The Moon: A New Destination for America

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A human return to the Moon is part of the new Presidential Vision for Space Exploration, now endorsed as national policy by the Congress. The Moon is valuable for three reasons: science, inspiration, and resources. A number of scientific problems can be uniquely addressed on the Moon, including questions about the impact flux in the Earth-Moon system and the composition of the Sun billions of years ago. The Moon is a training ground and template for us to learn how to live, explore, and work productively on other planetary surfaces. The energy and material resources of the Moon have the potential to revolutionize the spaceflight paradigm. For all these reasons, the Moon will be a stepping stone for journeys much farther into the universe.

I. Introduction

On January 14, 2004, President Bush visited the Headquarters of the National Aeronautics and Space Administration in Washington DC to announce a new vision for America's space program. Prominent among the many goals and objectives outlined that day was to explore and use the Moon. Although we conducted our initial visits there over 30 years ago, recent important discoveries indicate that a return to the Moon offers many advantages and benefits to the nation. In addition to being a scientifically rich object for study, the Moon offers abundant material and energy resources, the feedstock of an industrial space infrastructure. Once established, this infrastructure will revolutionize space travel, assuring continuous, routine access to cislunar space (i.e., the space between and around Earth and Moon) and beyond. The value of the Moon as a space destination has not escaped the notice of other countries – at least four new robotic missions are being flown or prepared for flight by Europe, India, Japan, and China. Advanced planning for human missions in many of these countries is already underway.

Why the Moon? Although many reasons can be advanced for this selection, the Moon's principal virtue is closeness and accessibility. A miniature world of surprising complexity and subtlety, the Moon offers us a place to learn the skills we need to move into the Solar System. By reducing our dependence on logistics from Earth, we will begin to establish a human foothold off-planet. There we will learn how to explore, live and work productively on another planetary surface, and extract usable resources (both materials and energy).

Beyond exploitation, the Moon has scientific value in its own right. It has a surprisingly complex history, shaped by both internal (magmatism and crustal deformation) and external (impact) geological events. Its surface is a time-capsule recording events in this part of the universe for over 4 billion years. This record can be recovered and will tell us about the conditions in former universes and ancient solar systems. Finally, as a stable, unchanging platform, it is a superb location to build sensitive, distributed aperture observatories for studying both the near-space of the Earth, Sun and environs and the distant heavens beyond.

The principal reasons for returning to the Moon can be subdivided into three categories: science, inspiration, and resources. I will consider each reason in turn, noting specific and unique aspects that make the Moon both a destination and a strategic object.

II. Science

Our return to the Moon will be a boon to science. Although many different and diverse disciplines will benefit from their own detailed studies and investigations (many of which are detailed in LEXSWG[1,2]), some of the most interesting science will result from coordinated, interdisciplinary studies that take advantage of some of the unique aspects of the Moon's history and environment.

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A. The Moon records the Sun and universe

The Moon has no atmosphere and no global magnetic field. Consequently, its surface is bombarded by particles of all types, both solar and galactic. This bombardment has taken place continuously over the last 4 billion years, although at a very low rate for most of this period. Surface changes on the Moon during that time are related to impact gardening and churning of the regolith, a process well characterized from the Apollo data and samples[3]. Thus, in principle, we can recover from the Moon a detailed record of the particle impingement history on the lunar surface, allowing us to view the ancient Sun and galaxy not as they are now, but as they existed in the distant past, something not possible on Earth.

