

1 **The Effect on the Lunar Exosphere of a Coronal Mass Ejection Passage**

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20 *In preparation for J. Geophys. Res. Planets*

21 *SSLAM special issue*

22 *Oct. 10, 2011*

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27 Pages: 62

28 Figures: 5

29 Tables: 10

30 Index Terms: 6250, 0328

31

31 Running Head: Effect of CME on the Lunar Exosphere

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41 **Abstract**

42

43 Solar wind bombardment onto exposed surfaces in the solar system produces an energetic  
44 component to the exospheres about those bodies. The solar wind energy and composition  
45 are highly dependent on the origin of the plasma. Using the measured composition of the  
46 slow wind, fast wind, solar energetic particle (SEP) population, and coronal mass ejection  
47 (CME), broken down into their various components, we have estimated the total sputter  
48 yield for each type of solar wind. We show that the heavy ion component, especially the  
49  $\text{He}^{++}$  and  $\text{O}^{+7}$  can greatly enhance the total sputter yield during times when the heavy ion  
50 population is enhanced. Folding in the flux, we compute the source rate for several species  
51 during different types of solar wind. Finally, we use a Monte Carlo model developed to  
52 simulate the time-dependent evolution of the lunar exosphere to study the sputtering  
53 component of the exosphere under the influence of a CME passage. We simulate the  
54 background exosphere of Na, K, Ca, and Mg. Simulations indicate that sputtering increases  
55 the mass of those constituents in the exosphere a few to a few tens times the background  
56 values. The escalation of atmospheric density occurs within an hour of onset. The  
57 decrease in atmospheric density after the CME passage is also rapid, although takes longer  
58 than the increase. Sputtered neutral particles have a high probability of escaping the moon,

59 by both Jeans escape and photoionization. Density and spatial distribution of the  
60 exosphere can be tested with the LADEE mission.

61

62 Keywords: Exosphere, Moon, Sputtering, Monte Carlo Simulation,

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65 **1. Introduction**

66

67         The lunar exosphere is, in a sense, the visible interface between the lunar surface  
68 and the interplanetary medium. Volatiles are degassed due to the effect of the solar flux  
69 onto the surface, and both volatile and less volatile material can be ejected from the surface  
70 by more energetic and violent processes such as sputtering by the solar wind, and by  
71 hypervelocity impact of dust, meteoroids and, less often, asteroids and comets. Transport  
72 of volatiles through the exosphere can lead to cold-trapping of volatiles in the polar  
73 regions, and less permanent sequestration of volatiles on the nightside. These processes  
74 are of practical interest to lunar explorers who may rely on polar-trapped volatiles, and to  
75 those interested in space weather related phenomena that may impact earth-orbiting  
76 spacecraft.

77         The lunar exosphere is sparse and highly variable. The multiple mechanisms  
78 releasing constituents from the surface into the exosphere are time-varying, often with  
79 comparable release rates. Meanwhile, lifetimes of particles in the atmosphere of the Moon  
80 are similar to the timescale of the variability in the sources. Thus transient phenomena are  
81 capable of contributing the bulk of the total atmosphere. In fact, the volatiles released by

82 an Apollo landed mission doubled the total atmospheric mass of the Moon temporarily  
83 (Vondrak, 1992). One such transient phenomenon is the sputtering of excess material into  
84 the atmosphere from an interplanetary coronal mass ejection (ICME). Although sputtering  
85 does not provide the bulk of the lunar atmosphere during normal conditions, we consider  
86 the enhancement that might result when an ICME impacts the lunar surface. Increased  
87 space weathering events during the active phase of the solar cycle may lead to more rapid  
88 cold-trapping of volatiles.

