Briefing to the NASA Review of U.S. Human Space Flight Plans Committee

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Good morning. I'm pleased to have this opportunity to appear before the committee and share my opinions regarding the role of human explorers in solar system exploration. I should stress that my opinions are my own and do not represent the views of the National Research Council or any other organization.

I'd like to begin by very briefly reviewing some of the most important questions in planetary science, as expressed in the most recent NRC decadal survey. These questions are significant because they were derived from scientific first principles, without particular regard for the means by which they might be answered. The complete list of questions can be found in the NRC report entitled "New Frontiers in the Solar System: An Integrated Exploration Strategy", and I encourage you to look at that report. I'll just mention some of the highlights here:

- What processes marked the initial stages of planet and satellite formation?
- What is the history of volatile compounds, especially water, across the solar system?
- What is the nature of organic matter in the solar system, and how has this matter evolved?

- Why have the terrestrial planets differed so dramatically in their evolutions?

- What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in the solar system?

- Does (or did) life exist beyond Earth?

These are big questions, and they span all of planetary science.

That decadal survey also described a suite of robotic missions that could address these scientific questions. Again, a complete list of missions is available in the NRC report. They include:

- Kuiper Belt-Pluto Explorer

- South Pole-Aitken Basin Sample Return

- Jupiter Polar Orbiter With Probes

- Venus In Situ Explorer

- Comet Surface Sample Return

- Europa Geophysical Explorer
- Mars Science Laboratory

This is, of course, not an exhaustive list of the kinds of missions that could be flown in the time period of interest to this committee. But it does illustrate the breadth of techniques that must be applied to answer the most important scientific questions identified by the NRC.

The first point I would like to make is that **most of the missions that address the important questions in planetary science would not benefit from the presence of human explorers**. Planetary flybys, planetary orbiters, atmospheric entry probes, and landers to environmentally hostile bodies like Venus are all best done robotically, and I believe they will continue to be.

However, **there is an important subset of planetary exploration that can benefit from human space flight**. These are missions to the surfaces of solid bodies whose surface conditions are not too hostile for humans.

It is conceivable that in the distant future, humans could explore some planetary surface environments that seem too hostile today, including the polar regions of Mercury, the moons of the outer planets, and comet nuclei. For the time period of greatest interest to this committee, however, **I believe that humans can only realistically explore the**

surfaces of the Moon, Mars, and some asteroids. I will therefore restrict the remainder of my comments to these bodies.

Much has been said about the relative merits of human and robotic exploration of planetary surfaces. My own opinion is that both have advantages and disadvantages, and that, given sufficient resources, the best approach is one that uses each in the most effective way.

My views on this subject were shaped in part by my experiences doing research in ice-covered lakes in the Dry Valleys of Antarctica. There we used robotic techniques – remotely operated underwater vehicles – to perform the initial exploration of the lake bottom. The robot provided a safe, effective, and inexpensive way of answering the most basic questions about a complex and hostile environment. After those questions had been answered, we then used scuba gear to investigate the lake bottom ourselves. The key point is that the first-order knowledge that we gained from the robotic exploration allowed us to make expensive and hazardous dive operations much more scientifically productive than they would have been otherwise. Armed with the knowledge that we had gained from the robots, we had well defined objectives and plans for each dive that let us tackle the most complicated questions on the lake bottom very quickly and effectively.

Given enough time, could we have built robots that could have done the same jobs that we did in our scuba gear? Probably. But we would have needed many cycles of design, use, and redesign. Humans have an extraordinary ability to function in complex environments, to improvise, and to respond quickly to new discoveries. Robots, in contrast, do best when the environment is simple and well understood, and the scientific tasks are well defined in advance.

There are also lessons to be learned from the missions of the Mars rovers Spirit and Opportunity. One is that rovers like these accomplish their tasks far more slowly than humans in the same environment would. What Spirit and Opportunity typically achieve in a day, a human explorer could do in less than a minute. The Opportunity rover has traversed about 17 km in its five and a half year lifetime; this is less than the distance covered by two astronauts in their Lunar Roving Vehicle in a single EVA on Apollo 17.

The rovers have other limitations as well. Spirit and Opportunity have of course exceeded our wildest expectations regarding their longevity, their operational flexibility, and their science return. But they have also encountered challenges for which they were not designed and that they consequently have been unable to meet. The rovers cannot dig deep holes in the regolith, cannot climb and descend steep slopes, cannot turn over rocks, often cannot position their cameras where they are most needed, and cannot traverse some common forms of loose debris without getting stuck. All of these limitations have impacted their science return, and all of them arise from the complexity of their landing sites. Again, given enough time for multiple design and redesign cycles, all of these problems probably could be solved robotically. But humans in the same environment could adapt to this complexity much more effectively.

These experiences raise an important point: **Because the capabilities of humans most surpass those of robots in complex environments, the scientific value that humans add is in proportion to the complexity of the environment to be explored.**

So which bodies are complex and which are less so? The Moon is an airless body that has experienced mostly impacts, volcanism, and modest tectonism over its history. Only impacts have occurred recently. Asteroids are more poorly understood, but are probably broadly similar in their complexity.

Mars, in contrast, is a more complicated world. It has experienced all the geologic processes that operated on the Moon and asteroids, and many more: wind transport and deposition, water transport and deposition, glacial and periglacial processes, widespread tectonism, and others. Aqueous alteration and hydrothermal activity have yielded complex mineralogy that holds clues to past environmental conditions. And there are intriguing clues that Mars once had habitable conditions at its surface, and may have habitable niches below the surface even today. All of this complexity means that **human explorers can, in principle, contribute more to the scientific exploration of Mars than they can to any other body in the solar system** for the foreseeable future.