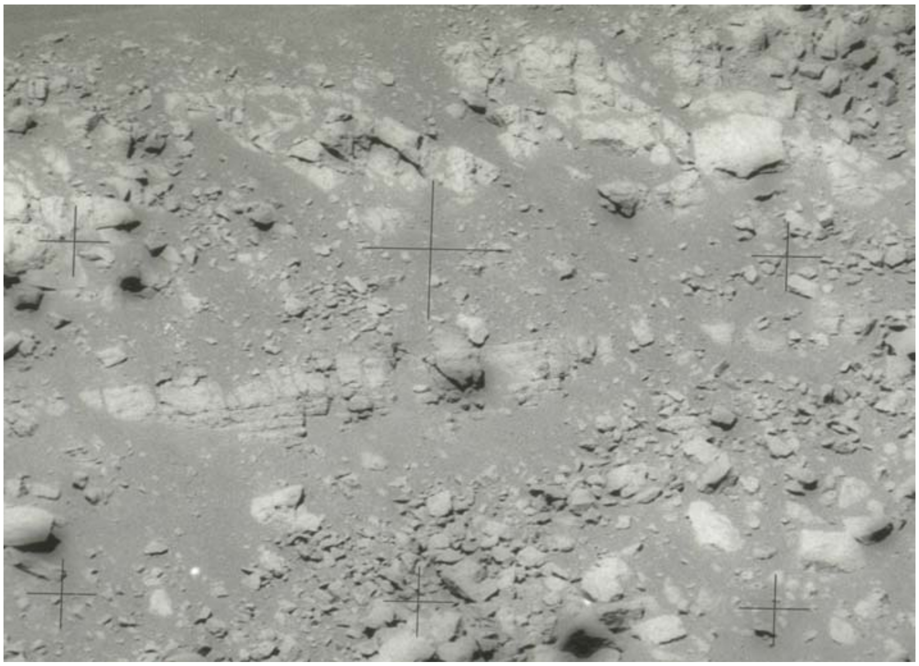

Figure 1. The western wall of the lunar Hadley Rille at the Apollo 15 landing site. The massive basalt flows seen in the upper part of this image are mare basalts emplaced about 3.1 billion years ago. The layered outcrop shown below these flows are KREEP basalts, erupted 3.85 billion years ago[22]. Between these two flows, there must be a regolith formed on the older KREEP basalts. This regolith would record the solar and galactic particle flux occurring on the Moon between 3.85 and 3.1 billion years ago, a 750 million year history. Many such "paleoregoliths" exist on the Moon, allowing us to study these ancient environments in detail.

As an example, the lunar maria consist of basaltic lava flows emplaced over many hundreds of millions of years. Individual flows may be very voluminous, but are of low viscosity and are emplaced over brief intervals of time. The maria consist of these flows, emplaced rapidly in a few days, but with eruptions occurring at intervals of millions of years. As soon as a flow is erupted and emplaced, it begins to collect exposure information from space, including the implantation of atoms of solar wind gas, including hydrogen as well as all of the light elements. This implantation occurs even as the surface is being disaggregated and ground into a powdery surface regolith by impacts.

If an ancient basalt flow that has built up a regolith is covered by another eruption millions of years later, there exists between the basalt layers an ancient regolith, exposed to space for a specific interval of time and afterwards shielded from any such effects (Fig. 1). Such ancient regoliths record an ancient Sun, whose output may have been significantly different from the current one. As evidence that this may be the case, analysis of Apollo deep drill cores suggest that the isotopic composition of nitrogen has changed with time, a change not predicted nor a consequence of any of the current models of stellar evolution[4].

Finding and studying paleoregoliths will give us a detailed picture of the ancient universe. As high-energy particles leave a record in the dust grains of the lunar surface, we may even be able to isotopically date from these paleoregolith samples, ancient galactic events, such as nearby supernova. These buried regoliths have clear time-separation planes in their underlying and overlying lava flows. We can study these ancient records through trenching or drilling. Study of the ancient particle record in the lunar regolith will give us new insights into the history of the solar system and galaxy.

B. The Moon records Earth impact history

Of all the scientific benefits of Apollo, an appreciation of the importance of impact, or the collision of solid bodies, in planetary evolution must rank highest[5]. Before we went to the Moon, we had to understand the physical and chemical effects of these collisions – events completely beyond the scale of human experience. Of limited application at first, this knowledge turned out to have profound consequences. We now believe that large-body collisions periodically wipe out species and families on Earth, most notably, the extinction of dinosaurs 65 million years ago[6]. The telltale residue of such large body impacts in Earth's past is recognized because of knowledge garnered from Apollo. Additional knowledge still resides on the Moon. The Earth's surface record has been largely erased by the dynamic processes of erosion and crustal recycling, but the ancient lunar surface retains this impact history. We will examine this record in detail and learn about its evolution as well as our own.