89         Furthermore, the exosphere is a source of ions in the solar wind interaction with the  
90 moon (e.g. Winske et al., 1985; Cladis et al., 1994). Neutrals in the lunar exosphere are  
91 subject to ionization by photons, protons, and electrons. Once ionized, they are accelerated  
92 by the motional electric field of the solar wind and influence the solar wind interaction  
93 through momentum transfer and plasma instabilities. The Solar Storm-Lunar Atmosphere  
94 Modeling (SSLAM) Lunar Extreme Workshop (LEW) investigated the entire lunar surface-  
95 exosphere-space plasma system during a space weather event at the moon (Farrell et al.,  
96 this issue). The SSLAM LEW followed the effects of the solar storm of 2 May 1998 from its  
97 effects on the lunar surface (Hurley et al., this issue), through the exosphere (this paper),  
98 the exo-ionosphere (Sarantos et al., this issue), to the plasma interaction (Krauss-Varben et  
99 al., this issue; Travnicek, this issue) and the resulting electromagnetic environment

100 (Zimmerman et al., this issue; Farrell et al. this issue) and its effects on dust (Stubbs et al,  
101 this issue; Glenar et al., this issue). SSLAM provided the opportunity to examine feedback  
102 between the components of the system. This paper presents the effects of the solar storm  
103 on the exosphere, which is derived from the surface and provides feedback for the plasma  
104 environment.

105       Because the morphology of the exosphere is a function not only of the rate at which  
106 atoms are ejected, but also their energy distributions, radiation pressure, thermal  
107 accommodation, sticking at the surface, and possible chemical reactivity, we consider four  
108 species: Na, K, Mg, and Ca. The first two species are known to exist about the moon, having  
109 been observed by ground-based telescopes (Potter and Morgan, 1985; 1986), and the latter  
110 two are known to exist at Mercury (Bida et al., 2000; McClintock et al., 2009) and are  
111 expected to also exist at the moon. Mg and Ca have not yet been detected in the ambient  
112 lunar exosphere (Stern, 1999), although they were detected in the vapor plume after the  
113 Lunar CRater Observation and Sensing Satellite (LCROSS) impact (Gladstone et al., 2010).  
114 We use the measured solar wind composition, density and velocity for various solar wind  
115 types, and we use the most recent information on sputtering by highly charged ions. We  
116 first describe the Monte Carlo model, then we describe the solar wind measurements and



117 sputtering values that we employ, and next we show the models for the four species  
118 considered.

119

## 120 **2. Lunar Atmospheric Model**

### 121 *2.1 Model History and background.*

122         In a surface-bounded exosphere, particles are not expected to interact with other  
123 exospheric particles, but only interact with the surface (Stern, 1999; Killen et al., 2007).  
124 Because the exosphere is collisionless, different species or different sources of a single  
125 species can be modeled separately using Monte Carlo techniques without having to  
126 incorporate interactions. This makes Monte Carlo modeling a useful tool for deciphering  
127 important physical processes at play in the creation and maintenance not only of the lunar  
128 exosphere but also of other exospheres in the solar system, including those at Mercury, Io  
129 and Europa.

130         One can use various assumptions in the modeling to create a set of “base  
131 atmospheres” that will have a characteristic distribution of particles for the assumed initial  
132 distribution and physics involved. Different base atmospheres can be combined in  
133 proportion to their source rates to produce an aggregate atmosphere. Although photon-  
134 stimulated desorption (PSD) has been shown to provide the bulk of the lunar Na and K

135 atmosphere during normal conditions, we consider the enhancement that might result  
136 when a CME impacts the lunar surface. Because the morphology of the exosphere is a  
137 function not only of the rate at which atoms are ejected, but also their energy distributions,  
138 radiation pressure, thermal accommodation and sticking at the surface, and possible  
139 chemical reactivity, we consider four species, Na and K which are volatiles, and Mg and Ca  
140 which are more refractory.

