SPECTRAL AND THERMOPHYSICAL PROPERTIES OF LUNAR SWIRLS FROM THE DIVINER LUNAR RADIOMETER.
T. D. Glotch[1] and J. L. Bandfield[2], P. G. Lucey[3], P. O. Hayne[4], B. T. Greenhagen[4], J. A. Arnold[1], R. R. Ghent[5], and D. A. Paige[6] [1]Department of Geosciences, Stony Brook University, timothy.glotch@stonybrook.edu, [2]Space Science Institute, [3]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, [4]Jet Propulsion Laboratory, [5]Department of Earth Sciences, University of Toronto, [6]Department of Earth, Planetary and Space Sciences, University of California Los Angeles.

Introduction: Lunar swirls are high-albedo markings on the Moon that occur in both mare and highlands terrains in the presence of local crustal magnetic fields[1-2]. Data from the Lunar Reconnaissance Orbiter Diviner Lunar Radiometer support the hypothesis that the swirls formed as a result of deflection of the solar wind by local magnetic fields [3]. Diviner data show a shift to shorter wavelengths of the wavelength-dependent Christiansen Feature, consistent with retarded or abnormal space weathering at the swirls. Daytime temperature measurements show that the cm-scale surface roughness of the Reiner Gamma swirl is indistinguishable from the surrounding terrain, contrary to the dust-lofting [4] or micrometeorid/comet swarm impact formation mechanisms [5-7] for the swirls, which would be expected to alter the swirl regolith structure. Night-time temperature data and a thermal model indicate that the < 1K temperature difference between the Reiner Gamma swirl and the surrounding terrain can be completely accounted for by their differing albedoes. Taken together, these data support the solar wind standoff model for swirl formation.

Christiansen Feature Position: We have measured the CF positions of 12 lunar swirls and compared them to the CF positions of immediately surrounding terrain. For swirls that have anomalously low albedo dark lanes, we have also determined the dark lane CF positions. Swirl CF's are shifted to shorter wavelengths by an average of 0.06 µm, with the largest shifts of 0.09 µm found for the Van de Graaf crater and Descartes swirls and the lowest shift of 0.02 µm found for the Rima Sirsalis swirl. In every case measured, swirl dark lane CF values were within 0.01 µm of the off-swirl terrain. Figure 1 shows the CF distributions for the Reiner Gamma swirl.

Surface Roughness: In addition to CF measurements, Diviner's ability to determine the physical characteristics of the lunar surface help to constrain swirl formation mechanisms. We have determined the surface roughness, defined as root mean square (RMS) slope on the Reiner Gamma swirl and the local terrain just off the swirl. To do this, we determined the mean temperature difference on and off the swirl between Channel 3 and Channel 6 for every hour between 6 am and 6 pm local time. We then compared the results to modeled [8] temperature differences for cm-scale surface roughnesses ranging between 5 and 40° RMS. Our resuls show that surface roughnesses on and off the Reiner Gamma swirl are nearly identical, with values between 25° and 30° RMS (Figure 2). These roughnesses are in line with previously estimated sub-mm to cm-scale surface roughnesses for typical lunar surfaces of 16-25° [9].

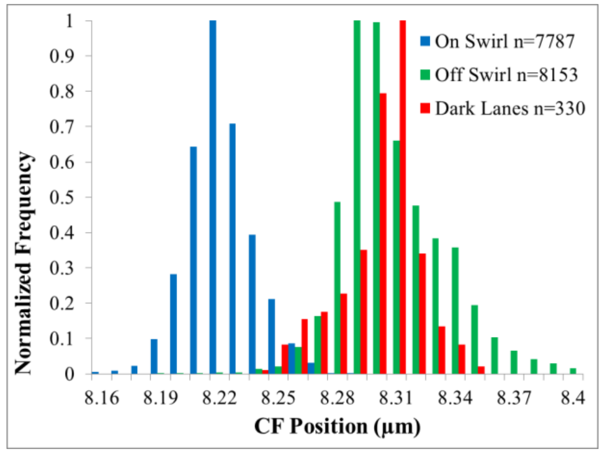

Figure 1. CF position distributions measured on the Reiner Gamma Swirl (blue), in typical off-swirl terrain (green), and within the anomalously low albedo dark lane (red).

