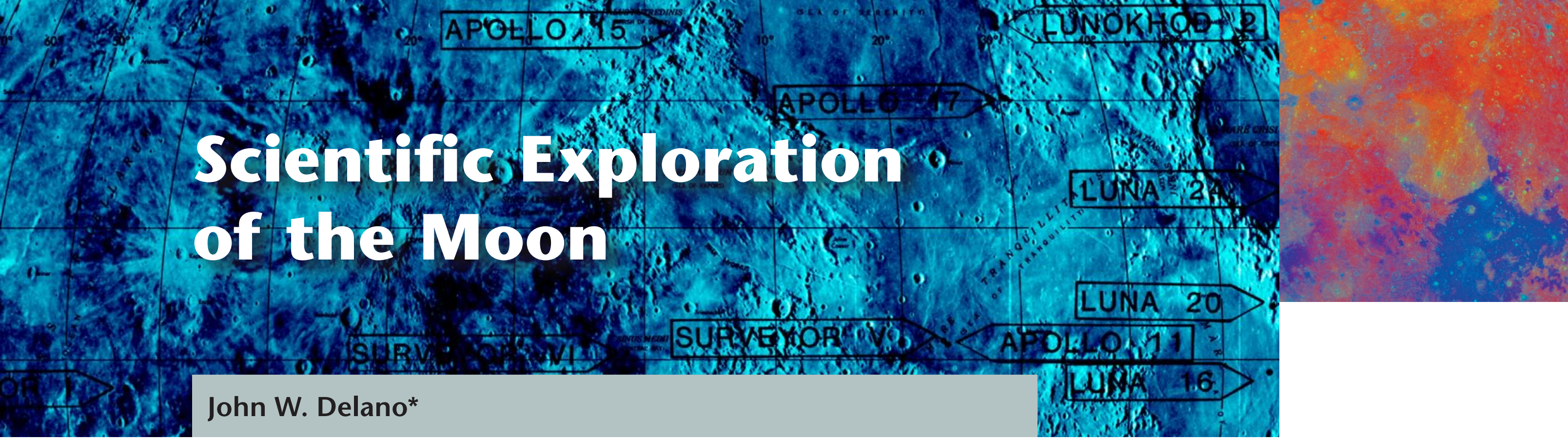

Scientific Exploration of the Moon

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The Moon is a geochemically differentiated object. It has a feldspathic crust (highlands regions) composed of three petrological suites. Underlying that crust is a compositionally heterogeneous upper mantle from which ferrobasalts and picrites (mare regions) were generated. Lunar samples retain a memory of the time-dependent flux of meteorites and comets, which has implications for the origin of sustainable life on Earth and the orbital evolution of the outer planets. Permanently shadowed regions at the lunar poles may contain reservoirs of volatile ices, which would have important resource potential for scientific bases. Geophysical data show that the Moon has a thick, seismically active lithosphere, a partially molten zone beneath that lithosphere, and a small metallic core. The pace of scientific exploration has quickened since 2003 with the successes of spacecraft from Europe, Japan, the People's Republic of China, and India. Upcoming launches of spacecraft from these same nations and the United States herald a new era of lunar discoveries.

Keywords: maria, highlands, terminal cataclysm, volatiles, volcanism, magma ocean

INTRODUCTION

The Moon has been of scientific interest to cultures throughout much of recorded history. During the second and third centuries BCE, Aristarchus and Eratosthenes estimated the diameter of the Earth. With that information, they estimated the diameter of the Moon and the Earth–Moon distance using the size of the Earth's shadow on the Moon during a lunar eclipse. In 1610, Galileo used his 20x telescope to report that the Moon was not a perfectly smooth sphere, in contrast to what had been theologically presumed, but rather had prominent mountains and valleys. Isaac Newton was able to estimate the mass of the Moon using his understanding of gravity, which ultimately led to our appreciation that the Moon has a bulk density (3.34 g/cm^3) indicative of it being composed dominantly of rock (i.e. its metallic core must be small). The origin of the craters on the Moon was a hotly debated issue until late in the 20th century, but they are now known to be the result of bombardment by meteorites and comets (Koeberl 2001). An excellent overview of lunar science by Neal (2008) is recommended.

