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How magnetic field direction influences lunar swirl morphology

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The bright lobes and dark lanes of lunar swirls are associated with horizontal and vertical magnetic field lines, respectively

1. Introduction

Swirls are sinuous patterns of anomalously high albedo and distinct spectral characteristics that accompany many of the Moon's crustal magnetic anomalies [1–4]. Swirls are found in diverse locations across the lunar surface and vary in scale with some spanning more than 100 kilometers. Understanding these unique natural laboratories, where space weathering and magnetism intersect, may help shed light on important questions in lunar science including the Moon's dynamo history [5,6] and the distribution of water over its surface [4].

One model for swirl formation suggests that crustal magnetic fields act as mini magnetospheres, protecting localized portions of the surface from the optical maturation (darkening) effects of solar wind ion bombardment [7]. In this model, incoming solar wind ions are magnetically deflected by the Lorentz force, $\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$, leaving portions of the surface relatively free from the darkening effects of the solar wind. The cross product in the Lorentz law means the deflection force should be maximized where the magnetic field is perpendicular to the incoming solar wind and minimized where field lines are parallel to the solar wind. Since darkening will be most pronounced near solar noon, this translates roughly to horizontal and vertical fields, respectively.

Here, we test this prediction using maps we derive [8] from Lunar Prospector 3-axis magnetometer measurements and Clementine 750 nm reflectance maps. We focus on two anomalies, Reiner Gamma and Airy, which exhibit distinct magnetization directions [9,10]. We also use simple dipole moment models to estimate how the fields might appear at lower altitudes.

Our results confirm the predicted relationship between reflectance and magnetic field direction, lending strong support to the solar wind deflection model and offering a potential explanation not only for the general form of the swirls but also for the frequently observed, intra-swirl, dark lanes.

2. Results at Reiner Gamma

At Reiner Gamma, the rock magnetization is dominantly horizontal and north-pointing [9,10] such that field lines are south-pointing at the spacecraft altitude over the anomaly (Figure 1a). While a map of total magnetic field strength (Figure 1b) fails to match the form of the albedo anomaly, a map of the horizontal component alone (Figure 1c) shows that high horizontal field strength corresponds well with the brightest portions of the surface. We have noted similar correspondences at other swirls, as have others [11]. More quantitatively, Figure 2 illustrates that as field strength increases (indicated by the transition from cooler to warmer colours), magnetic field direction becomes increasingly important in determining surface reflectance.