One of the most intriguing problems in modern paleontology is the suggestion that impact extinctions of life have occurred periodically throughout Earth's history[7]. Several of the recent mass extinctions preserved in the fossil record occur at quasi-regular intervals of 26 million years. If extinctions are driven by impacts, there should be evidence of such impact events in the geological record. On Earth's dynamic, active surface, impact craters are rapidly eroded and erased. However, the Moon's ancient surface preserves these epochs in exquisite detail. The myriad craters on the Moon are preserved, allowing us to address the issue of impact episodicity on a statistical basis. By determining the ages of a few hundred craters, we can unequivocally establish or falsify the periodic nature of the impacting flux. Such studies may provide a window onto our future.

The same study methodology can also be applied to the other end of the cratering time spectrum – the earliest heavy bombardment. The rugged highlands of the Moon attest to an early, violent episode of impacting. Whether this occurred as the tail-end of a steadily declining flux[8] or was a discrete episode of cataclysmic violence[9] remains a contentious issue. Because the Moon records the early history of the Earth-Moon system, the resolution of this problem has significant implications for the environment and history of the early Earth, a time when life apparently emerged on our own planet[10].

C. The Moon records itself – A miniature museum of planetary processes

Generally considered a simple, primitive body, the Moon is actually a small planet of surprising complexity. The period of its most active geological evolution (between 4 and 3 billion years ago) corresponds to a missing chapter of Earth history. The processes that work on the Moon – impact, volcanism, and tectonism (deformation of the crust) – affect all the rocky bodies of the inner solar system, including the Earth. Because the Moon has no atmosphere or running water, its ancient surface is preserved in nearly pristine form and its geological story can be read with clarity and understanding.

Very large impact features, those with diameters exceeding hundreds of kilometers, are found in the most ancient terrains of all the rocky planets. However, on larger planets such as the Earth, erosion and crustal dynamism have erased many salient geological details of these features, making the details of how these features form and subsequently evolve mysterious. Because the Moon is small and has little indigenous heat, ancient basins and craters on the Moon may be as well preserved today as when they were created. These features, which have such profound consequences during the early evolution of the planets, make the Moon a geological museum of ancient processes, some of which can only be partly comprehended via the study of Earth analog features and processes.

While the Moon is currently dead geologically, we have reason to suspect that it's internal evolution continued for over 3 billion years, with the very youngest lava flows on the Moon having erupted as recently as 1 billion years ago. This is astonishing for such a small planetary body. Study of the extent of the Moon's igneous evolution will give us new insight and appreciation of the thermal evolution of planets. Such knowledge is critical to fully understanding the divergent evolutionary paths taken by the terrestrial planets Mercury, Venus, Earth and Mars.

III. Inspiration

A simple and basic attribute of the Moon is that it is a destination in space. As such, it serves many purposes beyond those of science. The Moon is a complete world, with its own challenges, vistas, opportunities and mysteries. Its proximity to Earth allows us to reach it quickly and easily in spaceflight terms. While a world of its own, it has the virtue of being closely linked to the Earth in many senses. A space transportation system capable of reaching the Moon can routinely access all points in space between Earth and Moon, i.e., cislunar space, particularly important for our emerging space-based economy.

A. A school for exploration

Planetary exploration requires skill sets best learned on the job – you explore to learn how to explore. While we have made impressive discoveries in our 50 years of space exploration, we have very little practical experience in the exploration of planetary surfaces. Such experience would inform and guide us on such issues as the optimum strategies for exploring an area, the proper allocation of human and robotic resources, and the development and practical implementation of exploration templates to permit the maximum return of knowledge for minimal amounts of investment.

The perennial debate in the space community is: Should humans or robots explore space? Although the occasional pathological case can be cited, most now agree that people and machines both have significant and unique roles to play in the exploration of space. What remains unclear is exactly how robotic and human mission elements can work synergistically to accomplish greater exploration objectives than either could by working alone.

Studies are currently underway to understand how a robotic field assistant could aid a human geologist on the Moon[11]. In this scenario, a robotic entity accompanies a human on exploration traverses, serving as a tool caddy, pack mule, database repository and miniature analysis laboratory. The human explorer makes all the strategic decisions – where to sample, which outcrops are significant, how to evaluate subtle field relations, while the robot does all the menial, repetitive, or dangerous field tasks (e.g., retrieve a sample from a precarious locale.) Such a complementary arrangement would seem to take advantage of the respective strengths of both humans and machines. However, technical limitations could reduce the effectiveness of such an arrangement. Field tests to date show that the human explorer spends an inordinate amount of time keeping the robot assistant running properly[11]. Doing field tests in real planetary environments (such as the Moon) could give us valuable experience in designing exploration strategies for destinations farther a field.

