MARS EXPLORATION SCIENCE IN 2050.

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A Look Forward to 2050: In 2050, the authors will be 60-75, at the end of long careers in Mars exploration. In 2050, a week of mission ops work could be working via virtual link—not just with rovers and orbiters—but with Mars astronauts, either present on Mars or based on Earth and prepping for a future mission. Mars astronauts may have conducted one or more sorties and brought samples back to Earth for examination in terrestrial labs. Mars astronauts may also assist in operating robotic explorers on Mars: monitoring weather and seismology, drilling the polar ice and extracting water for chemical and isotope measurements, imaging the surface, and collecting surface samples and drill cores for analyses in the astronaut habitat. Thus, some of the Mars astronauts will work with geologists on Earth (as did Apollo astronauts); others will be working as Mars geologists on-site (perhaps some of us). Below we discuss some existing programmatic aspects and steps to create this 2050 vision.

Key Mars science questions for post-2020: Some pressing questions for ancient and modern Mars can be solved via either robotic or human missions; others necessitate robots, with human explorers providing little added value (Table 1).

Table 1. Major open Mars science questions, derived from the 2014-2023 NAS Decadal Survey

The 4 Major Mars Science Questions		Methodology (least to most informative, cost not-withstanding)
1	What are the nature, ages, and origin of the diverse suite of geologic units and aqueous environments evident from existing data; what climatic conditions were they formed under; and were any of them inhabited?	High-resolution orbital measurements, in situ rovers, robotic sample return, human-facilitated measurements/sampling
2	What is the present climate; is liquid water present; how does climate change under timescales of orbital variation; is there present-day life?	Orbital monitoring, landed weather station network, landed measurements, sample return
3	What are the inventory and dynamics of carbon compounds and trace gases in the atmosphere and surface; what processes govern their origin, evolution, and fate?	In situ rovers, orbital characterization of polar CO_2 and H_2O reservoirs, sample return, human-facilitated measurements
4	What are the internal structure and dynamics and how have these evolved over time?	Landed network seismic and heat probe; in situ rovers, sample return, human-facilitated measurements

While upcoming missions like Mars 2020 will help to address some of these questions, all will still require further investigations. The search for life on Mars is crucial and deeply coupled to fundamental questions of its evolution, embedded in Questions 1-2. Nonetheless, chemical and physical processes that lead to uninhabited habitats are equally important for understanding the prevalence of life in the universe.

HEOMD strategic knowledge gaps: Human exploration of Mars requires deeper understanding about the planet's physical environment in addition to new technical capabilities. For instance, key knowledge gaps for both NASA-sponsored and commercial human exploration include a) the availability of water resources (ice, hydrated minerals, atmospheric harvesting), b) the extent of weather variability (e.g., dust storms), c) local winds and thermal tides, which affect the ability to land safely, and d) evidence that extant life is not widespread in martian surface materials. Key technologies include e) a Mars communication and positioning network, f) successful demonstration of a human-scale landing system, and g) in situ production of purified oxygen and fueling of an ascent stage.

Importance of joint HEOMD-SMD missions, commercial collaboration: At this juncture in 2017, a subset of science questions and human exploration needs naturally merge, specifically, science questions 1-3 and human-exploration related knowledge gaps a-d. Synergistic measurement opportunities include: i) refined mapping of hydrated minerals at <10m/pixel with improved IR spectroscopy to quantify precise mineral and water abundance, ii) measurements of ice inventories, including in the near-subsurface at <20m/pixel scale where pole-facing slopes can still be ice-rich at low latitudes, iii) a suite of weather-related data, and iv) continued characterization of martian surface materials to determine whether extant life is present as well as identify potential chemical hazards to astronauts. Barriers exist to HEOMD/SMD/commercial collaboration (cultural, commercial-government mixed funding rules, and programmatic budgeting). Nevertheless, the coupling of needed measurements makes combined missions a resource-efficient approach for the mid-2020s to early 2030s. SMD could take the lead on some with HEOMD contribution, and vice versa. Science and HEOMD payloads, perhaps even including rovers, can be carried by SpaceX craft. Collaboration to obtain data of mutual interest or a paid berth for investigations ("pay for the ride") may be appropriate in certain instances.

