Dust Transport in Plasmas Interacting with Complex Magnetic Fields Close to a Non-Conductive Surface. M. Dropmann[1,2], R. Laufer[1], G. Herdrich[2,1], L. S. Matthews[1], T. W. Hyde[1], [1]Center for Astrophysics, Space Physics and Engineering Research (CASPER), Baylor University, One Bear Place 97310, Waco, TX-76798-7310, Email: Michael_Dropmann@baylor.edu, Truell_Hyde@Baylor.edu [2]Institute of Space Systems (IRS), Universität Stuttgart, Raumfahrtzentrum Baden-Württemberg, Pfaffenwaldring 29, 70569 Stuttgart, Germany.

Introduction: The interaction between magnetic fields and plasma close to a non-conductive surface has been investigated experimentally in a capacitively driven GEC RF reference cell [1]. Such interactions are believed to be responsible for the formation process of lunar swirls, bright albedo patterns found on the lunar surface, which appear to be correlated to strong crustal magnetic fields [2]. These magnetic fields, having a strength of more than 100 nT, are sufficient to magnetize the electrons in the solar wind plasma although ions remain largely unaffected. The subsequent effect on the electrons may lead to space charge regions, resulting in strong electric fields. These fields may then both alter the ion flux towards the lunar surface and direct the transport of levitating dust, providing a possible source for lunar swirls.

In this paper, an analog experiment is presented which allows study of the interaction of a magnetic field with a plasma in the laboratory using dust particles as probes. Electric forces acting on the dust particles are measured allowing the direction and strength of the electric fields in the plasma to be determined. Further, dust deposition patterns in the experiment have been analyzed to draw conclusions about the surface potential.

Method: The experiment presented here is a scaled analog experiment and exhibits similar properties to a lunar plasma environment at magnetic anomalies even though the scale of the problem has been reduced to a few centimeters. At this scale a magnetic field of up to a few 100 mT is necessary to magnetize the electrons while ions still remain unmagnetized. At a pressure of 5 Pa, electrons have a mean free path of approximately 7 mm, leading to weak cross field diffusion such as found in the lunar environment.

In previous experiments a cylindrical neodymium dipole magnet of 6.35 mm diameter and length was placed horizontally (vertically) on the lower electrode of the plasma source and covered by a glass plate of 50.8 mm diameter [3,4]. For this experiment a structure has been built to hold multiple magnets, allowing field structures which more closely resemble those found at lunar magnetic anomalies. Using Lunar Prospector magnetometer data, Hemingway and Garrick-Bethell have approximated the magnetic field structure found at the Reiner Gamma and Airy formation by multiple magnetic dipoles below the lunar surface [5]. Based on this data, a miniaturized model of the magnetic field has been developed employing neodymium dipole magnets.

During the experiment, 12 micron melamine formaldehyde (MF) particles were dropped into the plasma. The particles were illuminated using a fanned laser beam and the trajectories were recorded at 2000 fps employing a Photron CCD high speed camera. By moving the laser parallel to the camera axis, 3D maps of the forces acting on the particles were then generated. The forces measured are assumed to be primarily caused by electric fields in the plasma as the particles attain a negative charge due to electron collection. This allows the electric field strength and direction to be estimated based on assumptions for the particle charge.

Results and Discussion: The levitation height of the particles, where the upward electric force equals gravity, was determined. For the case of a vertically oriented dipole magnet, the levitation height is shown in figure 1. Given the dipole axis of the magnet is vertically oriented, the experiment exhibits rotational symmetry, as confirmed by the data. At system center, defined to be directly above the magnet, the levitation height is at maximum at 4 mm. Progressing outwards towards the edge of the glass plate the levitation height decreases to a minimum of 2 mm at a radial position of 6 mm before increasing again to a local maximum of 3 mm at a radial

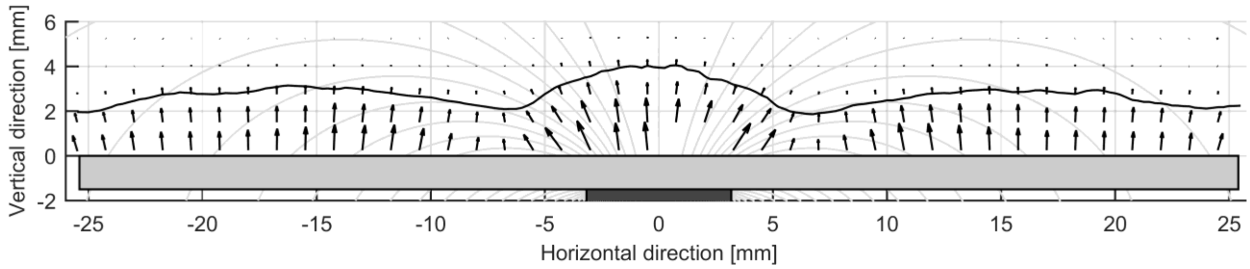

Figure 1. Levitation height (black line) and forces (arrows) acting on MF micro-particles in a plasma sheath perturbed by a vertically oriented dipole magnet. The gray lines represent the magnetic field lines, the light gray box the glass surface and the dark gray box a vertically oriented dipole magnet.