Figure 2. A telepresent robot might extend human "reach" into hostile or remote environments[12]. In this concept, the robotic rover with very high resolution vision and tactile feedback is under the direct and instantaneous control of a human operator at a remote site, thus fooling the human into thinking that they are "present" at the remote locality. This would enable true field study on the planets by melding a human mind with a robotic body. Such techniques can be evaluated on the Moon.

Another aspect of the human-robot issue is the potential of robotic telepresence. This mode of exploration projects a human mind into a remote robotic surrogate (Figure 2). High resolution vision, tactile feedback and coordinated, mirrored movements with articulation comparable to human arms and hands, all relayed at near-instantaneous rates, can fool the human brain into thinking it is actually present at the remote location. Robotic telepresence has been suggested as a tool to permit "human" exploration of planetary surfaces without people physically present[12]. Whether telepresence is a useful exploration technique is not known, largely because the unusual and demanding environments posed by planetary exploration are difficult to simulate on Earth. Experimenting with telepresent robots on the Moon can help us evaluate whether this exploration tool will be useful in future planetary missions, particularly those in which actual human presence is not feasible, such as the surface of Venus.

B. A place to live and work off-planet

The Moon is a natural space station, ready to inhabit. Its location is well known and its proximity to Earth permits people to visit its surface for varying increments of time. On this alien planetary surface, we can spend extended isolated time periods with the invaluable benefit of being close to Earth in case problems develop. The dynamics of group interactions in such an environment will build a valuable database as we contemplate planetary missions with durations measured in years instead of months.

The Moon is an important testing ground for the effects of partial gravity on biological systems. Extended absences from Earth's gravity have negative effects on human physiology, including decalcification of the skeletal system and muscle atrophy. We already know a great deal about the extent of these effects from the voluminous data provided by Skylab, Mir, and ISS. What is completely lacking is information on the possible effects of fractional gravity on human systems. Future planetary destinations possess gravitational fields smaller than the Earth's. Do the negative physiological consequences seen in the microgravity of free space occur in fractional g environments? Do new consequences, currently not envisioned, occur as a result of extended presence in such environments? These are critical questions for the implementation of human space exploration and the Moon is a natural laboratory to address these issues.

Although the social dynamics of small, isolated human communities have been studied extensively, extended human presence on the Moon permits us to understand these dynamics in a new and unforgiving environment. Effective group work ethics and productivity are important to establish off-planet human communities and the Moon will serve as the place to develop organizational principles that will inform future journeys into the Solar System.

C. A stepping-stone to the rest of the Solar System

On the Moon, we will develop and test systems, procedures, and hardware adaptable to the exploration of other objects in the Solar System. The new Exploration Systems Architecture Study[13] has specific features illustrating this concept. The Lunar Lander uses a cryogenic propulsion system, partly for its high performance but also because it is an extensible system to other planetary missions, particularly a human Mars mission. The lander uses both cryogenic oxygen-hydrogen and oxygen-methane propellant systems, both candidates for future Mars landing craft. A variety of other systems will be developed for future use, including those for surface power, mobility, habitation and thermal control.

Not only hardware, but operational strategies and crew allocations can be experimented with and optimized on the Moon. How many crew are optimum for a field exploration party on the Moon? The Apollo experience suggests that two crew members make an effective exploration team but sometimes the workload is too oppressive. We can determine the optimum size and operations strategy for geological or biological field exploration by doing actual field science on the Moon. Likewise, construction of advanced scientific installations, such as a large telescope or infrastructure at the lunar outpost are workable problems in field logistics and human resources. Such challenges tie directly into the human-robotic interplay and balance mentioned earlier. In such cases, experience accrued on the Moon will enhance safety and efficiency as we venture farther.