141         Crider and Vondrak (2000; 2002) developed a Monte Carlo model of the migration  
142 of particles in a surface bounded exosphere for application to the Moon similar to those  
143 developed by others (see Hodges, 1973; Arnold, 1979; Butler, 1997; Wurz and Lammer,  
144 2003). The model follows the path of a particle under the effects of gravity and radiation  
145 pressure once it is released into the exosphere with an energy selected from a distribution  
146 function for the selected source process (section 2.2). In flight, one of three things can  
147 happen. The particle may escape the planet's gravitational field, may be photoionized or  
148 photodissociated, or may return to the surface. For the particles that return to the surface  
149 intact, they may bounce elastically for another ballistic hop, they may thermalize or  
150 exchange energy with the surface and be released with a new energy, or they may stick to  
151 the surface. At some point, the particles will either be lost from the atmosphere or will  
152 arrive in a cold trap. The Monte Carlo model records particle positions and velocities at

153 user-defined times, flux to specific points on the surface, and loss rates. Most components  
154 of the model are modular such that various sources, losses, and physics can be selected by  
155 the user to explore the effects these have on the atmosphere. These modules are described  
156 in the following subsections.

157

## 158 *2.2 Model Description*

### 159 *2.2.1 Ballistic motion*

160 After release from the surface at a given position with velocity vector selected from  
161 an appropriate distribution function, as discussed below, the model calculates the particle's  
162 trajectory under gravity and radiation pressure using a fourth order Runge-Kutta (RK-4)  
163 algorithm. Migrating particles follow a ballistic trajectory once released from the surface  
164 because the lunar atmosphere is collisionless. Without radiation pressure, the final  
165 position and time of flight can be found analytically assuming a spherical Moon (Vogel,  
166 1966). Earlier lunar publications using this model have only used the analytic function and  
167 no radiation pressure (Crider and Vondrak 2000; 2002). At Mercury, radiation pressure is  
168 significant, especially for Na and K (see Potter et al., 2007) whereas at the Moon, the  
169 radiation pressure is less important and can be ignored unless one is studying the lunar tail  
170 region (e.g. Smyth and Marconi, 1995a; b). The RK-4 algorithm has been implemented to

171 follow the trajectory of the particles using the equation of motion (Killen et al., 2010;  
172 Hurley, 2011). The results presented here use the equation of motion, but neglect radiation  
173 pressure.

174         The current model assumes the Moon is a sphere with radius 1738 km. There are  
175 large-scale topographic features that might affect bulk properties of the atmosphere, but at  
176 present are not modeled except for cold traps. Small-scale effects, i.e. the "fairy castle"  
177 effect (Hapke and Cassidy, 1978) also are not considered directly in the present work.

178

### 179         2.2.2. *Source functions*

180         The Monte Carlo model of the migrating gases takes a source function (including  
181 spatial and energy distributions) and simulates the trajectories of large numbers of  
182 particles ( $10^5$ - $10^6$ ). It is able to incorporate the different source functions required for the  
183 different processes at work on the Moon, including photon-stimulated desorption, thermal  
184 desorption, ion sputtering, micrometeoroid release, outgassing, or large impact events (see  
185 e.g. Killen and Ip, 1999).

186         An input flux and spatial distribution is assigned as appropriate for the source: solar  
187 UV radiation for photon-stimulated desorption, solar particle flux for ion sputtering, and  
188 micrometeoritic or meteoritic flux for impact vaporization. At the Moon, solar wind flux

189 dies off with solar zenith angle due to the curvature of the Moon, unlike at Mercury where  
190 the solar wind flux onto the surface depends on the locus of open magnetic field lines,  
191 which is highly variable. Ion flux is greatly reduced on the night side of the Moon (Ogilvie  
192 et al., 1996). When the Moon is inside the earth's magnetosphere it is shielded from the  
193 solar wind, but it may traverse the plasma sheet, which contains high energy plasma rich in  
194 oxygen ions from the Earth. Micrometeorite release, in contrast, is expected to be isotropic  
195 over the surface of the Moon, at least within a factor of two. A cometary impact or asteroid  
196 impact is localized to a specific position, and meteor streams are directional.

