

- Schedule
  - Planning meeting, 21-23 October 2019
  - In-person meeting, 28-30 January 2020
  - Extended virtual meetings, 20-22 April and 14-15 May 2020
  - Additional meetings of entire panel or sub-groups held virtually
  - Status updates presented to MEPAG, 13 Nov 2019, 28 Feb and 17 Apr 2020
- Activities
  - Presentations heard at in-person and virtual meetings on status of the NASA Mars program, science goals and objectives, mission status, mission concepts, technology development and capabilities, human-mission development, commercial opportunities, planetary protection
  - Inputs:
    - Planetary Sciences Decadal Survey, *Visions & Voyages*, 2012
    - One-page confidential mission-concept summaries solicited from the community as input into discussion of potential missions, due 22 November; ~55 received
    - Updates on MEPAG Goals revisions; overviews from PIs of Mars Planetary Mission Concept Studies

Appendix B: Detailed Findings



MASWG Key Findings (1 of 5)

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.
   - The incredible ancient and modern rock and volatile record preserved at Mars provides an unparalleled opportunity to understand the origin and history of the solar system and the potential for life beyond Earth. That extensive and diverse rock record that is accessible on its surface today.
   - The recent history of climate change, including that of the Martian volatiles H_2O and CO_2, is preserved in its polar and mid-latitude ices and layered terrains, and the physics by which that happened are observable in the dynamic changes seen on Mars today.
   - The Martian subsurface, with its clues to the formation of the planetary crust and interior and as a possible refuge of extant life, is largely unexplored.

3. For both science and exploration by humans, Mars has two compelling advantages:
   - Beyond the Earth-Moon system, Mars is the most easily accessible planet for exploration by robots and by *in situ* human explorers.
   - As noted above, Mars retains accessible physical-chemical records of its early history (rock & sediments), of the recent geologic past (ice & dust), and of the long evolution of its atmosphere (gases & their isotopes), some of which are no longer accessible even on Earth.

MASWG Key Findings (2 of 5)

4. Mars Sample Return represents a major step forward, is the key flagship mission for Mars, and should be completed. However, as 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.
   - Spacecraft capabilities are evolving and the mission class required to achieve a specific mission objective can change. Combinations of smaller missions have the potential to achieve larger-class science or can point the way/location for more-capable future missions.
   - Small spacecraft in the $100-300M[1] full-life-cycle cost range have technical capabilities that are rapidly advancing and could make several high-priority scientific measures. (See Finding #6)
   - While small spacecraft missions provide a new and exciting avenue of research, they alone cannot accomplish the most challenging science objectives. Discovery- and New-Frontiers-class missions allow more-capable spacecraft and more-detailed observations (e.g., higher spatial/spectral resolution, multiple instruments, landed mobility, networks). In combination, major progress can be made characterizing habitable ancient environments, surface-atmosphere interactions, ice distribution and emplacement, and the deep subsurface.
   - Flagship-class missions after Mars Sample Return likely are required for some key objectives. Examples include exploration of polar-cap interiors (e.g., ice cores or surface energy balance through the polar night) and more-detailed subsurface exploration (drilling and/or sounding from the surface at multiple locations, working in caves or other extreme terrains).

[1] *Cost assumptions in this document are of a budgetary and planning nature and do not constitute a commitment.*

MASWG Key Findings (3 of 5)

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.
   - Our growing knowledge from orbiters has pinpointed key locations that require surface access (e.g., detailed characterization and dating of diverse ancient environments), some requiring precision landing and/or extended mobility.
   - Mars surface access is not presently thought to be doable within the Discovery cost cap without significant re-use of hardware (as with *Phoenix*) or a fully contributed payload (*InSight*).
   - Reducing the cost for access to the Mars surface would be a game changer for the quality and diversity of science possible with small spacecraft, Discovery, and even New Frontiers at Mars.
   - There may be an opportunity to leverage technologies, commercial providers or contracting approaches analogous to the lunar CLPS (Commercial Lunar Payload Services) program.
   - Small spacecraft capabilities relative to cost, requirements, and performance should be addressed—investment and work are needed to realize the potential here.
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.

