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NASA Planetary Science Vision 2050

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Abstract

In response to a request from NASA's Planetary Science Division, a community group is currently preparing a report that lays out a vision for planetary science research and exploration in the decades until 2050. This report builds on a highly successful workshop held in March 2017 at NASA Headquarters.

1. Introduction

In October 2016, NASA's Planetary Science Director chartered a group of planetary scientists and technologists to hold a community workshop and write a report on a very long-range vision for planetary science in the coming decades until 2050, with discussion on the technical requirements to achieve that vision. Specifically, the charter for the Planetary Science Vision (PSV) 2050 Workshop was to:

- present a compelling, 35-year science vision within the frame work of the future decades (2020s, 2030s, and 2040s);
- take the Planetary Science decadal survey[1] as the starting point and build upon it;
- be science based, with notional technologies and missions;
- take into account community input through the workshop (papers, posters, presentations); and
- prepare a Vision 2050 Report summarizing the workshop results.

The charter for the PSV 2050 report, which is currently under development, is to:

- have a compelling, over-arching planetary science theme for each decade as the next phase in Solar System Exploration;
- contain one or multiple paths forward (science areas and technologies needed) towards a long-range vision;
- consider cross-cutting opportunities with other disciplines as well as the larger context of international planetary science and human exploration;
- be built on science investigations goals, leading to notional missions that achieve the science as appropriate;
- consider the technology needed to achieve specific goals; and
- identify challenges (e.g., measurement challenges, technology challenges….) that will need early investment to become viable.

This report will not be a mini-decadal survey with recommendations and priorities; nor is it an implementation plan; it is a long-range vision document with options, possibilities and a visionary future.

2. Current Status

NASA's Planetary Science Division (PSD) hosted the community workshop at NASA headquarters in Washington, DC on February 27–28 and March 1, 2017. Presentations and abstracts from the workshop, as well as video of the oral and poster presentations, and planning materials developed during and since the meeting, can be found at http://www.lpi.usra.edu/V2050/. This workshop provided PSD with community input on a very long-range vision for planetary science in the future.

The workshop gathered leading experts in Solar System planetary science and related disciplines, together with experts in space technologies, to identify potential science goals and enabling technologies that can be implemented by the end of the 2040s and would support the next phase of Solar System exploration.

Despite the relatively short timelines for submission of abstracts to the workshop, we received an overwhelming response, with over 240 abstracts submitted focused on the following themes:

- Life - explore and find locations where life could have existed or could exist today; improve our understanding of the origin and evolution of life;

- Origins of Planetary Systems – explore and observe the objects in the solar system to understand how they formed and evolve;
- Workings of Planetary Systems – advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve;
- Planetary Defense and Resources – identify and characterize objects in the solar system the pose threats to Earth or offer resources for future exploration;
- Technology – technological and instrumental capabilities needed for future exploration, which stretch beyond the current decadal priorities; and
- Policy, Pathways, Techniques, and Capabilities – innovative concepts that did not fit easily into any of the other themes.

The workshop was structured to have a modest number of oral presentations that mostly addressed broader visions for the future in each of the themes, followed by moderated panel discussions that were designed to maximize participation by the audience, both in the meeting room and remotely. Evening poster sessions allowed presentations of concepts better suited to that medium. While the meeting space ultimately limited onsite participation, livestreaming of the presentations allowed interaction with a far larger group, both within the planetary science community and with interested members of the public.

Since the workshop, we have been working to draw together the scientific threads of the meeting into a coherent science plan. Overarching questions that came out of the meeting asked the following:

- Where do we come from?
- Are we alone? / Are we unusual?
- Where are we going?

Crosscutting themes specifically include Life and Planetary Systems (including Exoplanets).

Once we have worked up the science plan for the coming decades, we intend to focus on the capabilities required to achieve the vision, including technology requirements, workforce issues, public engagement, and linkages to other divisions and directorates within NASA, to other US federal agencies, and to international organizations.

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A Long-Range Vision for the Exploration of Mars

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Abstract

In response to a request from NASA's Planetary Science Division, a large community group met Feb. 27-Mar. 1, 2017 to develop a collective vision of planetary science research and exploration in the decades until 2050. The workshop was organized around themes (Life, Workings, Origins, Defense and Resources, Policies, Technologies) and not by destination solar system objects. However, after the workshop, we compiled the primary ideas from all of the themes that relate to Mars. Thus, this document does not describe a set of positions that have been validated via widespread discussion and debate, but instead a reporting of various aspects of a Mars vision as presented in the abstracts, posters, and oral talks at the Vision 2050 workshop (e.g., 1-5).

