Lunar Prospector: Overview

Alan B. Binder

Lunar Prospector is providing a global map of the composition of the moon and analyzing the moon's gravity and magnetic fields. It has been in a polar orbit around the moon since 16 January 1998. Neutron flux data show that there is abundant H, and hence probably abundant water ice, in the lunar polar regions. Gamma-ray and neutron data reveal the distribution of Fe, Ti, and other major and trace elements on the moon. The data delineate the global distributions of a key trace element–rich component of lunar materials called KREEP and of the major rock types. Magnetic mapping shows that the lunar magnetic fields are strong antipodal to Mare Imbrium and Mare Serenitatis and has discovered the smallest known magnetosphere, magnetosheath, and bow shock complex in the solar system. Gravity mapping has delineated seven new gravity anomalies and shown that the moon has a small Fe-rich core of about 300 km radius.

The early evolution of Earth and the moon are closely coupled. It is generally thought that the moon formed about 4.4 billion years ago from debris produced when a large (Mars-sized) planetesimal collided with the proto-Earth (*1*). Much of the early record of this event is preserved on the moon, where most of the crust is older than about 3 billion years and the only subsequent major crustal deformation was produced by impacts from comets and asteroids. In contrast, plate tectonics on Earth have destroyed most of the evidence of this event. Even after many years of study, however, we still have limited information on the global composition and interior structure of the moon at sufficient resolution to derive a detailed model of its origin. Mapping and sampling during the Apollo and Luna landing missions identified the major lunar terranes, ages, and rock types and provided our first glimpse of the farside of the moon, but coverage of the lunar poles was poor, and global selenophysical data were not obtained or were at low resolution. The recent Clementine mission produced global multispectral data that resulted in a map of Fe and Ti concentrations (*2, 3*). Clementine radar data also provided a tantalizing hint that the polar regions might be harboring ice (*4*). The goal of the Lunar Prospector (LP) mission is to test and extend these results by obtaining gravity, magnetic, and compositional data at high resolution of the entire moon. These data will enhance our view of the surface and interior of the moon and will improve our understanding of its origin and evolution.

LP is the first NASA supported lunar mission in 25 years and the third mission in NASA's Discovery Program (*5*). LP was launched on 7 January 1998 and has been mapping the moon since 16 January 1998 from its 118-minute, circular, polar orbit 100

Lunar Research Institute, 1180 Sunrise Drive, Gilroy, CA 95020, USA. E-mail: abinder@mail.arc.nasa.gov

km above the moon's surface. The main mapping mission will continue until January 1999. Then LP will map for 6 months at 25 km. The mission is expected to end in July 1999 when LP impacts the moon.

LP is a simple, small (296 kg), drum-shaped (1.37 m diameter, 1.28 m tall) spacecraft with minimal operational requirements. It is operated without a backup, is controlled from the ground (not by an onboard computer), and is spin stabilized. The spacecraft's spin rate is nominally 12.0 ± 0.1 rpm and its nominal attitude is with its spin axis normal to the ecliptic plane. The science instruments are mounted on three 2.5-m-long booms. The magnetometer is mounted on a 1.1-m-long boom extending beyond the main boom containing the electron reflectometer to isolate the magnetometer from the electronics.

A main goal of the LP mission is to map the surface abundances of a series of key elements (H, U, Th, K, O, Si, Mg, Fe, Ti, Al, and Ca), with special emphasis on the search for polar water ice deposits. If identified, polar ice deposits have the potential of opening the moon to cost-effective lunar and planetary exploration by providing water for life support and fuel for rockets. To obtain these data, LP uses a gamma-ray spectrometer (*6*) and a neutron spectrometer (*7–9*). U, Th, and K are most abundant on the moon in KREEP-rich rocks (KREEP material is an incompatible element–rich

material containing high amounts of potassium, rare earth elements, and phosphorus). These rocks are key to understanding lunar petrological and crustal evolution and may represent some of the last remaining melt after formation of the lunar crust. Global maps of the distributions of O, Si, Mg, Fe, Ti, Al, and Ca, which together make up over 98% of the mass of all lunar material, provide information on the mineralogy and bulk composition of the crust and hence the origin and development of the moon, as well as the availability of the resources needed for lunar construction.

The LP gamma-ray data (*6*) show that KREEP-rich material is concentrated in the rim areas of Mare Imbrium, the nearside maria and highlands near Imbrium, and the Mare Ingenii South Pole–Aitken basin area on the farside, while the highlands have a relatively low and uniform concentration of KREEP. The data support models that the Imbrium impact excavated KREEP-rich material from depth and distributed it over the moon. The large South Pole–Aitken basin impact exposes KREEP-rich rocks. Mare basalt volcanism and probably post-impact KREEP volcanism and KREEP injection into the upper crust are also responsible for the global distribution of KREEP-rich rocks on the moon (*6*). The gamma-ray data show that Fe is concentrated in the maria, which are large basalt flows mostly on the nearside of the moon, consistent with abundances inferred from Clementine data (*7, 8*).

