Determining the Origins of Lunar Remanent Crustal Magnetism

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Summary

The discovery of lunar magnetic fields of crustal origin was a major scientific surprise of the Apollo program. Solving the enigma of lunar remanent crustal magnetization will provide fundamental insights into the thermal history of the lunar core/dynamo, mantle, and crust, and into the processes by which crustal magnetization is acquired on airless bodies - for instance, large basin-forming impacts. Determining the origin and history of lunar crustal magnetism will require the return of oriented samples from the surface and surface magnetometer surveys of selected regions. Systematic high-resolution mapping of crustal magnetic fields from orbit provides an intermediate step that may be possible at an earlier date.

Value

Lunar magnetism potentially provides a useful tool for probing the thermal evolution of the Moon's crust, mantle, and core; as well as for illuminating the physics of large basin-forming impacts. Insights into lunar magnetization may help us understand Mars, which exhibits similar but much stronger crustal magnetism, and Mercury, which currently has a core dynamo field. Similar physical processes likely occur on other planetary bodies and during impact processes in general. The Moon therefore offers a valuable opportunity to further our understanding of magnetic fields observed on all solar system bodies.

Description

The Moon does not currently have an active core dynamo. However, like Mars, it has numerous localized remanent crustal magnetic regions distributed over its surface, with a spatial scale of a few kilometers to a few hundred kilometers. The existence of these regions points to the presence of strong magnetizing fields in the past (Hood et al. 2001; Halekas et al. 2001).

Measurements of remanent magnetism on the Earth provided crucial evidence for sea floor spreading and plate tectonics that led to a greatly increased understanding of the evolution of the Earth's interior and surface. New measurements of lunar and Martian magnetism hold similar promise. Low-resolution orbital mapping by the Apollo 15 & 16 subsatellites and by Lunar Prospector using magnetometers and electron reflectometers show strong surface magnetic fields in regions antipodal to the large impact basins formed ~3.65-3.85 billion years ago (Lin et al., 1988; Mitchell et al., 2008) and in some of the ejecta from those impacts. This evidence suggests that antipodal magnetism may result from shock remanent magnetization (SRM), possibly in combination with amplification of ambient magnetic fields by plasma produced in the impact process (Lin et al., 1988; Hood et al., 2001; Hood and Artemieva, 2008).

However, other evidence argues instead for a quite different source of the lunar magnetic field. Measurements of Apollo lunar samples suggest thermal remanent magnetization (TRM) acquired in a strong (of order ~1 Gauss) dynamo magnetic field active from roughly ~3.9-3.6 Gya (Fuller, 1974; Fuller and Cisowski, 1987). More recent sample measurements utilizing modern magnetic instrumentation and techniques (Lawrence et al., 2009; Garrick-Bethell et al., 2009) shed some doubt on this magnetic era, but may still provide some evidence for a primary thermal remanence in at least some samples. Meanwhile, impact basins themselves display magnetic anomalies, which, though not as strong as the antipodal anomalies, may also imply the presence of a dynamo field during their formation and/or cooling (Halekas et al., 2003).

Resolving these puzzles and understanding the origins of lunar magnetism would provide the basis for unraveling the thermal history of the lunar core, mantle, and crust, as well as the physics of basin-forming impacts. Both these effects are likely to be important for other solar system bodies, including Mars and Mercury.

Methodology

Sample Return: In order to determine the properties of lunar remanent crustal magnetization and ultimately determine its origin, a focused program of oriented sample return (and subsequent laboratory analysis) and surface magnetometer surveys is needed. Such a program could be efficiently accomplished in conjunction with sample and surface studies for other lunar science purposes. Determining the mode of remanent field acquisition (shock, thermal, etc.), and its strength, age, direction, coherence, and spatial scale would finally allow us to understand the physics of crustal magnetization and the magnetic history of the Moon. Robotic rovers or humans could collect oriented samples from cores or deep craters from key regions such as antipodal areas, mare basalts, magnetized ejecta, and large impact basins (preferably from multiple latitudes), and return them uncontaminated to the Earth for subsequent analysis.

Oriented samples of undisturbed basalt flows offer the best opportunity to test if and when a lunar core dynamo operated on the Moon. Sampling bedrock may be done at, for instance, the flanks of rilles or craters, or by drilling through regolith. If drilling is used, care must be taken to utilize non-magnetic drill materials, as is the standard procedure on Earth. In addition to oriented bedrock cores (or as a preliminary step), samples of melt sheets and crater materials also are important. These samples, which have formed throughout lunar history, are perfect for studying lunar magnetism across all epochs, and can provide abundant samples from an unequivocal single source, providing the statistics and confidence that lunar paleomagnetism has so far lacked.

Sample Curation: Samples collected during the Apollo missions were not protected from magnetic fields on the spacecraft, and they have been continuously stored without shielding from Earth's geomagnetic field. This has resulted in some samples being remagnetized by fields more than 100 times stronger than the ambient surface fields in which they had been sitting for billions of years. However, for a modest investment compared to the cost of returning the samples, the sample storage containers on the Moon and Earth can be wrapped in a layer of μ-metal, shielding them from external magnetic fields.

Surface magnetometer surveys: A portable flux-gate magnetometer (the "LPM") was carried on Apollo 14 and 16 (Apollo 14 and 16 Preliminary Science Reports, 1971, 1972). However, because the devices were tripod-mounted and had to be deployed sufficiently far from the non-magnetically-clean spacesuits, only two measurements were taken on Apollo 14, and only five on Apollo 16. However, these measurements suggested surface fields that vary dramatically over sub-kilometer scales. Such measurements provide crucial constraints on the spatial coherence of crustal magnetization, an important piece of evidence to its origin and history. For future robotic and human missions to any location on the Moon, a flux-gate magnetometer could be mounted on a rover to permit continuous measurements. This would ideally entail a long boom and a magnetically clean rover; however, some progress could be made using an inboard/outboard dual-magnetometer system with only a short boom, by using the inboard magnetometer measurements to subtract the rover-generated fields from the outboard magnetometer signal, as demonstrated in space on the non-magnetically-clean spacecraft Venus

Express (Zhang et al, 2008).

Orbital Measurements: Depending on the phasing of future lunar exploration, intermediate progress could also be made prior to these steps by a small lunar-orbiting spacecraft with magnetometers and plasma instrumentation, which could provide high spatial resolution mapping of the intensity and orientation of the crustal field by targeting low periselenes (<~15 km) over key regions. These measurements would be compared with surface geology in order to constrain the age distribution of crustal magnetism and to quantify its relationship with impact basins, ejecta, and antipodal regions. Sample target regions include the key South Pole Aitken basin, the adjacent strongly magnetized regions antipodal to the Crisium, Imbrium, and Serenitatis basins, the nearby demagnetized Orientale basin, and Moscoviense and Mendel-Rydberg - two basins with central magnetic anomalies.

In order to obtain optimal coverage, careful planning of orbital parameters in advance and preferably long mission duration (> 2 years with a low-altitude periapsis) to ensure a variety of orbit plane orientations, is necessary. To reduce external solar wind and magnetospheric disturbances, it would also help to carry out the mission during solar minimum conditions (e.g., ~2015-16). In addition to producing improved maps of the lunar crustal field (especially in key regions), an orbiter could achieve other secondary science, including producing refined estimates of the lunar induced moment and electromagnetically sounding the lunar electrical conductivity profile (Hood et al., 1982; 1998), and investigating the lunar electromagnetic and plasma environment.