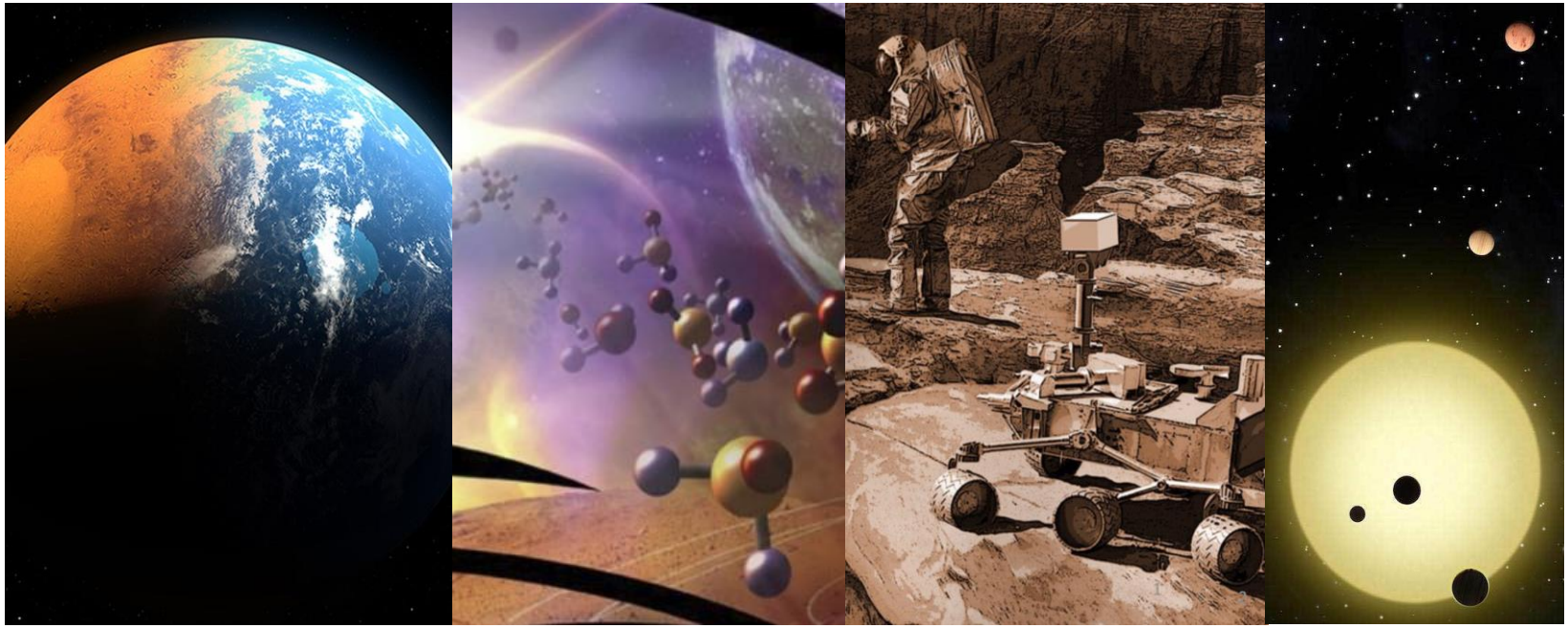
MASWG Key Findings (4 of 5)

8. There is tremendous value in developing collaborations between the many different governments and entities interested in Mars exploration.
   - Government-sponsored missions have come from the European Space Agency, Russia (and, previously, from the USSR), Japan, India, the United Arab Emirates, and China. In addition, commercial efforts are being developed or are under discussion by SpaceX, Blue Origin, and other companies.
   - Collaboration makes missions affordable to participant countries or entities that could not afford to carry them out alone. And public/private partnerships have the ability to enhance exploration significantly.
   - A particular need to enable small spacecraft at Mars would be for the program to identify as early as possible rideshare (launch) opportunities amongst all public/private providers and to delineate requirements and timing, including the release of mass margin for secondary payloads by international and commercial entities.

