Dust Rotation and Swirl Morphology in Lunar Magnetic Anomalies

by

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It is believed that lunar magnetic anomalies (LMAs) are an essential component to lunar swirl morphology. The influence of individual dust rotations on swirl morphology, however, has not been previously explored. Therefore, in order to test the hypothesis that these rotations might influence swirl morphology, we have simulated the rotation of magnetized lunar dust grains as they travel through a simulated LMA. We then analyze the resultant landing pattern to determine whether the orientation of the surface dust might affect the photometric properties of these lunar swirls.

Dedication

To all of the fluffy kitties.

Acknowledgements

Here's where you acknowledge folks who helped. But keep it short, i.e., no more than one page, as required by the Grad School Specifications.

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Chapter 1

Introduction

Lunar swirls are one of the most enigmatic features on the lunar regolith. They are identified by their sinuous albedo patterns and high reflectivity of visible and near infrared radiation [1]. The Reiner Gamma swirl (RG) is the largest known swirl of its type and has a unique tadpole formation spanning 100 km across Oceanus Procellarum [1]. Like all lunar swirls, RG is accompanied by a relatively strong lunar magnetic anomaly (LMA) [4].

The origin of LMAs is a controversial topic.

The origin and geometries of these LMA fields are not well understood, but their surface strength is believed to be on the order of thousands of nanoTeslas (nT) [**?**], while orbital data taken $30km$ above the surface has measured fields on the order of $10nT$ [4]. Understanding swirl morphology can inform us of the unique surface characteristics of many airless bodies. Presently, there are two main theories concerning the formation of lunar swirls, the solar wind standoff model and the dust lofting model, neither of which sufficiently explains all of the observed phenomenon associated with lunar swirls [3][4].

In order to consider the efficacy of these competing theories, it is first important to understand the space weathering process that darkens the lunar surface material. The two leading theories concerning the process of space weathering are both dependent on the formation of submicroscopic metallic iron (SMFe). First are the effects of solar wind sputtering, in which the solar wind will saturate the lunar surface with hydrogen ions, leading to a physical reaction with the lunar surface to form SMFe [5]. The second process, known as the vapor deposition model, suggests that meteorite

bombardment will vaporize glass agglutinates, thereby depositing iron bearing silicate vapors on surrounding dust particles [6]. It is generally considered, however, that the most likely explanation is a combination of both effects. First, the implantation of hydrogen due to solar wind will produce an oxide coating in the lunar regolith, then this coating will produce an iron-bearing silicate vapor upon a collision event. This vapor will then be deposited on the surrounding dust as SMFe [6].

The solar wind standoff model therefore attempts to explain how a LMA might limit the formation of SMFe. The theory is dependent on two facotrs: (1) the influx or uncovering of optically immature subsurface dust in swirl regions, (2) the presence of a magnetic field horizontal to the lunar surface strong enough to reflect the solar wind, thereby preventing solar wind sputtering [7]. There are two main proposals as to how a swirl might have an influx or uncovering of subsurface dust. First is due to the observed proximity correlation between lunar swirls and fresh impact craters []. This suggests that these collisions may have brought fresh dust into the swirl region. Second, it has been proposed that micrometeorite bombardment might superficially scour the lunar surface, uncovering fresh dust while also contributing to the formation of the surrounding magnetic field []. The crater proposal is limited by the fact that not all swirls, asd and asdf for example, have a fresh impact crater nearby []. The micrometeorite bombardment hypothesis also has a limitation in that micrometeorite bombardment is known to produce many of the lunar regolith's agglutinates []. This, however, is inconsistent with ultraviolet reflectance observations of the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC), which found an absence of surface agglutinates in many swirl regions [8]. The most significant shortcoming of the solar wind standoff model, however, is a lack of demonstrable reflection of the solar wind by any LMA other than the one found near Reiner Gamma [9].