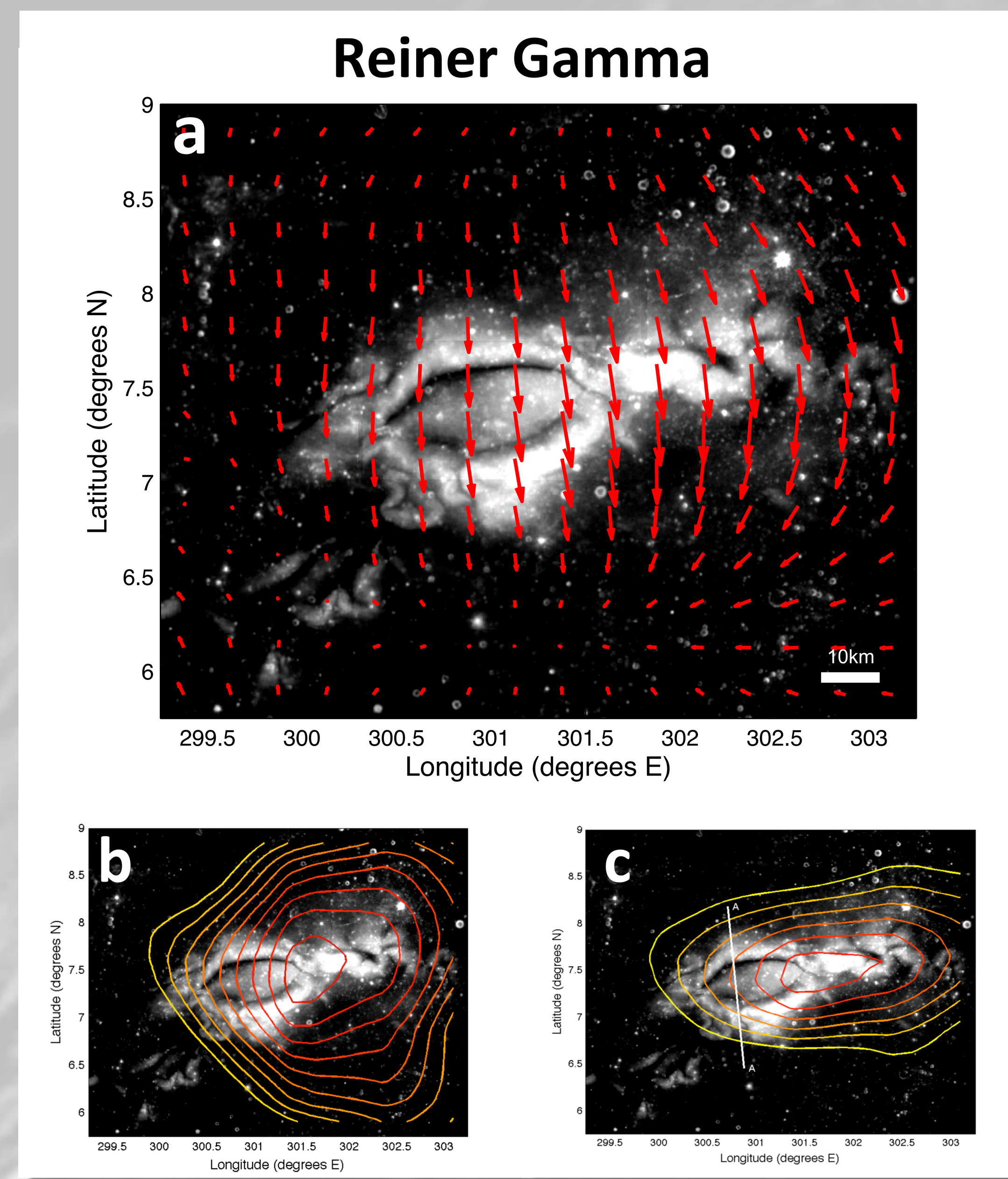

Figure 1: Magnetic field maps derived from Lunar Prospector data over Clementine 750 nm reflectance maps at the Reiner Gamma anomaly. Panel (a) shows the direction of field lines at the spacecraft altitude (36 km) with arrow lengths showing relative horizontal field strength. Panel (b) shows contours of the total magnetic field strength (min contour: 5 nT; contour interval: 1 nT). Panel (c) shows contours of the horizontal component alone (min contour: 5 nT; contour interval: 1.5 nT). The transect labeled AA is for use with Figure 5.