The development of a cislunar transportation system is highly significant both for the future of space travel and for America's position in the world. Right now space is an international arena, one in which any nation is free to develop and fly space systems for a variety of purposes. The keeping of the peace in space relies on both treaty and goodwill among nations. The positions of myriad satellites within geostationary orbit is largely arranged by gentlemen's agreements. This has sufficed, but what if a rogue nation makes belligerent moves on our own or other nations' satellites? We need the flexibility to protect our national assets and assure free movement of goods and services throughout space, in the same manner that the British navy assured such qualities on the world's oceans during the 19th century. Currently, we do not have the ability to move freely throughout cislunar space; exploiting

IV. Resources

Space is an unlimited source of materials and energy. In order to create a true space faring civilization, we must start learning how to cut the cord with the Earth. This involves not only learning how to use what we find in space, but also learning how to recognize the potential value of a resource. In short, we must learn to play the hand nature has dealt us. The sooner we begin using the resources of near-Earth space, the sooner we can create new capability. These skills will increase our exploratory reach as well as prepare for the day that humanity establishes settlements off the Earth.

The Moon is an object of fairly ordinary composition yet it contains the materials necessary to both support human life on its surface and to create a cislunar transportation infrastructure. With such a transport system, we can both routinely access cislunar space and go to the planets.

A. Energy – See the light

The Moon is constantly bathed in solar energy. At any given time, half the lunar surface is illuminated, unmasked by obscuring clouds or atmospheric absorptions. The Moon rotates once every 28 days, creating a day/night cycle of extended length. However, the spin axis of the Moon is nearly normal to the ecliptic (the spin axis is inclined about 1.5°), making the poles of the Moon an interesting lighting environment. Over the course of a month, the sun appears to move slowly in a great circle, sometimes slightly dipping above and sometimes below, the horizon. Areas below the mean surface level, such as crater floors, never see sunlight while high points may be in the sunlight for extended periods.

Clementine images provide us with some indications about the nature of polar lighting[14,15] (Figure 3). It appears that small areas (a few square kilometers in extent) are in permanent sunlight at the north pole, while other areas near the south pole are in sunlight for more than 75% of the lunar day. These data were taken during only one season (summer in the north and winter in the south) and are not definitive. However, they indicate that places exist on the Moon that are in near-permanent sunlight and will facilitate establishment of a foothold on the Moon. In these areas, we can set up an outpost exclusively using solar energy, a relatively inexpensive, reliable energy source. During the small times when these sites are in eclipse, stored energy from fuels cells can bridge the time until the sun emerges. Moreover, because sunlight at the poles hits the Moon at grazing incidence, the polar lit areas never see the extreme temperature swings experienced at the equator where temperatures can range between -150° C to over 100° C. At the polar areas, the constantly grazing incidence results in temperatures of about -50° ± 10° C. Such a benign thermal environment greatly facilitates surface operations and outpost emplacement.

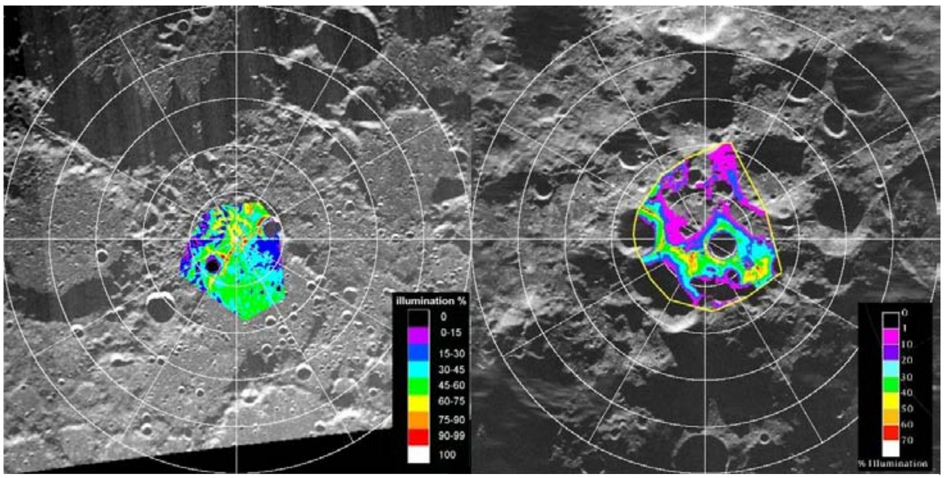

Figure 3. Maps showing the percentage of the lunar day given terrain near the poles are sunlit[14,15]. These maps are based on Clementine data, which only saw the Moon for 71 days, during northern summer. Although seasonal variation is expected to be slight, it may be significant enough such that and these conditions may be different during the opposite season.

