

## Note

# Surveying the South Pole–Aitken basin magnetic anomaly for remnant impactor metallic iron



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## ABSTRACT

The Moon has areas of magnetized crust (“magnetic anomalies”), the origins of which are poorly constrained. A magnetic anomaly near the northern rim of South Pole–Aitken (SPA) basin was recently postulated to originate from remnant metallic iron emplaced by the SPA basin-forming impactor. Here, we remotely examine the regolith of this SPA magnetic anomaly with a combination of Clementine and Lunar Prospector derived iron maps for any evidence of enhanced metallic iron content. We find that these data sets do not definitively detect the hypothesized remnant metallic iron within the upper tens of centimeters of the lunar regolith.

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## 1. Introduction

For several decades studies have shown that portions of the lunar crust are strongly magnetized relative to their surroundings (e.g., Dyal et al., 1974; Hood et al., 2001; Mitchell et al., 2008; Purucker et al., 2012; Purucker and Nicholas, 2010); yet the source and process by which these regions became magnetized is yet to be fully understood. Magnetization in these regions has been attributed to a variety of mechanisms, including plasma processes related to impact of a cometary coma, magnetized basin ejecta, and magmatic intrusions or dike swarms magnetized by an early core dynamo. Difficulties discerning a source for these anomalies begin with the absence of unique associated geologic structures. Impact basins, impact basin ejecta, and basin antipodes are associated with some of the magnetic anomalies (Richmond, 2005), but most of these show weak magnetization relative to the globally observed dynamic range. Further, there are many of these same structures that are not associated with magnetic anomalies. In fact, the only consistent feature always associated with a magnetic anomaly are the unusual albedo marking known as lunar swirls (Blewett et al., 2011).

It is difficult to reconcile the strengths of many of these anomalies with lunar samples, as most lunar materials (i.e., silicates) are very weakly magnetic relative to terrestrial materials. Measurements of mare basalt and pristine highlands rock magnetization show that they are substantially weaker than mid-ocean ridge basalts (by 2–4 orders of magnitude) (Wang et al., 2005). An additional complication is that the lithologies that comprise lunar magnetic anomalies are not rigorously constrained mineralogically. As a result, it is difficult to discern if the magnetization of materials in these anomalies is derived from crystallization or from impact shock (Fuller and Cisowski, 1987; Gattacceca, 2010).

Recently, Wieczorek et al. (2012) suggested that a unique cluster of magnetic anomalies on the southern farside of the Moon is attributable to remnant metallic

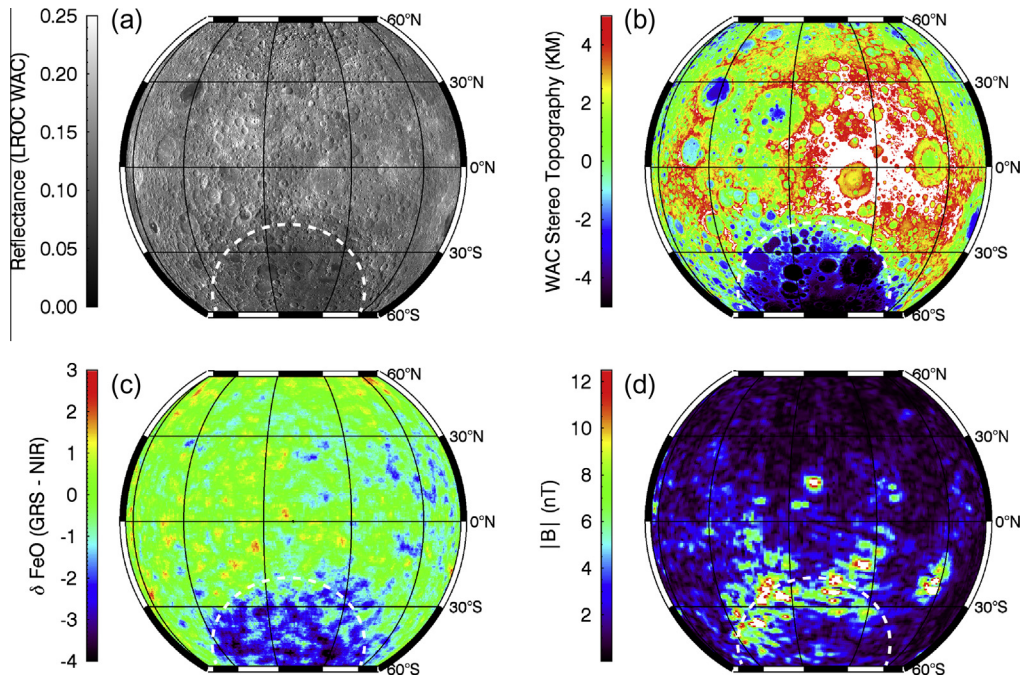
iron from the impactor that created South Pole–Aitken basin (SPA) (Fig. 1a and d; Wieczorek et al., 2012). In that study, Wieczorek et al. (2012) argued that the distribution of projectile materials roughly coincided with the distribution of magnetic anomalies near the northern rim of SPA. Wieczorek et al. (2012; Fig. 2) noted that typical chondritic projectile materials are approximately 2 times more magnetic than average lunar crustal materials. If the SPA-forming projectile were similar to an undifferentiated chondrite, then the thickness of the ejecta needed to account for the magnetism of materials north of SPA would only need to be a few hundred meters thick. The thickness would be substantially less if the projectile were differentiated into core, mantle, and crustal components. Despite the apparent validity of the dynamic modeling and reasoning this study provided, the authors did not present strong evidence that “excess” metallic iron is present in the SPA rim materials, e.g., in the form of a positive remote detection. Determining the origin of the magnetic anomalies is important for understanding the lunar surface and subsurface crust and its evolution. Therefore, we evaluate this hypothesis by determining if an excess of metallic iron can be detected and discriminated from other measurements of iron derived from remote data sets.

