

A New Large-Scale Map of the Lunar Crustal Magnetic Field and Its Interpretation

Lon Hood, Cecilyn Torres, Joana Oliveira, Mark Wieczorek, Sarah Stewart

► To cite this version:

Lon Hood, Cecilyn Torres, Joana Oliveira, Mark Wieczorek, Sarah Stewart. A New Large-Scale Map of the Lunar Crustal Magnetic Field and Its Interpretation. Journal of Geophysical Research. Planets, 2021, 126 (2), 10.1029/2020JE006667. hal-03365555

HAL Id: hal-03365555 https://hal.science/hal-03365555

Submitted on 12 Aug2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



JGR Planets

RESEARCH ARTICLE

10.1029/2020JE006667

Key Points:

- A new large-scale map of the lunar crustal magnetic field covering most latitudes at a constant altitude of 30 km has been produced.
- Anomalies on the near side tend to be aligned radial to the Imbrium impact basin; the strongest anomalies are located antipodal to Imbrium.
- These results are consistent with the idea that iron from the Imbrium impactor was mixed into ejecta deposited downrange & at the antipode.

Supporting Information:

• Supporting Information S1

Correspondence to:

L. L. Hood, lon@lpl.arizona.edu

Citation:

Hood, L. L., Torres, C. B., Oliveira, J. S., Wieczorek, M. A., & Stewart, S. T. (2021). A new large-scale map of the lunar crustal magnetic field and its interpretation. *Journal of Geophysical Research: Planets, 126*, e2020JE006667. https://doi.org/10.1029/202JE006667

Received 24 AUG 2020 Accepted 17 DEC 2020

A New Large-Scale Map of the Lunar Crustal Magnetic Field and Its Interpretation

Lon L. Hood¹, Cecilyn B. Torres¹, Joana S. Oliveira^{2,3}, Mark A. Wieczorek⁴, and Sarah T. Stewart⁵

¹Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, ²ESA/ESTEC, Noordwijk, Netherlands, ³Space Magnetism Area, Payloads & Space Sciences Department, National Institute for Aerospace Technology, Torrejón de Ardoz, Spain, ⁴Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France, ⁵Department of Earth and Planetary Sciences, University of California, Davis, CA, USA

Abstract A new large-scale map of the lunar crustal magnetic field at 30 km altitude covering latitudes from 65°S to 65°N has been produced using high-quality vector magnetometer data from two complementary polar orbital missions, Lunar Prospector and SELENE (Kaguya). The map has characteristics similar to those of previous maps but better resolves the shapes and distribution of weaker anomalies. The strongest group of anomalies is located on the northwest side of the South Pole-Aitken basin approximately antipodal to the Imbrium basin. On the near side, both strong isolated anomalies and weaker elongated anomalies tend to lie along lines oriented radial to Imbrium. These include named anomalies such as Reiner Gamma, Hartwig, Descartes, Abel, and Airy. The statistical significance of this tendency for elongated anomalies is verified by Monte Carlo simulations. Great circle paths determined by end points of elongated anomaly groups and the locations of five individual strong anomalies converge within the inner rim of Imbrium and intersect within the Imbrium antipode zone. Statistically significant evidence for similar alignments northwest of the Orientale basin is also found. The observed distribution of anomalies on the near side and the location of the strongest anomaly group antipodal to Imbrium are consistent with the hypothesis that iron from the Imbrium impactor was mixed into ejecta that was inhomogeneously deposited downrange in groups aligned radial to the basin and concentrated antipodal to the basin.

Plain Language Summary The origin of crustal magnetic anomalies on airless silicate bodies like the Moon in the solar system is a fundamental unresolved problem of planetary science. Here, we report production of a new large-scale map of the lunar crustal field that better resolves the shapes and distribution of weaker anomalies. The strongest group of anomalies is located on the south-central far side approximately antipodal (diametrically opposite) to the Imbrium impact basin. On the near side, both strong isolated anomalies and weaker elongated anomalies tend to lie along lines oriented radial to Imbrium. These include named anomalies such as Reiner Gamma, Hartwig, Descartes, Abel, and Airy. The statistical significance of this tendency is verified by Monte Carlo simulations. Great circle paths determined by end points of elongated anomaly groups and the locations of strong isolated anomalies converge within the inner rim of Imbrium and intersect within the Imbrium antipode zone. The observed distribution of anomalies is consistent with the hypothesis that iron from the Imbrium impactor was mixed into ejecta that was inhomogeneously deposited downrange in groups aligned radial to the basin and concentrated antipodal to the basin.

1. Introduction

While partial progress has been made during the last 10 years on the interpretation of lunar magnetism, important unresolved issues remain which limit our ability to apply it to understand better the history of the Moon.

On the positive side, laboratory analyses of returned samples have improved, leading to two main conclusions: (a) at least some mare and highland igneous samples acquired their primary magnetization via thermoremanence, requiring slow cooling in a steady magnetic field; and (b) the surface magnetizing field for such samples with ages between \sim 3.56 and 4.25 Gyr had amplitudes reaching 70 µT (0.7 Gauss), declining

© 2021. American Geophysical Union. All Rights Reserved. rapidly to $\leq 4 \ \mu$ T by 3.19 Gyr (Garrick-Bethell et al., 2009; Shea et al., 2012; Suavet et al., 2013; Tikoo et al., 2014). These results, combined with orbital evidence for magnetic anomalies within impact basins of Nectarian age (Halekas et al., 2003; Hood, 2011; Oliveira et al., 2017), strongly support the existence of a steady, long-lived internal magnetizing field during early lunar history. Leading contenders for the origin of the internal magnetizing field include a former core dynamo (Weiss & Tikoo, 2014) and dynamo activity in an early basal magma ocean (Scheinberg et al., 2018).

On the negative side, the interpretation of lunar magnetic anomalies remains unresolved with some groups suggesting igneous sources consisting of dike intrusions (Hemingway & Tikoo, 2018; Purucker et al., 2012; Tsunakawa et al., 2014; 2015;) and other groups suggesting sources in the form of impact basin or crater melt sheets and ejecta deposits (Garrick-Bethell & Kelley, 2019; Hood et al., 2013, 2001; Oliveira et al., 2017; Wieczorek et al., 2012). The latter issue extends also to Mercury where likely sources have been interpreted as both volcanic plains (Johnson et al., 2015) and impact basin ejecta deposits (Hood, 2015, 2016; Hood et al., 2018). Also, while it is agreed that an internal magnetizing field existed during the Imbrian period, orbital data suggest a much weaker Imbrian field strength than do lunar sample paleointensities (Halekas et al., 2003; Hood & Spudis, 2016). Finally, while it is agreed that most of the strongest crustal anomalies occur on the southern far side in the vicinity of the ancient South Pole-Aitken (SPA) impact basin, the interpretation of these anomalies remains uncertain. On the one hand, these anomalies are concentrated around the northern edge of SPA. On the other hand, concentrations of relatively strong anomalies are also centered on the antipodes of the Imbrium, Serenitatis, Crisium, and Orientale impact basins (Lin et al., 1988; Mitchell et al., 2008). Some analysts, therefore, suggest an SPA-related origin (e.g., Purucker et al., 2012; Wieczorek et al., 2012) while others suggest an origin involving the antipodal effects of basin-forming impacts (e.g., Hood & Artemieva, 2008; Hood et al., 2013).

In the work reported here, an alternate approach toward constructing a large-scale map of the lunar crustal field is taken to provide new constraints on the origin of the crustal magnetic anomalies. Two polar orbital missions, Lunar Prospector (LP) launched in 1998 and the SELENE (Kaguya, KG) mission launched in 2007, provide a nearly global set of vector magnetometer measurements at relatively low altitudes (Hood et al., 2001; Lin et al., 1998; Tsunakawa et al., 2010). While valuable large-scale maps of the crustal field have already been produced using these data (e.g., Purucker & Nicholas, 2010; Ravat et al., 2020; Richmond & Hood, 2008; Tsunakawa et al., 2015), it is argued here that maps of improved accuracy over individual regions can be constructed by selecting only the best magnetometer measurements (lowest altitude with least amount of external field contamination) over those specific regions. Once the best measurements are identified, an equivalent source dipole (ESD) technique (e.g., Mayhew, 1979; von Frese et al., 1981) can be applied to normalize the measurements to a constant altitude. Individual regional maps can then be joined together to produce a large-scale map.

In Section 2, the methods for data selection and ESD mapping are described in more detail and applied to produce a large-scale map of the crustal field magnitude at 30 km altitude covering latitudes from 65°S to 65°N. In Section 3, the characteristics of this map in relation to previous maps are summarized. In Section 4, anomalies mapped more accurately using these methods on the near side south of Imbrium and on the far side northwest of Orientale are examined in detail. This leads to evidence favoring an impact-related hypothesis for the origins of both weak and strong anomalies, including the strongest anomalies, which are found mainly in the Imbrium antipode zone on the south-central far side. A summary and discussion are given in Section 5.