1. The Community's Vision for Mars: Common Strategic Elements

We have identified three common strategic elements that underlie the future vision of many members of the Mars community:

- As part of a broader program of planetary science, we have high-priority long-term scientific objectives for Mars that will not be closed with the missions currently planned (i.e., launches planned through 2020).
- We have made—and expect to continue to make in the near future from ongoing and planned missions—scientific discoveries that have/will raise important new questions that require follow-up. In particular, this includes substantial new knowledge since 2010 on the environmental diversity of ancient Mars, possibly late periods with liquid water (driven by obliquity cycles), large reservoirs of water and CO_2 volatiles as ices, and unexplained methane generation and destruction.
- Mars remains the most coveted destination for the human spaceflight program. As such, on a multi-decadal timescale, we need to plan for synergy between the robotic and human branches of Mars exploration.

2. Long-Term Motivation for Mars Exploration

A critically important aspect of formulating a vision for the future exploration of Mars is to establish the long-term motivations.

Key science considerations include:

- Astrobiology: Life. We need to understand in detail the biological pathways of Mars and the Earth. If Mars had/has life, what was its character; does it persist to the present? If Mars never had life, why not, and what are the key points of divergence between it and Earth?
- Workings and Astrobiology: Early Habitats. We need to understand the first billion years or so of Mars' geological history—a period that is almost entirely missing from the Earth's geologic record. When and how was Mars' early thick atmosphere lost (stellar activity, magnetic field decline)? How did heavy impact bombardment affect the atmosphere and surface (timing and response)? How did the climate sustain liquid water in spite of a faint young sun? This is crucial to understanding the earliest geological processes and environments available for life on Earth-like worlds. It is a record only accessible on Mars.
- Origins and Workings: Long-Term Evolution of Terrestrial Bodies: Comparisons of the atmospheres of Mars, Venus, Earth that lead to quantitative predictive models for climate and weather are important for understanding the origin, divergent evolution, and modern dynamics of these three terrestrial planets. How are geophysical and atmospheric processes coupled, as revealed by study of Mars' internal dynamics, crustal structure, volcanic history, and variation in obliquity? Lessons from Mars (and

Venus) are crucial for interpreting Earth-like exoplanets (with variable insolation, size, density, orbital parameters, atm. chemistry, etc.).

Additional considerations associated with the broader space exploration enterprise include:

- Human Exploration of the Solar System: Mars is a crucial destination for potential future human exploration. It is of interest to national space agencies of multiple countries as well as commercial entities. It is the only destination with the potential for long-term inhabitation from in situ resources.
- **Technology**: Sample return technologies (MAV, fetch rover) have reached a level of maturation suitable for implementation of sample return. Miniaturization—partially driven by the CubeSat revolution—has resulted in new enabling technologies for networks of Mars weather/comm. satellites, highly capable but low-mass landed payloads on small rovers or helicopters, and higher capability orbiter instruments at equivalent or low mass.
- General: The MEPAG Goals document lists a number of high-level objectives that will not be closed by 2035, and that should be considered in long-range planning to 2050.

3. The Importance of Hypothesis-Driven Science at Mars

The engine that drives planetary (including for Mars) scientific exploration forward is discovery response and hypothesis formulation and testing. As previous questions about Mars were answered, they raised new questions that could not have been anticipated earlier. We have seen this play out for >200 years in the scientific exploration of the Earth. The exploration process is iterative, as it progresses forward and we understand the system at a deeper and more connected level. In the case of Mars, we have a critical opportunity to capitalize on our existing hard-earned discoveries that cannot be wasted.

Although many human- and science-driven measurement needs overlap, some science questions are fundamentally different from those solely in service of exploration.

- Example #1: Rather than solely “what?” and “how much?”, scientific questions about a hydrated mineral deposit are also “when?”, “how?”, and “why?”.
- Example #2: Measurements for understanding the timing and processes behind early planetary evolution fall largely within the province of science alone.

As such, a science-driven robotic and sampling program at Mars can and should continue, independent of but complementary to activities related to the human spaceflight program, incorporating the enhancements that human capabilities can provide as they become available.