MASWG Key Findings (5 of 5)

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.
   - The presence of humans on Mars will advance scientific exploration. Measurements that support planning for robotic exploration also can support the scientific exploration by humans on Mars, and vice-versa.
   - Scientific observations can fill planning knowledge gaps, but need to be properly prioritized.
   - The programmatic infrastructure required for robotic exploration may serve as a seed for the much more extensive infrastructure required to support activities by humans on and near Mars.
   - Forward and backward planetary protection challenges of humans on Mars need to be addressed (see Appendix B).

Appendix C: Science Contamination Control and Planetary Protection Considerations for the Future MEP



Contamination and Planetary Protection Considerations (1 of 2)

Overview

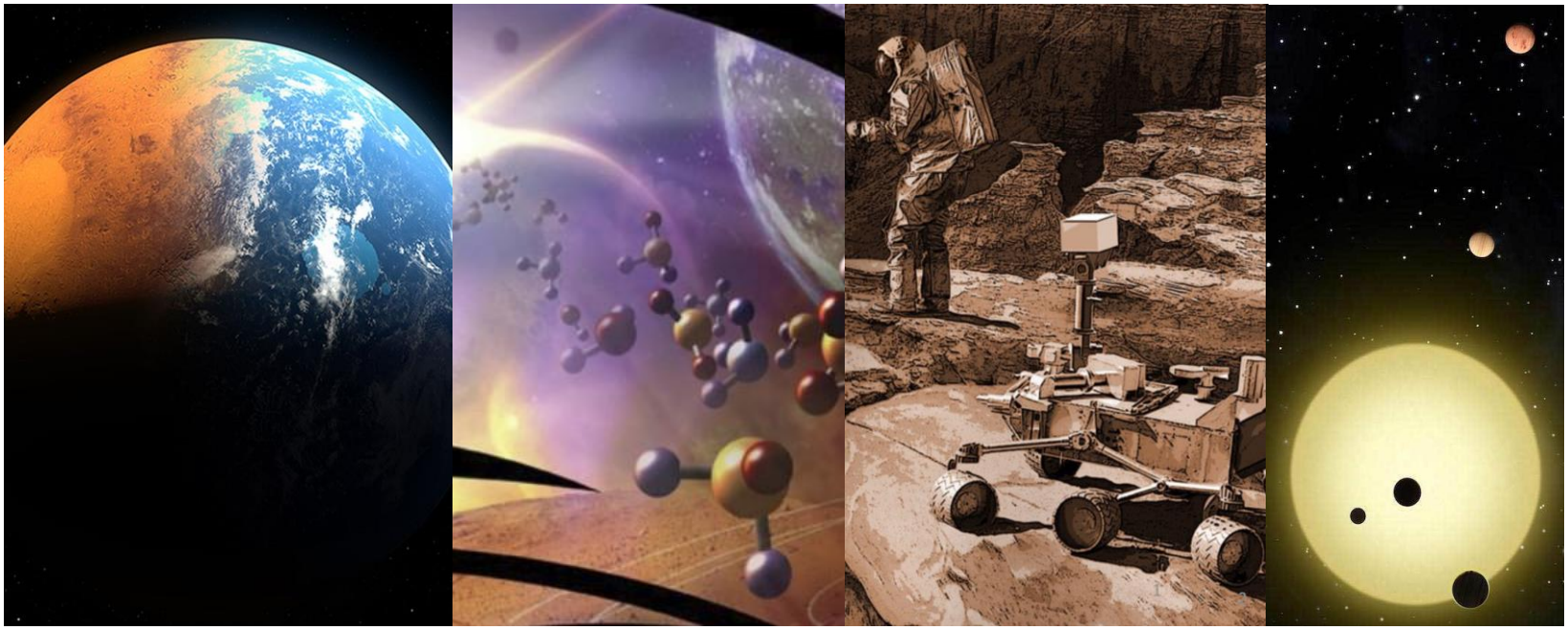
- A future Mars Exploration Program (MEP) as envisioned by MASWG must deal with three major constituencies:
  - Science with new investigations, instruments and technologies
  - Commercial/entrepreneurial providers (see CoMPS concept)
  - Human spaceflight to the surface of Mars
- A special concern is contamination by and among all three groups that may affect future scientific investigations and possible back contamination of the Earth's biosphere.
  - These concerns were codified in the Outer Space Treaty of 1967 and have been interpreted by NASA and COSPAR for more than 50 years.
  - Planetary protection (PP) policy and practice addresses viable organisms
  - Scientific investigations are concerned about confounding issues, e.g., organic contaminants
- To update current NASA practice, there have been 3 PP studies conducted within the past 3 years:
  - NASEM 2018, Planetary Protection Policy Development Process (P3D)
  - NASA Planetary Protection Independent Review Board (PPIRB) 2019
  - NASEM 2020, comparison of P3D 2018 and PPIRB