2. Data Processing and Crustal Field Mapping

In this study, 5-s averages of LP magnetometer measurements from the low-altitude phase of the mission (March–June 1999) and 4-s averages of KG magnetometer measurements from the lowest-altitude phase of that mission (April–June 2009) are used. Both sets of data are freely available online as documented in the acknowledgments. Only a small fraction of these measurements (those obtained when the Moon was in a lobe of the geomagnetic tail or when the Moon was in the solar wind but the spacecraft was in the lunar wake) are suitable for mapping crustal fields. Even these measurements must be carefully screened to minimize contributions from sporadic external field contamination events. The radial field component is

least contaminated due to the finite electrical conductivity of the subsurface, which allows currents to be induced that suppress radial field temporal fluctuations while amplifying tangential temporal fluctuations (see, e.g., Figure 4 of Hood et al., 1982).

It should be noted that KG geodetic position errors of up to several km occurred during the low-altitude mission phase, which can especially affect maps constructed using along-track field differences (Goossens et al., 2020; Ravat et al., 2020). If these errors were mainly horizontal over a given region, they will not appreciably affect the direct mapping reported here. However, if they were entirely vertical at a given location, errors of up to 15% in estimated field amplitudes could be produced by the altitude normalization process.

Prior to selecting data for mapping, all LP and KG magnetometer data were processed to convert from a body-centered selenographic (X, Y, Z) coordinate system to an east, north, and radial system. All measurements were divided into individual orbits and each orbit was further divided into two parts depending on whether the spacecraft was "ascending" (i.e., moving from south to north during its equator passage) or "descending" (moving from north to south). As will be seen below, this is a useful division because the two-halves of the orbits were usually on either the sunward or antisunward side of the Moon. Next, the three vector field components were "detrended" by least squares fitting and removing a quadratic polynomial. This had the effect of high-pass filtering the data to minimize any contributions of longer-wavelength external fields while not altering in any way the short-wavelength fields. (Spectral band-pass filtering techniques can alter the shapes of short-wavelength anomalies.) Permanent internal lunar fields with wavelengths longer than about 20° of latitude are not found on the Moon (unlike Mercury) so the detrending method is sufficient for this purpose. Then "stack plots" (i.e., a series of plots of a given field component along a series of orbit passes from 90°S to 90°N latitude) were constructed for all of the available ascending and descending orbit passes during both the LP and KG missions. Each plot was labeled with the spacecraft altitude and longitude during crossings of a selected latitude (e.g., 0°).

In most but not all cases, ascending orbit passes had reduced external field contamination relative to descending passes. This was because the ascending passes during the low-altitude mapping phases of both missions tended to be on the antisunward side of the Moon. This provided some shielding from solar wind plasma-related disturbances, especially during the majority (~85%) of the time when the Moon was outside of the geomagnetic tail. For simplicity, only ascending passes were therefore used in the mapping reported here. Examples of stack plots of detrended KG radial field component data from ascending passes during May 19–21, 2009 and corresponding LP ascending pass data from April 13–15, 1999 are shown in Figures 1 and 2, respectively. Both of these time intervals were from periods when the Moon was in the solar wind but the spacecraft was in the lunar downstream cavity.

Due to the slow lunar rotation rate, successive orbit tracks of a low-altitude polar-orbiting spacecraft are separated by only $\sim 1^{\circ}$ of longitude (about 30 km on the surface) at the equator. If the spacecraft altitude is comparable to or larger than the orbit track separation, real crustal anomalies will approximately repeat on successive orbits while external field fluctuations will not. Hence, a simple visual scan of radial field stack plots over a region can often narrow the choice of which lunations (months) of data in either the LP or KG mission contain the best radial field measurements over that region.

For example, the LP radial field component plots in Figure 2 cover nearly the same region as the KG plots of Figure 1. It is visually evident that the LP data in Figure 2 contain more short-wavelength field fluctuations than do the KG data in Figure 1. In part, this is because the LP data were obtained at somewhat lower altitudes (16.8–20.2 km) than were the KG data (21.5–24.7 km), which causes crustal fields to have larger amplitudes. However, it is also because external field variability was larger during the time of the LP measurements in 1999 than during the time of the KG measurements in 2009.

As shown in Figure S1 of the Supporting Information Material, the low-altitude part of the KG mission fortuitously occurred near the bottom of a deep solar minimum in 2009 while low-altitude LP measurements were obtained under solar maximum conditions in 1999. This contributed to generally larger external field fluctuations during the LP mission. Nevertheless, as will be seen below, LP measurements of crustal fields are often superior to KG measurements, especially in the Northern Hemisphere, because they were obtained at lower altitudes in a favorable plasma environment.





Figure 1. Radial magnetic field component at latitudes of 90°S to 20°N along a series of Kaguya orbits after quadratic detrending. The longitude and altitude above the mean lunar radius of the spacecraft at times when it crossed the 30°S latitude line are listed at left. Red arrows indicate anomalies that form one elongated group discussed in the text.

In addition to visual examinations, a more quantitative method for assisting in the selection of the most suitable measurements for mapping over a given region was also applied. It consists of calculating the square root of the mean of the squared differences between radial component measurements at a given latitude along an adjacent pair of orbit segments. These root mean square (RMS) differences are smaller when external field fluctuations are reduced in amplitude. They provide a useful criterion for data selection when the spacecraft altitude is comparable to or larger than the orbit track separation over a region of interest. Figure 3 plots RMS differences in nT for successive pairs of orbits using the data of Figures 1 (KG) and 2 (LP). The LP data give RMS differences averaging about 1 nT larger than those for the KG data. It is, therefore, clear that the KG data from May of 2009 are more suitable for mapping the crustal field over this particular region than are the LP data from April of 1999.

The same differencing technique is also useful as a supplement to visual identification of individual orbit segments that contain excessive external field contamination. Such orbit segments were either deleted from the analysis or, in rare cases, replaced with an artificial segment in which the radial field component is interpolated between two nearby orbits. However, for orbits when the spacecraft altitude is much less than the track separation, some of the differenced data is due to real crustal fields. This can result in overestimation of the RMS due to external field fluctuations, potentially leading to data being unnecessarily discarded. Therefore, for those segments (a small fraction of the total), only segments containing visually obvious external field spikes and high-frequency noise were eliminated. Finally, if the measurement altitude is too low (say, 5 km) compared to the orbit track separation of as much as 30 km, local sources with small horizontal extents along individual passes may dominate the measurements leading to an inaccurate map. Generally speaking, measurements obtained along successive orbits at altitudes lower than about half of the orbit track separation were not considered in this study.

We emphasize that the selection and editing of the best available measurements over a given region is an imperfect process. For example, if external sources happen by chance to repeat at the same location during two or three consecutive orbits, an "apparent" anomaly would be mapped. However, redundant coverage during multiple lunations is available, albeit at different altitudes. Examinations of similar stack plots from these different lunations can greatly reduce the probability of such a chance occurrence.

Figure 4 summarizes the final time periods of LP and KG data that were selected within 16 regional sectors to produce a large-scale map covering all longitudes at latitudes from 65°S to 65°N. As indicated by the blue outlines in the figure, primarily LP data were selected for 9 of the 16 sectors, while, as indicated by the red outlines, primarily KG data were selected for 5 of the sectors. In the two remaining sectors, a combination of KG and LP data were selected. Note that several sector boundaries (e.g., that at 90°W, 30°S to 0°N) were shifted to include more KG data. KG data are mainly selected for the southern half of the near side, consistent with the evaluation of Figures 1 and 2 described above. However, due to the location of the KG periapsis in the Southern Hemisphere, LP data were mainly selected in the Northern Hemisphere.

Most of the time intervals listed in Figure 4 were from periods when the Moon was in the solar wind or terrestrial magnetosheath and the spacecraft was in the lunar wake. The only exceptions were LP data from May 27 to 30, 1999 and KG data from May 7 to 12, 2009 when the Moon was in a lobe of the geomagnetic tail. The dominance of wake intervals was necessary to obtain complete longitude coverage and led to the simplification of using only ascending orbit passes, as noted above.

Even within these selected time intervals, significant episodes of short-term external field fluctuations were present along individual orbit passes. To minimize the contribution of these episodes to the final map,





Figure 2. As in Figure 1 but along a series of Lunar Prospector orbits covering approximately the same longitude range.

simple editing (removing) of part or all of the orbit pass was applied. At low latitudes, the orbit track separation is about 30 km, which is comparable to the mapping altitude. Eliminating one orbit pass does not compromise the final map because, as will be seen below, two-dimensional (2D) filtering of the binned orbital data to produce the final map effectively interpolates the data across this missing orbit. Cases when two consecutive orbits required editing occurred only rarely for the high-quality data selected here. For those rare cases, the edited data in at least one orbit was replaced with artificial data interpolated from orbit tracks on either side of the affected pass. These rare cases occurred in regions that do not affect any of the interpretations given here.