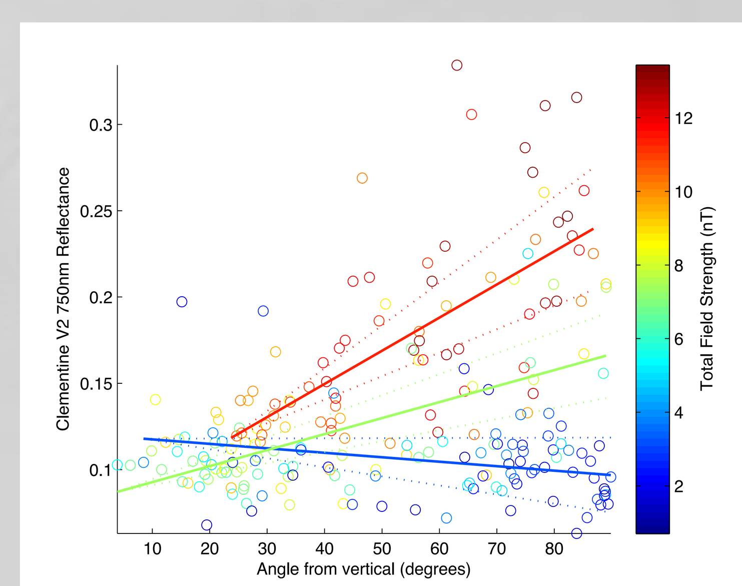

Figure 2: Correlation between magnetic field direction and reflectance at Reiner Gamma. 'Angle from vertical' is 90º where field lines are horizontal. Data points are colour-coded by total field strength and lines are fitted for the weakest third (blue), middle third (green), and strongest third (red) of the data points, with dotted lines showing 95% slope confidence intervals.

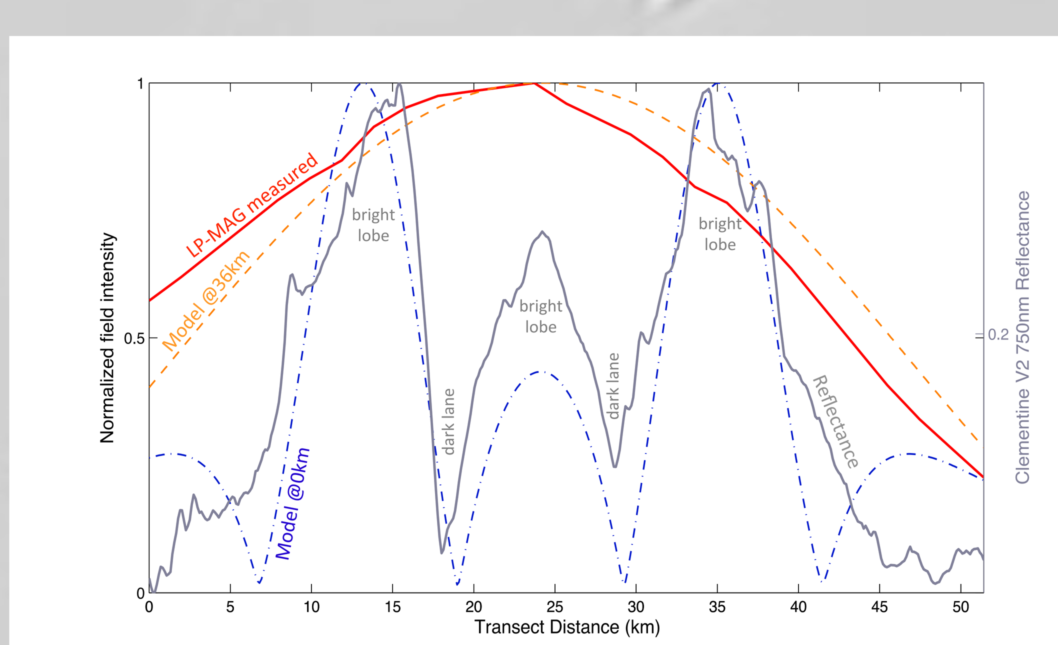

Figure 5: Profiles of normalized horizontal magnetic field intensity (left axis) and reflectance (right axis) along the transect labeled AA in Figure 1c. Red line: the horizontal field as measured by the Lunar Prospector magnetometer at the spacecraft altitude. Grey line: Clementine 750 nm reflectance. The dashed lines represent the horizontal field predicted at the spacecraft altitude (orange) and at the surface (blue) based on a model of two north-pointing dipoles buried beneath the 13 km and 35 km points along the transect.