On July 20–21, 1969, Apollo 11 astronauts Neil Armstrong and Buzz Aldrin became the first humans in history to visit another object in our solar system. In recognition of the 40th anniversary of that historic achievement, this issue of *Elements* is dedicated to the individuals (past, present, and future) dedicated to the scientific exploration of the Moon and beyond.

SAMPLES FROM THE MOON

Prior to the return of the first lunar samples to the Earth by the Apollo 11 astronauts in July 1969, data obtained from robotic spacecraft from the United States (Ranger, Surveyor, Lunar Orbiter) and the Soviet Union (Luna, Zond) were not sufficient to answer some of the most basic questions about the Moon's history, chemical composition, and mineralogy. For example, was the Moon a geochemically differentiated object? Or was it a primordial object? The Nobel laureate Harold Urey, who made historic contributions in isotopic chemistry (discovery of deuterium), geochemistry (chemical analyses of meteorites), and origin-of-life studies (Urey-Miller experiments), proposed that the Moon's low density was due to its being a hydrated, undifferentiated object (Urey 1968), perhaps similar to some primordial meteorites (carbonaceous chondrites). However, when the Apollo 11 astronauts returned to Earth with samples of high-Ti ferrobasalts that had crystallized from ~1150°C lavas (e.g. Ringwood and Essene 1970) ~3600 million years (Ma) in the past (Turner 1970), it became clear that the Moon was a complex, geochemically differentiated object. In addition, millimeter-sized pieces of feldspathic rocks extracted from the Apollo 11 regolith were interpreted as being exotic samples that had been ballistically transported from compositionally different regions of the Moon. In a seminal paper, Wood et al. (1970) proposed that the high-Ti ferrobasalts and the exotic feldspathic pebbles might be petrogenetically related. From that point onwards, most compositional and isotopic data on lunar samples have generally strengthened that view. Most lunar scientists now believe that the Moon underwent a global melting event (i.e. production of a magma ocean) probably involving the outer several hundred kilometers of the Moon near the time of its origin. Crystallization of that magma ocean formed a feldspathic crust and complementary mafic cumulates in the upper mantle. Subsequently partial melting of those mafic cumulates produced the compositionally diverse suites of ferrobasaltic and picritic magmas. While this general concept forms an important paradigm in lunar science, two articles in this issue, by Jeffrey Taylor (dealing with the feldspathic rocks) and by Timothy Grove and Michael Krawczynski (dealing with the basaltic and picritic rocks), show that the geochemical processes and relationships are even more complex and interesting.

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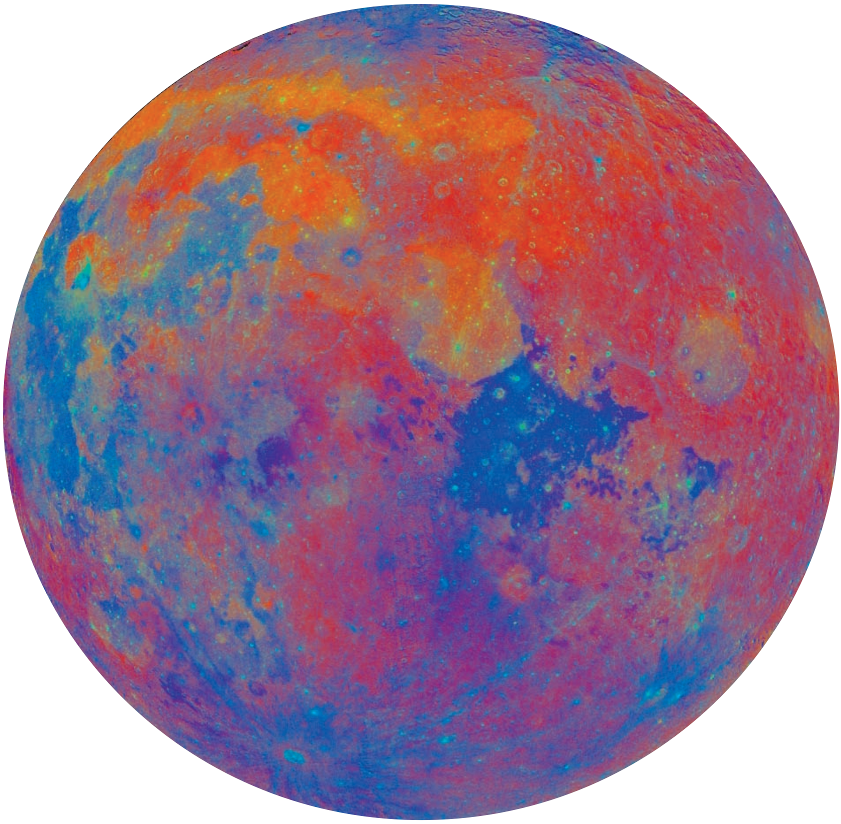