To produce a map at constant altitude, a classical ESD technique was employed (e.g., Hood, 2015; 2016). In its simplest form, this involves assuming that the sources of the crustal field can be represented as an array of point dipoles on a spherical surface with some specified orientation, horizontal separation, and depth beneath the lunar mean radius. The amplitudes (positive or negative) of the individual dipole moments are then adjusted iteratively until a minimum variance between the observed magnetic field and the model magnetic field is obtained. Only one observed field component, that is, the radial field component since it is least affected by external field fluctuations, needs to be considered. The resulting solution for the effective crustal magnetization distribution is nonunique because of the specified dipole orientation (usually vertical). But the final array of dipoles can be used to calculate the approximate field at a constant altitude. Only upward or moderate downward continuation of the field from the spacecraft altitude is advisable to avoid amplification of any external field noise in the data. A survey of the LP and KG data showed that most of the Moon is covered at altitudes less than 40 km. Since the orbit track separation is about 30 km at the equator, a map constructed at much lower altitudes than this (say, 15 km) would

risk introduction of errors due to excessive downward continuation. Therefore, a uniform mapping altitude of 30 km was chosen.





In order to produce a map covering most of the Moon (except the polar regions), an equivalent source model was assumed in the form of an array of 541 by 196 (106,036) vertically oriented separated by two-thirds degrees in latitude and two-thirds degrees in longitude covering latitudes from 65°S to 65°N and all longitudes. This dipole separation was chosen because it is somewhat less than the 1° orbit track separation at the equator (to ensure a nearby dipole at each measurement point) but is not so small as to require excessive computation time. The array was placed on a spherical surface at a depth below the mean lunar radius chosen such that the RMS deviation of the model radial field from the observed radial field at the spacecraft altitude was a minimum. Trial calculations at depths of 5-25 km at 5 km intervals yielded a minimum RMS deviation over most areas for a depth of 15 km. Therefore, the depth of the dipole array was chosen to be 15 km. All dipole moment amplitudes were initially set to zero. The iterative computational method has been described in Hood (2015) with minor revisions in Hood (2016).

To increase computational efficiency and to allow selection of optimal orbital data tailored to each region as described above, 16 overlapping partial maps, each covering 105° of longitude and 40° of latitude were first constructed and then joined together to produce a complete map



60°N	May 19, 10.9 hr – May 23, 7.6 hr, 1999 Jun 15, 23.8 hr – Jun 15, 9.7 hr, 1999 Jun 19, 13.2 hr – Jun 22, 1.1 hr, 1999	Mar 19, 13.9 hr – Mar 23, 5.6 hr, 1999 Apr 15, 1.6 hr – Apr 16, 0.4 hr, 1999 May 19, 2.9 hr – May 19, 10.9 hr, 1999 Jun 13, 1.5 hr – Jun 15, 9.7 hr, 1999	Mar 12, 6.4 hr – Mar 16, 12.4 hr, 1999 Apr 12, 21.7 hr – Apr 14, 13.2 hr, 1999 May 11, 22.5 – May 12, 4.7 hr, 1999	Mar 11, 11.3 hr – Mar 12, 6.4 hr, 1999 Apr 5, 9.9 hr – Apr 7, 19.4 hr, 1999 May 29, 13.1 – May 30, 2.7 hr, 1999 May 27, 12.9 – May 29, 11.8 hr, 1999 Jun 22, 2.4 hr – Jun 23, 19.7 hr, 1999
30⁰N	May 19, 12.2 hr – May 23, 7.6 hr, 1999 Jun 19, 13.2 hr – Jun 22, 1.1 hr, 1999	May 24, 13.8 hr – May 27, 19.3 hr 2009 May 27, 19.3 hr 2009 Apr 15, 1.6 hr – Apr 16, 0.4 hr, 1999	Mar 11, 11.3 hr – Mar 16, 12.4 hr, 1999 May 10, 3.9 hr – May 12, 4.7 hr, 1999	Mar 11, 11.3 hr – Mar 12, 6.4 hr, 1999 Apr 5, 9.9 hr – Apr 7, 19.4 hr, 1999 May 29, 13.1 – May 30, 2.7 hr, 1999 May 27, 12.9 – May 29, 11.8 hr, 1999 Jun 22, 2.4 hr – Jun 23, 19.7 hr, 1999
2005	May 19, 12.2 hr – May 23, 7.6 hr, 1999 Jun 19, 13.2 hr – Jun 22, 1.1 hr, 1999	May 20, 14.4 hr – May 27, 19.3 hr, 2009	May 13, 2.7 hr – May 20, 14.4 hr, 2009	Mar 11, 11.3 hr – Mar 12, 6.4 hr, 1999 Apr 5, 9.9 hr – Apr 7, 19.4 hr, 1999 May 29, 13.1 – May 30, 2.7 hr, 1999 May 27, 12.9 – May 29, 11.8 hr, 1999 Jun 22, 2.4 hr – Jun 23, 19.7 hr, 1999
50°S	Apr 30, 21.3 hr — May 1, 3.5 hr, 2009 May 6, 9.9 hr — May 7, 3.4 hr, 2009 May 26, 18.3 hr — May 28, 4.7 hr, 2009 May 28, 11.5 hr — Jun 2, 23.4 hr, 2009	May 20, 14.4 hr – May 27, 19.3 hr, 2009	May 13, 2.7 hr – May 20, 14.4 hr, 2009	May 7, 3.4 hr – May 10, 21.1 hr, 2009 Apr 5, 8.0 hr – Apr 5, 23.5 hr, 1999 May 11, 13.3 hr – May 12, 12.4 hr, 2009 Apr 6, 23.0 hr – Apr 7, 14.4 hr, 1999 May 4, 21.7 hr – May 5, 3.8 hr, 1999 May 13, 10.2 hr – May 14, 5.6 hr, 2009
18	0°W 9	0°W 0°I	90	PE 180°F

Figure 4. Listing of time intervals during either the LP or KG missions that were selected for mapping in individual sectors. Regions mapped using LP data are outlined in blue; regions mapped using KG data are outlined in red. The lower right sector was mapped using a combination of KG and LP data. Individual orbits within the selected time intervals were further edited or interpolated to minimize short-term external field fluctuations (see the text). LP, Lunar Prospector.

covering all longitudes and latitudes from 65°S to 65°N (see Figure 4 for a schematic diagram). Specifically, maps were first constructed to cover latitudes of 65°S to 25°S, 35°S to 5°N, 5°S to 35°N, and 25°N to 65°N. Longitude ranges were 265°E to 10°E, 350°E to 95°E, 85°E to 190°E, and 170° to 275°E. To produce the first two partial maps covering the near side (265°E to 95°E), computations were done in six overlapping subsectors, each with an array of 61 by 61 dipoles and covering 40° of longitude. For example, the map of the near side from 5°S to 35°N was divided into subsectors with longitude ranges from 265°E to 305°E, 295°E to 335°E, 325°E to 5°E, 355°E to 35°E, 25°E to 65°E, and 55°E to 95°E. Similarly, to produce the other two partial maps of the far side (85°E to 275°E), six subsectors were employed with longitude ranges from 85°E to 125°E, 145°E to 185°E, 175°E to 215°E, 205°E to 245°E, and 235° to 275°E. The 10° overlap between all subsectors minimized any edge effects of the computations near the vertical subsector boundaries because the last 5° of one subsector map and the first 5° of the next subsector map were discarded. To further minimize any discontinuities at horizontal boundaries, the calculated dipole moments were interpolated to produce a set of moments that varied smoothly with latitude in the 10° of overlap.

Contour maps are chosen to display the ESD solution because (a) they are more accurate than color-shaded maps, especially those with nonlinear color scales; and (b) they can be superposed on geologic or topographic maps. In preparation for contour mapping, the set of 106,036 vertically oriented ESDs on a spherical surface 15 km below the mean lunar radius was first applied to calculate the field magnitude along the original spacecraft orbit tracks but at a constant altitude of 30 km above the mean lunar radius. To produce an evenly spaced array and fill in edited intervals with interpolated data, all field magnitude data were first sorted into one-third degrees latitude by two-thirds degrees longitude bins and smoothed twice using a 3×3 moving average (boxcar) filter. Specifically, starting at the lower left corner of the map, a 3×3 section of bins was stepped bin by bin across the map in longitude with the central bin value replaced with the mean of the nine bins in the section at each step. The section was then moved one bin up in latitude and the process was repeated. This first application produced an array with a resolution of 1° in latitude by 2° in longitude. The filter was then applied a second time to the data smoothed during the first application producing an array with an effective resolution of one and two-thirds degrees in latitude by three and one-





Figure 5. Superposition of a contour map of the lunar crustal field magnitude at 30 km altitude onto LOLA topography over LROC WAC shaded relief. The contour interval is 1 nT. Elevations above the mean lunar radius range from ~ -9 km in craters within the South Pole-Aitken basin to ~ 7 km in the highlands on the eastern central far side. LOLA, Lunar Reconnaissance Orbiter Laser Altimeter; LROC WAC, Lunar Reconnaissance Orbiter Wide Angle Camera.

third degrees in longitude. The smoothing typically reduces the amplitude of anomalies along individual orbit tracks by $\sim 10\%$.