4. Summary and Conclusions

In summary, the best way to follow up on the discoveries that have been and will be made is:

1) Provide a pathway for hypothesis-driven science to advance
2) Plan for the robotic and human exploration programs to converge

Acknowledgements

U.S. government sponsorship for DWB is acknowledged. A powerpoint with summary of this abstract is available at http://www.lpi.usra.edu/V2050/target-strategies/mars-strategy.pdf

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Technology for NASA's Planetary Science Vision 2050. Notes from the Feb 2017 Workshop

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1. Abstract

NASA's Planetary Science Division (PSD) initiated and sponsored a very successful community Workshop held from Feb. 27 to Mar. 1, 2017 at NASA Headquarters. The purpose of the Workshop was to develop a vision of planetary science research and exploration for the next three decades until 2050. This abstract summarizes some of the salient technology needs discussed during the three-day workshop and at a technology panel on the final day. It is not meant to be a final report on technology to achieve the science vision for 2050.

2. Introduction

The V2050 Workshop was intended to envision where planetary science would be in 2050. The program of oral and poster presentations was organized around the following five major themes:

- LIFE
- ORIGINS
- WORKINGS
- DEFENSE AND RESOURCES
- POLICY, PATHWAYS, TECHNIQUES AND CAPABILITIES (PTC).

There were also synopsis presentations for each theme at the end of the Workshop. On the technology side we have taken note of the many technical needs identified either during science presentations, Q&A sessions, or during the final technology panel discussion. We present here a preliminary summary of the main technology challenges to be addressed in order to realize PSD's V2050 science objectives. Many of the technologies needed will probably take more than a decade or more of development to mature.

3. V2050 Technology

3.1 Instrumentation for LIFE, ORIGINS,WORKINGS, Planetary Defense and Resources, and PTC. We list here a few high-level aspects of instrumentation that will need to be developed for V2050:

- Biosignature detection at the nanoscale; non-DNA specific/agnostic sample retrieval and life detection approaches; automated microfluidic systems; advanced spectrometers; penetrator science packages (including asteroids as targets); *in-situ* coring; advanced cryogenic sample return including targets in the outer solar system; immersive virtual reality for sample selection/collection; etc.
- Advanced remote sensing: significantly better spatial and spectral resolution, improved models, high definition camera; sustainable (staffing and funding) advanced Earth-based laboratory analysis tools; etc.

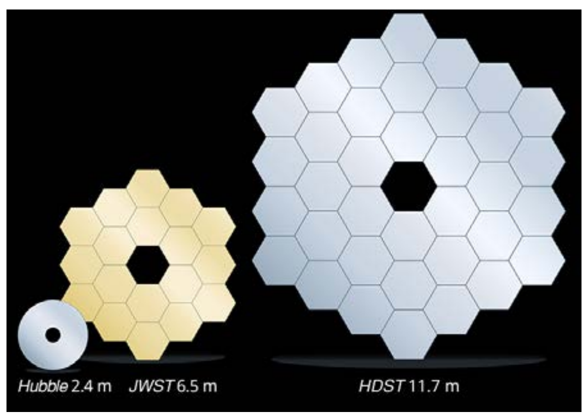

Fig 1: Such next generation large observatories as the High Definition Space Telescope (HDST) would be instrumental for investigation of exoplanets as well our own solar system in the decades ahead. Even bigger clusters of these could be assembled in space for dual astrophysics and planetary science applications. *Courtesy C. Godfrey (STScI)*

3.2 Platforms and architectures. We list here a few high-level platforms and architectures needs discussed during the V2050 Workshop:

- Solar-system-wide infrastructure for navigation and communication; multi-target mission architectures; large space-based observatories (Fig. 1), including in-space, self-assembly of extraordinary structures;
- Modular/standard spacecraft with standard interfaces/volumes for customized instruments to reduce cost of mission and access to space; smallsats, cubesats, chip sats/femtosats; mother-daughter spacecraft; swarm spacecraft systems for distributed multi-point measurement and long-term monitoring; "sciencecrafts".

3.3 Flight system technology. We list here a few high-level needs mentioned during V2050:

- Compact Radioisotope Thermoelectric Generators; surface power systems; energy storage (all-temperature); advanced power for outer solar system bodies (KBO); aerial mobility.
- Upgraded/advanced DSN and beyond; advanced *in situ* resource utilization (ISRU) methods – water, fuel, building material; mobile submersibles for distant oceans; autonomous operations for landing and hazard avoidance; fully autonomous spacecraft; ubiquitous intelligence in machines; advanced computing (including on-board data mining); scalable robotic systems: lander/rover access, mobility and robustness; reconfigurable systems to handle unexpected environments.

3. 4 Advanced propulsion/transportation

- Propulsion technology to get to the outer planets (robotic as well as human missions); radioisotope electric propulsion; photonic propulsion.
- Technology to access new and challenging terrains of interest – surface transportation.