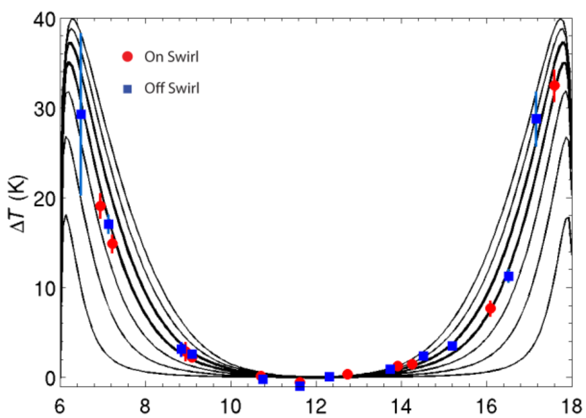

Figure 2. Channel 3-Channel 6 temperature difference plotted against local time for regions on the Reiner Gamma Swirl and Surrounding terrain. Curves are from the roughness model of [8]. Diviner data best match a cm-scale surface roughness of 25-30° both on and off the swirl.

Thermophysical Characteristics. We also use Diviner night-time temperature data and a sophisticated thermal model [10-11] to determine the surface thermophysical characteristics on and off the Reiner Gamma swirl, including vertical structure and particle size of regolith fines. We constructed 128 ppd night-time temperature maps using Diviner Channel 8 (50-100 μm) brightness temperatures acquired between local times of 19:30 and 05:30. These values are positive or negative deviations from the scene average normalized for local time variations. The average normalized temperature on the Reiner Gamma swirl is -0.8 ± 1.5 K as opposed to the average off-swirl temperature of -0.3 ± 1.8 K (1-σ standard deviations). The swirl, on average, is only ~0.5 K colder than the off-swirl surface. The measured temperature difference, though small, can be tied directly to the physical properties of the swirl surface. To do this, we use a thermal model to constrain the differences in regolith properties between the swirl and non-swirl surfaces. This standard lunar regolith model [10-11] uses Diviner night-time temperature data to constrain the upper regolith density profile. Figure 3 shows that the temperature difference between the on-and off-swirl surfaces can be accounted for completely by the albedo difference between the swirls. Additionally, we added a 2 mm low thermal inertia (~30 J m^{-2} K^{-1} $s^{-1/2}$, ~50% of the standard model) layer on top of the standard swirl model. Such a low thermal inertia layer would be expected from the admixture of additional fine particulates with typical lunar regolith, as would be predicted by the dust transport model of swirl formation [4]. Our results show that even this 2 mm thick layer would produce night-time temperatures much lower than those that are observed. Put another way, the swirls are surficial features that, thermophysically, are nearly indistinguishable from the surrounding terrain.

Discussion and Conclusions. Each of three separate analyses based on Diviner data support the solar wind stand-off model of swirl formation [3] and contradict the dust lofting [4] and impact swarm [5-7] hypotheses. Measurements of the Diviner CF positions on and off the swirls are consistent with retarded or abnormal space weathering at the swirls. They are inconsistent with a dust-lofting mechanism that would enrich the swirl surfaces in feldspar-bearing fines [4]. Diviner daytime temperature measurements compared to a roughness model show that the surface structure of the Reiner Gamma swirl is nearly indistinguishable from that of the surrounding terrain. The dust lofting mechanism would likely lead to a smoother surface, while recent impact swarms would lead to a rougher surface. Finally, night time temperature measurements, in conjunction with a standard regolith thermal model show

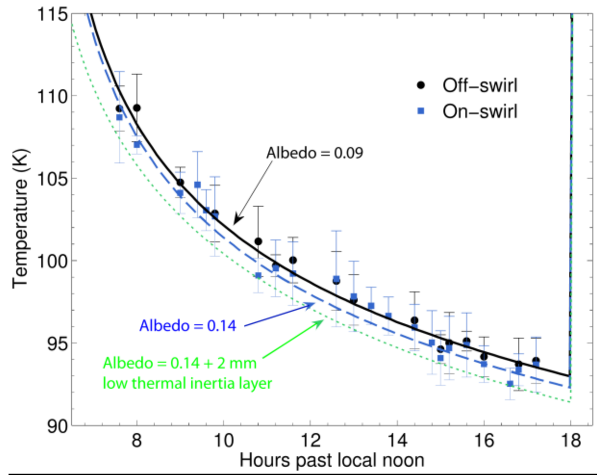

Figure 3. Diviner night-time temperature observations on (blue dots) and off (black dots) the Reiner Gamma swirl. The black solid line and blue dashed line show predicted temperatures. Predicted temperatures for a 2 mm thick low thermal inertia layer on top of the standard swirl thermal model (green dotted line) are too low to explain Diviner observations.

that the temperature difference between the Reiner Gamma swirl and the off-swirl surface can be completely explained by the albedo difference between the two. Adding even a 2 mm thick low thermal inertia layer, as might be caused by an enrichment of fine lofted dust produces temperatures that are much to low to match Diviner's observations.

Taken together, Diviner data and models complement VNIR measurements from M^3 [12-13] and radar measurements from Mini-RF [14], which support the surficial nature of the lunar swirls and their formation through the solar wind standoff mechanism.

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