The final contour map of the field magnitude is shown in Figure 5 (contour interval 1 nT). It is superposed on a Lunar Reconnaissance Orbiter Wide Angle Camera (WAC) shaded relief map using topography derived from Lunar Reconnaissance Orbiter Laser Altimeter data (Smith et al., 2010). Because lunar elevations range from about -9 km in the deepest parts of the SPA basin to about +7 km in parts of the central farside highlands, the map altitude above the actual surface ranges from roughly 23–39 km. An alternate version of the field map with a contour interval of 0.5 nT (starting at 1 nT) is shown in Figure 6. The field map at 30 km altitude, including the vector components as well as the field magnitude, has been archived in the NASA Planetary Data System (Hood, Torres et al., 2020).



Figure 6. As in Figure 5 but contoured at an interval of 0.5 nT starting at 1 nT. The locations of four groups of anomalies centered approximately antipodal to young large lunar basins are indicated. The Imbrium group containing the strongest anomalies (four exceeding 8 nT) is located on the northwest side of the SPA basin. SPA, South Pole-Aitken.

3. Overview and Comparisons With Previous Maps

Most general characteristics of the field maps in Figures 5 and 6 are consistent with those of previous largescale maps of the lunar crustal field (e.g., Purucker & Nicholas, 2010; Ravat et al., 2020; Tsunakawa et al., 2015). For example, fields are relatively weak across the north-central near side in an area occupied by Mare Imbrium and Oceanus Procellarum. Relatively weak fields are also found within and near Mare Orientale and across the north-central far side. The vast majority of anomalies (notable exceptions being those within impact basins) are not obviously related to the underlying terrain. The largest group of strong anomalies is found on the northwest side of the SPA basin centered near 165°E, 30°S (approximately antipodal to Imbrium). Other large groups of strong anomalies are centered at about 165°W, 20°S (antipodal to Serenitatis), 95°E, 20°N (antipodal to Orientale), and at about 125°W, 20°S (antipodal to Crisium). The antipodal grouping of anomalies is seen somewhat more clearly in Figure 6 than in Figure 5. Four anomalies in the Imbrium antipode (northwest SPA) group centered on Mare Ingenii have smoothed amplitudes exceeding 8 nT. It is, therefore, the most magnetic region on the Moon. The northern edge of that group, including anomalies near the craters van de Graaff and Aitken, was first mapped using Apollo 15 subsatellite magnetometer data (e.g., Hood, Coleman, Russell et al., 1979). On the near side, relatively isolated strong anomalies include the Reiner Gamma anomaly (8°N, 302°E; smoothed amplitude ~9 nT), the Abel anomaly (33°S, 88°E; ~9 nT), the Descartes anomaly (11°S, 15°E; ~8 nT), the Hartwig anomaly (9°S, 280°E; ~6 nT), and the Airy anomaly (18°S, 3°E; ~5 nT).

One previous crustal field map that is most nearly comparable to the present map is that of Tsunakawa et al. (2015), who also analyzed a combination of LP and KG data but using a surface vector mapping (SVM) method. The latter map is available from http://jlpeda.jaxa/jp/globalSVM20150511.zip (H. Tsunakawa, priv. comm., 2019). It is provided in several forms including at 30 km altitude at 0.5° intervals, which is most nearly comparable to the present map. Figure S2 of the SM plots this map in the same format as Figure 5. To ensure a direct comparison, the map data at 0.5° intervals was binned and filtered two-dimensionally in the same manner as described above for the map of Figure 5. In many respects, the two maps are in very good agreement and some of the differences are a measure of current mapping uncertainties of the lunar crustal field. In some areas, the Tsunakawa et al. (2015) map may actually be more accurate than the current map. For example, it more accurately depicts the true amplitude of the Gerasimovich (Crisium antipode) anomaly, which is the strongest single anomaly on the Moon. Also, the spatial resolution of the unfiltered Tsunakawa et al. (2015) map is better than that of the current map. However, one important difference that reflects an improvement of the current mapping approach is that Figure 5 shows more weaker anomalies and the distribution of these anomalies differs significantly from that of Figure S2. As discussed in the next section, these weaker anomalies are important for understanding the likely origin of both strong and weak anomalies and are mapped more accurately in Figure 5 because of improved data selection.

4. Relationship of Anomalies to Imbrium and Orientale

4.1. Imbrium

A large number of relatively weak anomalies are present on the southern near side in the maps of Figures 5 and 6. To examine these anomalies in more detail, Figure 7 shows a slightly more accurate and smoother map of the central near side produced by detrending the radial component data over a smaller latitude range (45°S to 45°N) and sorting the altitude-normalized data into larger bins (0.5° latitude by 1° longitude) prior to 2D filtering. For simplicity, only KG data were used at all latitudes and longitudes.

Noticeable in Figure 7 is a tendency for anomalies to be aligned radial to the Imbrium basin (dashed lines). It has previously been noted that the Rima Sirsalis anomalies and the Reiner Gamma anomalies tend to be oriented radial to the center of Imbrium (e.g., Halekas et al., 2001). As seen in the figure, at this resolution (about 2.5° latitude by 5° longitude), the Reiner Gamma anomalies are extended in such a direction. Also, a further radial extension of this line passes through the Hartwig anomaly. As indicated by the other dashed lines, two other groups of weaker anomalies appear to also be aligned radial to Imbrium. One group is centered at about 18°S, 3°E (referred to here as the Airy group) and the other is centered at around 8°S, 45°E (referred to as the Eastern group). Note that the two Crisium anomalies, one of which is somewhat elongated, are not considered here because they most probably have sources originating at the time of the Crisium impact (e.g., Hood, Oliveira et al., 2021).





Figure 7. As in Figures 5 and 6 but for the central near side using only selected KG data. The contour interval is 0.5 nT starting at 1 nT and several named anomalies are labeled. Dashed lines identify anomalies that appear to be aligned radial to the Imbrium impact basin. (See the text.) Anomalies that form the Airy elongated group near 0° E are identified by red arrows in Figure 1.

Figure S3 of the Supporting Information Materials is a map in the same format as Figure 7 but constructed using the SVM map data of Tsunakawa et al. (2015) at 30 km altitude. It was filtered two-dimensionally in the same way as was done for the data input to Figure 7. A number of weaker anomalies are mapped in Figure 7 that are not mapped in Figure S3. Most of these are supported to be real by their approximate repetition on consecutive orbit passes. Also, some of the weak anomalies south of Imbrium have previously been mapped using low-altitude Apollo 16 subsatellite magnetometer data (Hood, Coleman, Russell et al., 1979). Some of these were found to correlate with exposures of the Fra Mauro Formation, which is primary Imbrium basin ejecta (Hood, 1980). It is, therefore, concluded that these anomalies are more accurately mapped in Figure 7 than in Figure S3. In particular, a weak anomaly at 8°S, 359°E is an important part of the elongated group centered at about 18°S, 3°E in Figure 7. Without this anomaly, only three groups of elongated anomalies oriented radial to Imbrium are identifiable in Figure S3. All of these anomalies are visible in stack plots of the radial field component as repeating anomaly patterns on successive orbits (red arrows in Figure 1).

It is important to investigate whether the alignments of elongated anomalies radial to Imbrium that are seen in Figure 7 could have happened by chance and what the probability of such a chance occurrence is. To estimate this probability, Monte Carlo simulations were conducted. As illustrated in Figure S4a of the Supporting Information Materials, the observed elongated Reiner Gamma, Rima Sirsalis, Airy, and Eastern anomaly groups were represented schematically as elongated ovals in these simulations. Considering these as the only elongated anomaly groups within a few basin diameters of Imbrium, a large number (3,000) of randomly selected orientations of the oval axes was then tested to determine if linear extensions of a given oval axis pass within the outer main rim of Imbrium. Because of the low latitudes, a linear extension approximation is reasonable. The fraction of successful orientations was then used to estimate the probability of a chance occurrence for one or more anomaly groups.

