Topical White Paper

Mapping of localized magnetic anomalies on the Moon using nanophase iron

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Abstract

The solar wind, coronal mass ejections and solar particle events represent a continuous stream of ionizing radiation which causes damage to electronics, communications signals and astronauts. The Moon has no magnetic field for protection against these emissions, however, it does have multiple locations of localized magnetic anomalies, often close to impact craters, which experience small miniature magnetospheres. These provide the perfect location to observe radiation interactions and may improve space weather impact prediction on Earth.

Introduction

Lunar Prospector was designed for a low polar orbit investigation of the Moon, to map surface composition including polar ice deposits, measurements of magnetic and gravity fields, and studies of lunar outgassing events [1]. One of four scientific instruments on board, the Magnetometer and Electron Reflectometer (MAG/ER) measured particularly strong magnetic fields in the regions antipodal (on the exact opposite side of the Moon) to the large Mare Imbrium and Mare Serentatis basins. The field antipodal to Mare Imbrium is so strong it can deflect solar wind particles and form its own small magnetospheric system [2].

The origin of crustal magnetic anomalies and the nature of the original magnetizing fields are only partially understood. It is generally accepted that the lunar magnetic anomalies originated from natural remanent magnetization of the lunar crust acquired in a certain ambient magnetic field, however, paleomagnetic studies of Apollo return samples suggest thermoremanent magnetization or shock remanence in some ambient field. Current theories revolve around basin-forming impact, comet impact and existence of a global magnetic field from an ancient lunar dynamo [3].

Space weathering refers to the process whereby materials exposed to the harsh space environment are gradually altered in both physical and compositional properties to some degree. Space weathering processes can be loosely grouped in two broad categories related to (i) random impacts by small particles or debris found throughout the solar system or (ii) irradiation by electromagnetic radiation or atomic particles from the Sun, galactic sources, or magnetosphere. Further phenomena, which may or may not be related, involve the measurement and observation of nanophase iron, created from space weathering. On the Moon, space weathering has been attributed to the creation of tiny particles of metallic iron denoted npFe0 in the literature [4].

An *in situ* study of the nanophase iron, in the location of the magnetic anomalies, would provide a unique tool for measuring the behaviour and characteristics of the anomalies. There is potential for the nanophase iron to become suspended within the mini magnetospheres and align their individual magnetic moments within the local field. The iron particles could be used as multiple mini compasses, mapping out the exact nature of the anomalies.

Space Weather results from the complex interaction of the Sun with planetary bodies in our solar system. The Sun constantly emits particles, fields and plasma which interact with spacecraft and larger bodies. The solar wind, coronal mass ejections and solar particle events represent a continuous stream of ionizing radiation which causes damage to electronics, communications signals and astronauts [5]. Whilst Earth is mostly protected from this radiation by a magnetic field which extends up to 60,000 km (sunward) and 300,000 km (magnetotail), this very same magnetosphere also traps charged particles within it, giving rise to our so called van Allen belts

[6]. The two main belts stretch from 640 km to 58,000 km and have been studied extensively, particularly with the Van Allen Probes Mission [7]. Considering that GPS satellites orbit at 20,200 km (in order to orbit the Earth twice in one 24-hr period) and communications/weather satellites orbit at 36,000 km altitude (orbiting Earth once per 24-hr period), both orbits are well within these radiation intense regions. Currently, satellite designers and manufacturers include radiation hardening into such spacecraft, however, it would be ideal to study the effects of this radiation on the satellites in experiments, before the expensive process of launching the satellites into orbit.

Proposed Science

The experiments proposed here represent two of the three priorities for the Biological and Physical Sciences (BPS) Research in Space 2023-2032 (BPS2023) survey. The study of localized magnetospheres in miniature, is science that can only be done in space and that has an anticipated value to humans on Earth. Localized study of these miniature magnetospheres could help us to better understand the interaction of the solar wind with the Earth's magnetosphere and thus provide better prediction of impacts to Earth from solar events. Earlier warning, or prediction of the solar storm in 1989 that caused the entire state of Quebec, Canada to lose electrical power [8] may be possible.

The second priority is that which makes use of the reduced gravity environment; the nanophase iron will be easier to levitate in 0.166g and should help to characterize and study the miniature magnetospheres better.