position of 15 mm. Levitated particles in the plasma exhibit damped oscillatory motion around their stable levitation point; if their horizontal velocity is small, the particles are trapped at the levitation height minima, which in the present case occur at a radial displacement of 6 mm. Once the plasma is extinguished, the particles fall back to the surface and form a circular pattern on the glass plate (figure 2) which coincides with the levitation height minima.

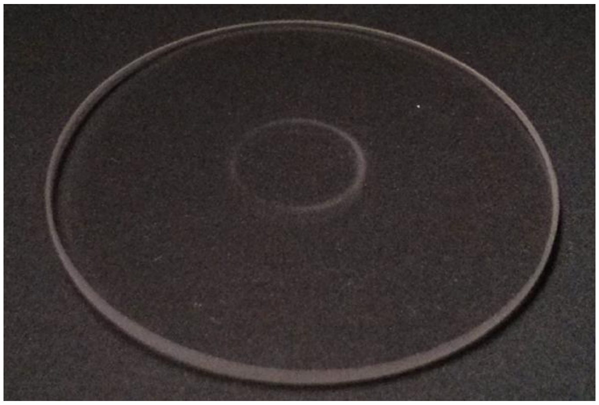

Figure 2. Ring shaped dust deposit on the glass plate after several experimental runs.

Particle levitation height is further an indicator of the surface potential as the negatively charged dust particles are repelled by a surface having a negative charge. The higher the levitation height the more negative the surface is. This indicates that the negative surface charge has a maximum at system center above the magnet. The levitation height minimum thus indicates a minimum in negative surface charge. Figure 1 shows that this minimum coincides with the position where the magnetic field lines are parallel to the surface. Given the magnetic field inhibits the cross field movement of the plasma electrons, a reduced electron flux is expected here leading to the decreased negative surface potential. These assumptions concerning the differences in surface potential are further confirmed by the direction of the horizontal force components as shown by the intrusion of the dust particles into regions of less negative surface charge. The electric forces caused by these potential differences can also have a significant effect on the ion flux towards the surface; the ion flux is decreased towards more positively charged surface sections while more negatively charged regions experience a higher flux.

Conclusions and implications for lunar swirls. Experiments have shown that a magnetic field can create significant changes to the plasma sheath close to a surface. The thickness of the sheath and resulting levitation height vary based on the direction of the magnetic field. Further, strong horizontal electric forces transport particles parallel to the surface into regions where the magnetic field lines are horizontal. It should be noted that the plasma sheath is, when compared to the size of the problem, significantly thinner in the lunar environment as compared to the experiment. Consequently the observed vertical forces are expected to be much weaker within a lunar environment. Particles trapped above regions of lesser negative surface charge, as previously mentioned, fall back to the surface when plasma conditions change and form a pattern on the surface. Similar processes in the lunar plasma environment may therefore lead to transport of bright fine-grained feldspathic dust on the moon, supporting the theory of dust transport as one possible mechanism for the creation of swirls. It should be noted however, that in the lunar environment dust may also charge positively due to the photoelectric effect, altering the direction of dust transport. The same horizontal electric forces acting on the dust will also influence the ions and thus alter the ion flux. Since ions, are directed in the opposite direction of the dust and thus reach the surface in regions where the magnetic field lines intersect with the surface, this would lead to faster surface maturation in these areas and slower maturation in shielded areas. The results presented here therefore support both the dust transport [6] and ion shielding theories [7] while also suggesting that a combination of these may provide much of the physics underlying the origin of lunar swirls.

References: [1] Olthoff J. K. and Greenberg K. E. (1995) *J. Res. Natl. Inst. Stand. Tech., 100,* 327. [2] Hood L. L. and Williams C. R. (1989) *Proc. 19th Lunar Planet. Sci. Conf.,* 99-113. [3] Dropmann M. et al. (2014), *45th LPSC,* Abstract #1742. [4] Dropmann M. et al. (2014), *56th APS-DPP,* Abstract #BO3.00005. [5] Hemingway D. and Garrick-Bethell I. (2012) *JGR, 117,* E10012. [6] Garrick-Bethell I. et al. (2010) *Icarus, 212(2),* 480-492. [7] Hood L. L. and Schubert G. (1980) *Science, 208(4439),* 49-51.