197         The ejected products are assigned an initial velocity from the surface drawn from  
198 the distribution function appropriate to the release mechanism (Hofer, 1991; Roth, 1983).  
199 Both source processes and surface interactions are species-dependent, resulting in various  
200 energies and compositions of the ejected products. The solar wind ions implant themselves  
201 into the regolith and cause physical and chemical sputtering with an efficiency dependent  
202 on their kinetic and potential energy. Physical sputtering and backscattering are relatively  
203 high-energy release mechanisms, whereas chemical sputtering and thermal processes eject  
204 atoms at lower energies on average.

205         In order to correlate the source rate with an atmospheric distribution, we assign a  
206 start time to the particles in the simulation at random within a specified time window. This

207 introduces a source rate into the model (the number of simulation particles in a simulation  
208 time window), which enables scaling to a physical source rate after running. This is  
209 possible because of the collisionless nature of the exosphere. Each modeled source is  
210 described below.

211

#### 212 2.2.2.1 Photon-stimulated desorption

213 Photon-stimulated desorption (PSD) was first suggested as a source for Mercury's sodium  
214 exosphere by McGrath et al. (1986), and subsequently as a source for the lunar sodium  
215 exosphere (Potter and Morgan, 1988). Subsequent laboratory work used electron-stimulated  
216 desorption as a proxy for PSD to establish a desorption cross section of  $Q = (3 \pm 1) \times 10^{-20} \text{ cm}^2$  at  
217 5 eV (Yakshinskiy and Madey, 1999). The solar flux at  $h\nu > 5\text{eV}$  is  $2 \times 10^{14} \text{ photons cm}^{-2} \text{ s}^{-1}$ , and  
218 the surface number density of Na atoms,  $\sigma$ , is about  $3 \times 10^{12} \text{ cm}^{-2}$ . The PSD source flux calculated  
219 using this rate would be

220

$$221 \quad \Phi^{\text{PSD}} = F_{\text{ph}} \cos(\psi) Q\sigma / R^2, \quad (1)$$

222

223 where  $\sigma$  is the Na surface coverage, taken to be  $f_{\text{Na}} \times 7.4 \times 10^{14} \text{ cm}^{-2}$ ,  $\psi$  is the solar zenith angle,

224 and  $R$  is the distance from the sun. The fractional abundance of lunar sodium is 0.005. The

225 theoretical cross section for PSD desorption was determined to be overly efficient unless the loss  
226 processes for Na were also extremely efficient (e.g. Killen et al., 2001). Cassidy and Johnson  
227 (2005) calculated a correction factor of a factor of three to account for trapping of the ejected  
228 atoms in the regolith. In this model, we consider PSD yields beginning with the Yakshinskiy and  
229 Madey (1999) yield reduced by a factor of three as suggested by Cassidy and Johnson (2005),  
230 and subsequently consider the consequences of further reduction of yields in the absence of ion-  
231 flux to the surface, and of an ion-flux enhancement of those baseline yields. Observations of the  
232 lunar exosphere inside the Earth's magnetosphere (Potter et al., 2000) supported a feedback  
233 between ion impact and photon-stimulated desorption (Sarantos et al., 2008; 2010). Sarantos et  
234 al. (2008; 2010) suggested that the effective PSD yields consistent with the observations  
235 were reduced by up to a factor of six from the experimental PSD yield by Yakshinskiy and  
236 Madey (1999). The velocity of a particle released by PSD is taken from a thermal velocity  
237 distribution with a temperature of 1200 K.

238

#### 239 2.2.2.2 Impact vaporization

240 Vaporization due to meteoritic impact was considered as a possible source of the sodium  
241 and potassium exospheres of Mercury (Morgan et al., 1988; Cremonese et al., 2005) and for the  
242 moon (Potter and Morgan, 1988). The importance of impact vaporization was shown by Hunten

243 et al. (1998) who observed a brightening of the lunar sodium tail after the passage of the Moon  
244 through the Leonid meteor stream. Impact-induced exospheres produced by micrometeoritic  
245 debris of mass < 0.1 g were modeled for both Mercury and the Moon by Cintala (1992). More  
246 recently, meteors of mass > 0.1 g were considered as sources of a transient atmosphere  
247 (Mangano et al. 2007).