FIGURE 1 False-color (multispectral) image of the Moon constructed from images acquired by the US Galileo spacecraft in December 1992. The colors reflect the compositional and mineralogical variations of the lunar surface. IMAGE (SSI-LUNMOS6-7) FROM THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA), JET PROPULSION LABORATORY (JPL), AND THE U.S. GEOLOGICAL SURVEY (FLAGSTAFF, ARIZONA)

> We shall not cease
> from exploration,
> And the end of all
> our exploring
> Will be to arrive where
> we started
> And know the place
> for the first time.
>
> —T. S. Eliot, "Little Gidding" in *Four Quartets*

The Moon's compositional and mineralogical complexity, and the history of events that have formed it, is vividly illustrated by the false-color (multispectral) mosaic of the Moon obtained by the Galileo spacecraft in December 1992 (FIG. 1) as it was embarking on its voyage to the planet Jupiter. Data from alpha-particle, X-ray, and gamma-ray spectrometers onboard spacecraft that have orbited the Moon (e.g. Apollo, Lunar Prospector) have further constrained the nature of the compositional variations. Analysis of lunar samples returned by the six Apollo missions and the three Soviet Luna missions from known locations on the Moon have been, and continue to be, important in building a greater scientific understanding of the Moon. In addition, ~54 lunar meteorites (i.e. lunar rocks that landed on the Earth after being blasted off the Moon by impact events) are currently known. Although the source locations of these lunar meteorites are not known, they have significantly expanded our understanding of the Moon's compositional diversity and history (Korotev 2005).

THE MARIA

The darker-colored regions—the maria—that we see on the lunar surface during a full Moon were thought centuries ago to be bodies of water (an example of Earth chauvinism). The mare regions, which are located principally on the Earth-facing side of the Moon (FIG. 2), are now known to be stratigraphic sequences of high-FeO basaltic and picritic lavas. While most of the mare lavas sampled by the Apollo and Luna missions have crystallization ages in the range of 4200–3100 Ma, a lunar meteorite (~2870 Ma; Borg et al. 2004) and remote sensing data (~1000 Ma; Schultz and Spudis 1983; Hiesinger et al. 2003) indicate that mare volcanism persisted over a larger interval of time. The mare lavas often occur filling large, circular, impact-produced basins (FIGS. 1, 2, AND 3), which were sampled by the Apollo 11 (Mare Tranquillitatis), Apollo 12 (Oceanus Procellarum), Apollo 15 (Mare Imbrium), Apollo 17 (Mare Serenitatis), Luna 16 (Mare Fecunditatis), and Luna 24 (Mare Crisium) missions (FIG. 3). The compositional diversity of these mare volcanic rocks and glasses is remarkable. For example, the abundance of TiO_2 varies by a factor of ~80 from 0.2 wt% to 16.5 wt%. This compositional range is thought to reflect not only the compositional heterogeneity of the mafic upper-mantle cumulates from which they were derived, but also the complex processes associated with lunar magma petrogenesis. Although the maximum lithostatic pressure in the Moon is only ~4.7 gigapascals (~47 kilobars), pressure-dependent, melt/solid density crossovers may have played a role during mare petrogenesis (Delano 1990; Circone and Agee 1996).

Mare volcanic rocks represent our best geochemical probes of the Moon's deep interior (possibly to depths of ~400 km). As discussed in the article by Timothy Grove and Michael Krawczynski (2009 this issue), the processes that led to the remarkable compositional range of these mare basalts and picrites are both fascinating and complex (see also Neal 2008).