Contamination and Planetary Protection Considerations (2 of 2)

Issues Raised by the Three Studies

- Possible recategorization of missions to Mars as Category II (minimal reporting and an organic inventory)
  - Significant interest from commercial providers to develop landing sites
  - Cat II for Mars missions would require substantial scientific study (what is the mission and its objectives)
  - Leads to discussion of landing/exploration zones vs areas of high scientific interest at which contamination would be a major problem
- Small-spacecraft PP cost challenges
  - NASA should evaluate whether PP costs are a burden on small spacecraft developers and whether there is a cost floor
  - Suggest OPP may help support small spacecraft providers with some analysis
- PP requires a new independent advisory process
  - It is critical that Mars science be at the table and that this new advisory process be coupled to any MEP advisory group
- Humans to Mars
  - Science and Human Exploration must work together to agree on what efforts (measurements and missions) need to occur before humans land on Mars.
  - Can “exploration zones” be defined successfully? Research on contamination control for science and PP must be funded and conducted
  - For back contamination what human testing and quarantine is required?

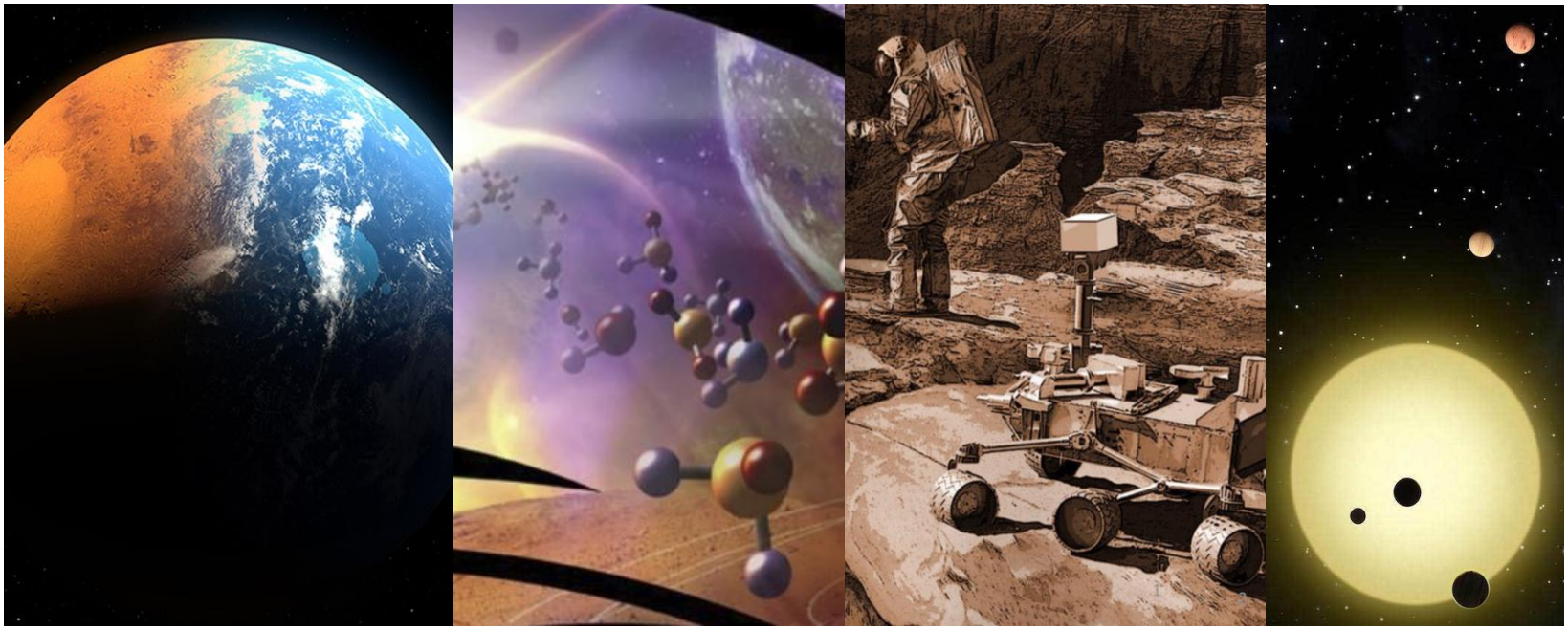
Appendix D: Mars and Exoplanet Science



Mars and Exoplanet Science

- >4000 exoplanets have now been discovered, primarily by the radial velocity and transit methods. For most exoplanets the only data we have are star type, orbital distance, planet radius and/or mass.
- Only a very small subset of these planets are amenable to follow-up atmospheric or surface characterization. Surface properties (temperature, pressure, liquid water) are likely to remain unobtainable except in special cases for at least the next decade.
- Hotter planets with shorter orbital periods are the most amenable to atmospheric characterization. Of the terrestrial-class planets (<1.6 Earth radius; no significant hydrogen envelope), Venus-like planets will be the easiest to observe. Earth-like planets, even around M-stars, will be extremely hard in the next 10 years. Planets with the same radius and received stellar flux as Mars likely will remain out of reach, as will direct analogs to outer solar system worlds like Europa and Titan.
