SCIENCE INVESTIGATIONS ENABLED BY MAGNETIC FIELD MEASUREMENTS ON THE LUNAR SURFACE.

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Introduction: Observations by the Lunar Surface Magnetometers (LSM) of the Apollo Lunar Surface Experiments Package (ALSEP) in the 1960s and 1970s established the basic understanding of the magnetic field variations on the lunar surface. The variations in the magnetic field include the fluctuations in the ambient plasma, the magnetic induction of the eddy electric currents in the lunar interior, the crustal magnetic field and its interaction with the solar wind, and possibly the ion cyclotron waves due to the pickup ions escaping from the lunar exosphere. Surface measurements of the lunar magnetic field can provide useful information not only about the Moon but also the space environment surrounding it.

The Apollo LSM measurements were obtained at locations that were not ideal for addressing many outstanding science questions identified after the Apollo era, but no surface magnetometer has been set up since the last Apollo LSM ended in 1975. The Lunar Geophysical Network mission concept reviewed by the latest planetary decadal survey [1] has identified four science objectives for which surface magnetic field measurements can play a major or supporting role. These science objectives are (a) to determine the nature and the origin of the lunar crustal magnetic field, (b) to determine the internal structure of the Moon, (c) to determine the distribution and origin of lunar seismic activity, and (d) to determine the bulk composition of the Moon. NASA's Deep Space Gateway concept, including the support/servicing of lunar landers, can enable new surface magnetic field measurements to meet these science objectives.

This paper presents a few examples of the geophysical and heliophysics investigations that can be made with magnetic field measurements on the lunar surface. The consideration includes scenarios where concurrent spacecraft magnetic field measurements near the Moon supported by the Deep Space Gateway or other programs are also available. The paper concludes by discussing the deployment methods of lunar surface magnetometers and the needed resources from the Deep Space Gateway or other programs.

Examples of Science Investigations:

Lunar interior. The magnetic field measurements by the Apollo LSM and Explorer 35 in the lunar orbit motivated a series of magnetic sounding studies of the lunar interior to constrain core size, mantle free-iron and alumina abundance, and interior temperature and thermal evolution. (see a review by [2]). The transfer-function method used in these studies compares the wave spectrum measured on the surface with that measured in the lunar orbit. The advantage of this method is that the frequency-dependent transfer function can be used for immediate interpretation of the internal electrical conductivity as a function of depth.

Unresolved scientific questions on this topic include: (a) What is the electrical conductivity structure of the outermost 500 km of the moon and its lateral variations? This zone is important as it contains a possible transition from upper-mantle melt residuum to the pristine lower mantle, as well as differences in crustal composition and lithospheric thickness and heat flow associated with the primary geological provinces of the moon. (b) What it is the deep structure of the moon and its heterogeneity? A tighter average mantle conductivity profile will better constrain temperature and composition. Lateral variations in internal temperature could be evidence of mantle convection. Very long-period measurements could distinguish a molten silicate from an iron core. [3]

The transfer-function method requires simultaneous magnetic field measurements by one spacecraft monitoring the external condition near the Moon and one or more surface magnetometers. The surface magnetometers are best placed at locations with minimal crustal magnetic field, and the locations can be on either the nearside or the farside. Because the driving signals are the magnetic fluctuations in the solar wind or the magnetosheath, farside locations can accrue relevant measurements faster.

Lunar Magnetic Anomalies and Lunar Swirls. Portions of the lunar crust are highly magnetized, which, when considered together with sample paleointensities, indicates the existence of an early high-field epoch. Other strong magnetic anomalies are correlated with basin ejecta materials and with lunar swirls of high-albedo markings.

The origin of lunar swirls is still a mystery. All lunar swirls are co-located with lunar magnetic anomalies, but the reverse does not hold true. At present, the proposed formation hypotheses can be summarized in three categories: (a) the solar wind standoff mechanism, (2) micro-meteoroid and comet impacts, and (c) magnetic and electrostatic sorting of high-albedo dust.