## 2. Data and methods

The abundance of meteoritic metal in lunar materials is relatively well known from Apollo samples and generally considered to be relatively small (Morris, 1980). Sample studies by Morris (1980) report ~0.2 wt.% submicroscopic metallic iron for lunar regolith and soils, while Korotev's (1987, 2000) analysis of Apollo impact melts, likely from the Imbrium impact event, found ~1 to 2 wt.% macroscopic metallic iron. However, the impactor that formed SPA would likely have been ~10 times as massive as that which formed Imbrium (Wieczorek et al., 2012). Given that chondritic materials contain a few tens of wt.% metallic iron, it is likely that any remnant SPA impactor materials in the regolith would be more substantial relative to Imbrium impact melts and very plausibly detectable by orbital remote sensing if found within the upper tens of centimeters of the regolith (~detection limits of gamma-ray spectroscopy). In the context of near infrared (NIR) reflectance spectroscopy, the presence of metallic iron is difficult to quantify for several reasons.

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**Fig. 1.** Observations of the lunar farside via (a) LROC WAC monochrome, (b) LRO GLD100 topography (Scholten et al., 2012), (c)  $\delta\text{FeO}$ , and (d) Lunar Prospector total field magnetic data of Purucker and Nicholas (2010). SPA boundary is denoted by white dotted line. Areas colored white in (b) are  $>5$  km.

In general, metallic iron is relatively featureless in the NIR, with no prominent absorption features that could reveal its presence in a surficial mixture (Cahill et al., 2012; Cloutis et al., 1990, 2010). Furthermore, metallic iron is one of the mineral species, along with ilmenite, unlikely to be directly accounted for in Clementine spectral reflectance (CSR) NIR iron-determination methods due to the positioning of the wavelength bands employed by these algorithms (i.e., 750 and 950 nm; Blewett et al., 1997; Fischer and Pieters, 1994; Lawrence et al., 2002; Le Mouélic et al., 2000; Lucey et al., 1998, 2000, 1995; Wilcox et al., 2005).

To demonstrate how spectral reflectance varies with metallic iron abundance we performed a test with radiative transfer theory (Hapke, 1993, 2001, 2012; Lucey and Riner, 2011) using the optical constants of orthopyroxene (Trang et al., 2013), metallic iron (Cahill et al., 2012), and plagioclase (Lucey, 2002), respectively. The spectrum of a noritic anorthosite assemblage (75 vol.% plagioclase; 25 vol.% orthopyroxene; Mg' of 75) was modeled and then the assemblage was modified in two ways. In the first test, macroscopic metallic iron was added to the assemblage in 0.5 vol.% increments. Fig. 2a shows that the addition of this macroscopic metallic iron causes little change in an assemblage's absolute spectral reflectance or absorption feature characteristics. This test also shows, in Fig. 2b, that while the total wt.% of FeO increases substantially, the total FeO measured by the spectral reflectance algorithm of Lawrence et al. (2002) increases by a negligible amount ( $\sim 0.04$  wt.%).