Importance of independent SMD Mars science. Mars exploration cannot operate solely within the sphere of HEOMD, however. The NASA mission of pioneering the future of space exploration and expanding scientific discovery requires a continued focus by SMD on measurements that add new knowledge to our understanding of the workings of our Sun, Earth, solar system, and the universe. Mars occupies a key scientific position, not only to understand whether there may have been an independent origin of life, but also to understand the processes governing the fates of terrestrial planets. Such is of heightened importance in light of ongoing discoveries of extrasolar rocky planets with atmospheres and the desire to understand their long-term habitability. Although many HEOMD and science-driven measurements overlap, some science questions are fundamentally different from those solely in service of exploration. For example, rather than solely "what?" and "how much?", scientific questions about a hydrated mineral deposit are also "when?", "how", and "why?". Thus, while a subset of measurements are synergistic, measurements for understanding the timing and processes behind early planetary evolution fall largely within the province of science and remain crucial to our expanding knowledge. As such, a robotic and sampling program at Mars can and should continue, incorporating the enhancements that human capabilities can provide as they become available. A notable example is complex sampling techniques, including deep drilling beyond a few meters to collect samples of rock and ice. In 2030 and beyond, even as commercial and government human exploration of Mars may expand, SMD should play a critical role in designing the precursor measurements prior to astronaut exploration (e.g., the search for life; see below), prioritizing the measurements and extravehicular activities to be made by astronauts to key locales, and the criteria for human selection and return of samples.

Role for robotic sample return The demonstration of a successful launch off of Mars lends credence to the technical ability to do the same successfully with much more massive human craft. Critically, robotic sample return could facilitate uncontaminated return of samples from Mars special regions, where the chance for extant life is highest—in contrast to other terrains for which collection by a human is less likely to interfere with scientific measurement. Return of samples to Earth need not be purely robotic: an in Mars-orbit human-assisted capture of samples launched off the surface could simplify containment verification and safe sample landing on Earth. With both commercial and government programs oriented toward human exploration, the search for indigenous Mars life, prior to introduction of Earth organisms, becomes a scientifically pressing issue that is critical for evaluating the possibility of an independent origin and evolution of life on our neighboring planet. Thus, a single or multiple late 2020s/early 2030s sample return, perhaps facilitated by humans, is a logical exploration step. Sample return from multiple sites is preferable. In general, the scientific value of sample return is likely to be greater with humans on the martian surface, as semi real-time human decisions are not likely to be surpassed by advances in machine learning on the timescale of the next few decades.

Importance of more 2020-2050 Mars science mission opportunities: Exploration from orbit has identified hundreds of key locales of geological significance for understanding ancient Mars, information on volatile cycling and loss, and important data on daily and seasonal weather changes. Orbiters have also identified key resources for human exploration. The last decade of data have demonstrated that, like Earth, Mars is diverse. True exploration requires measurement at multiple locales, varying in space and time. This dictates a future mission architecture with many more craft to interrogate these locations. One might ask: doesn't this cost more money? Not necessarily. Consider two cases. First, modern Mars atmospheric dynamics – tides, dust, temperature, volatile cycling – can be examined with relatively simple instruments, geared specifically toward these purposes. Multiple identical craft are beneficial because temporal and spatial resolution provided by diverse orbits are vital, and they are presently missing. The instruments carried by these multiple crafts would be less expensive than multipurpose instruments (e.g. THEMIS, TES, and CRISM), which have been designed for geological, polar, and atmospheric studies. A mid-size orbiter for detailed water resources information will likely still precede astronaut exploration but the fleet of small sats providing weather information would also serve as communications relays, populating the Mars system in the 2030s. As infrastructure around Mars grows, these "standard" small sats might transition away from the science community to commercial space companies. Second, the highly successful MER rovers were plural: two distinct sets of science data from two different sites cost less than or equivalent to the single-site Mars 2020 rover. A similar approach was highly successful historically (e.g., Mariners, Vikings, Voyagers). Our knowledge of the environmental diversity of ancient Mars has expanded in tandem with advances in instrument miniaturization, meaning that even the simple MER-like rovers at multiple sites would enormously expand our knowledge of Mars. By standardizing the "spacecraft bus" (in this case not an orbiter but a rover) and requiring instruments to accommodate themselves to it, the costly systems-instrument interface problems on MSL and M2020 can be avoided. These rovers could be sent independently, or coupled with a human program, allowing for the measurement and sampling, controlled in semi-real time. Multiple smaller missions also can expand participation in Mars exploration, opening it up to many more commercial, international, and academic participants than currently possible.

Conclusions: Time is of the essence for developing a synergistic SMD/HEOMD architecture with regard to Mars exploration to support humans in coming decades. A collaborative program could enable the Mars planetary science community to work alongside the engineers developing enabling technologies, deepening opportunities for engagement. The 2020s could focus on an orbital mapping effort for localized exposures of current and past volatiles (and resources) as well as astrobiological investigations for extant life, which should be pursued vigorously before humans begin *in situ* exploration. This could be accomplished by a mid-size orbiter and multiple small, MER-class rovers with next generation instrumentation to meet science needs. The focus in the late-2020s and into the 2030s could shift toward return and analysis of samples from Mars, perhaps facilitated by humans on a Mars flyby mission, and emplacement of the weather/comm small sat. network. In the 2040s and 2050s, human exploration of the surface would be performed, enabled by robotic drills, rovers, stations, and instruments, and include human return of samples, greatly enhancing our capacity to carry on outstanding science in the Mars system.