Explore Our Stepping Stone – First Understand What The Moon Offers

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The Moon – we have "been there," but hardly "done that." The lunar surface is almost the size of Asia; we (the U.S. and U.S.S.R.) have obtained samples from nine sites within a thin strip much smaller in area than India, and never deeper than three meters. All the astronauts and all of the lunar rovers together have traversed a distance less than 5% of that trodden by Amundsen is his Antarctic expedition in 1911. There are major geological terranes e.g., South Pole-Aitken, for which we have little information.

We (also including ESA, Japan, China and India) survey the Moon remotely from many spacecraft, but spacecraft and instruments break. For instance, the *Kaguya* (*SELENE*) Charge Particle Spectrometers (alpha and cosmic ray) and the entire *Chandrayaan-1* spacecraft have suffered tragically fatal breakdowns that have robbed us of vital and unique data. Aspects of lunar science crucial to human exploration of the Moon and the rest of the Solar System will not be understood until these data sets are replaced. No plan exists to do this. (We return to this issue below.)

Besides being a test bed for technologies to explore the planets, especially Mars, the Moon offers resources that realistically might eliminate obstacles to the rest of the Solar System. Water is the paramount issue, to maintain human life and provide the nearly ideal chemical rocket fuel. The energy required to lift mass from the Moon is only 4.5% of that from Earth, so potentially just humans (plus their life support and tools) need depart from Earth. (For example, two Delta II Heavy rockets to launch the weight of the two Mars Exploration Rovers from Earth could be replaced hypothetically by a single Pegasus from the Moon, or a Saturn V by a Delta II.) Fuel, structures (aluminum, titanium, silicon, iron) and oxygen can derive from the Moon. For the velocity changes needed within the Solar System, however, propellant (hence water) is the critical issue for human transportation.

Where is the water? Oxygen composes 40% of lunar regolith; hydrogen is rare, about 50 ppm. Certainly, hydrogen could be harvested by a thermal "rake" that concentrates gases driven from regolith heated by solar radiation. (Similar technology might someday harvest ^{3}He to fuel fusion reactors.) Great attention is paid to prospects of water trapped in permanently shadowed craters at the lunar poles, and this seems a plausibly more convenient reservoir. We *have* found water on the Moon, however, in volcanic glasses driven from the deep lunar interior. These imply an abundance of water at great depths in the range of many hundreds of ppm. Exactly where this water came from, how and where it reached the surface, and whether it still does as vapor is highly uncertain, demanding major study. It is conceivable that such water has collected in the polar regions, but underground rather than as a thin surface layer. This will demand significant robotic and likely human missions to probe. Even if all lunar hydrogen reservoirs prove problematic, 94% of the propellant mass is O_2. H_2 could be transported from Earth, and O_2 derived from lunar regolith H-reduction/electrolysis processes, essentially recovering H_2 as a catalyst at the end.

The techniques that can be developed on the Moon that will prove crucial on Mars include telerobotics. This technique is ideally suited for the Moon, only a 3 second round trip from the people of Earth. In addition to astronauts, telerobots will someday explore the Moon. (In fact, Lunakhod 1 and 2 were early realizations of this.) For Mars from Earth, the round trip time is anywhere from 7 minutes to one-half hour, but likely humans will use telerobotics to explore Mars from orbit e.g., based on Phobos, where the round trip is less than 1 second. Telerobotics will be convenient for exploring Mars. If Mars harbors life, telerobotics may become essential for Martian exploration while maintaining satisfactory planetary protection protocols.

The lunar surface is a harsh environment, but most hazards can be ameliorated by covering one's habitat with about a foot's depth in regolith: temperature swings, radiation and micrometeorites are essentially neutralized by this easy approach, and elegant tools for handling regolith are developing rapidly. A remaining issue is the mechanical effect of dust, both on machines and human lungs. Mars suffers from all of these effects to significant degree, and there is additional uncertainty regarding the chemical reactivity and/or toxicity of Martian dust. Technological insight developed for these hazards on the Moon is likely to aid in dealing with Mars.

Perhaps Mars can be terraformed in 1000 years, but the primary attraction is the possibility of life arising beyond Earth. We know so little about that subject, however, that one could equally surmise that life is more likely on the moons Europa or Enceladus. How would we react in the year 2025, having thrown our efforts into reaching Mars, when we find a vital ecosystem in orbit around Jupiter or Saturn? We need to have goals commensurate with our knowledge, not our presumptions. We need to learn first how to explore another world, and what we can explore now is the Moon.

Manifest and varied scientific questions unique to the Moon must be explored. The Moon is the world whose structure and evolution fundamentally most inform us about Earth. The formation of the Moon altered the crust, mantle and core of Earth in ways not fully understood that may be crucial to understanding how our planet works, and why it is so different from its "twin" Venus. Perhaps this bears on vital issues like the terrestrial magnetic field's currently rapid disappearance in its polarity flip e.g., the growing South Atlantic Anomaly. The old highlands regolith offers a unique, four billion year record of inner Solar System history. In contrast, some smaller regions seem to have undergone very recent geological activity in ways we fail to understand. The Moon offers the most accessible example of a solid-bounded exosphere, a ubiquitous Solar System venue heavily influenced by solar wind interaction. In contrast, most of the Moon's atmospheric mass is composed of radiogenic ^{40}Ar, which certainly derives from the interior but via conduits mysterious to us. The argon outgassing appears to be episodic, and outgassing of radiogenic ^{222}Rn is localized and episodic by means unknown. The distribution of maria on the Moon and Mercury differ radically for poorly understood reasons. There are many more open questions regarding the Moon.

To take best advantage of human exploration of the Moon or another world, we need to do our "homework" by first sending robotic spacecraft in our stead. There has been a robust, international program of lunar probes, but despite the intensity of effort and significant redundancy, some of the most vital and unique instruments have failed. Due to a malfunctioning guidance system, *Chandrayaan-1* is being placed into a high orbit deleterious to many of its science goals. Particularly, the NASA-sponsored Moon Minerology Mapper (M^3) will suffer greatly from degraded resolution. M^3 was the only instrument, for instance, capable of isolating hydrated minerals via hyperspectral imaging. The otherwise successful *Kaguya* (*SELENE*) suffered an electrical failure that seems to have limited results from its alpha particle spectrometer, the only instrument sufficiently sensitive to lunar outgassing events. In principle, the *LADEE* satellite could study the spatial distribution of neutral species in the lunar atmosphere, but in its planned equatorial orbit it will at best make a global composition measurement. Since the rocket exhaust from a single Orion/Altair mission will more than double the mass of the lunar atmosphere, the National Research Council's *Scientific Context for the Exploration of the Moon* calls upon NASA to establish the lunar atmosphere's composition, sources of origin, spatial distribution and propagation to the poles. *LADEE* with its current scientific payload retasked into a nearly polar orbit (perhaps 70^{o} inclination) could address most of these goals, perhaps in the second phase of an extended mission. In general that we need another round of reconnaissance, with these and other instruments on polar orbits, before we have finished our homework prior to crewed lunar missions.