THE HIGHLANDS

Rocks and regoliths from the lighter-colored regions of the Moon, known as the highlands, comprise most of the lunar farside (FIG. 2) and are also petrologically diverse. As discussed in the article by Taylor (2009 this issue), three petrologic suites of highlands rocks are now confidently recognized: the ferroan anorthosites, the magnesian suite, and the alkali suite. The ferroan anorthosites are likely to have been formed during the global magma-ocean event associated with the Moon's rapid accretion. Plagioclase flotation in that magma ocean is widely considered to have been part of the process that led to the formation of the ferroan anorthosites at ~4450 Ma. The magnesian and alkali suites were formed later, but prior to ~3800 Ma, by later melting of cumulates formed during the magma-ocean event.

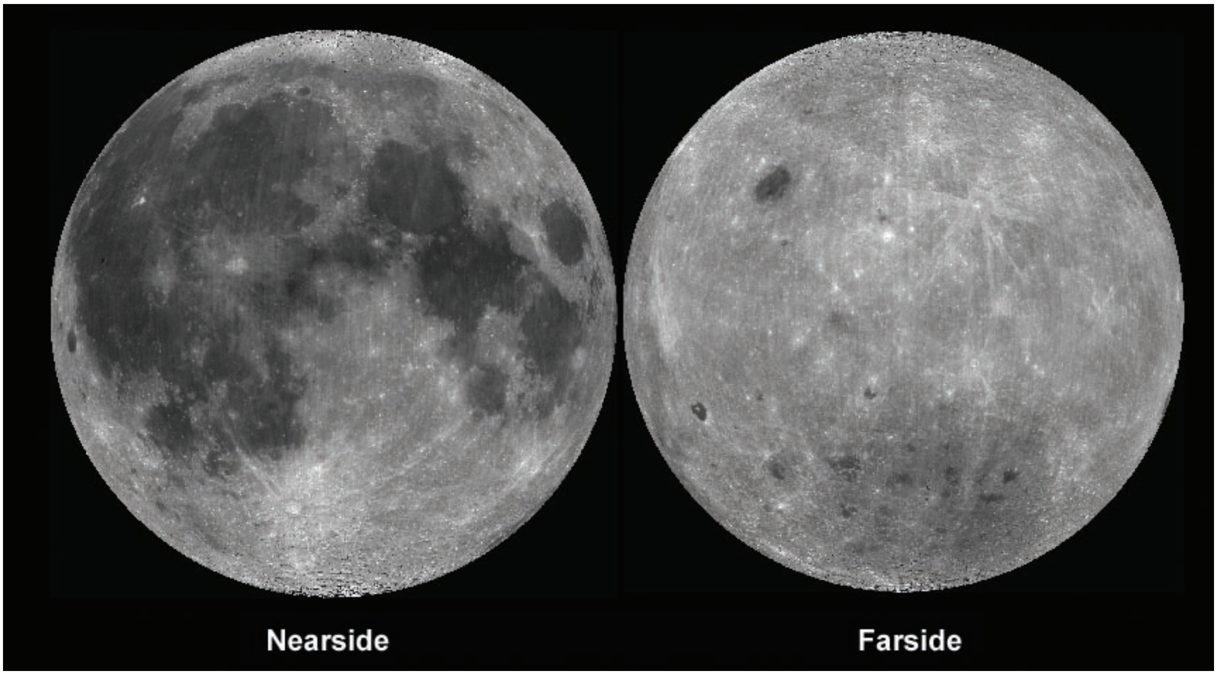

FIGURE 2 Global map of the Moon's albedo acquired by the Clementine spacecraft in 1994. This image shows the nearside and farside of the Moon in Lambert equal-area projection. Note the scarcity of maria on the farside compared to the nearside. The relatively dark area at center-bottom of the farside image is the South Pole–Aitken basin, which may have rock excavated from the Moon's upper mantle. The Clementine spacecraft was a mission for the U.S. Department of Defense and the Ballistic Missile Defense Organization. The mission was operated by the Naval Research Laboratory. Clementine's instruments were built by Lawrence Livermore National Laboratory. Image from the Lunar and Planetary Institute (Houston, Texas); image processing by the U.S. Geological Survey (Flagstaff, Arizona)