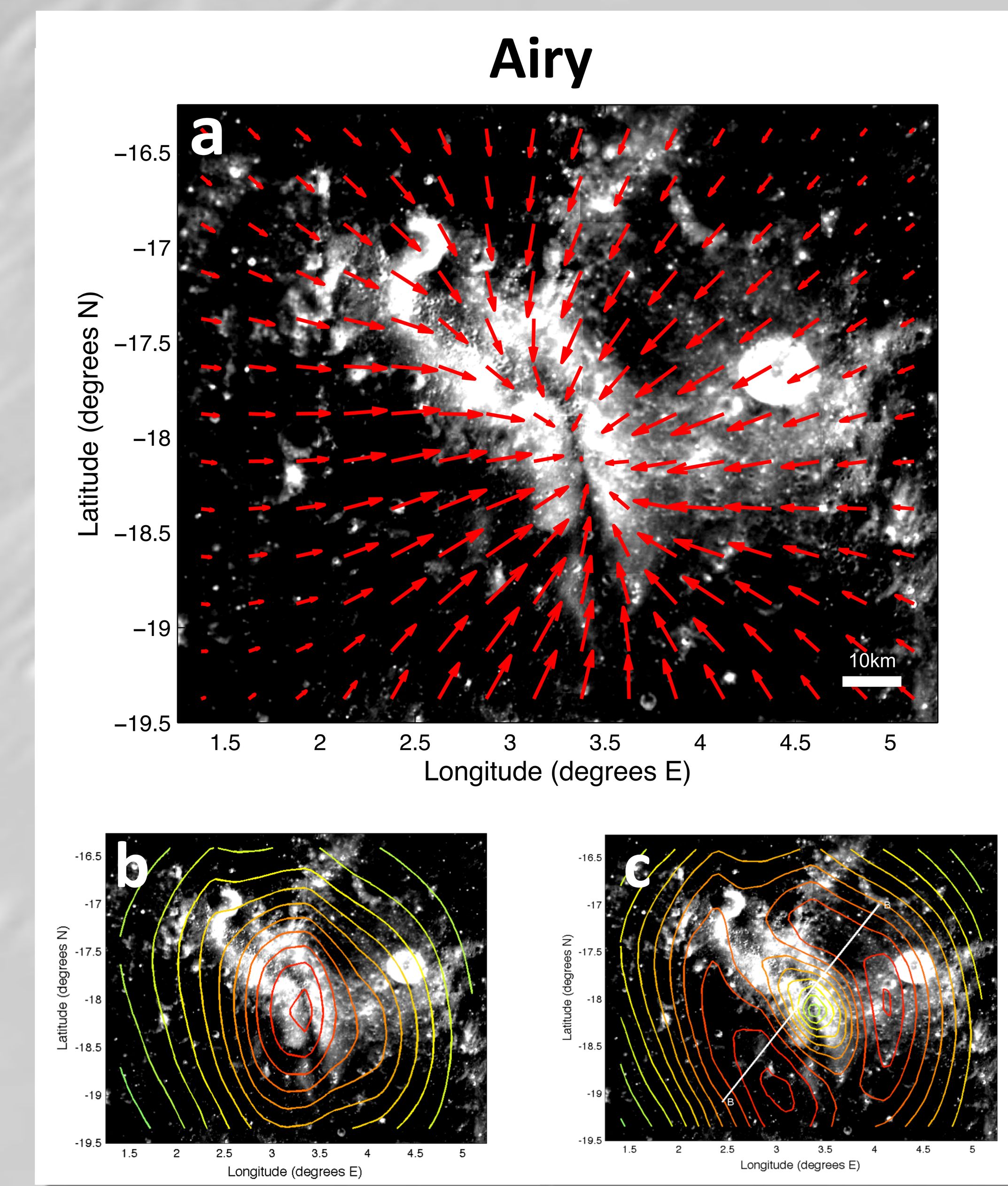

Figure 3: Magnetic field maps derived from Lunar Prospector data over Clementine 750 nm reflectance maps at the Airy anomaly. Panel (a) shows the direction of field lines at the spacecraft altitude (28 km) with arrow lengths showing relative horizontal field strength. Panel (b) shows contours of the total magnetic field strength (contour interval: 1 nT). Panel (c) shows contours of the horizontal component alone (contour interval: 0.5 nT). The transect labeled BB is for use with Figure 6.