248 This model for impact vaporization is based on the impedance matching method  
249 (Melosh, 1989; Morgan and Killen, 1998; Killen, 2003) and the total influx is an input  
250 parameter.

251 Some differences in the current impact-vaporization code from that described in  
252 Morgan and Killen (1998) are that the peak pressure of the impact is calculated using the  
253 equations in Melosh (1989), chapters 3 and 4, and not using the approximation described  
254 in Lange and Ahrens (1987). The peak pressure,  $P_p$ , is given by

255

$$256 P_p = \rho (C_t u_t + S_t u_t^2),$$

257

258 where  $\rho$  is the density in the target,  $u_t$  is the change in particle velocity across the shock in  
259 the target,  $C_t$  has dimensions of velocity and is empirically determined, and  $S_t$  is  
260 dimensionless and is also empirically determined. The constants C and S for the target and



261 impactor are input parameters and can be found in Melosh (1989) Table AII.2 for various  
262 materials such as iron, diabase, sandstone, quartz, dunite and water. In addition to these  
263 parameters the critical pressure for vaporization is a function of enthalpy required for  
264 vaporization,  $H_v$ , which is an input parameter, for these runs set to that for regolith  
265 determined by Cintala (1992). The temperature at which a given constituent vapor boils off  
266 a mineral is the temperature of vaporization of the individual component (Ahrens and  
267 O'Keefe, 1972). Thus the more volatile components will vaporize first, at significantly lower  
268 impact velocities than those required for complete vaporization. We estimate the critical  
269 pressure for vaporization of individual gases by scaling the critical pressure for  
270 vaporization of regolith as defined by Cintala (1992) by the ratio of the enthalpies required  
271 for vaporization (Chase *et al.*, 1985), given in Table 1. Our function for the minimum impact  
272 velocity required for vaporization has the form of a quadratic:

273

$$274 \quad v_{\min} = a + b \cdot m + c \cdot m^2, \quad (2)$$

275

276 where the constants a, b and c are given in Table 2 as a function of rock type and impactor  
277 type. Aluminum was chosen as the impactor because the properties of aluminum are  
278 closest to those of stony-iron meteorites, and it has been used in many laboratory tests. The

279 mean velocity of expansion of a vapor cloud created from a hyper-velocity impact is twice  
280 the sound speed in the medium regardless of the impact velocity. For regolith the sound  
281 speed is about 1.3 km/sec, thus the expansion velocity is on the order of 2 km/sec (Schultz,  
282 1996), comparable to lunar escape velocity, 2.38 km/sec. The temperature derived from  
283 this expansion speed is 5566 K. Because collisions with the regolith may decrease the  
284 expansion velocity, the simulations shown in this paper assume a vapor temperature of  
285 3000 K.

286         The observation of a 3000 K lunar exosphere at minimum column abundance inside the  
287 Earth's magnetosphere was interpreted by Sarantos et al. (2008) to constrain the impact vapor  
288 source at the Moon to approximately  $\leq 8.5 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ , given a residence time in the lunar  
289 exosphere of 6000 s from our Monte Carlo modeling.

290

#### 291         2.2.2.3 Ion sputtering

292         Potter and Morgan (1988) recognized that a sputter source could produce the very  
293 extended lunar sodium exosphere. Sputtering of Na by solar wind ions impinging onto the  
294 surface of Mercury through the cusps of the magnetosphere was suggested by Potter and  
295 Morgan (1990) to explain rapid variations in the observed Na exosphere, with high to mid-  
296 latitude enhancements appearing and disappearing on intervals less than a day. At