Landing Sites

Four sites are identified as significant for this study. Two nearside and two farside sites with the highest strength magnetic fields have been chosen. On the nearside, Reiner gamma and the Descartes crater are identified. Strong anomalies on antipodes of the lunar basins correspond to the chosen farside landing sites at Crisium antipode and Ingenii. All four sites are estimated to have 15 nT magnetic field strength at an approximate altitude of 30 km derived from Lunar Prospector vector magnetometer data [9]. Closer to the lunar surface, these fields should increase by several orders of magnitude.

Of these four sites, the most important is the impact crater Reiner on the Oceanus Procellarum. At 7.0°N 54.9°W it lies well within the most Fe abundant region of the Moon. According to the Clementine Fe map of the Moon [10], the low latitude regions contain up to 14 wt% iron and thus provide the most likely location of finding (and utilising) nanophase iron for local field mapping.

Another important consideration is the precise installation of any Commercial Lunar Payload Systems (CLPS) to these locations. The Reiner and Descartes craters are relatively small locations (30 km and 48 km in diameter, respectively) and so precise landing and deployment of any instrument payload is necessary. Lessons learned from the Clementine mission will greatly assist with such payload design [11].

Unique Science

Science objectives that can be uniquely achieved at these sites relate to a number of the Artemis objectives including;

- **Understanding planetary processes** *e.g. magnetosphere-radiation interactions*
- **Interpreting the impact history of the Earth-Moon system** *e.g. studies at localized magnetic anomalies created by impacts*

- **Observing the universe and the local space environment from a unique location** *e.g. utilising the unique combination of conditions on the lunar surface i.e. low gravity, vacuum and localized magnetic anomalies*
- **Conducting experimental science in the lunar environment** *e.g. deployment of scientific apparatus to study the localized magnetic phenomena*

Experimental Design

The instruments would need to survive through the night as continuous measurements are required. No mobility is necessary, the instruments can remain in one place. Analytical techniques would include neutron spectroscopy (utilising neutrons liberated by the lunar surface), Mossbauer spectroscopy, iron sample collection for bulk magnetization and/or susceptibility measurements and radiation detection capable of distinguishing between different types of ionizing radiation. No sample return is necessary. The challenge in designing the instruments is to have them operate within this intense radiation environment without failing due to electronic circuit damage.

Neutron spectroscopy

As protons impact the surface of the Moon, large amounts of neutrons are created under the near surface by spallation. The resulting thermal and epithermal neutron fluxes have been measured by the Lunar Reconnaissance Orbiter using the Lunar Exploration Neutron Detector (LEND) instrument and used as an indication of the amount of water-equivalent-hydrogen on or under the surface [12]. Neutron spectroscopy measurements of levitating Fe nanoparticles have been conducted on Earth [13], but would be far more efficiently and reliably conducted on the lunar surface. Flux and orientation of mobile Fe nanoparticles could be determined with this technique, as well as precise ratios of Fe isotopes in these regions. Self-assembly of iron oxide nanoparticles has been observed using small-angle neutron scattering on Earth [14] and this may also occur on the lunar surface. It may even be possible to measure the hyperfine interaction within some of the heavier compounds within the lunar surface [15].

Mossbauer spectroscopy

Mössbauer spectroscopy of Apollo lunar samples has been conducted on Earth [16]. *In situ* Mössbauer spectroscopy would be useful to determine the iron oxidation state of lunar samples. This would provide a direct comparison with the Apollo equatorial samples, to see if there was any impact of Earth-based contamination on the returned samples. Mössbauer spectroscopy can also be used to determine the electronic spin-state, coordination number, coordination environment, and often the number of crystallographically unique iron sites which would serve as a way to corroborate measurements taken by other instruments in the suite. The MIMOS II instrument has been reliably working on the Perseverance rover for some time [17].

Radiation detectors

The Lunar Lander Neutrons and Dosimetry experiment aboard China’s Chang’E 4 lander has made the first ever measurements of the radiation exposure to both charged and neutral particles on the lunar surface. They measured an average total absorbed dose rate in silicon of 13.2 ± 1 μGy/hour and a neutral particle dose rate of 3.1 ± 0.5 μGy/hour [18].

Additional placement of detectors to measure alpha, beta, gamma, neutron, proton, electron, positron flux directly inside the localized magnetic anomalies would provide some fascinating complimentary data to the Chang’E 4 data.

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