NANOSWARM: A CUBESAT DISCOVERY MISSION TO STUDY SPACE WEATHERING, LUNAR MAGNETISM, LUNAR WATER, AND SMALL-SCALE MAGNETOSPHERES. I. Garrick-Bethell[1,2], C. M. Pieters[3], C. T. Russell[4], B. P. Weiss[5], J. Halekas[6], D. Larson[7], A. R. Poppe[7], D. J. Lawrence[8], R. C. Elphic[9], P. O. Hayne[10], R. J. Blakely[11], K.-H. Kim[2], Y.-J. Choi[12], H. Jin[2], D. Hemingway[1], M. Nayak[1], J. Puig-Suari[13], B. Jaroux[9], S. Warwick[14]. [1]University of California, Santa Cruz, igarrick@ucsc.edu, [2]Kyung Hee U., [3]Brown U., [4]UCLA, [5]MIT, [6]U. of Iowa, [7]UC Berkeley, [8]APL, [9]Ames, [10]JPL, [11]USGS, [12]KASI (South Korea), [13]Tyvak, [14]Northrop Grumman.

Introduction: The NanoSWARM mission concept uses a fleet of cubesats around the Moon to address a number of open problems in planetary science: 1) The mechanisms of space weathering, 2) The origins of planetary magnetism, 3) The origins, distributions, and migration processes of surface water on airless bodies, and 4) The physics of small-scale magnetospheres. To accomplish these goals, NanoSWARM targets scientifically rich features on the Moon called swirls (Fig. 1). Swirls are high-albedo features correlated with strong magnetic fields and low surficial water. NanoSWARM cubesats will make the first near-surface measurements of solar wind flux and magnetic fields at swirls. NanoSWARM cubesats will also perform low-altitude neutron measurements to provide key constraints on the distribution of polar hydrogen concentrations, which are important volatile sinks in the lunar water cycle (Fig. 1). NanoSWARM's results will have direct applications to the geophysics, volatile distribution, and plasma physics of numerous other bodies, in particular asteroids and the terrestrial planets.

Lunar swirls and polar volatiles: The science targets of NanoSWARM are rich in phenomena that are at the intersection of many fields in planetary science. Swirls are regions that have strong magnetic fields, unique spectral features, and relatively low abundances of surface OH/H_2O molecules. The lunar South Pole is unique because of its permanently shadowed terrain, and inferred abundance of hydrogen. Below we describe the four science objectives of NanoSWARM.

Space weathering: Space weathering processes alter surfaces exposed to the harsh space environment. On the Moon space weathering results in darkening, reddening, and reduction of absorption band strength. Understanding how these changes manifest is critical for interpreting the spectra of all airless bodies, and particularly Mercury and asteroids [1-3]. Despite advances from returned lunar and asteroid samples and spacecraft spectral studies, key questions remain in understanding how space weathering operates. In particular, the relative importance of micrometeoroids vs. the solar wind is actively debated [3, 4], yet is important due to its variable flux in different parts of the solar system. In addition, the effect of variable Fe° and FeO content of the surface is not known. NanoSWARM addresses these outstanding problems by making the first *in situ* measurements of variable solar wind flux, directly over surfaces with variable spectral and FeO properties (lunar swirls).

Lunar magnetism: The first spacecraft to leave the Earth and pass the Moon, Luna-1 in 1959, carried with it a magnetometer. Luna-1 measured no global magnetic field, but in the subsequent decades, we have found that portions of the lunar crust are magnetized, as well as samples returned by the Apollo program [5]. We have also come to conclude that a lunar dynamo is required to magnetize most, if not all of these materials [6]. However, important questions remain about the type of dynamo, its power source, its duration, and what it implies about the thermal history of the Moon. NanoSWARM will make very high frequency measurements of lunar magnetic anomalies at low altitudes. These measurements will be of such a resolution that they are similar to aeromagnetic surveys on Earth, enabling the use of a wide range of derivative-based formalisms to constrain the depth, boundaries, and magnetization of the source bodies [7]. Similar techniques applied to GRAIL gravity data have led to important discoveries about the Moon's thermal history [8].

Lunar water: Understanding the distribution of water in the solar system is a key goal in planetary science. In the last 20 years, there have been important discoveries about the distributions of water and other volatiles on the Moon and other airless bodies. Lunar Prospector discovered a broad signature of hydrogen at both lunar poles, and M3 discovered a latitude dependent signal of surface-bound OH/H_2O. However, critical questions remain about the origins and distributions of lunar surface water, such as how much OH/H_2O is generated by solar wind interactions, and is the polar hydrogen distribution definitively correlated with geological structures, such as permanently shadowed craters [9]? By correlating variable solar wind proton fluxes near the surface, with variable surface OH/H_2O abundances at swirls inferred from M3 measurements, NanoSWARM addresses the first question. By performing very low-altitude neutron spectroscopy over the Moon's South Pole, NanoSWARM addresses the second question [10].