In part because of the sensitivity of the neutron spectrometer and largely because LP passes over the poles each orbit, the first 2 months of NS epithermal neutron flux data were sufficient to show that H concentrations are high at each pole (*9*). The signature in the north polar area ($>80°$) is about 30% stronger than in the south polar area ($<-80°$). Although other explanations for the enhancement are possible, the data suggest that significant quantities of water ice are located in permanently shadowed craters in both polar regions (*9*).

The neutron spectrometer data indicate that the flux of thermal neutrons is sensitive to the Fe and Ti contents of lunar surface soils and rocks and hence provide an addi-

Table 1. Summary of the instruments on Lunar Prospector.

Experiment	Objective
Gamma ray spectrometer (GRS) (*6*)	Global maps of concentrations of Fe, Ti, K, Th, and other elements on the lunar surface
Neutron spectrometer (NS) (*7–9*)	Global maps of concentrations of H, Fe, Ti, Ca, Al, and other elements on the lunar surface
Magnetometer/electron reflectometer (MAG/ER) (*10*)	Global maps of low-intensity magnetic fields on the lunar surface
Alpha particle spectrometer (APS)	Detection of released gases from the lunar surface
Doppler gravity experiment (DGE) (*11*)	Doppler tracking of the spacecraft to derive the gravity field map of the moon

tional way of mapping the distribution of these elements. The maps define three distinct rock types and regions: (i) The Fe- and Ti-rich mare basalts; (ii) rocks of intermediate Fe and Ti contents that make up the floor of the South Pole–Aitken basin and the mountainous rims of the nearside circular maria and (iii) Fe- and Ti-poor anorthositic rocks of the highlands (7).

A comparison of the thermal neutron data on the Fe and Ti concentrations (7) and those produced from Clementine spectral data (2) show that while the correlations are good, there are discrepancies, especially in the rim area of Mare Imbrium. These discrepancies may be due to the presence of high amounts of Sm and Gd (rare earth elements with exceptionally large neutron absorption cross sections) in the KREEP-rich deposits of Imbrium ejecta (Table 1).

The LP mission is also mapping the lunar gravity (10) and magnetic (11) fields. Before the LP mission, no spacecraft had been in low polar orbit. Hence we did not have an accurate gravity map of the moon. Gravity data provide information of crustal and upper mantle structure by delineating areas of the crust with anomalous density. They are also needed to calculate the fuel requirements for the orbital mapping portion of the mission. LP calculates the gravity field by accurately tracking how the orbit of the spacecraft is perturbed (the Doppler gravity experiment). The magnetic data will reveal the distribution and strengths of the numerous small magnetic fields of the moon. These data will allow us to determine how the magnetic fields formed and possibly help to delineate deposits of useful resources. Together, the gravity and magnetic data can be used to infer the size of the suspected lunar Fe core. Although thought to contain less than a few percent of the lunar mass (as compared to Earth's core, which contains 30% of Earth's mass), the exact size of the core provides an important constraint on how the moon formed.

The magnetic maps to date (11) show that strong magnetic fields fill the antipodal regions of the Mare Imbrium and Mare Serenitatis basins. The magnetic fields antipodal to Imbrium are strong enough to form the smallest known magnetosphere, magnetosheath and bow shock system in the solar system. These results support the hypothesis that shock remnant magnetization of lunar rocks was associated with the large basin forming impacts early in lunar history (11).

Two weeks after LP achieved its mapping orbit, the data needed to define the lunar gravity field for operational purposes were obtained. The gravity data show that to maintain a 100 ± 20 km altitude orbit, a maneuver is required every 56 days; the velocity change required is 0.22 m/s per day. The gravity data have also been used to improve the mapping of previous-

ly known nearside lunar mass concentrations (mascons), revealed three new mascons in the limb regions of the nearside, and partially resolved four new mascons on the farside. The data imply that the moon does have a small Fe-rich core of about 300 km radius (10).

Finally, LP will map the frequency and locations of gas release events by detecting gaseous Rn and its daughter nuclei with the alpha particle spectrometer. This mapping program will help determine the current level of lunar tectonic and post-volcanic activity. Also, because other gasses such as N_2, CO_2, and CO, which are essential for life support, may be released with the Rn, the maps may indicate where these resources may be obtained for future human activities on the moon.

