Modeling Multi-Species Lunar Swirls in a Dusty Plasma Medium. C. Carmichael, M. Cook, Graeson Griffin, Parker Adamson, Lorin Matthews, and T. W. Hyde, Center for Astrophysics, Space Physics and Engineering Research, One Bear Place #97283, Baylor University, Waco, TX, 76798-7283, USA.

Introduction: Lunar swirls are high albedo sweeping patterns spread across the lunar surface. Swirls are located near or on magnetic anomalies varying in length from 1-5 kilometers [1,3]. The formation of lunar swirls has been intensely studied, although a single theory to date has not been dubbed as a catalyst. The primary viable theories which have been proposed include Cometary Impact, Dust Transport, or Dust Shielding. This work examines swirl formation assuming dust transport model. In this framework, solar winds charge dust grains on the lunar surface. The subsequent interaction between the lunar magnetic field and these charged grains can cause the regolith to be sorted, preferentially accumulating into the swirl patterns observed on the lunar surface [2,4].

In this work, the viability of the dust transport model is tested by creating lunar swirl patterns experimentally by mimicking the lunar environment in a Gaseous Electronics Conference Radiofrequency Cell [5]. Additionally, the characterization of charged dust dynamics in a magnetic field is an avenue for establishing dust mitigation techniques which are essential for upcoming lunar missions.

Method: Recent research suggests the geometry of the underlying magnetic sources for the formation of lunar swirls must be constrained within certain limits: the anomaly source depth cannot be greater than the transition length L (figure 1), the width of the swirl can never exceed twice this transition length and the sources of the magnetization must be both narrow and shallow to produce a swirl. These conditions are implied from necessary rock magnetizations, the origin of the lunar rock's natural remnant magnetization, and the sinuous morphology of lunar swirl complexes [3].

The above implies the source of such surface magnetic anomalies could be caused by dikes or lava tubes [3]. In this research, magnetic anomalies were simulated using shallow dipole magnets, arranged in a similar manner to known swirl patterns. The majority of magnet holders used to produce those formations were produced using Art of Illusion 3D modeling software and printed employing an Ender 3 3D printer in accordance with the previously listed geometric constraints. The 3D printer uses PLA plastic, which when exposed to high temperatures can melt. However, sample formations were exposed to a plasma produced at 20 Watts for 2 minutes and no defects were observed. The remaining plates used were milled Teflon plates made in accordance with the required geometric constraints.

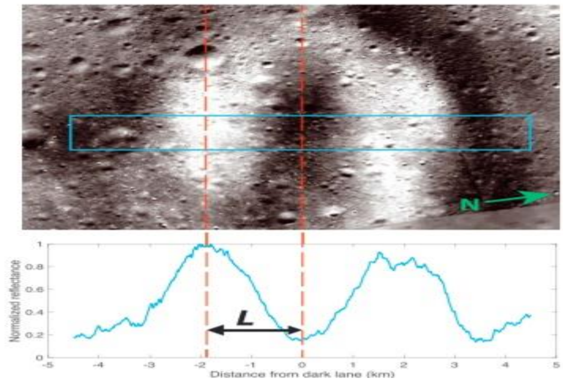

Figure 1: The transition length L is the distance between the highest and lowest measured albedo point for each swirl. Constraints imposed by this research [2] dictated the dimensions of the magnet formations.

Using a GEC RF Cell (see figure 2), an Argon plasma was produced employing a RF source. Experiments were performed at 5-25 Watts, for pressures ranging from 20-120 mTorr. Laser fans or backlights were used to illuminate the regolith simulant particles depending on reflectivity of the grains [5]. Regolith simulants used included: JSC-1 (100 microns), Lunar Mare (63 microns), & Lunar Highland (90 microns), with varying mean radii particle sizes and mineral compositions.

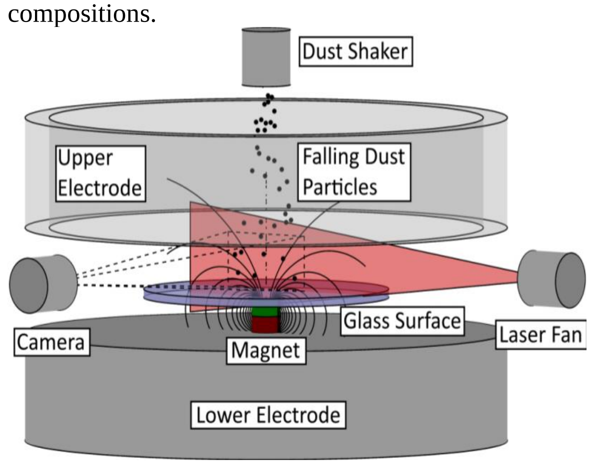

Figure 2: Inner chamber of the GEC RF Cell [2].