As would be expected, the probability of a chance occurrence for a single anomaly group increases with increasing size of the basin and with decreasing distance of the group from the basin. For example, assuming an elongated group at the location of Reiner Gamma, orientations that passed within the 1,322 km diameter outer rim of Imbrium occurred about 30% of the time while assuming an elongated group at the location of the Eastern group in Figure 7, orientations whose linear extensions passed within the outer rim occurred only 17% of the time. Assuming that elongated groups exist at both the Reiner Gamma and Eastern locations, the probability that both group extensions would simultaneously pass by chance within the main rim decreases to 5%. Adding the Rima Sirsalis location and requiring that all three group extensions should pass





Figure 8. As in Figure 7 but extended southward to 65°S. The contour interval is 0.5 nT starting at 0.5 nT. Great circle paths passing through individual anomalies at points given in the text are shown.

within the main rim reduces the probability to 1%. Finally, adding the Airy group location and requiring all four extensions to pass within the main rim reduces the probability to only 0.2%.

However, while the four considered elongated groups are the most prominent in Figure 7 (in terms of amplitude and length), it could be argued that other elongated groups exist that are not oriented radial to Imbrium. For example, two weaker and less elongated groups are centered near 5°N, 320°E and near 5°N, 5°E. Both are relatively close to Imbrium but neither is oriented radial to Imbrium. Considering these as well as the four original groups (a total of six groups), the probability that four of the six group extensions would by chance pass within the outer Imbrium rim increases to 3.2%, still a low probability. Of course, other elongated groups exist at much larger radial distances from Imbrium but their extensions have a proportionally lower probability of passing within the outer Imbrium rim. Finally, accepting all extensions that pass within the outer Imbrium rim is a generous assumption because, as will be seen below, the four original group extensions actually pass within the inner Imbrium rim. It is, therefore, concluded that the observed radial alignments of anomalies on the lunar near side with Imbrium are statistically significant.

There is also evidence that relatively strong isolated anomalies on the southern near side tend to be aligned with anomaly groups that are elongated radial to Imbrium. Figure 8 is a plot similar to that of Figure 7 but with its southern boundary at 65°S. The contour interval is 0.5 nT starting at 0.5 nT. Because of the cylindrical projection, lines extending radially outward from Imbrium are not straight except at low latitudes. At this scale, it is therefore necessary to calculate great circle paths to investigate whether isolated anomalies lie along such lines. This is done by first selecting "end points" in a given anomaly group. Specifically, end points selected for the Airy group are at 23°S, 6°E and at 8°S, 2°W. End points selected for the Eastern group are at 15°S, 53°E and at 4.5°S, 40.5°E. End points selected for the Rima Sirsalis group are chosen at 12°S, 58°W and at 4°S, 55.5°W. End points for the Reiner Gamma group are chosen at 7°N, 60°W and at 11°N, 55°W. It is then straightforward to calculate the great circle path (e.g., Kos and Brčić, 2011; Lenart, 2011) and evaluate whether it passes near the center of Imbrium or near other mapped anomalies. As seen in the figure, these calculations first confirm that the low-latitude anomalies of Figure 7 are oriented approximately radially outward from Imbrium on the spherical surface defined by the mapping altitude. Also, the great circle path determined for the Eastern anomaly group curves northward to pass through the Abel anomaly located at 33°S, 88°E (~5.2 basin radii from the center of Imbrium). As seen in the southeastern corner of the map, a relatively strong but unnamed anomaly group is present near 45°S, 66°E (~4.9 basin radii from the center of Imbrium). Choosing end points at this location and at the Descartes anomaly (11°S,





Figure 9. As in Figures 5 and 8 but with great circle paths extended to the Imbrium antipode zone (large dashed circle). The solid black circle approximates the Imbrium main rim; the inner dashed circle approximates the inner rim as interpreted by Neumann et al. (2015; see their Figure S9).

16.5°E), the corresponding great circle path also passes near the center of Imbrium. These two anomalies are therefore also aligned approximately radial to Imbrium. Finally, the unnamed anomaly group at 45°S, 66°E is extended radially outward from Imbrium along the great circle path. It, therefore, represents a fifth elongated anomaly group on the southern near side that is aligned radial to Imbrium.

The probability of a chance occurrence of isolated anomalies along great circle paths that pass through elongated anomaly groups oriented approximately radial to Imbrium was investigated using a Monte Carlo method (Figures S5 of the Supporting Information Materials). As discussed above based on Figures 7 and 8, five such elongated anomaly groups can be defined. Five isolated strong anomalies (amplitudes > 3.5 nT) are also identified on the southern near side as shown schematically in Figure S5a. Three of these (Descartes, Abel, and Hartwig) lie very near great circle paths passing through end points of the elongated groups (the Reiner Gamma group, the Eastern group, and the unnamed group centered at 45° S, 66° E). These great circle paths also pass within the inner rim of Imbrium (dashed semi-circle in Figure S5a). The remaining two strong anomalies (an unnamed anomaly at about 62° S, 335° E and a double-peaked unnamed anomaly at about 38° S, 4° E) do not lie along such great circle paths.

To estimate the probability that three of five strong anomalies would by chance lie near such great circle paths, the locations of the five elongated groups were held fixed while the longitudes of the five isolated strong anomalies were varied at random within the limits of the study area (dashed red lines in Figure S5a). A large number (5,000) of cases was considered with the latitudes of the strong anomalies held fixed and the longitudes chosen at random. The number of isolated strong anomalies that were located within a specified distance (e.g., 5° of longitude) of any of the five great circle paths was determined in each case. Figure S5b shows an example of a case in which two of the five isolated anomalies were located by chance within 5° of one of the great circle paths. This happened about 27% of the time. However, when three of the five anomalies were required to lie within this distance of any of the five great circle paths, the probability of a chance occurrence decreased to 5.6%. If the acceptable distance was reduced to 4° of longitude, the probability of this happening by chance was reduced further to about 3%. The alignments shown in Figure 8 are therefore considered to imply a statistically significant physical relationship of the Hartwig, Descartes, and Abel anomalies to Imbrium.

Great circle paths that pass near the center of Imbrium must necessarily pass near the Imbrium antipode. Figure 9 confirms that this is the case by plotting them on the map of Figure 5. The five paths passing through elongated anomalies oriented radial to Imbrium on the southern near side intersect in the Imbrium antipode zone where the strongest group of anomalies is found.





Figure 10. As in Figure 6 but for the region from 180°W to 0°W. The contour interval is 0.5 nT starting at 1.0 nT. The solid black and dashed circles approximate the Orientale main and inner rims, respectively (see Figure S7 of Neumann et al., 2015). Great circle paths passing through pairs of anomalies northwest of Orientale that also pass within the Orientale inner rim are shown.

4.2. Orientale

A careful examination of Figures 5 and 6 also suggests the possibility that a group of anomalies northwest of Orientale could be associated with this basin, which is the youngest on the Moon. Figure 10 is a more detailed map of the western hemisphere with a contour interval of 0.5 nT starting at 1 nT. Nine anomalies with mapped amplitudes > 2 nT are located north and northwest of the basin. Much stronger anomalies are found west and west-northwest of the basin but these could be associated with the Serenitatis and Crisium antipode groups. Six of these nine anomalies are visible on the Tsunakawa et al. (2015) map of Figure S2. None of the nine anomalies is clearly elongated radial to Orientale as was the case for four groups of anomalies south of Imbrium. However, as shown in Figure 10, each of the nine anomalies lies along a great circle path that passes through at least one other anomaly and within the inner rim of Orientale (dashed circle).

To estimate the probability that the alignments of great circle paths in Figure 10 could have occurred by chance, Monte Carlo experiments were designed as illustrated in Figure S6 of the Supporting Information Materials. Figure S6a shows the observed anomaly locations within the study area and plots the same great circle paths shown in Figure 10. In the simulations, the latitudes of all anomalies were held fixed while the longitudes were chosen at random within the study area (defined by dashed red lines in the figure). In each simulation, great circle paths were calculated between each anomaly and all other anomalies to test whether a given path passed within the inner Orientale rim. Figure S6b shows an example of one simulation in which only four of the nine anomalies produced qualifying great circle paths. After conducting 3,000 such simulations, it was found that all nine anomalies with random locations produced qualifying great circle paths by chance about 3.5% of the time. The alignments shown in Figure 10 are therefore considered to imply a statistically significant physical relationship of the nine anomalies to Orientale. However, if only eight of the nine anomalies are required to produce such great circle paths, the likelihood of a chance occurrence increases to about 17%. So formal statistical significance is sensitive to whether all nine anomalies produce qualifying great circle paths.



5. Summary and Discussion

As described in Section 2, a new approach has been applied to produce a large-scale map of the lunar crustal magnetic field. It consists of improved data selection tailored to specific regions followed by altitude normalization using an ESD technique. The approach made use of high-quality, low-altitude magnetometer data from two complementary polar orbiting missions, LP and SELENE (Kaguya). The resulting maps (Figures 5–9) resolve more details of weaker anomalies than previous maps and provide an alternate determination of the relative amplitudes of anomalies around the Moon. It was found, for example, that the strongest group of anomalies on the Moon is on the south-central far side, located on the northwest side of the SPA basin approximately antipodal to the relatively young Imbrium basin. Three other anomaly groups are antipodal to young large basins: Serenitatis, Crisium, and Orientale. The antipodal concentrations of anomalies have been recognized since the earliest large-scale mapping was done using the electron reflection technique (Lin et al., 1988; Mitchell et al., 2008).