TIME-DEPENDENT FLUX

The bombardment history of the Earth–Moon system is a topic of wide interest in many areas of the Earth and planetary sciences. The distinct difference in areal density of craters (Fig. 2) on the lunar mare (~3500 Ma) versus the lunar highlands (~4450 Ma) indicates that the flux of cosmic debris (meteorites and comets) was initially high and declined to near-present levels by ~3800 Ma (Shoemaker 1998; Koeberl 2006). Information on this time-dependent flux is scientifically important (e.g. National Research Council 2007) since it may have influenced the time when sustainable life became possible in our solar system (Schopf 2006; Zahnle et al. 2007). The time-dependent flux may have been characterized by spikes that may reflect the orbital evolution of the outer planets (Ryder 2002; Tsiganis et al. 2005; Bottke et al. 2007; Michel and Morbidelli 2007). In addition, knowledge of how this flux varied through time would allow the ages of planetary surfaces to be estimated from remote sensing methods (i.e. from the numbers of craters per unit area; Wilhelms 1990). As discussed by Norman (2009 this issue), impact-produced melt rocks, whose provenance is often difficult to determine, are an important source of chemical and isotopic information for constraining the time-dependent flux during the first 700 million years of solar system history. Did this flux of bombarding debris decline monotonically with time, or did one or more spikes occur (e.g. "terminal lunar cataclysm")? As described in Hand (2008), it would be helpful to know the age of the impact event that formed the South Pole–Aitken basin, the oldest-known basin on the Moon (Fig. 2; see also review by Neal 2008). Amelin (1998) and Trail et al. (2007) have suggested that Hadean-age zircons from the Jack Hills of Western Australia may have an isotopic memory of the Earth when it was affected by a Late Heavy Bombardment at ~3950 Ma.

POLAR REGIONS

Some craters in the Moon's polar regions (Fig. 4) are permanently shadowed and therefore could serve as cold traps for volatiles (Arnold 1979). As discussed by Paul Lucey (2009 this issue), the physics and chemistry of volatiles delivered to the Moon by impacting comets are complex. Could these permanently shadowed regions (Fig. 5) contain volatiles (e.g. water ice) that could be an important resource for the inhabitants of scientific stations on the Moon? The possibility of water ice being located within these permanently shadowed craters has led to investigations using robotic spacecraft and ground-based radar facilities. At present, the results are inconclusive. The most recent images acquired by Japan's SELENE/KAGUYA lunar orbiter (Haruyama et al. 2008) set important upper limits on the quantity of ice exposed in Shackleton Crater (19 km diameter; Fig.5) in the Moon's south polar region. This crater was formed by an impact event at ~3500 Ma (Spudis et al. 2008). The rim of Shackleton Crater has been discussed as a possible site for a permanent scientific research station (Spudis et al. 2008). Such a station could be established there when astronauts return to the Moon in approximately 2020 during NASA's Constellation program (Neal 2008; David 2009) using the Ares-I and Ares-V launch vehicles currently under development.

A US mission known as LCROSS (Lunar Crater Observation and Sensing Satellite), consisting of two spacecraft that will search for reservoirs of volatiles on the Moon, is scheduled to be launched in early 2009. One spacecraft is an impactor that will be targeted to hit a permanently shadowed region at high speed to generate a transient plume of debris. The plume will be chemically analyzed by its companion spacecraft for the possibility of water vapor (and other volatiles) before that spacecraft also impacts the polar region (see figure 6 of Lucey 2009 this issue).