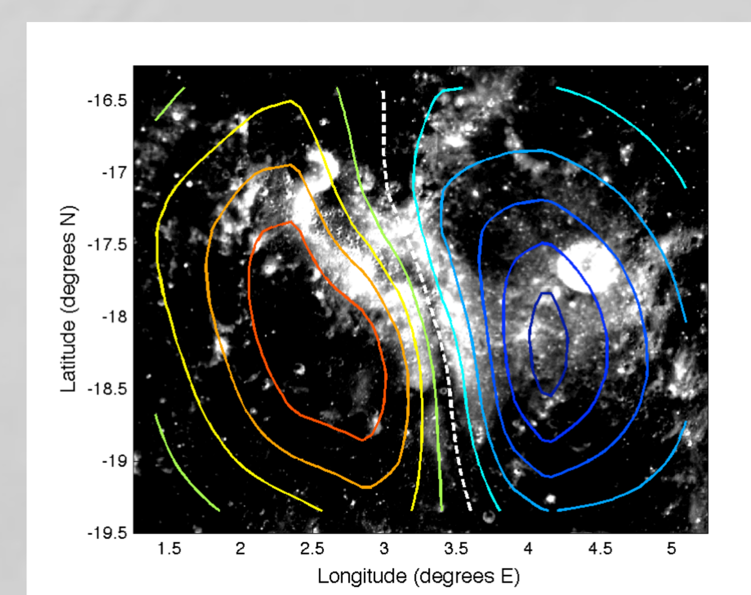

Figure 4: East-west component of magnetic field (measured by Lunar Prospector) over Clementine 750 nm reflectance map at Airy (contour interval: 1 nT). Contour line colours indicate magnitude of eastward field strength, with warm colours indicating east-pointing fields and cool colours indicating west-pointing fields. The dashed white line indicates zero field strength in the east-west direction.