As shown in Section 4, examinations of mapped anomalies on the southern near side and eastern far side suggest physical associations with the Imbrium and Orientale impact basins, the two youngest large lunar basins (Figures 7–10). Strong as well as weaker anomalies tend to lie along lines oriented radial to Imbrium. Five anomaly groups are also elongated radial to Imbrium; Monte Carlo simulations support a statistically significant relationship of these anomalies to Imbrium. Included are the five named anomalies on the near side: Reiner Gamma, Hartwig, Descartes, Abel, and Airy. A fifth unnamed anomaly group centered at 45°S, 66°E lies along the same radial line as the Descartes anomaly and is elongated parallel to this line. As shown in Figure 9, great circle paths passing through these nearside anomalies converge within the inner rim of Imbrium and intersect in the Imbrium antipode zone where a cluster of unusually strong anomalies is found.

On the basis of these results, it is suggested that the Imbrium impact played a role in the origin of many of the strongest magnetic anomalies on the Moon. Notable exceptions include anomalies that lie internal to impact basin rims (e.g., the Crisium anomalies in Figure 7) and are associated with the formation of those basins. A more detailed treatment of internal basin anomalies is the subject of a companion paper (Hood, Oliveira et al., 2021).

Several hypotheses for the origin of anomalies aligned radial to an impact basin are possible. First, the Imbrium impact may have produced radial fractures that led to later magmatic intrusions that are the anomaly sources. The Rima Sirsalis anomaly, for example, lies near an extensional graben that probably resulted from lithospheric stresses related to the formation of Imbrium. A dike-like source could therefore be suggested (Srnka et al., 1979). Volcanic sources of lunar anomalies are difficult to exclude on the basis of sample data alone. While lunar volcanic basalt samples typically contain only ~0.08 wt% of metallic iron, it has been proposed that subsolidus reduction of basaltic lavas containing ilmenite (FeTiO₃) could produce more than 1 wt% of metallic iron in slowly cooled magmatic bodies (Hemingway & Tikoo, 2018). However, detailed mapping of the Rima Sirsalis anomaly showed that it is offset from the graben and is centered over a smooth plains unit that is interpreted as impact basin ejecta, probably from Imbrium (Hood et al., 2001). Also, while the Rima Sirsalis anomaly is located only a few basin radii from the center of Imbrium, many of the radially aligned anomalies identified here (e.g., Abel) are located at distances of thousands of km from the basin. A tectonic-related origin for these anomalies involving magmatic intrusions is less plausible.

Second, ejecta from the Imbrium impact may have been enriched in iron from the impactor and was deposited in groups that tended to align radial to the basin. Some support for this hypothesis comes from numerical simulations of lunar basin formation via the impact of iron-rich planetesimals reported by Wieczorek et al. (2012). These simulations, which used a CTH shock physics code in three dimensions with self-gravity, were for the special case of the SPA basin-forming impact. However, simulations for smaller basins such as Imbrium should give qualitatively similar results although the details may be different. These simulations showed that for oblique impacts (>50° from the vertical), most of the iron-enriched melt was deposited inhomogeneously downrange of the basin interior. Several simulations showed alignments of iron-enriched ejecta deposits radial to the basin center. For example, the simulated impact at 15 km/s of a 100 km radius differentiated projectile with a 55 km radius iron core onto the Moon at an impact angle of 60° from the vertical produced two iron-enriched ejecta deposits aligned radial to the basin and located 5–7 basin radii

from the impact point (see Figure S3c of their Supporting Information Materials). Also, a similar simulation at 45° from the vertical produced a wider distribution of external deposits with radial alignments away from the downrange direction (see their Figure S3b). The inhomogeneous mixture of impactor iron into some ejecta deposits but not others demonstrated in these simulations provides an explanation for why some great circle paths and not others show anomalies aligned radial to Imbrium.

The nearside anomalies that are aligned radial to Imbrium are widely distributed on the southern side of the basin but a majority are on the southeastern side. If these anomalies have an Imbrium ejecta-related origin, then the impact that produced Imbrium may have been oblique with a trajectory from northwest to southeast. The Reiner Gamma, Hartwig, and Rima Sirsalis anomaly sources would then represent a minority of materials ejected to one side nearly perpendicular to the impactor trajectory. The Imbrium impact ejecta interpretation is consistent with previous interpretations of the Descartes anomaly, which correlates with a higher-albedo region in the Descartes mountains near the Apollo 16 landing site (Hood et al., 2013; Richmond et al., 2003). Lunar impact melt breccias are composed of welded-together material from basin-forming impacts. They contain \sim 1–2 wt% of macroscopic metallic iron that was derived from the cores of differentiated planetesimals that impacted the Moon, producing basins such as Imbrium (Korotev, 1987; 2000).

Accepting the iron-enriched ejecta explanation for the radially aligned nearside anomalies, it follows that the cluster of strong anomalies in the Imbrium antipode zone is probably a consequence of convergence of such ejecta at the antipode. The antipodal zones of several lunar basins contain unusual hilly and lineated terrain that correlates with the occurrence of magnetic anomalies (e.g., the walls of the Ingenii basin at the Imbrium antipode; Hood et al., 2013; Richmond et al., 2005). The origin of the unusual terrain continues to be debated but impacts of converging ejecta and secondaries in these regions may have played an important role. Similar unusual terrain is found antipodal to the Caloris basin on Mercury (e.g., Murray et al., 1974; Strom & Sprague, 2003). Antipodal effects of impact basin ejecta convergence have been supported by ballistic calculations on a spherical Moon (Moore et al., 1974) and by 3D impact simulations by N. Artemieva (Hood & Artemieva, 2008). The latter simulations indicated that antipodal ejecta convergence is favored for impact angles that are at least moderately oblique (i.e., nonvertical). Enhanced magnetic fields due to converging ionized vapor in the antipodal zones of basin-forming impacts have also been proposed to have played a role in producing stronger magnetizations in basin antipode zones (Hood & Artemieva, 2008). However, such fields would have been short-lived (Oran et al., 2020) and impactor iron enrichment of the ejecta in these zones could equally explain the observed strong anomalies without any ambient field amplification.

If most of the strong nearside anomalies have sources consisting of iron-enriched Imbrium basin ejecta, then the Imbrium impactor must have been unusually enriched in iron. In part, this could be because the impactor was larger and differentiated with a metallic core. In contrast, the younger but smaller Orientale impact apparently produced fewer and weaker anomalies including at its antipode where anomalies are only about half as strong as near the Imbrium antipode. As discussed near the end of Section 4 in relation to Figure 10, there is some apparently statistically significant evidence for alignments of nine anomalies northwest of Orientale along great circle paths that converge within the inner rim of this basin. In this regard, it is important to note a study of the distribution of lunar light plains northwest of the Orientale basin by Meyer et al. (2016). It was found that the light plains are distributed partly along lines radial to Orientale, implying an Orientale-related origin. A southeast to northwest trajectory of the Orientale impactor would be consistent with both the magnetic anomaly mapping and the light plains distribution. Light plains such as the Cayley Formation are products of "fluidized" ejecta flows following basin-forming impacts and are strong candidates as sources of lunar magnetic anomalies (Halekas et al., 2001; Strangway et al., 1973). The weak anomalies mapped here do not obviously correlate with the locations of the light plains mapped by Meyer et al. (2016). However, this is not unexpected based on the numerical results of Wieczorek et al. (2012), which indicate that impactor iron is very inhomogeneously mixed into ejecta. Finally, although the Reiner Gamma and Hartwig anomalies are also aligned approximately radial to Orientale (Figure 10), no other strong anomalies are aligned radial to this basin while many others are aligned radial to Imbrium. An Imbrium-related origin for these two anomaly sources is therefore favored but an Orientale-related origin cannot be absolutely excluded.

A problem related to the origin of lunar magnetic anomalies is the origin of curvilinear albedo markings ("swirls") that are associated with most but not all strong anomalies (Hood, Coleman, & Wilhelms, 1979;

Hood, Coleman, Russell et al., 1979; Hood & Williams, 1989). An especially unusual pattern of swirls is associated with the elongated Reiner Gamma anomaly group, for example. One likely process involved in producing these albedo markings is magnetic deflection of the solar wind ion bombardment, which plays a role in darkening freshly exposed surface materials with time (e.g., Hood & Schubert, 1980). Other processes involving strong crustal fields may also have been involved in swirl formation, for example, "refreshing" of albedos via deposition of secondary crater ejecta containing iron whose trajectories may have been altered by the magnetic fields. A detailed discussion is beyond the scope of this paper. However, future work should consider whether radial alignments with impact basins can be found not only with the magnetic anomalies considered here but also with the broader mapping of lunar swirls across the Moon (e.g., Denevi et al., 2016).