297 Mercury, the solar wind only impacts the surface along open field lines, or near the open-closed  
298 boundary region (Sarantos et al., 2007; Kallio and Janhunen, 2003), but the solar wind impacts  
299 the entire sunward side of the Moon whenever the Moon is outside of the Earth's magnetosphere.  
300 Kinetic energies of solar wind ions are on average 1 keV/amu, near where the sputtering  
301 efficiency peaks (Johnson, 1990). Sputtering by  $H^+$ , which normally accounts for 85% of the  
302 total kinetic energy carried by the solar wind, is relatively inefficient.  $He^{2+}$  accounts for  
303 about 13% of the kinetic energy carried by the normal (slow and fast) solar wind, and is  
304 generally assumed to account for most of the space weathering effects. In addition,  
305 although heavy ions ( $Z>6$ ) account for only about 2% of the kinetic energy carried by the  
306 normal solar wind, they also carry  $\sim 1$  keV each in potential energy due to ionization  
307 (Krachner et al., 2003). The sputter yield of protons is low, and the fraction of heavy ions in the  
308 slow and fast solar wind is low. However, the fraction of heavy ions in the solar wind increases  
309 dramatically in a CME or solar magnetic cloud. Sputtering yields by heavy ions have been  
310 considered both theoretically (Sporn et al., 1997; Shemansky, 2003; Kallio et al., 2008) and  
311 experimentally (Meyer et al., 2011) and have been shown to be orders of magnitude more  
312 efficient than sputtering by protons.

313         The charge state of the impinging ion has little effect on the sputter efficiency of  
314 highly conducting targets (conductors and semiconductors), but has considerable effect on

315 insulators (Aumayr and Winter, 2004). Sputtering of surfaces by highly charged projectiles  
316 in which the potential energy of ionization contributes significantly to the yield is called  
317 potential sputtering. Models for potential sputtering predict the formation of a short-lived  
318 multiply excited atom with highly excited outer shell electrons, and with some empty inner  
319 shells. Potential energy of the projectile is converted into kinetic energy of emitted  
320 electrons and electronic excitation of a small surface area. In insulator targets, in which  
321 perturbations of the electronic structure cannot be rapidly dissipated within the target,  
322 structural surface modifications result: defect formation, desorption and sputtering.  
323 Measured sputter yields of 1.5 keV  $\text{Xe}^{9+}$  onto  $\text{Al}_2\text{O}_3$  show an approximately 40-fold increase  
324 in the sputter yield due to  $\text{Xe}^{28+}$  over that of  $\text{Xe}^{9+}$ , and yields of  $\text{SiO}_2$  bombarded by 1 keV  
325  $\text{Ar}^{9+}$  show a 2.6-fold increase in yield for  $\text{Ar}^{8+}$  over those of  $\text{Ar}^+$ . Both of these materials  
326 appear to have a finite sputter yield at zero kinetic energy of the projectile. On the other  
327 hand, for a highly ionic oxide such as  $\text{MgO}$ , even though potential energy greatly increases  
328 the sputter yield, potential energy does not induce sputtering in the absence of kinetic  
329 energy of the projectile. Okabayashi et al. (2005) studied secondary ion emission from solid  
330 surfaces irradiated with highly charged ions. In the case of a water adsorbed Si surface,  
331 they found that the yield of  $\text{H}^+$  strongly depended on the charge state of the projectile, but

332 that the yield of Si<sup>+</sup> is independent of the charge for Ar<sup>q+</sup> projectiles. Si<sup>+</sup> and SiOH<sup>+</sup> ions  
333 were therefore ejected primarily by a kinetic sputtering process.

334 The normalized energy distribution for particles sputtered from a solid,  $f(E_e)$ , with the  
335 energy  $E_e$  of the sputtered particle, has been given as (Sigmund, 1969)

336

337 
$$f(E_e) = \frac{6E_b}{3 - 8\sqrt{E_b/E_c}} \frac{E_e}{(E_e + E_b)^3} \left\{ 1 - \sqrt{\frac{E_e + E_b}{E_c}} \right\}, \quad (3)$$