- Despite these challenges, the broader intellectual links between Mars and exoplanet science are profound. Examples:
  - Atmospheric collapse on tidally locked planets vs. the CO_2 cycle on Mars
  - Atmospheric loss to space, particularly non-thermal escape
  - Evolution of habitability of water-poor planets
  - Chemical evolution and the role of redox in habitability and biosignatures
- Thus, Mars can serve as the natural laboratory or proxy for these numerous worlds in terms of understanding the fundamental physical, chemical, geophysical, geological and biological processes that may occur there and what may control the pathways of their planetary evolution.

Appendix E: Expanded Executive Summary



Executive Summary (1 of 4)
Science Rationale: Mars Is A Compelling Target For Both Science And Exploration

Mars has a uniquely accessible archive of the long-term evolution of a habitable planet. *Mars contains a physical and chemical record of planetary processes spanning more than 4 billion years that is unique in the solar system because of its preservation, accessibility, and importance to understanding planetary habitability. This record includes information on planetary formation, interior and crustal processes, atmospheric and climate evolution, and potentially the origin and evolution of life on another planet.*

- **Outstanding access to environments fundamental in the search for past and/or present signs of life.**
- **Unparalleled opportunity to study climate and habitability as an evolving, system-level phenomenon.**
- **Best place in our solar system to study the first billion years of evolution of a terrestrial, habitable planet.**
- **Outstanding opportunities for elucidating the climate and possible biological history of Mars inform our understanding of the evolution of exoplanets.**
- **Compelling destination for human exploration and science-engineering synergism.**