3.5 Technology for extreme environments – high level needs:

- High- and low-temperature tolerant systems; high radiation tolerance; high temperature electronics; advanced manufacturing (3D printing); technology for highly corrosive environment.

4. Synergy with Human Exploration (HEOMD)/ Commercial Space.

- In-space assembly of large structures will require working hand-in-hand with human space program.
- Human-aided sample retrieval/return; ISRU;
- Orion crew vehicle use as relay for surface activity (rover, robots, avatars); the Moon as technology tested for human-aided science elsewhere in the solar system

5. Common threads

A number of ideas proposed highlight common threads. One is that all means of exploration should be integrated together. Another one being that budget (and political) constraints should be considered and that a balanced and prioritized program will still be needed. A few other suggested ideas are listed below:

- Diversity of workforce is very important (such as gender, age, race etc.)
- Collaboration between: the various disciplines of planetary science; engineering and science; Planetary Science, Heliophysics, Astrophysics, Earth Science, and Human Exploration; public/crowd-sourcing/open innovation; planetary, industry and commercial space developers.
- Current planetary atmospheric models need to be advanced to cover global climate system models. models that merge datasets from sample analysis, experimentation, and remote-sensing/ telescopic/ robotic observations will be needed

6. Summary and Conclusions

The above is a preliminary summary of the technology discussion at the V2050 Workshop. A report is expected to be finalized soon. In addition to the Planetary Decadal Survey, a number of other roadmapping activities are being developed or have already been completed, and will need to be taken into consideration to have a more complete vision for the planetary science in 2050.

Acknowledgements

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The Next Generation of Observations of Planets Beyond Our Solar System

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Abstract

This presentation will give an overview of the planetary and exoplanetary observing capabilities of future astrophysics flagship missions that are under study in advance of the next Astrophysics Decadal Survey in the United States. This includes the UV-Optical-Infrared (LUVOIR) Surveyor, and the Habitable Planet Explorer (HabEx). Both missions are general-purpose space-based observatories with a wavelength range spanning from the far-UV to the near-infrared. The two missions differ in their levels of quantitative ambition, but either would enable revolutions in many areas of astronomy, including planetary science within and beyond our Solar System.

1. Background – The Astrophysical and Chemical Characterization of Exoplanets

Because LUVOIR and HabEx are both being considered for the next decadal survey, either must be capable of advancing our understanding of astronomical targets, including exoplanets, far beyond what will be achieved by the next two decades of observations from other space- or ground-based facilities. Either mission must move past the detection of potentially habitable worlds and their astrophysical characterization. Detection of such worlds is happening now with Kepler and ground-based measurements, and will continue with TESS (Transiting Exoplanet Survey Satellite), PLATO, and WFIRST (Wide Field Infrared Survey Telescope).

Any flagship mission under consideration for the timeframe beyond WFIRST that attempts to characterize exoplanet must also move beyond the chemical characterization of gas giants. This has begun with observations from Spitzer, Hubble, and ground-based telescopes and will see major advances with JWST (James Webb Space Telescope), ground-based Extremely Large Telescopes (ELTs), and WFIRST's exoplanet coronagraph.

2. The Future – Chemical and Astrobiological Characterization of Potentially Habitable Worlds

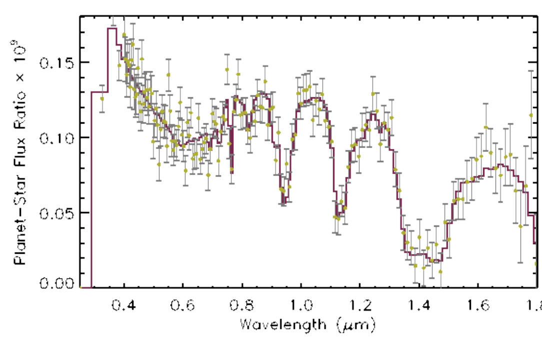

Figure 1: The spectrum of Earth, observed by a LUVOIR-/HabEx-like mission. This observation is at a SNR of 10 at 0.55 μm, assuming 30% throughput per channel. This spectrum would be consistent with any of the following scenarios: (1) a 10-hr observation of an Earth-like world 5 pc away with a 5m version HabEx; (2) a 30-hr observation of an Earth-like world 7 pc away with a 5m version of HabEx; (3) a 10-hr observation of an Earth-like world 12 pc away with a 12m version HabEx; or (4) a 30-hr observation of an Earth-like world 17 pc away with a 12m version of HabEx. *Figure courtesy Tyler Robinson* [1].