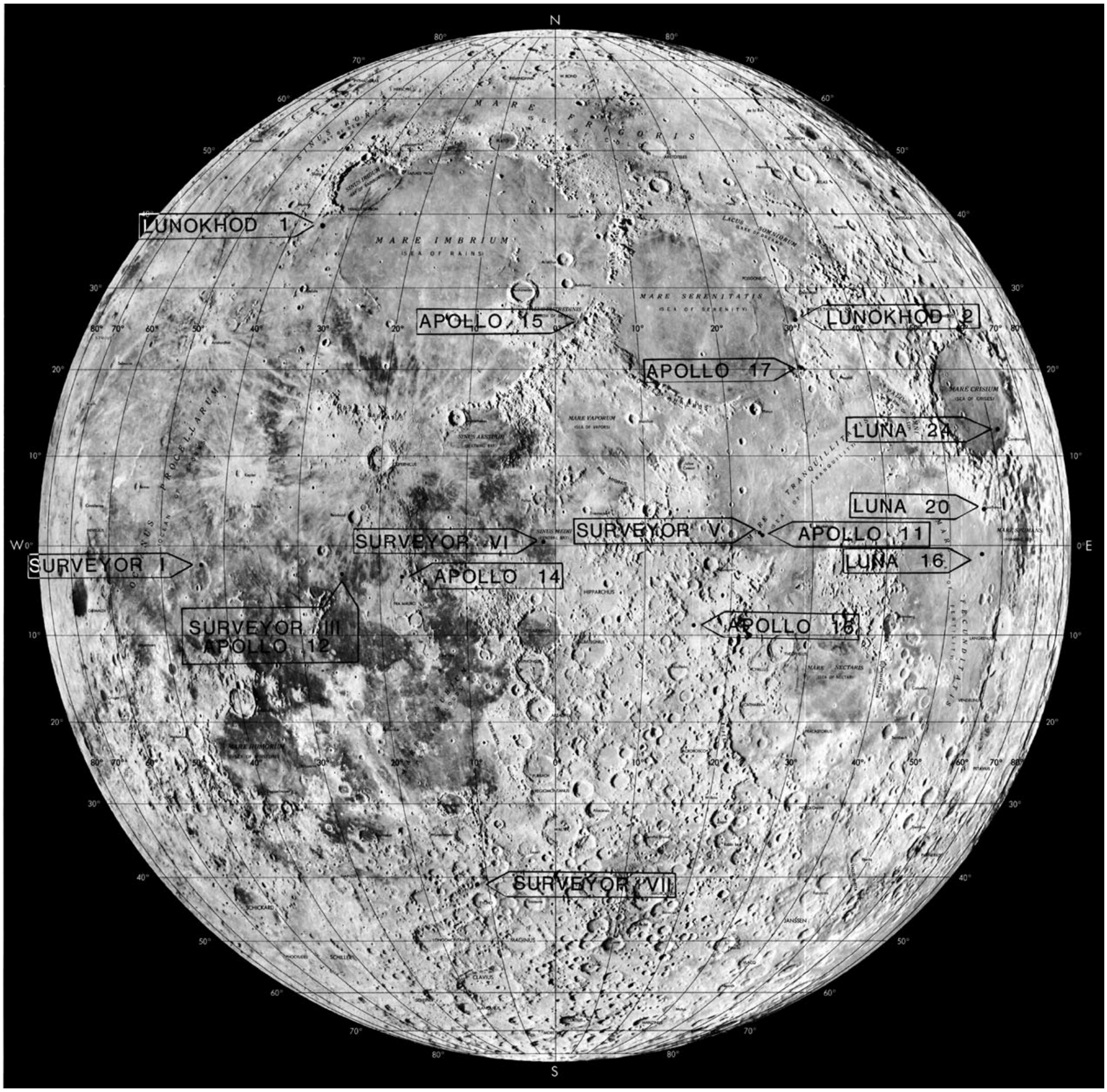

FIGURE 3 Lunar map showing the locations of most missions that soft-landed on the Moon (landing sites of the Soviet Luna 9 and Luna 13 spacecraft in Oceanus Procellarum are not shown). MAP FROM THE LUNAR AND PLANETARY INSTITUTE (HOUSTON, TEXAS)

GEOPHYSICS OF THE MOON'S INTERIOR

The geophysical investigation of the Moon's interior began in earnest with the discovery (Muller and Sjogren 1968) of significant Bouguer gravity anomalies (total variation of 900 mgal; Konopliv et al. 1998) from analysis of high-precision tracking data obtained by US Lunar Orbiter spacecraft. The Apollo seismic array at the Apollo 11, 12, 14, 15, and 16 landing sites operated from 1972 to 1977. Data received from this array provided an unprecedented view into the Moon's deep interior, which is the topic of the article by Mark Wieczorek (2009 this issue). See also Wieczorek et al. (2006) for a more comprehensive, multidisciplinary review.