The surface investigation of lunar swirls is perhaps best made by a rover that conducts a magnetic survey and sample analysis. Swirls can also be surveyed by low-altitude satellites [4], and surface magnetometers at fixed locations can support satellite observations by identifying the temporal features in the magnetic field. An interesting observation target of is the much-studied Reiner Gamma magnetic anomaly on the nearside. The two swirls on the farside that lie directly opposite to Mare Imbrium and Mare Orientale are also of high interest because of their possible connection to impacts.

Ion Cyclotron Waves at the Moon. The restored Apollo LSM data have shown clear narrowband ion cyclotron waves when the Moon is situated in the terrestrial magnetotail ([5] and Figure 1). Two mechanisms have been proposed to explain the excitation of these waves: the first mechanism involves the absorption of ions at the lunar surface and the resulting temperature anisotropy, and the second mechanism is the excitation of ion cyclotron waves by the pickup ions from the lunar exosphere.

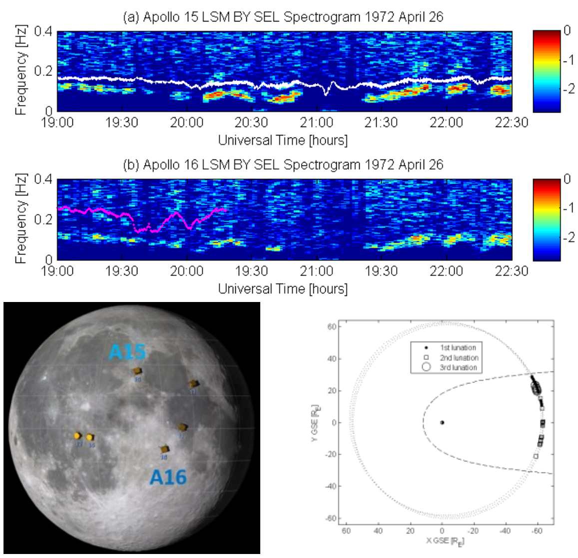

Figure 1. *Upper*: (a) A series of narrowband ion cyclotron waves with frequencies ~0.1 Hz observed by the Apollo 15 LSM. The white trace indicates the local proton gyrofrequency at the Apollo 15 site. (b) Similar waves simultaneously observed by the Apollo 16 LSM. The magenta trace shows the proton gyrofrequency inferred from the magnetic field measured by the Apollo 16 sub-satellite orbiting the Moon (but with 24-sec time resolution that is too low to measure cyclotron waves associated with light ions). Lower Left: The locations of Apollo 15 and 16 ALSEP sites. *Lower Right*: The locations of narrowband ion cyclotron waves observed by the Apollo 15 LSM over three lunations in 1972. The plot is centered at the Earth.

Because pickup ions are the end loss process for all surface volatiles, understanding the role of pickup ions in exciting ion cyclotron waves can help determine whether these waves provide hints to the source and distribution of the associated lunar volatiles. A recent study based on Kaguya and Geotail observations of the narrowband waves in the magnetotail, however, suggests that these waves are observed much less often in orbit [6]. It is unclear whether the spacecraft altitude or motion affects the detection of these waves, or if the wave source is on the nearside closer to the ALSEP sites.

The ultimate answers to these outstanding questions require joint space-based and surface-based observations with sufficient time resolution. It is best to measure not only the magnetic field but also the velocity distribution of ions to provide the critical information for determining the responsible mechanisms for wave excitation.

Deployment of Lunar Surface Magnetometers: Magnetometers can be deployed on the lunar surface easily by astronauts, who can identify the location suitable for installation near the lander, carry and install the magnetometer to the desired location, and align the magnetic sensors with the chosen coordinates. The technology available today also allows robotic deployment. In both scenarios, the major deployment requirement is that the sensor should be placed at a location with minimal magnetic interference from the lander/rover or other instruments.

Resources Needed from the Deep Space Gateway: A modern surface magnetometer can be made compact and low-power. The weight of sensors and electronics in each magnetometer system is approximately ~2 kg. The power consumption without heating is approximately ~3 W or less. The volume of the magnetometer system is likely to be dominated by the support structure and the cable to be determined by the lander/rover design.

If the surface instrument is to be deployed by an astronaut, the installation and alignment can be completed within an hour. A robotic installation without the help by astronauts can also be designed.

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