B. Materials – Find the ice

A consequence of the existence of permanently dark areas around the poles is that cold traps are created in which any volatile elements or substances may be retained within them. The Moon as a whole is depleted in volatiles[16] and those of external origin that may be added to the Moon (via impacts) are not stable in the lunar surface's extreme thermal environment. However, in the dark cold regions near the poles, any volatile that enters cannot re-emerge – it is permanently trapped in dark areas as cold as 50 degrees above absolute zero. Although cold-trapping would be a very slow process, over billions of years significant quantities of volatiles could accumulate. As water is the most common volatile constituent in the solar system (making up more than 99% of the mass of cometary cores), water ice would be the principal volatile component of the polar dark areas.

During the 1994 Clementine mission, an experiment was improvised that suggested water ice exists in dark areas near the south pole of the Moon[17,18]. Subsequently, the NASA Lunar Prospector mission found elevated quantities of hydrogen at both poles[19]. Although the exact physical nature of the polar volatiles is debated, it is clear that significant quantities of hydrogen are available in the polar dark areas. Hydrogen is significant for two reasons. First, hydrogen in the form of water will support significant levels of human activity on the Moon, permitting long-term habitation. Second, hydrogen and oxygen are important fuels, both for fuel cells to generate electricity during eclipse periods and most importantly, to provide rocket propellant for the cislunar transportation infrastructure.

The Moon as a source for rocket fuel can completely change our paradigm of spaceflight. Currently, all space assets are built as one-offs – designed, launched, operated and eventually discarded – largely because we do not possess the ability to routinely travel throughout cislunar space to service, maintain and upgrade these assets. By returning to the Moon and establishing a space-based infrastructure, including the ability to refuel off-Earth, we achieve a primitive state of self-sufficiency in space only dreamed of since the beginning of the Space Age. By using lunar polar water, we open a new chapter in the history of spacefaring – the use of off-planet resources. The creation of such capability is a principal objective of the new Vision for Space Exploration[20].

In addition to polar water, the Moon is a source for a variety of ordinary substances that, while not intrinsically valuable for export, have great value in the creation of usable infrastructure on the Moon itself. The bulk regolith of the surface can be used for a variety of construction and shielding purposes. Soil piled over surface habitats can protect people from the hard radiation environment of the lunar surface. Regolith exposed to microwaves glazes it into glasses and ceramics, useful for a variety of purposes. Iron and aluminum are possible by-products of oxygen extraction from the lunar soil and have great utility in the establishment of industrial infrastructure on the Moon.

C. How on Earth? – Getting started in using space resources

To many, the concept of using space resources has a patina of science fiction, in part caused by assumptions that significant industrial capability will be needed to achieve some of these objectives. In fact, utilization of space resources can begin very simply, with minimal investment in equipment and time. For example, the use of bulk regolith for radiation shielding only requires that it cover the pre-fabricated habitat modules. Such covering can be done with small surface roving vehicle equipped with a variety of earth-moving tools. In addition, the machines needed to harvest the water ice in the dark regions of the poles can be quite small. A conceptual studies indicate that small robotic rovers and a desk-sized processing plant that can produce enough water to support a significant human presence on the Moon[21]. Only a slightly larger version of such a system is needed to begin propellant production that allows access to the Moon, the cornerstone of the cislunar transport system.

Using space resources begins with small steps, introduced at scale-appropriate levels to accomplish carefully determined mission objectives. We begin the mission of returning to the Moon by learning how to extract and use local resources to live and work productively on another planetary surface.

V. Conclusions

"If God wanted Man to become a spacefaring species, He would have given Man a Moon." – Krafft Ehricke

The Moon is our stepping stone into the wider universe beyond. On the Moon we will learn by doing – living, working, exploring, and prospering. We will obtain the skills necessary to move out into the Solar System and make humanity a spacefaring species. The Moon's proximity, utility, and intrinsic interest make it an appropriate and exciting destination for America in the new century.

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