In 2011, NASA plans to launch the Gravity Recovery and Interior Laboratory (GRAIL) mission to dramatically improve our knowledge of the Moon's gravity field (FIG. 6), and hence the structure of the Moon's interior. GRAIL will accomplish this feat by using a strategy successfully demonstrated by the Earth-orbital GRACE (Gravity Recovery and Climate Experiment) mission, which mapped the Earth's gravity field. Not only will the GRAIL mission provide a clearer view of the Moon's interior, but it will also improve the ability of spacecraft to accurately navigate to the Moon's surface (Neal 2008; David 2009).

Another aspect of lunar geophysics involves the laser ranging retroreflectors (FIG. 7) that were deployed on the Moon by US Apollo (11, 14, 15) and Soviet Lunokhod (1, 2) missions (FIG. 3). By accurately measuring the round-trip travel time of laser pulses sent from ground-based facilities to these laser retroreflectors, the average Earth–Moon distance has been found to be increasing at the rate of 38 millimeters per year (Williams et al. 2005). Physicists have used this array to perform additional experiments to establish the upper limit on the time-dependent variation of the gravitational constant, G.

A NEW ERA OF LUNAR EXPLORATION

Prior to 2003, the Moon had been successfully explored by spacecraft from the United States (Ranger 7, 8, 9; Surveyor I, III, V, VI, VII; Lunar Orbiter I, II, III, IV, V;

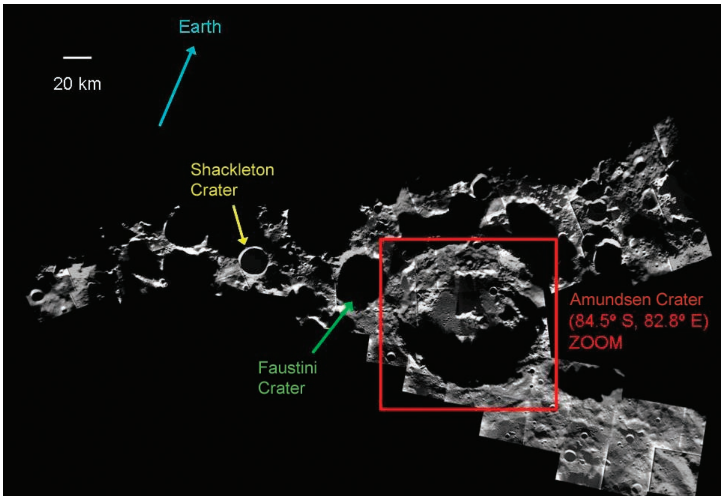

Figure 4 Mosaic of 40 images showing the Moon's south polar region as obtained by the European Space Agency (ESA) mission SMART-1. Shackleton Crater (Fig. 5) is indicated by the yellow arrow. Mosaic (SEMJVZL5NDF) from the ESA/SMART-1/Space-X (Space Exploration Institute)/AMIE camera team

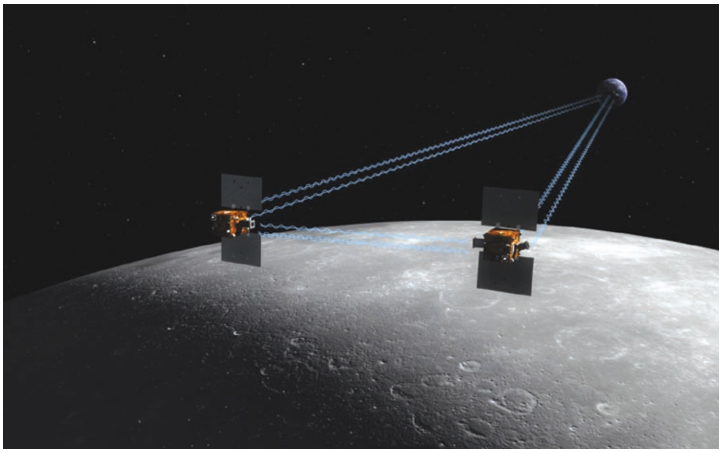

Figure 6 Artist's concept of twin spacecraft belonging to the 2011 GRAIL mission. These spacecraft will orbit in tandem to map variations in the Moon's gravity field with unprecedented accuracy. Image from NASA/JPL