Finally, these results emphasize further the value for understanding lunar crustal magnetism of fully realistic 3D impact simulations that track the fate of impactor-added iron in impact melt and ejecta such as those performed by Wieczorek et al. (2012). Similar simulations should be conducted for Imbrium-sized and smaller lunar basin formation and for the formation of Caloris-sized basins on Mercury with its stronger gravity field.

Data Availability Statement

Lunar Prospector calibrated magnetometer data are available from the Planetary Plasma Interactions (PPI) node of the NASA Planetary Data System (https://pds-ppi.igpp.ucla.edu). Kaguya (SELENE) vector magnetometer data are available from the Japan Aerospace Exploration Agency (JAXA) at http://darts.isas.jaxa. jp/planet/pdap/selene. The shaded relief maps with Lunar Orbiter Laser Altimeter data superposed used in the construction of several figures are available from the U.S. Geological Survey in Flagstaff, Arizona (https://astrogeology.usgs.gov). A digital version of the large-scale field map at 30 km altitude shown in Figures 5, 6, and 9, including the three vector field components as well as the field magnitude, is available for download from the Planetary Plasma Interactions node of the NASA Planetary Data System at UCLA (Hood, Torres et al., 2020; https://doi.org/10.17189/1520494).

Acknowledgments

This study was supported at the University of Arizona by Grant no.80NSS-C18K1602 from the NASA Lunar Data Analysis Program. The authors thank two anonymous reviewers and the associate editor for valuable criticisms that led to improvements in both the analysis and the written description. In addition, the first author thanks Dr. Robert Grimm for an early suggestion in December 2019 to calculate great circle paths to evaluate radial alignments of anomalies with Imbrium. Thanks also to Jeff Andrews-Hanna for improving the locations of the main and inner Imbrium rims depicted in Figure 9.

References

- Denevi, B. W., Robinson, M. S., Boyd, A. K., Blewett, D. T., & Klima, R. L. (2016). The distribution and extent of lunar swirls. *Icarus*, 273, 53–67. https://doi.org/10.1016/j.icarus.2016.01.017
- Garrick-Bethell, I., & Kelley, M. R. (2019). Reiner Gamma: A magnetized elliptical disk on the Moon. *Geophysical Research Letters*, 46, 5065–5074. https://doi.org/10.1029/2019GL082427
- Garrick-Bethell, I., Weiss, B. P., Shuster, D. L., & Buz, J. (2009). Early lunar magnetism. Science, 323(5912), 356–359. https://doi.org/10.1126/science.1166804
- Goossens, S., Mazarico, E., Ishihara, Y., Archinal, B., & Gaddis, L. (2020). Improving the geometry of Kaguya extended mission data through refined orbit determination using laser altimetry. *Icarus*, *336*, 113454. https://doi.org/10.1016/j.icarus.2019.113454
- Halekas, J. S., Lin, R. P., & Mitchell, D. L. (2003). Magnetic fields of lunar multi-ring impact basins. *Meteoritics & Planetary Sciences*, 38(4), 565–578. https://doi.org/10.1111/j.1945-5100.2003.tb00027.x
- Halekas, J. S., Mitchell, D. L., Lin, R. P., Frey, S., Hood, L. L., Acuña, M. H., & Binder, A. B. (2001). Mapping of crustal magnetic anomalies on the lunar near side by the Lunar Prospector electron reflectometer. *Journal of Geophysical Research*, *106*(E11), 841–927. https://doi. org/10.1029/2000JE001380
- Hemingway, D. J., & Tikoo, S. M. (2018). Lunar swirl morphology constrains the geometry, magnetization, and origins of lunar magnetic anomalies. Journal of Geophysical Research: Planets, 123(8), 2223–2241. https://doi.org/10.1029/2018JE005604
- Hood, L. L. (1980), Bulk magnetization properties of the Fra Mauro and Reiner Gamma Formations. In N. W. Hinners (Ed.), *Proceedings* of the 11th Lunar and Planetary Science Conference (pp. 1879–1896). Houston, TX: Pergamon Press, Inc.
- Hood, L. L. (2011). Central magnetic anomalies of Nectarian-aged lunar impact basins: Probable evidence for an early core dynamo. *Icarus*, 211(2), 1109–1128. https://doi.org/10.1016/j.icarus.2010.08.012
- Hood, L. L. (2015). Initial mapping of Mercury's crustal magnetic field: Relationship to the Caloris impact basin. Geophysical Research Letters, 42(24), 10565–10572. https://doi.org/10.1002/2015GL066451
- Hood, L. L. (2016). Magnetic anomalies concentrated near and within Mercury's impact basins: Early mapping and interpretation. Journal of Geophysical Research: Planets, 121(6), 1016–1025. https://doi.org/10.1002/2016JE005048
- Hood, L. L., & Artemieva, N. A. (2008). Antipodal effects of lunar basin-forming impacts: Initial 3D simulations and comparisons with observations. *Icarus*, 197(2), 485–502. https://doi.org/10.1016/j.icarus.2007.08.023
- Hood, L. L., Coleman, P. J., Jr, Russell, C. T., & Wilhelms, D. E. (1979). Lunar magnetic anomalies detected by the Apollo subsatellite magnetometers. *Physics of the Earth and Planetary Interiors*, 20(2-4), 291–311. https://doi.org/10.1016/0031-9201(79)90052-9
- Hood, L. L., Coleman, P. J. Jr, & Wilhelms, D. E. (1979). Lunar nearside magnetic anomalies. In N. W. Hinners (Ed.), *Proceedings of the 10th Lunar and Planetary Science Conference* (pp. 2235–2257). Houston, TX: Pergamon Press, Inc.