Dust particles dropped through the argon plasma accumulated charge. The charged falling dust grains were tracked using a HX50 camera. The resulting data allowed the accelerations of the dust grains to be calculated with their forces determined from the parameters of the plasma. The accelerations and velocities of the falling dust particles were plotted (figure 3) using data from a particle tracker in MOSAIC.

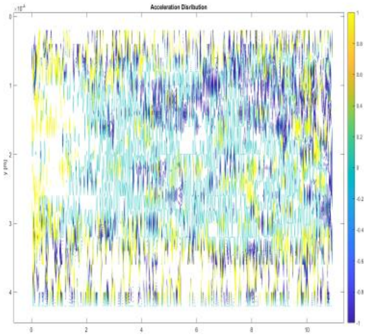

Figure 3: Areas of highest and lowest acceleration for dust particles dropped as defined in text. The particles travel from left to right.

Equation 1 shows the possible forces involved for these dust particles.

$$\mathbf{F^g} + \mathbf{F^b} + \mathbf{F^e} + \mathbf{F^t} + \mathbf{F^i} + \mathbf{F^n} = \mathbf{M^p a^p} \qquad (1)$$

The forces listed in equations 1-6 are, $\mathbf{F^g}$ (Gravity), $\mathbf{F^b}$ (Magnetic field force), $\mathbf{F^e}$ (electric field force), $\mathbf{F^t}$ (thermophoretic force), and the two drag forces $\mathbf{F^i}$ (ion drag), & $\mathbf{F^n}$ **(**neutral drag) and are defined as:

$\mathbf{F^g} = 4\pi r^3 \rho g/3$ (2)

r is the particle radius, ρ is the dust density, and g is the acceleration due to gravity,

$\mathbf{F^b} = q(v \times B)$ (3)

q is the charge of the dust; v is the velocity and B is the magnetic field strength,

$\mathbf{F^e} = qE$ (4)

q is the charge of the dust and E is the applied electric field. The thermophoretic force is negligible since a thermal gradient is not applied.

$\mathbf{F^i} = 3\pi r^2 k_B T_i \sigma_i$ (5)

k_B is the Boltzmann constant, T_i is the ion temperature, and σ_i is the ion density.

$\mathbf{F^n} = 4\pi r^2 N \delta m_n \sqrt{(8 k_B T_n/\pi m)}/3$ (6)

δ is determined by reflection or absorption of the neutral gas particles (1.44 for argon), N is the neutral gas density, m_n is the neutral mass of argon, T_n is the temperature of the neutrals and m is the mass of the dust.

Results: Four magnet formations were used for each of the regolith simulants tested. We note here that smaller particle sizes had an easier time forming swirl patterns compared to larger sized dusts. Interestingly, JSC-1 was the most effective simulant at forming patterns. This may be due to JSC-1 having a larger distribution of particle sizes compared to the other simulants. A reproduced "negative" of the Reiner Gamma lunar swirl is shown in figure 4. Additional formations of lunar swirls have been manufactured and are being tested to see if different shapes of lunar swirls can be reproduced. An example PLA plate constructed using an original lunar swirl pattern is shown in figure 5. Later experiments will include sideways orientation of the magnets instead of flat placement to avoid buildup of particles.

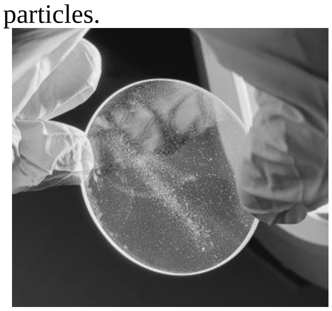

Figure 4: Swirl reproduction using JSC-1. The large line of dust is caused by the trajectory of the dust dropper across the plate.

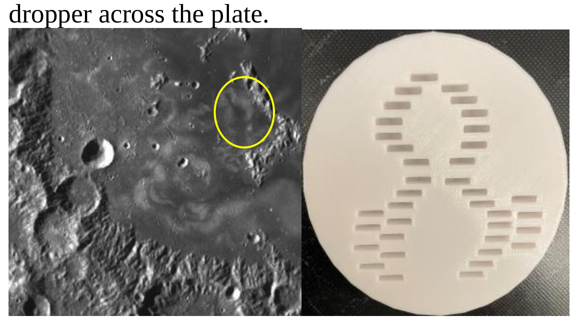

Figure 5: 3D printed plate for lunar swirl pattern shown

Conclusion: In this work, the dynamics of charged dust grains traveling in a magnetic field were investigated. These results were used to examine the reproduction of the Reiner Gamma lunar swirl and other swirl patterns. Possible measurements of lunar surface conditions while employing this technique could lead to magnetic field line extrapolation as well as establish constraints on particle charge from trajectory data. Observing the manner in which charged dust travels along magnetic field lines is a first step towards the development of advanced dust mitigation techniques in the future.

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