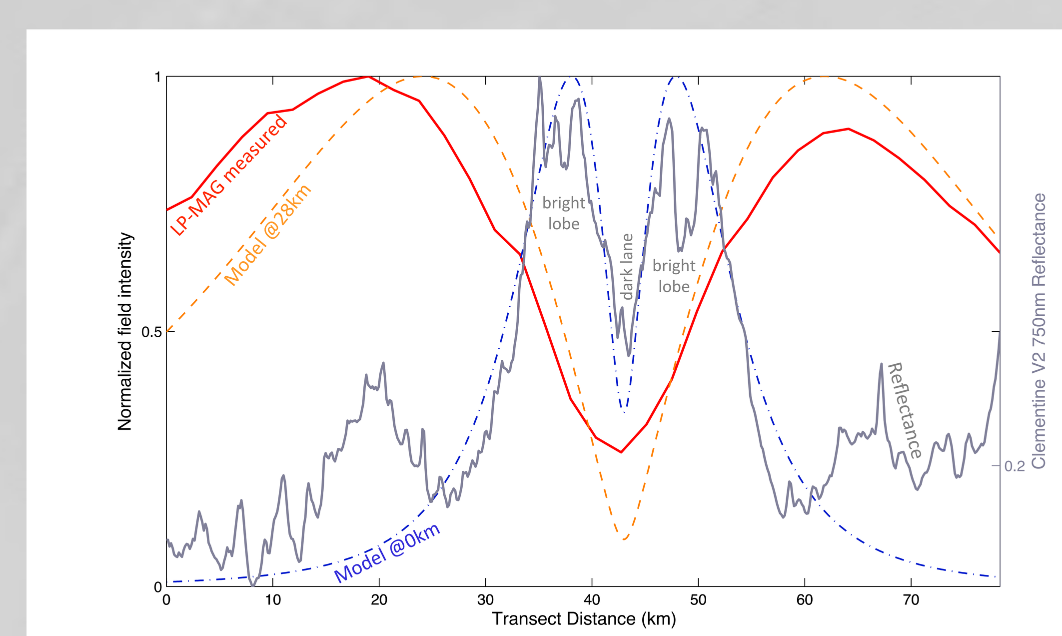

Figure 6: Profiles of normalized horizontal magnetic field intensity (left axis) and reflectance (right axis) along the transect labeled BB in Figure 3c. Red line: the horizontal field as measured by the Lunar Prospector magnetometer at the spacecraft altitude. Grey line: Clementine 750 nm reflectance. The dashed lines represent the horizontal field predicted at the spacecraft altitude (orange) and at the surface (blue) based on a model of a single downward-pointing dipole beneath the 43 km point along the transect.

3. Results at Airy

At Airy, the rock magnetization points mainly downward [10] such that magnetic field lines at the spacecraft altitude tend to point inward and then downward toward the centre of the anomaly (Figure 3a). As with Reiner Gamma, a map of the horizontal magnetic field (Figure 3c) shows potentially relevant structure not seen in a map of the total field (Figure 3b). The relationship between the form of the albedo anomaly and the horizontal magnetic field is most strikingly revealed in a map of the east-west component of the magnetic field (Figure 4). Here, the dark lane through the centre of the anomaly shows exceptional alignment with the line representing zero east-west magnetic field strength (dashed white line). Near solar noon (when darkening effects should be most intense), solar wind ions falling along this line would experience little deflection, leaving them to concentrate along the line itself.

4. Discussion

These two examples appear to be illustrating distinct aspects of the solar wind deflection phenomenon: whereas the Reiner Gamma example demonstrates that swirls are brightest where magnetic field lines are horizontal, the Airy case shows that dark lanes can be associated with vertical magnetic field lines. However, a look at magnetic field direction closer to the surface reveals that both effects can be observed at each of the two anomalies. Despite the single, broad lobe in the horizontal magnetic field profile at Reiner Gamma (red line in Figure 5), and the wide spacing between the two lobes in the horizontal field profile at Airy (red line in Figure 6), there may be finer structure and closer spacing, respectively, that would be apparent in lower altitude measurements. Based on models, with magnetic sources approximated by buried dipoles, Figures 5 and 6 show that, despite the appearance at spacecraft altitudes (orange dashed lines), if magnetic field measurements could be taken at sufficiently low altitudes (blue dashed lines), the positions of the bright lobes and dark lanes could align closely with the peaks and valleys, respectively, in the horizontal magnetic field profiles. The low altitude measurements required to test this hypothesis could soon be possible as NASA Ames Research Center, UC Berkeley, and UC Santa Cruz are currently cooperating to develop a low-cost spacecraft mission with exactly this capability [12].

While our models for magnetization are not unique, they agree with observations and can account for the alternating bright and dark bands while making it clear why no such fine structure would be observable at the spacecraft altitude. We conclude that observations of magnetic field direction strongly support the solar wind deflection model for swirl formation. We further predict that very close to the surface, field lines will be horizontal over the brightest parts of swirls and vertical over the intra-swirl dark lanes.

References/Acknowledgements

[1] Hood and Williams, (1989) *19th LPSC*. [2] Richmond et al. (2005) *JGR 110*, E05011. [3] Garrick-Bethell et al. (2011) *Icarus 212*. [4] Kramer et al. (2011) *JGR 116*, E00G18. [5] Dwyer et al. (2011) *Nature 479*. [6] Le Bars et al. (2011) *Nature 479*. [7] Hood and Schubert (1980) *Science 208*. [8] Hood et al. (2001) *JGR 106*, E11. [9] Kurata et al. (2005) *GRL 32*. [10] Hemingway and Garrick-Bethell (2012) *JGR 117*. [11] Shibuya et al. (2010) *EPSC abstract #166*. [12] Garrick-Bethell et al. (2011) *LEAG abstract #2038*. We would like to acknowledge Lon Hood for his assistance early in our work.

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