Small-scale magnetospheres: The study of small-scale magnetospheres has the potential to inform a number of basic phenomena in space physics. For example, the interaction of magnetized asteroids with the solar wind is not well understood, yet it is important for understanding the magnetization of these small bodies [11]. By imaging the 3D plasma flux at swirls, NanoSWARM will provide an in-depth study of small-scale magnetosphere processes.

Synergies: A common theme in NanoSWARM is how measurements of particles and fields can inform a diverse number of processes in planetary science. For example, understanding the products of space weathering is key to interpreting planetary spectra, but this process also influences the generation of species which eventually may be trapped at the lunar poles. As another example, detailed models of field-particle interactions at small-scale magnetospheres can predict the variable amounts of H and He that penetrate the magnetic field at swirls, and each of these species has different space weathering effects.

Mission design: NanoSWARM uses a mother ship placed into a low, circular, polar lunar orbit. The mother ship releases cubesats on impact trajectories into the hearts of lunar magnetic anomalies. The cubesats transmit high frequency measurements of magnetic fields and proton fluxes, in real time, up until the last tens of milliseconds. The measurements are taken at an altitude an order of magnitude lower, and two orders of magnitude more frequently than the best existing data. Cubesats are released towards a variety of targets that reflect diversity in surface composition, spectral properties, and magnetic field strength, and they impact at multiple local times of day.

A second set of cubesats is released into a polar orbit with a periapsis over the South Pole, in order to measure neutron fluxes at altitudes lower than the Lunar Prospector and LRO missions.

The cubesats that target magnetic anomalies carry two instruments with flight heritage: a fluxgate magnetometer and a solar wind proton sensor. The cubesats that orbit over the South Pole carry a neutron spectrometer based on MESSENGER's instrument.

International payload: An important advantage of the standardization provided by cubesats is that contributed payloads are easier to accommodate. Cubesats contributed by KASI and Kyung Hee University in South Korea will add important additional measurements to the mission.

Conclusions: NanoSWARM is a new type of mission architecture that makes first-of-a-kind measurements of the Moon, to inform a number of important problems in planetary science. The technologies and methods used by NanoSWARM will enable many new cubesat missions in the next decade, and expand the cubesat paradigm into deep space. The mission architecture also provides outstanding educational and public outreach opportunities.

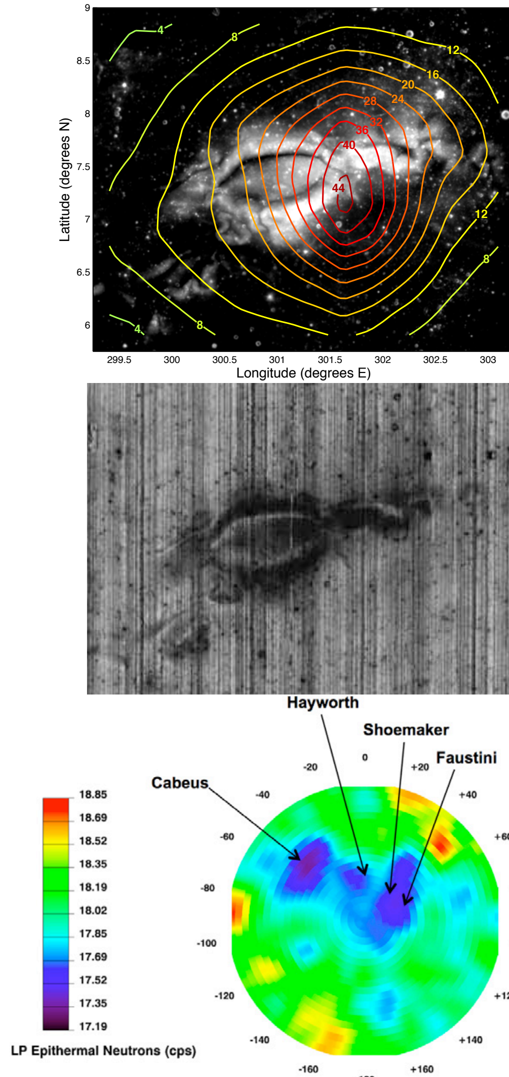

Figure 1: NanoSWARM targets scientifically rich regions on the Moon. Reiner Gamma swirl with superimposed magnetic field contours in nT (top, 130 km horizontal, best available data). Reiner Gamma 2.8 µm absorption strength from M3, a proxy for OH/H_2O abundances [12] (middle). South Pole epithermal neutron counts, a proxy for H abundances [10] (bottom).

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