338

339 where  $E_b$  is the surface binding energy of the sputtered particle and  $E_c$  the cut-off energy for  
340 sputtered atoms. The cut-off  $E_c$ , which is the maximum energy that can be imparted to a  
341 sputtered particle by a projectile particle with energy  $E_i$ , is given by the limit imposed by a  
342 binary collision between a projectile atom,  $m_1$ , and the target atom,  $m_2$ , (to be sputtered) as

343

344 
$$E_c = E_i \frac{4m_1m_2}{(m_1 + m_2)^2}. \quad (4)$$

345

### 346 2.2.3 Surface interaction

347 When the particle comes back into contact with the surface, there are a variety of  
348 processes that can occur. These surface-atmosphere interactions in the extreme vacuum

349 environment of atmosphereless bodies introduce an array of interesting physics questions  
350 that are still not well-studied, but can have an effect on atmospheric distribution. When the  
351 atmospheric particle reencounters the planet, it may stick to the surface (discussed in  
352 Section 2.2.4). It may adsorb to the surface long enough to partially or fully thermalize to  
353 the local surface temperature and then be reemitted. Or it may rebound on contact  
354 retaining all or most of its incident energy. The code allows the user to select from a wide  
355 range of surface interactions. Comparing the results with different assumptions provides  
356 insight into how the surface-atmosphere interface affects atmospheric properties.

357       The user specifies parameters for the energy exchange at the surface for particles  
358 that return to the surface and are re-emitted. It includes a thermalization coefficient ( $w$ )  
359 and a conservation coefficient ( $f$ ) that governs the energy exchange between the particle  
360 and the surface. The weights applied to  $v_t$ , a velocity from the Maxwellian distribution at  
361 the local surface temperature (thermal accommodation) and to  $v_i$  the incident particle  
362 velocity (rebound) total unity. This way, any degree of thermal accommodation is possible  
363 with the code. The inbound and thermal velocities are added in quadrature with appropriate  
364 weights to compute the outbound velocity. The conservation coefficient is applied afterward to  
365 provide a separate means of damping particles:

366 
$$v_f = \sqrt{f(wv_t^2 + (1-w)v_i^2)}$$

367

368 In all of the work presented here, we assume  $f=1$ , *i.e.*, there is no separate damping of energy.

369 All of the energy exchange with the surface occurs through the thermal accommodation. We

370 used values of 0.2 and 0.5 for  $w$  as explained below.

371 If a particle is reemitted, the direction of release occurs with an isotropic angular

372 distribution. However, given the microstructure of the regolith, this is a simplification. The

373 reemitted particle is followed on all of its ballistic hops until it is lost from the system

374 either to sticking, escape, or photoionization.

375

376 *2.2.4 Loss processes*

377 *2.2.4.1 Sticking*

378 When the particle encounters the surface, the code determines whether the particle will

379 stick or be re-emitted depending on the sticking functions assigned to the simulation. If there is

380 no sticking, the particle is re-emitted as described in section 2.2.3 until it is lost by some other

381 process. For cold-trap sticking, the particle sticks if it lands in a cold-trap location as defined in

382 the simulation. The probability of sticking depends on the surface temperature for temperature-

383 dependent sticking.

384 For the Moon, we approximate the surface temperature (in Kelvin) by the function

385

386  $T = 300 \cos^{1/4} \theta + 100,$  for  $\theta < 90^\circ$  (5)

387

388

389 where  $T$  is the surface temperature and  $\theta$  is the solar zenith angle. The nightside temperature is  
390 100 K.

391 For long-term sticking, the probability of sticking could be a function of temperature  
392 or could be based on the surface composition. The user specifies a probability function for  
393 sticking that can be based on the temperature, can be a day-night functionality, can allow  
394 for a set number of bounces before sticking, can allow no sticking, or can be a fixed  
395 probability where sticking is queried on every return to the surface. If a particle sticks to  
396 the surface in the code, its time and position are recorded. This output is then available as  
397 input for other runs where the distribution of adsorbed particles needs to be known.  
398 Alternatively, the code can immediately consider the later reemission of a stuck particle.  
399 For example, when nightside sticking is enabled, the code can assume that the particle is  
400 reemitted at the dawn terminator by a specified release process (thermal desorption or  
401 photon-stimulated desorption). This way, one can follow a particle until it is lost from the  
402 planet by escape or photoionization rather than just recycling to the regolith.