Given the strong scientific appeal of Mars, it is reasonable to ask whether or not there is high priority science to be done at the Moon. Looking at the most recent planetary decadal survey, **the answer is an unequivocal and emphatic "yes".** Several of the most important questions in planetary science deal with understanding how planets form, how they evolve, and why the terrestrial planets are so different from one another. Understanding the Moon is central to these questions. That's why the South Pole-Aitken Basin Sample Return mission featured so prominently in the decadal survey report, and why the GRAIL mission was recently selected as part of NASA's Discovery program. So there is unquestionably a great deal of important science remaining to be done at the Moon. However, it is my personal opinion that **most of the really important lunar science can be done robotically**, for the reasons I have outlined above.

Let me now address four specific questions regarding the role of humans in scientific exploration of the solar system:

1) If human explorers are going to be sent to planetary bodies, what is the most cost effective science they can do?

2) What important science does sending humans *enable*?

3) What science can robotic systems do to help enable human exploration?

4) What can humans and robotic systems accomplish together?

Regarding the first question, if NASA is going to take on the substantial costs and risks of sending humans to another planetary body, there are important scientific tasks that those humans can accomplish for relatively little additional cost and risk. The best example is sample return. Human explorers will have to come back to Earth, and when they do it will be relatively straightforward for them to bring samples with them. Moreover, humans can do a better job than robotic systems of selecting and collecting samples, particularly on a geologically complex body like Mars.

Let me stress that humans are not required to return samples from the Moon, asteroids, or Mars. But **if humans are going to visit these bodies, collecting and returning high-quality samples is one of the most scientifically important and cost effective things they can do.** Laboratory instruments surpass flight instruments in quality, so the best scientific work will be done with well-documented returned samples. And samples can increase in scientific value with time: Some of the best science ever done with the Apollo samples is being done today using instrumental techniques that did not exist when the samples were collected, by scientists who had not yet been born.

Next, I'd ask what high priority science is enabled by the presence of humans; i.e., what simply cannot be done without humans there? The answer may be nothing, if we're willing to wait long enough, enabling enough cycles of design and redesign. But there are some very important tasks that will require so much equipment and infrastructure that it's hard to imagine it all working without humans on-site to operate and maintain it. Perhaps the best example is deep drilling on Mars. If habitable conditions exist on Mars today, they may be restricted to depths of hundreds of meters or more, where liquid water is stable under current martian conditions. **Deep drilling could be one**

of the most important scientific tasks carried out on Mars, but the equipment required to do it could be very difficult to operate and maintain without humans.

Robotic precursor missions can do much to enable human exploration, as first shown by the Ranger, Surveyor, and Lunar Orbiter missions that preceded Apollo. Orbital and landed missions can be used to select landing sites for their safety and scientific potential. Precursor landed missions can characterize the environmental conditions on a planet's surface and the threats they may pose to human health. This could be particularly important on Mars, where fine airborne dust is pervasive. Precursor missions can also characterize the environment from an engineering perspective, allowing better design of vehicles, habitats, and suits for humans. And precursor missions can be used to search for potential resources, including ice and other water reservoirs on Mars, possible ice at the lunar poles, and materials ranging from hydrocarbons to metals on asteroids.

Also, **there can be valuable opportunities for humans and robots to work together in exploring planetary surfaces.** The most recent space shuttle mission demonstrated this potential, with five EVAs conducted in tandem with operations of the robotic arm on the space station, the robotic arm on the shuttle, and the arm on the Japanese Kibo laboratory. As robotic technology advances, I believe that human explorers on the Moon, asteroids, or Mars will make extensive use of robotic systems just as the astronauts on the shuttle and space station do. For example, astronauts in orbit or on the surface of asteroids or Mars will be able to teleoperate rovers without the long time lags and the need for autonomy required by teleoperation from Earth. Essentially all of the science that humans will do on these bodies can be aided by judicious use of robotic systems, just as we used robotic systems to amplify the science return from our dives in the Dry Valley lakes.

Finally, I would be ignoring a critical issue if I did not comment on the cost effectiveness of human vs. robotic exploration. I have argued that humans, or humans aided by robots, can carry out scientific exploration of planetary surfaces, particularly complex ones, more effectively than robots alone. But **if good science were the only goal, then I think one of the clear lessons of 50 years of space exploration is that robots alone are more cost effective.** There are a few examples, like deep drilling on Mars, of high-priority science that may never be practical without humans present. But there is more than enough important planetary science to be done purely robotically – including exploration of the surfaces of the Moon, asteroids and Mars – for decades to come.

Also, I am wary of arguments that say, in effect, "we're going to do this anyway, so what science can we add to it?" Such arguments have not served NASA well in the past. When science is an afterthought, it can be the first thing to go when schedules slip and budgets get tight.

I do not mean to say that human exploration is bad for planetary science; it need not be and should not be. And I am well aware that science is not the only motivation for human exploration; indeed, I am a strong advocate of human exploration for many other reasons. But **if science is to be served well by a program of human exploration, then science must be a full partner in planning and executing that program.** And if science is going to be one of the major goals of human exploration, not just an add-on, then **care should be taken to concentrate the human explorers' efforts in the scientifically complex settings where they can contribute most.**