EXPLORING THE MOON IN THE 21st CENTURY

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INTRODUCTION

In 2019, we are celebrating the 50th anniversary of NASA's momentous Apollo expeditions to the Moon. The samples brought back by the astronauts, and the fieldwork those astronauts performed on the lunar surface, cemented the Moon's status as the cornerstone of the solar system. It is not an exaggeration to say that the Apollo expeditions transformed our understanding of our solar system, and, in fact, most of the discoveries made in planetary science since the 1960s can trace directly, or indirectly, from the scientific results of those Apollo expeditions.

Although some erroneously proclaim that the Moon is "Been there, done that", nothing could be further from the truth. After a long hiatus, beginning in the first years of the 21st century, there has been a resurgence of interest in the Moon, including the Kaguya mission by the Japanese Aerospace Exploration Agency (JAXA); the Chandrayaan-1 mission by the Indian Space Research Organizations (ISRO); four Chinese missions:- 2 orbiters (Chang'E-1 and -2) and two landed missions with rovers (Chang'E-3 and -4); as well as four NASA missions: the Lunar Reconnaissance Orbiter (LRO), the Lunar Crater Remote Observation Sensing Satellite (LCROSS), the Lunar Atmosphere and Dust Environment Explorer (LADEE), and the Gravity Recovery and Interior Laboratory (GRAIL). Taken collectively, the results from these missions have shown that the Moon is a far more interesting, and far more valuable, destination for future exploration than was perceived even during the Apollo era. Results from recent lunar missions have only increased the interest in a vigorous program of lunar exploration and utilization.

The 50th anniversary of Apollo 11 presents the perfect opportunity to take a look to the future. The Moon now presents an entirely new paradigm for planetary exploration through incremental, affordable investments in cislunar (i.e., between Earth and Moon) infrastructure. But how do we do that?

ROADMAP TO THE FUTURE

The Lunar Exploration Analysis Group (LEAG), the community group started in 2004 that organizes and leads the large and diverse lunar exploration community, has developed the Lunar Exploration Roadmap (LER) (LEAG 2016). Featuring inputs from engineers, planetary scientists, commercial entities, and policymakers, the roadmap presents a cohesive strategy to make concrete advances along the following three themes:

1. ***Science*** Use the Moon for scientific research by addressing fundamental questions about the Moon, our solar system, and the Universe around us. Like the four terrestrial planets (Mercury, Earth, Venus, Mars), the Moon has a crust, a mantle, and a core and is, therefore, one of the most accessible destinations to cohesively address questions about early evolution of planetary interiors. The Moon retains a record of the formation, evolution, and impact history of Earth and the inner solar system, as well as an otherwise inaccessible record of the Sun's evolution and history. Finally, this is another area where the Apollo expeditions represent a strength: there are five decades worth of planetary science hypotheses that lunar geological fieldwork will address. The lunar surface could also provide a unique and stable long-term platform for astronomy. In particular, manned radio observatories or optical interferometers on the far side of the Moon could produce dramatic advances in astrophysics. The LER prioritizes science concepts and goals from the 2007 National Research Council Scientific Context for the Exploration of the Moon report (NRC 2007), which were subsequently affirmed and amplified by the LEAG's "Advancing Science of the Moon" report (LEAG 2017).

2. ***Sustainability*** Use the Moon to learn how to live and work productively off-planet, for increasing periods, to enable extended off-planet human settlement. The Moon has abundant material and energy resources that can be used to decrease the costs and dramatically increase the capabilities of future solar system exploration. Lunar resources, in particular, offer an enduring opportunity for commercial investment and bringing cislunar space fully into Earth's economic sphere of influence while building international partnerships. Commerce is a key aspect of ensuring the sustainability of future space activity. Public–private partnerships, growing from initial government-funded lunar resource extractions and utilizations, will provide the capabilities required for any future sustained human space operations.

3. ***Feed Forward*** Use the Moon to prepare for future missions to other destinations. The Moon is the only viable deep-space test-bed for testing technologies, systems, and operations to enable cost-effective human operations beyond low-Earth orbit. The Moon's combination of radiation, hard vacuum, and low-gravity provides a unique laboratory to study the physiological, biological, and biomedical aspects of long-duration operation on planetary surfaces. Irrespective of the innumerable ways in which lunar exploration is required for the success of future voyages to Mars and beyond, establishing a lunar outpost will establish the comprehensive workforce and industrial base required to successfully make voyages to Mars, dwarf planet Ceres, and beyond.

Figure 1 The South Pole of the Moon, pictured here in an oblique view from NASA's *Lunar Reconnaissance Orbiter*, is the landing site for the seventh human lunar landing. Image courtesy of NAC M1195011983LR (NASA/GSFC/Arizona State University).

A VISION FOR LUNAR EXPLORATION IN 2050

Successfully implementing the LER will result in a variety of benefits for the United States of America, and the world. While predicting events three decades hence is fraught with uncertainty, the LER offers a path for a dramatically altered landscape for planetary science and exploration by the year 2050. The Moon's attainability offers intriguing possibilities where lunar surface operations are commonplace, with at least several hundred people living and working on the Moon full-time. Examples of the kinds of activities we foresee include:

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