DEVELOPING A PREDICTIVE CAPABILITY FOR LUNAR SURFACE CHARGING DURING SOLAR ENERGETIC PARTICLE EVENTS. J. S. Halekas[1], G.T. Delory[1], T.J. Stubbs[2,3], W.M. Farrell[2], and R.P. Lin[1,4], [1]Space Sciences Laboratory, U.C. Berkeley, [2]NASA Goddard Space Flight Center, [3]University of Maryland, Baltimore County, [4]Physics Department, U.C. Berkeley. Corresponding author's e-mail: jazzman@ssl.berkeley.edu.

Introduction: The Moon has a tenuous exosphere and only weak and localized crustal magnetic fields, leaving most of its surface exposed to solar UV and X-rays as well as solar and magnetospheric plasma and energetic particles, all of which act to electrically charge the surface. During its orbit around the Earth, the Moon is exposed to highly variable charging currents in the solar wind, lunar wake, terrestrial magnetosphere, and during solar energetic particle (SEP) events. The nightside surface can reach very large negative potentials when exposed to energetic plasma such as that encountered in the terrestrial plasma sheet or during SEP events. We investigate lunar surface charging during SEP events, with the aim of developing a predictive capability.

Lunar surface charging: The lunar surface charges to a potential such that the currents to it balance locally. On the sunlit hemisphere of the Moon, photoelectron currents usually dominate, and the surface charges to a small positive potential. On the night side, on the other hand, currents from electrons tend to dominate, and the surface charges to a negative potential. Charging theory predicts an equilibrium positive potential in sunlight on the order of a few times the photoelectron temperature and an equilibrium negative potential in shadow on the order of a few times the electron temperature (which can vary over orders of magnitude) [1,2]. Apollo-era and Lunar Prospector (LP) observations generally confirm these expectations [3]. In particular, LP observes the largest negative lunar surface potentials during plasma sheet crossings and SEP events, when the Moon is exposed to energetic (high temperature) plasma. Large negative surface charging only occurs outside of the magnetosphere during SEP events, with a nearly perfect correlation between extreme lunar charging and large solar proton events.

Lunar Prospector surface charging measurements: We can use LP data to explore the charging of the lunar surface in various environments, by utilizing electrons measured at spacecraft altitude as a remote probe of the lunar surface potential [3,4,5,6]. Negative charging of the lunar surface affects electron distributions in two ways. First, radial electric fields produce energy-dependent electron reflection (which we can differentiate from energy-independent adiabatic magnetic reflection from crustal magnetic fields). In addition, field-aligned electric fields accelerate secondary electrons from the surface, producing a high-flux beam of electrons traveling upward along the magnetic field line. We can use either of these features of the electron distribution to remotely sense negative lunar surface potentials. Fig. 1 shows measurements of surface potentials reaching a peak of -4.5 kV during a large SEP event in May 1998.

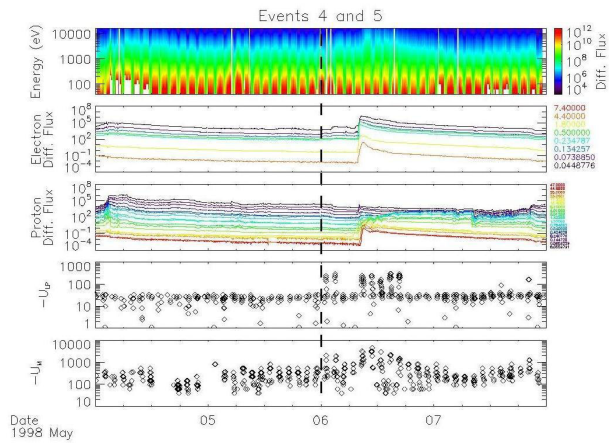

Figure 1: Electron fluxes measured at the Moon by LP, upstream electron and proton fluxes measured by Wind, ACE, and SOHO, and magnitude of negative spacecraft and surface potentials.

Implications of charging during SEP events: Quantitative measurements of surface charging during SEP events may prove important, because kilovolt-scale surface potentials could have potentially significant consequences for robotic and/or human lunar surface exploration. Spacecraft charging and electrostatic discharge are historically the leading causes of spacecraft failures in orbit [7], and could also impact operations on the lunar surface. Charging during SEP events could prove even more hazardous because of the combination of enhanced charging and radiation dosage. Meanwhile, the same charging processes that affect the surface should also influence individual dust grains. If surface electric fields can overcome surface cohesion and Van der Waals forces, they could lift charged dust grains form the surface and transport them vertically and/or laterally. We cannot easily predict the extent of hazards to exploration from charged dust, but significant additional hazards could result from dust [8]. All of these considerations provide us with ample reason to investigate lunar charging during SEP events.