One of the main science objectives for these future flagship observatories will be to directly image rocky-sized planets in the habitable zones of other stars, measure their spectra (Figure 1), analyze the chemistry of their atmospheres, and obtain top-level information about their surfaces. Such observations will allow us to evaluate the habitability of these worlds, and search for potential signs of life in their spectra. We will review the specific observational strategies needed for astrobiological assessments of exoplanetary environments, including the wavelength range and spectral resolution required for these habitability analyses and biosignature searches.

3. The Connection Between Exoplanet Astrobiology and Solar System Planetary Science

We must consider the search for habitable environments and signs of life on exoplanets in the context of Solar System exploration, and vice versa. The selection of targets for these future exoplanet observations must be informed by our understanding of how planets work, which is constantly improving based on our exploration of worlds closer to home.

These links go in the other direction, as well. The history of exoplanet discoveries has upended expectations set by the knowledge of our Solar System. For example, the very first planets we discovered were so-called “hot Jupiters” that had a combination of physical and orbital properties unlike anything in the Solar System. The theories we have developed to explain the wealth of data from these discoveries has in turn influenced our thinking on the evolution of planets inside the Solar System, due to a new grasp of the ways that planets can migrate over time. Similar lessons are beginning to come from the chemical characterization of exoplanets, as well, and these lessons will accelerate with the dozens of transit observations by JWST. Based on this history, we should expect the unexpected when it comes to a future search for habitable environments and life. We plan to obtain spectra for up to dozens of rocky worlds in the habitable zone, and up to hundreds of worlds overall. The comparative planetology enabled by those data will allow us to test myriad hypotheses on global-scale planetary feedbacks such as the carbonate-silicate and ice-albedo feedbacks.

Finally, we must compare and contrast the strategies to search for habitable environments and life. The search for life on exoplanet will be remote, whereas most searches for life in the Solar System will be *in situ*, or will be remote measurements that are precursors to *in situ* measurements. This means that the detection techniques and associated instrumentation will differ dramatically. However, the fundamental science of astrobiology that underlies both endeavors is the same. Further, there is a similarity in the overarching frameworks that are arising in the communities focused on these various targets. Communities focused on each of these targets is now considering frameworks for astrobiological assessment that include a “follow the energy” approach, the complexity of individual molecules and of chemical networks, and the need to quantify our intuition on what constitutes a biosignature. These similarities allow us to share top-level strategies for the search for life, even if our detailed instruments and measurements exhibit significant differences.

4. The Search for Life Beyond Earth as a Global Endeavor

The expertise required to optimally perform this endeavor extends well beyond the capabilities of a single individual, team, or even nation. We need to fully incorporate lessons throughout the space sciences community – to better understand the stellar context of our observations, how the stellar forcing interacts with the planet, and how the planet itself contains myriad systems which interact. This means the inclusion of astronomers, planetary scientists, heliophysicists, and Earth scientists.

Accordingly, the search for another pale blue dot is one that should incorporate the talent integrated across our own pale blue dot. For example, the LUVOIR and HabEx missions have both included international participants in their study teams. Additionally, France’s Centre National D’Etudes Spatiales (CNES) is studying a high-resolution spectropolarimeter as one of LUVOIR’s instruments. These interactions will improve the quality of these studies, and build momentum for international collaboration as an element of these future flagship missions.

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Terrestrial planet evolution as constrained by element fractionation and atmospheric escape

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Abstract

The evolution and habitability of a planet cannot be viewed without its host star. Among other things, the host star significantly influences the volatile and water inventory, as well as the long term evolution of the planetary atmosphere. Both are important factors for the habitability of a planet. However, not only the star itself, but also the mass and size of a planet, its orbit and formation history, magnetic field and geological activity play a crucial role for the evolution of a terrestrial planet.

Isotope and element fractionations, like $^{36}Ar/^{38}Ar$, $^{20}Ne/^{22}Ne$, or K/U can retrieve details on the formation history of a planet, as well as of the early radiation history of its host star. In addition, $^{14}N/^{15}N$ can give clues on the history of the evolution of a potentially nitrogen dominated atmosphere. However, to build up and maintain such an atmosphere, different key factors have to play together, such as the orbital location of the planet or the EUV flux of the young star. In addition, whether the planet evolved plate tectonics or not seem to be crucial factors to retrieve and maintain a nitrogen dominated atmosphere.

Via the examples of Earth, Venus, and Mars, these key factors will be discussed within this presentation. It will also discuss the importance of life for the maintenance of nitrogen dominated atmospheres, and what can be learned for the potential detection of exoplanetary biospheres. Finally, potential science cases for future space missions will be briefly addressed.