Executive Summary (2 of 4)
Why A Mars Program Is Needed

A distinct and identifiable Mars robotic program, separately funded, is necessary to accomplish compelling science and as part of preparations for human missions. A program is needed to:

- Carry out integrated advance planning and development of missions to ensure they are coordinated with each other and progress can be made on specific, interconnecting major science and programmatic objectives.
- Utilize new mission capabilities, including small spacecraft and their payloads, in an integrated program which matches the mission(s) to the science. Focused missions can tell us where and how to deploy the more capable missions needed for the most demanding objectives.
- Develop key enabling technologies, such as low-cost landing capability, surface accessibility with mobility, and advanced instrumentation.
- Provide coordination and common infrastructure to get smaller missions to Mars and to return their data back to Earth. This could serve as pathfinders for the Mars-proximity systems needed to support Mars missions with humans.
- Negotiate with international and commercial partners to provide cost-effective capabilities needed to explore Mars while utilizing competition for missions and instruments wherever possible to get the best results for science and exploration.
- Interact with a Human Exploration Program as the Moon-to-Mars initiative moves forward to planning and implementing missions taking humans to the surface of Mars.
    - Provide key environmental data needed in the mission planning, including potential resources *in situ*, and deal with issues of Planetary Protection

Executive Summary (3 of 4)
Possible Mission Architectures

- We examined four different prototype science arcs to explore connections between missions and the role of missions in different cost/size classes. The four examples demonstrate that a program can be constructed addressing compelling science arcs:

  1. Diverse habitable environments
  2. Subsurface structure, composition & life
  3. Recent climate change as recorded in ice
  4. Climate variability and process.

- The mission classes populating these 4 arcs were (with rough life-cycle cost ranges[1]):

  Small Spacecraft (SSc: $100-300M)
  Discovery (DSc: $600-$1000M)
  New Frontiers (NFc: $1000-$1500M)
  Flagship (FLG: >$1500M)

- Small spacecraft have great potential for carrying out significant Mars science. However, while orbital small spacecraft are viable today, critical technology maturation and development are needed to land meaningful payloads successfully onto the surface at an affordable cost.
- More-capable missions (Discovery, New Frontiers, Flagships after MSR) would be needed to accomplish the most challenging objectives and discoveries.
- A compelling Mars Exploration Program should pursue 2 or more mission arcs (to be determined) in parallel with Mars Sample Return, dependent on the available funding in a dedicated, separate line for that purpose. Costs have the potential to be shared through both international and commercial collaborations.

[1] *Cost assumptions in this document are of a budgetary and planning nature and do not constitute a commitment by NASA.*

Executive Summary (4 of 4)

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 key to match the mission 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	■	■		
Transport of dust/aerosols and their relationship to atmospheric escape and climate	4	■	■		
Low-altitude global magnetic field survey, gravity mapping	2	▒	■		
Environmental transitions in the ancient record by high resolution orbital imaging spectoscopy	1	▒	■		
In-situ geophysics (subsurface ice/water w/ resistivity, GPR; seismo., magnetism)	2	▒	■	■	
In situ surface-atmosphere boundary layer interactions (trace gas measurements)	4	▒	■	■	
In situ, mobile geological explorers for characterizing ancient habitable environments, environmental change, organics detection	1	▒	▒	■	■
Global orbital radar mapping of ice reservoirs	3		▒	■	■
In situ mid-latitude ice sampling for characterization	3		▒	■	■
In situ polar layer deposit climate record determination	3			▒	■
In situ geochronology for Martian and solar system chronology	1,2,3			▒	■
In situ life/organics detection in Martian ice, deep subsurface	1,2,3			▒	■

▒ possible or partial priority science at this class ■ achieves priority science at this class