- Hood, L. L., Herbert, F., & Sonett, C. P. (1982). The deep lunar electrical conductivity profile: Structural and thermal inferences. Journal of Geophysical Research, 87, 5311–5326. https://doi.org/10.1029/JB087iB07p05311
- Hood, L. L., Oliveira, J. S., Andrews-Hanna, J., Wieczorek, M. A., & Stewart, S. (2021), Magnetic anomalies in five lunar impact basins: Implications for impactor trajectories and inverse modeling. *Journal of Geophysical Research: Planets*, e2020JE006668. https://doi. org/10.1029/2020JE006668
- Hood, L. L., Oliveira, J. S., Galluzzi, V., & Rothery, D. A. (2018). Investigating sources of Mercury's crustal magnetic field: Further mapping of MESSENGER magnetometer data. Journal of Geophysical Research: Planets, 123, 2647–2666. https://doi.org/10.1029/2018JE005683
- Hood, L. L., Richmond, N. C., & Spudis, P. D. (2013). Origin of strong lunar magnetic anomalies: Further mapping and examinations of LROC imagery in regions antipodal to young large impact basins. *Journal of Geophysical Research: Planets*, 118, 1265–1284. https://doi. org/10.1002/jgre.20078
- Hood, L. L., & Schubert, G. (1980). Lunar magnetic anomalies and surface optical properties. *Science*, 208(4439), 49–51. https://doi. org/10.1126/science.208.4439.49
- Hood, L. L., & Spudis, P. D. (2016). Magnetic anomalies in the Imbrium and Schrödinger impact basins: Orbital evidence for persistence of the lunar core dynamo into the Imbrian epoch. *Journal of Geophysical Research: Planets*, 121(11), 2268–2281. https://doi. org/10.1002/2016JE005166
- Hood, L. L., Torres, C. B., Oliveira, J. S., Wieczorek, M. A., & Stewart, S. T. (2020). Lunar crustal magnetic field mapNASA Planetary Data System. https://doi.org/10.17189/1520494
- Hood, L. L., & Williams, C. R. (1989). The lunar swirls–Distribution and possible origins. In Proceedings of the 19th Lunar and Planetary Science Conference (Vol. 19, 99–113). Houston, TX: Lunar and Planetary Institute.
- Hood, L. L., Zakharian, A., Halekas, J., Mitchell, D., Lin, R., Acuña, M., & Binder, A. (2001). Initial mapping and interpretation of lunar crustal magnetic anomalies using Lunar Prospector magnetometer data. *Journal of Geophysical Research*, 106(E11), 825–827. https://doi. org/10.1029/2000JE001366
- Johnson, C. L., Phillips, R. J., Purucker, M. E., Anderson, B. J., Byrne, P. K., Denevi, B. W., et al. (2015). Low-altitude magnetic field measurements by MESSENGER reveal Mercury's ancient crustal field. *Science*, 348(6237), 892–895.
- Korotev, R. L. (1987). The meteorite component of Apollo 16 noritic impact melt breccias. *Journal of Geophysical Research*, 92(B4), E491–E512. https://doi.org/10.1029/JB092iB04p0E491
- Korotev, R. L. (2000). The great lunar hot spot and the composition and origin of the Apollo mafic ("LKFM") impact-melt breccias. Journal of Geophysical Research, 105(E2), 4317–4345. https://doi.org/10.1029/1999JE001063
- Kos, S., & Brčić, D. (2011). Approximation models of orthodromic navigation. In A. Weintrit, & T. Neumann (Eds.), Methods and algorithms in navigation: Marine navigation and safety of sea transportation (pp. 133–140). Leiden, The Netherlands: CRC Press/Balkema.
- Lenart, A. S. (2011). Solutions of direct geodetic problem in navigational applications. In A. Weintrit, & T. Neumann (Eds.), *Methods and algorithms in navigation: Marine navigation and safety of sea transportation* (pp. 141–146). Leiden, The Netherlands: CRC Press/Balkema.
- Lin, R. P., Anderson, K. A., & Hood, L. L. (1988). Lunar surface magnetic field concentrations antipodal to young large impact basins. *Icarus*, 74(3), 529–541. https://doi.org/10.1016/0019-1035(88)90119-4
- Lin, R. P., Mitchell, D., Curtis, D., Anderson, K., Carlson, C., McFadden, J., et al. (1998). Lunar surface magnetic fields and their interaction with the solar wind: Results from Lunar Prospector. *Science*, 281(5382), 1480–1484. https://doi.org/10.1126/science.281.5382.1480 Mayhew, M. A. (1979). Inversion of satellite magnetic anomaly data. *Geophysical Journal*, 45, 119–128.
- Meyer, H. M., Denevi, B. W., Boyd, A. K., & Robinson, M. S. (2016). The distribution and origin of lunar light plains around Orientale basin. *Icarus*, 273, 135–145. http://doi.org/10.1016/j.icarus.2016.02.014
- Mitchell, D. L., Halekas, J. S., Lin, R. P., Frey, S., Hood, L. L., Acuña, M. H., & Binder, A. (2008). Global mapping of lunar crustal magnetic fields by Lunar Prospector. *Icarus*, 194(2), 401–409. https://doi.org/10.1016/j.icarus.2007.10.027
- Moore, H. J., Hodges, C., & Scott, D. (1974), Multi-ringed basins Illustrated by Orientale and associated features. In N. W. Hinners (Ed.), Proceedings of the 5th Lunar and Planetary Science Conference (pp. 71–100). Houston, TX: Pergamon Press, Inc.
- Murray, B. C., Belton, M. J. S., Danielson, G. E., Davies, M. E., Gault, D., Hapke, B., et al. (1974). Preliminary description and interpretation from Mariner 10 pictures. *Science*, 185(4146), 169–179. https://doi.org/10.1126/science.185.4146.169
- Oliveira, J. S., Wieczorek, M. A., & Kletetschka, G. (2017). Iron abundances in lunar impact basin melt sheets from orbital magnetic field data. Journal of Geophysical Research: Planets, 122(2), 2429–2444. https://doi.org/10.1002/2016JE005199
- Oran, R., Weiss, B. P., Shprits, Y., Miljkovic, K., & Tóth, G. (2020), Was the moon magnetized by impact plasmas? *Science Advances*, 6(40), eabb1475. https://doi.org/10.1126/sciadv.abb1475
- Purucker, M. E., Head, J. W., III, & Wilson, L. (2012). Magnetic signature of the lunar South Pole-Aitken basin: Character, origin, and age. Journal of Geophysical Research, 117, E05001. https://doi.org/10.1029/2011JE003922
- Purucker, M. E., & Nicholas, J. B. (2010). Global spherical harmonic models of the internal magnetic field of the Moon based on sequential and coestimation approaches. *Journal of Geophysical Research*, 115, E12007. https://doi.org/10.1029/2010JE003650
- Ravat, D., Purucker, M. E., & Olsen, N. (2020). Lunar magnetic field models from Lunar Prospector and SELENE/Kaguya along-track magnetic field gradients. *Journal of Geophysical Research: Planets*, 125, e2019JE006187. https://doi.org/10.1029/2019JE006187
- Richmond, N. C., & Hood, L. L. (2008). A preliminary global map of the vector lunar crustal magnetic field based on Lunar Prospector magnetometer data. Journal of Geophysical Research, 113, E02010. https://doi.org/10.1029/2007JE002933
- Richmond, N. C., Hood, L. L., Halekas, J. S., Mitchell, D. L., Lin, R. P., Acuña, M., & Binder, A. B. (2003). Correlation of a strong lunar magnetic anomaly with a high-albedo region of the Descartes mountains. *Geophysical Research Letters*, 30(7), 1395. https://doi. org/10.1029/2003GL016938
- Richmond, N. C., Hood, L. L., Mitchell, D. L., Lin, R. P., Acuña, M. H., & Binder, A. B. (2005). Correlations between magnetic anomalies and surface geology antipodal to lunar impact basins. *Journal of Geophysical Research*, 110, E05011. https://doi.org/10.1029/2005JE002405 Scheinberg, A. L., Soderlund, K. M., & Elkins-Tanton, L. T. (2018). A basal magma ocean dynamo to explain the early lunar magnetic field.
- Earth and Planetary Science Letters, 492, 144–151. https://doi.org/10.1016/j.epsl.2018.04.015 Shea, E. K., Weiss, B. P., Cassata, W. S., Shuster, D. L., Tikoo, S. M., Gattacceca, J., et al. (2012). A long-lived lunar core dynamo. *Science*, 335(6067), 453–456. https://doi.org/10.1126/science.1215359
- Smith, D. E., Zuber, M. T., Neumann, G. A., Lemoine, F. G., Mazarico, E., Torrence, M. H., et al. (2010). Initial observations from the Lunar Orbiter Laser Altimeter (LOLA). *Geophysical Research Letters*, 37(18), L18204. https://doi.org/10.1029/2010GL043751
- Srnka, L. J., Hoyt, J. L., Harvey, J. V. S., & McCoy, J. E. (1979). A study of the Rima Sirsalis magnetic anomaly. Physics of the Earth and Planetary Interiors, 20(2-4), 281–290. https://doi.org/10.1016/0031-9201(79)90051-7

Strangway, D. W., Sharpe, H., Gose, W., & Pearce, G. (1973). Lunar magnetic anomalies and the Cayley Formation. Nature, 246, 112–114.



Strom, R. G., & Sprague, A. L. (2003). Exploring Mercury: The iron planet (p. 216). New York, NY: Springer.

- Suavet, C., Weiss, B. P., Cassata, W. S., Shuster, D. L., Gattacceca, J., Garrick-Bethell, I., et al. (2013). Persistence and origin of the lunar core dynamo. Proceedings of the National Academy of Science, 110(21), 8453–8458.
- Tikoo, S. M., Weiss, B. P., Cassata, W. S., Shuster, D. L., Gattacceca, J., Lima, E. A., et al. (2014). Decline of the lunar core dynamo. *Earth and Planetary Science Letters*, 404, 89–97. https://doi.org/10.1016/j.epsl.2014.07.010
- Tsunakawa, H., Takahashi, F., Shimizu, H., Shibuya, H., & Matsushima, M. (2015). Surface vector mapping of magnetic anomalies over the Moon using Kaguya and Lunar Prospector observations. *Journal of Geophysical Research: Planets, 120*(6), 1160–1185. https://doi. org/10.1002/2014JE004785
- Tsunakawa, H., Takahashi, F., Shimizu, H., Shibuya, H., & Matsushima, M. (2014). Regional mapping of the lunar magnetic anomalies at the surface: Method and its application to strong and weak magnetic anomaly regions. *Icarus*, 228, 35–53.
- Tsunakawa, H., Shibuya, H., Takahashi, F., Shimizu, H., Matsushima, M., Matsuoka, A., et al. (2010). Lunar magnetic field observation and in situ global mapping of lunar magnetic anomalies by MAP-LMAG onboard SELENE (Kaguya). *Space Science Reviews*, *154*, 219–251. https://doi.org/10.1007/s11214-010-9652-0
- Tsunakawa, H., Takahashi, F., Shimizu, H., Shibuya, H., & Matsushima, M. (2015). Surface vector mapping of magnetic anomalies over the Moon using Kaguya and Lunar Prospector observations. *Journal of Geophysical Research: Planets*, 120(6), 1160–1185. https://doi. org/10.1002/2014JE004785
- von Frese, R. R. B., Hinze, W. J., & Braile, L. W. (1981). Spherical Earth gravity and magnetic anomaly analysis by equivalent point source inversion. *Earth and Planetary Science Letters*, 53(1), 69–83. https://doi.org/10.1016/0012-821X(81)90027-3
- Weiss, B. P., & Tikoo, S. (2014). The lunar dynamo. Science, 346(6214), 1198-1209. https://doi.org/10.1126/science.1246753
- Wieczorek, M. A., Weiss, B. P., & Stewart, S. T. (2012). An impactor origin for lunar magnetic anomalies. *Science*, 335(6073), 1212–1215. https://doi.org/10.1126/science.1214773