This suggests that any space weathering effects that might be observed in the region of lunar swirls would be due to the vapor deposition that occurs as a result of micrometeorite bombardment [7]. This is consistent with ultraviolet reflectance observations of the Reiner Gamma swirl from the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC), which found optically immature reflectance patterns around multiple lunar swirls as well as an absence of surface

agglutinates [8]. This suggests that micrometeorite bombardment, without the presence of solar radiation, might do more to excavate the lunar surface than to form glassy silicate melts [8]. This excavation might also uncover optically immature dust just below the top layer in the lunar regolith, thereby contributing to the formation of lunar swirls []. These observations do provide strong evidence for the solar wind standoff model, but the extent to which the solar wind is necessary in the soil darkening process is not well understood. The reflection of the solar wind, however, has not been sufficiently demonstrated for LMAs weaker than the one found at Reiner Gamma [9]. Therefore, the solar wind standoff model is not yet sufficient in explaining the process of swirl morphology.

The other leading theory in swirl morphology is the dust lofting model.

This invites continued exploration into all the possible contributions to their formation. It is therefore being proposed that magnetized dust grains, lofted off the lunar surface due to photoelectric emissions [10], might rotate due to the surrounding LMA, thereby producing a unique landing pattern that might affect the photometric properties of these lunar swirls. This hypothesis is motivated by the photometric properties of swirls that indicate smoother dust structures than the lunar background [11], as well as the increase of 2 wt% in the iron content of surface dust observed at the RG swirl compared to the surrounding area [12]. In order to test this hypothesis, we have developed a simulation that models the rotation of "needle-like" particles as they travel through a simulated lunar dipole field that has been compressed by the solar wind [13].

Bibliography

[1] Brett W Denevi, Mark S Robinson, Aaron K Boyd, David T Blewett, and Rachel L Klima. The distribution and extent of lunar swirls. Icarus, 273:53–67, 2016.

[2] LL Hood and CR Williams. The lunar swirls-distribution and possible origins. In Lunar and Planetary Science Conference Proceedings, volume 19, pages 99–113, 1989.

[3] Ian Garrick-Bethell, James W Head, and Carle M Pieters. Spectral properties, magnetic fields, and dust transport at lunar swirls. Icarus, 212(2):480–492, 2011.

[4] David T Blewett, Ecaterina I Coman, B Hawke, Jeffrey J Gillis-Davis, Michael E Purucker, and Christopher G Hughes. Lunar swirls: Examining crustal magnetic anomalies and space weathering trends. Journal of Geophysical Research: Planets, 116(E2), 2011.

[5] Bruce Hapke. Darkening of silicate rock powders by solar wind sputtering. The Moon, 7(3-4):342–355, 1973.

[6] Bruce Hapke. Space weathering from mercury to the asteroid belt. Journal of Geophysical Research: Planets, 106(E5):10039–10073, 2001.

[7] Timothy D Glotch, Joshua L Bandfield, Paul G Lucey, Paul O Hayne, Benjamin T Greenhagen, Jessica A Arnold, Rebecca R Ghent, and David A Paige. Formation of lunar swirls by magnetic field standoff of the solar wind. Nature communications, 6, 2015.

[8] Brett W Denevi, Mark S Robinson, Aaron K Boyd, Hiroyuki Sato, Bruce W Hapke, and B Hawke. Characterization of space weathering from lunar reconnaissance orbiter camera ultraviolet observations of the moon. Journal of Geophysical Research: Planets, 119(5):976–997, 2014.

[9] Paul Lucey, Randy L Korotev, Jeffrey J Gillis, Larry A Taylor, David Lawrence, Bruce A Campbell, Rick Elphic, Bill Feldman, Lon L Hood, Donald Hunten, et al. Understanding the lunar surface and space-moon interactions. Reviews in Mineralogy and Geochemistry, 60(1):83–219, 2006.

[10] MM Abbas, D Tankosic, PD Craven, JF Spann, A LeClair, and EA West. Lunar dust charging by photoelectric emissions. Planetary and Space Science, 55(7):953–965, 2007.

[11] V Kaydash, M Kreslavsky, Yu Shkuratov, S Gerasimenko, P Pinet, J-L Josset, S Beauvivre, B Foing, et al. Photometric anomalies of the lunar surface studied with smart-1 amie data. Icarus, 202(2):393–413, 2009.