The alpha particle data analysis has been complicated because large fluxes of solar alpha particles have been detected during increasingly frequent solar energetic particle events. Solar events have been occurring over half of the time since the analysis began, and the flux of alpha particles has increased during the storms by up to 3300 times the normal flux. Therefore, these results are not yet available.

References and Notes
1. W. Benz, W. L. Slattery, A. G. W. Cameron, *Icarus* **66**, 515 (1986); R. M. Canup and L. W. Esposito, *ibid.* **119**, 427 (1996); A. G. W. Cameron, *ibid.* **126**, 126 (1997).
2. P. G. Lucey, G. J. Taylor, E. Malaret, *Science* **268**, 1150 (1995).
3. D. T. Blewett, P. G. Lucey, B. R. Hawke, B. L. Jolliff, *J. Geophys. Res.* **102**, 16319 (1997); P. G. Lucey, D. T. Blewett, B. R. Hawke, *ibid.* **103**, 3679 (1998).
4. S. Nozette *et al.*, *Science* **274**, 1495 (1996).
5. Discovery missions are managed by the Principal Investigator (PI, the author) who leads a science team of Co-Investigators (Co-Is), a NASA Center Partner (Ames Research Center) and an Industry Partner (Lockheed Martin). NASA Headquarters' role is limited to that of overall management, but with minimum oversight, review, and program control. The LP science team consists of the PI and five Co-Is: M. Acuna, W. Feldman, L. Hood, A. Konopliv, and R. Lin. LP has a total budget of $63 million and was developed in only 22 months. Its cost is about one-third that of the other six current and past Discovery missions and is about 10% of the cost of earlier NASA lunar and planetary exploration missions.
6. D. J. Lawrence *et al.*, *Science* **282**, 1484 (1998).
7. W. C. Feldman *et al.*, *ibid.*, p. 1489.
8. R. C. Elphic *et al.*, *ibid.*, p. 1493.
9. W. C. Feldman *et al.*, *ibid.*, p. 1496.
10. A. S. Konopliv *et al.*, *ibid.*, p. 1476.
11. R. P. Lin *et al.*, *ibid.*, p. 1480.
12. I thank all the volunteers of Lunar Exploration, Inc., the Space Studies Institute, and the National Space Society who worked for over 6 years to make LP a reality, the small team of dedicated Lockheed Martin engineers who refined the original LP spacecraft design and then built, tested, and prepared LP for launch in 22 months, the LP science team engineers who built the science instruments, the various vendors who supplied critical hardware in record time, Spaceport Florida for preparing the launch facility, the Lockheed Martin Athena 2 launch vehicle team for insuring that LP was properly launched, the Thiokol team, who made the TLI stage, the Goddard Space Flight Center team, who do the trajectory analysis, the Deep Space Network, and the command and control teams. LP is supported by NASA.

Improved Gravity Field of the Moon from Lunar Prospector

A. S. Konopliv, A. B. Binder, L. L. Hood, A. B. Kucinskas, W. L. Sjogren, J. G. Williams

An improved gravity model from Doppler tracking of the Lunar Prospector (LP) spacecraft reveals three new large mass concentrations (mascons) on the nearside of the moon beneath the impact basins Mare Humboltianum, Mendel-Ryberg, and Schiller-Zucchius, where the latter basin has no visible mare fill. Although there is no direct measurement of the lunar farside gravity, LP partially resolves four mascons in the large farside basins of Hertzsprung, Coulomb-Sarton, Freundlich-Sharonov, and Mare Moscoviense. The center of each of these basins contains a gravity maximum relative to the surrounding basin. The improved normalized polar moment of inertia (0.3932 ± 0.0002) is consistent with an iron core with a radius of 220 to 450 kilometers.

The gravity field of the moon has been investigated since 1966 when the Russian Luna 10 was placed in orbit around the moon and provided dynamical proof that the oblateness of the moon's gravitational potential (1) was larger than the shape predicted from hydro-

A. S. Konopliv, A. B. Kucinskas, W. L. Sjogren, J. G. Williams, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. A. B. Binder, Lunar Research Institute, Gilroy, CA 95020, USA. L. L. Hood, University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ 85721, USA.

static equilibrium. Soon thereafter, Muller and Sjogren (2) differentiated the Doppler residuals from Lunar Orbiter (LO)–V to produce a nearside gravity map that displayed sizable positive gravity anomalies within the large circular mare basins. These positive anomalies, located in nearside equatorial regions with low topography, showed areas with mass concentrations (or "mascons") in the lunar interior. Inherent in the mascons—as buried, mostly uncompensated mass anomalies—is information on the impact pro-