Apollo 8, 10, 11, 12, 14, 15, 16, 17; Lunar Prospector; Clementine) and the former Soviet Union (Luna 2, 3, 9, 10, 11, 12, 13, 14, 16, 19, 20, 22, 24; Zond 3; Lunokhod 1, 2). Beginning in 2003, scientific exploration of the Moon has become increasingly international. Successful orbital missions by robotic spacecraft have been conducted by Europe (SMART-1: Small Missions for Advanced Research in Technology), Japan (SELENE/KAGUYA: Selenological and Engineering Explorer), the People's Republic of China (Chang'e-1), and India (Chandrayaan-1). These missions are the dawn of a new era in the scientific exploration of the Moon (Neal 2008; David 2009). This new era is recognized by the SELENE/KAGUYA image on the front cover of this issue and by the SMART-1 images (Figs. 4, 5) in this article. This increased tempo in lunar exploration is also made evident by the spacecraft that are scheduled to be launched within the next three years (refer to Neal 2008 for further information). These are:

- NASA Lunar Reconnaissance Orbiter (LRO: 2009)
- NASA Lunar Crater Observation and Sensing Satellite (LCROSS: 2009; colaunch with LRO)
- CNSA Chang'e-2 (2010)
- NASA Gravity Recovery and Interior Laboratory (GRAIL: 2011)
- NASA Lunar Atmosphere and Dust Environment Explorer (LADEE: 2011; colaunch with GRAIL)
- CNSA Chang'e-3 (2011)
- ISRO Chandrayaan-2 (2011)

In addition, an International Lunar Network consisting of scientific instruments robotically deployed on the lunar surface to form strategic nodes of geophysical instruments may begin operation in about 2013.

During their careers, the authors of the invited articles in this issue have made major contributions to our current scientific understanding of the Moon. These articles provide important information bearing on several of the key questions highlighted by Jolliff et al. (2006), National Research Council (2007), and Neal (2008).

Figure 5 This image of Shackleton Crater (19 km diameter) in the south polar region of the Moon was obtained by the European Space Agency (ESA) mission SMART-1. Since the interior of this crater is permanently shadowed, it may contain trapped volatiles that would be a valuable resource for a proposed scientific outpost on the rim of the crater (Spudis et al. 2008). Image (SEMFUPOFHTE) from the European Space Agency (ESA) and Space Exploration Institute (Space-X)

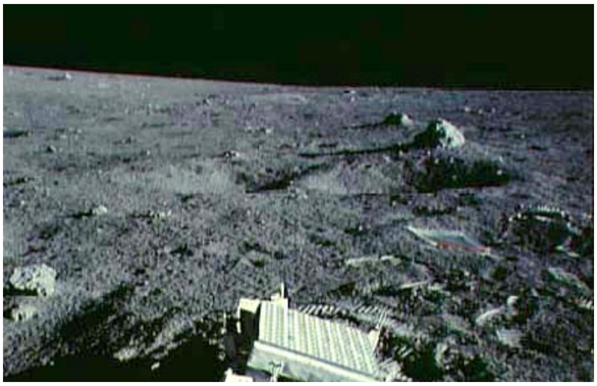

Figure 7 The laser ranging retroreflector (LRRR) at the Apollo 14 landing site (located in Fig. 3) measures 46 cm × 46 cm and contains an array of 100 silica-glass corner reflectors. This is one of four operational laser retroreflectors currently on the Moon. Image (AS14-67-9386) from NASA

If it can be said that the greatness of any nation is built on a record of its major achievements, then, for that mantle of greatness to be sustained, its citizens must be both highly educated and deeply inspired. This issue of *Elements* highlights the inspired efforts of talented individuals from many great nations who are engaged in the scientific exploration of the Moon.

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