Despite the fact that macroscopic metallic iron has little to no absorption features in the visible–NIR and is relatively undetectable with CSR algorithms, metallic iron has a substantial influence by reddening and darkening spectra in ways that are dependent upon particle size (Lucey and Riner, 2011). Therefore, we performed a second test in which all metallic iron was integrated into the assemblage as microphase and nanophase particles residing within glassy coatings of minerals or adhering to the mineral surfaces as patinas. Here, we applied the model detailed by Lucey and Riner (2011) combining both Mie and Maxwell–Garrett theory to account for both microphase ( $<1$   $\mu\text{m}$ ) and nanophase ( $<100$  nm) particles within an intimate mineral mixture, respectively. As noted by Lucey and Riner (2011), in the NIR any particle larger than  $1$   $\mu\text{m}$  will darken, but not redden (i.e., macrophase particles); particles smaller than  $100$  nm will redden and darken (i.e., nanophase particles). For sizes between  $100$  nm and  $1$   $\mu\text{m}$ , the specific behavior is strongly dependent on the particle size distribution (i.e., microphase particles). This test assumed a 1:2 ratio of nanophase to microphase metallic iron particles, consistent with the work of Morris (1980) for lunar regolith. The results of this test show additional complications associated with the sensitivity of NIR spectral algorithms to the contribution of metallic iron. Fig. 2c shows that proportionally small increases of nanophase and microphase iron particles ( $<0.25$  wt.%) will redden and darken the spectrum to the point that the absorption feature of orthopyroxene in this assemblage is greatly attenuated. The spectral effects are far more substantial than those caused by greater amounts of macroscopic iron (Fig. 2a). This test also shows that FeO as determined from spectral reflectance is increasingly underestimated even though the algorithm is devised to mitigate the effects of maturity on estimates of total FeO (Fig. 2d).

These results suggest that CSR methods for determining FeO are likely to underestimate the metallic iron budget in the lunar regolith. In contrast, gamma-ray spectroscopy (GRS) is useful for absolute determination of iron content, although GRS is unable to differentiate the mineral species in which the iron resides. Here we exploit a combination of NIR and GRS in an attempt to detect the possible presence of metallic iron. While CSR-derived FeO abundances show reasonable agreement with the Lunar Prospector (LP) Gamma-ray Spectrometer-derived FeO abundances, important differences (as much as  $\pm 6$  wt.%) remain for various locales on the Moon (Fig. 1c) (Lawrence et al., 2002). In some cases, these discrepancies are large enough that differing interpretations regarding surface composition and history are possible. Here we examine differences between CSR- and GRS-determined iron content to evaluate whether metallic iron could be an important constituent in the magnetic anomalies circumferential to SPA.

### 3. Results and discussion

An initial global analysis was performed by examining CSR relative to LP-GRS data for a set of magnetic anomalies. For the purposes of this study, we analyzed magnetic anomalies with total field strength of  $4$  nT and greater as determined from the maps of Purucker and Nicholas (2010). This threshold, while somewhat arbitrary, effectively discriminates between regions previously classified as magnetically anomalous and areas that are magnetically non-unique. The CSR FeO map was resampled to the spatial resolution (2 pixels/degree) of the LP-GRS FeO map, smoothed for a realistic statistical comparison (Maurice et al., 2004), and a residual map,  $\delta\text{FeO} = (\text{FeO}_{\text{GRS}} - \text{FeO}_{\text{CSR}})$ , was derived. The expectation is that the presence of metallic iron should be detected with GRS data, but not with CSR algorithms. At a minimum, CSR algorithms would underestimate FeO relative to GRS, if iron is dominantly present only in macroscopic form. Thus, excess metallic iron should produce a positive  $\delta\text{FeO}$ . If unusual amounts of metallic iron are not present,  $\delta\text{FeO}$  should be zero, or negative if mineralogical factors that lead to overestimation of iron are present. As explained by Lawrence et al. (2002), CSR algorithms are calibrated to returned lunar soils which have an over abundance of clinopyroxene relative to orthopyroxene. The spectral characteristics of orthopyroxene relative to the wavelength position of the bands used in the algorithm are such that FeO will be overestimated for surfaces containing abundant orthopyroxene. However, the magnetic anomaly dominantly does not coexist with orthopyroxene-rich regions, with localized exceptions around the northern and southwestern rims of the basin (Fig. 1).

Globally, we find that magnetic anomalies over the surface of the Moon show CSR FeO values that are higher by  $0.65$  wt.% compared with GRS FeO. Overall statistics for this initial global analysis are presented in Fig. 3a. Some areas where CSR overestimates FeO include SPA, Mare Tranquilitatis, Mare Humorum, as well as other smaller regionals. As mentioned before, pyroxene mineralogy is likely to have contributed toward the higher abundance determined by CSR. Areas in which GRS overestimates FeO relative to CSR include Mare Frigoris, and numerous localized regions in central Oceanus Procellarum.

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