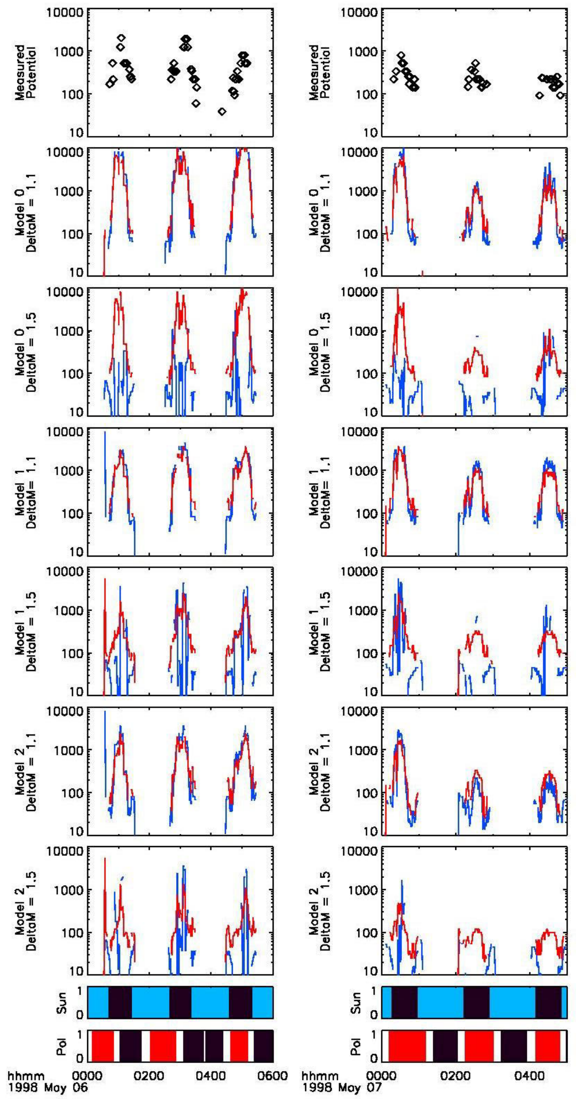

Figure 2: Magnitude of measured negative lunar surface potentials for two short time periods (several LP orbits each), and predictions from three different models (0,1,2), with Sternglass (blue) and Katz (red) secondary electron emission yield functions and two different peak secondary emission yields (1.1 and 1.5). Color bars show sun/shadow and magnetic connection to surface.

Predicting lunar surface potentials during SEP events: We developed three surface charging models, each with progressively more complicated assumptions, and several different assumed secondary electron yield functions, and compared them to our measurements, with the goal of working towards a predictive capability for lunar surface charging during SEP events. We show the results of a sample comparison for several orbits in Fig. 2. For eight of the eleven event periods we considered, surface potentials correlate with electron temperature and with the ratio of energetic electron flux to both energetic proton flux and total electron flux. For these eight events, charging models taking into account both thermal/suprathermal and energetic particle fluxes, as well as secondary emission, can successfully predict surface potentials. However, during the other three events, surface potentials do not correlate with the same measurable quantities, and charging models cannot reproduce measured potentials. In order to develop reliable and accurate models for lunar surface charging during SEP events, we will need better measurements of ion and energetic particle behavior in the lunar environment, secondary electron emission from lunar materials, and lunar surface potentials.

Conclusions: The high levels of penetrating radiation during SEP events will present a hazard to lunar explorers. In addition, robotic and/or human explorers may also encounter hazards associated with electrostatic discharge and/or dust effects produced by the large lunar surface potentials. If these risks prove serious, we will need to develop the capability to predict the level of surface charging expected during any given SEP event. With an appropriate plasma monitor in place, we could currently achieve this goal for some events, but not all. To develop a consistent and reliable predictive capability and understand the hazards to lunar explorers, we will need to know more about the lunar environment, including both low energy and energetic charged particle behavior, and the coupling between plasma and electric fields and the dusty lunar exosphere. In the coming years a number of missions, including ARTEMIS, Kaguya, and LADEE, should begin to fill in these voids in our knowledge. It is important to coordinate the observations from these missions in order to extract the greatest scientific benefit and prepare for future exploration.

References: [1] Manka R. H. (1973), in *Photon and Particle Interactions with Surfaces in Space*, 347-361. [2] Stubbs T.J. et al. (2007), in *Dust in Planetary Systems*, ESA SP-643, 181-184. [3] Halekas J. S. et al. (2008), *J.Geophys. Res*., 113, 10.1029/2008JA013194. [4] Halekas J.S. et al. (2002), *Geophys. Res. Lett.*, 29, 10.1029/ 2001GL014428. [5] Halekas J.S. et al. (2005), *Geophys. Res. Lett.*, 32, 10.1029/2005GL022627. [6] Halekas J.S. et al. (2007), *Geophys. Res. Lett*., 34, 10.1029/ 2006GL028517. [7] Bedingfield K.L. et al. (1996), *NASA Ref. Publ*. 1390. [8] Stubbs T. J. et al. (2007), in *Dust in Planetary Systems*, ESA SP-643, 239-244.