[12] Patrick C Pinet, Vladislav V Shevchenko, Serge D Chevrel, Yves Daydou, and Christine Rosemberg. Local and regional lunar regolith characteristics at reiner gamma formation: Optical and spectroscopic properties from clementine and earth-based data. Journal of Geophysical Research: Planets, 105(E4):9457–9475, 2000.

[13] Jan Deca, Andrey Divin, Bertrand Lembège, Mihály Horányi, Stefano Markidis, and Giovanni Lapenta. General mechanism and dynamics of the solar wind interaction with lunar magnetic anomalies from 3-d particle-in-cell simulations. Journal of Geophysical Research: Space Physics, 120(8):6443–6463, 2015.

Appendix A

Weird Exam Answers

About appendices: Each appendix follow the same page-numbering rules as a regular chapter; the first page of a (multi-page) appendix is not numbered. By the way, the following are supposedly authentic answers to English GCSE exams!

(1) The Greeks were a highly sculptured people, and without them we wouldnt have history. The Greeks also had myths. A myth is a female moth.

(2) Actually, Homer was not written by Homer but by another man of that name.

(3) Socrates was a famous Greek teacher who went around giving people advice. They killed him. Socrates died from an overdose of wedlock. After his death, his career suffered a dramatic decline.

(4) Julius Caesar extinguished himself on the battlefields of Gaul. The Ides of March murdered him because they thought he was going to be made king. Dying, he gasped out: Tee hee, Brutus.

(5) Nero was a cruel tyranny who would torture his subjects by playing the fiddle to them.

(6) In midevil times most people were alliterate. The greatest writer of the futile ages was Chaucer, who wrote many poems and verses and also wrote literature.

(7) Another story was William Tell, who shot an arrow through an apple while standing on his sons head.

(8) Writing at the same time as Shakespeare was Miguel Cervantes. He wrote Donkey Hote. The next great author was John Milton. Milton wrote Paradise Lost. Then his wife died and he wrote Paradise Regained.

(9) During the Renaissance America began. Christopher Columbus was a great navigator who discovered America while cursing about the Atlantic. His ships were called the Nina, the Pinta, and the Santa Fe.

(10) Gravity was invented by Issac Walton. It is chiefly noticeable in the autumn when the apples are falling off the trees.

(11) Johann Bach wrote a great many musical compositions and had a large number of children. In between he practiced on an old spinster which he kept up in his attic. Bach died from 1750 to the present. Bach was the most famous composer in the world and so was Handel. Handel was half German half Italian and half English. He was very large.

(12) Soon the Constitution of the United States was adopted to secure domestic hostility. Under the constitution the people enjoyed the right to keep bare arms.

(13) The sun never set on the British Empire because the British Empire is In the East and the sun sets in the West.

(14) Louis Pasteur discovered a cure for rabbis. Charles Darwin was a naturalist who wrote the Organ of the Species. Madman Curie discovered radio. And Karl Marx became one of the Marx brothers.

Appendix B

Ode to Spot

(Data, Stardate 1403827) (A one-page chapter — page must be numbered!) Throughout the ages, from Keats to Giorchamo, poets have composed "odes" to individuals who have had a profound effect upon their lives. In keeping with that tradition I have written my next poem . . . in honor of my cat. I call it. . . Ode. . . to Spot. (Shot of Geordi and Worf in audience, looking mystified at each other.)

> Felus cattus, is your taxonomic nomenclature
> an endothermic quadruped, carnivorous by nature?
> Your visual, olfactory, and auditory senses
> contribute to your hunting skills, and natural defenses.
> I find myself intrigued by your sub-vocal oscillations,
> a singular development of cat communications
> that obviates your basic hedonistic predilection
> for a rhythmic stroking of your fur to demonstrate affection.
> A tail is quite essential for your acrobatic talents;
> you would not be so agile if you lacked its counterbalance.
> And when not being utilized to aid in locomotion,
> It often serves to illustrate the state of your emotion.

(Commander Riker begins to applaud, until a glance from Counselor Troi brings him to a halt.) Commander Riker, you have anticipated my denouement. However, the sentiment is appreciated. I will continue.

> O Spot, the complex levels of behavior you display
> connote a fairly well-developed cognitive array.
> And though you are not sentient, Spot, and do not comprehend
> I nonetheless consider you a true and valued friend.