403 In these simulations, sticking is applied as a temperature-based function. For each time  
404 the particle comes into contact with the surface, the local surface temperature is queried. If the  
405 temperature is below the setting, the particle sticks.

406

#### 407 2.2.4.2 Photoionization

408 Photoionization rates depend on the ionization potential of the atom in question, and also  
409 on the solar flux available with energy at or exceeding the ionization energy. Since most of this  
410 energy comes in the form of UV radiation, the rate is dependent on the solar flux. The solar UV  
411 flux is currently available on the LISIRD website ([lasp.colorado.edu/LISIRD](http://lasp.colorado.edu/LISIRD)). We use the  
412 ionization cross sections computed by Huebner et al. (1992) either for quiet sun or for active sun,  
413 scaled to the orbital distance of the planet or moon at the time of observation. The rates are  
414 summarized in Table 3. For sodium, there has been a controversy about the photoionization rate,  
415 since the theoretical cross section from Chang and Kelly (1975) and the experimental cross  
416 section from Hudson (1964); Hudson and Carter (1967) differ by a factor of 2.7. Both Huebner et  
417 al. (1992) and Combi et al. (1997) recommend the theoretical cross section derived by Chang  
418 and Kelly (1975). We have therefore adopted the theoretical cross section. Huebner et al. (1992)  
419 did not publish a photoionization rate for calcium. However, Huebner calculated a rate of  $7.0 \times 10^{-7}$

420  $5 \text{ s}^{-1}$  at quiet sun and  $7.8 \times 10^{-5} \text{ s}^{-1}$  for active sun. The corresponding excess energies of the  
421 electrons are 0.38 eV and 0.47 eV, respectively (W. Huebner, personal communication).

422       The probability of photoionization or photodissociation during a given ballistic hop  
423 is based on the photoionization time (Huebner et al., 1992; Verner et al., 1996) and the  
424 time of flight in sunlight. If the particle remains intact and does not escape, the simulation  
425 finds the location where the particle reencounters the surface. If that location is poleward  
426 of a specified latitude (e.g.  $85^\circ$  for simulations of  $\text{H}_2\text{O}$ ), the program calculates the  
427 probability of the particle landing in a cold trap based on the total area in that latitude  
428 range assumed to be a cold trap (Margot et al., 1999; Bussey et al., 2003).

429

#### 430       2.2.4.3 Jeans Escape

431       The particle escapes the simulation when it crosses a predetermined boundary,  
432 generally set at 20 radii from the surface. The Hill sphere is at 35 radii, where the  
433 gravitational pull of Earth exceeds that of the moon.

434

### 435       2.3. *Steady State and Time-Dependent Models*

436       The model is run for many particles (usually 1 million) with a spatial and energy  
437 distribution matching the release mechanism. The positions and velocities of the particles are

438 recorded at pre-determined timesteps. For steady state, one weights each model particle by the  
439 source rate (Table 10). In steady state, the output time cadence is 1-minute intervals. For the  
440 time dependent runs, a time cadence of 10 minutes was chosen. At each time step, particles are  
441 weighted by the source rates from a time-profile. Binning the weighted model particles by  
442 volume produces density. Similarly, binning along a line of sight computes column density.

443

### 444 **3. CME Passage**

#### 445 *3.1 CME Introduction*

446 We have computed the total sputter yield on the lunar surface for an element normal to  
447 the solar wind (i.e. there are no geometrical effects included.) The solar wind types considered  
448 are fast wind, slow wind, and CME shock, bubble and flank. The density, velocity and fraction  
449 of  $\text{He}^{++}$  assumed for each of these wind types are given in Table 4. The densest component is the  
450 'CME', and the least dense is the magnetic bubble. The enrichment of heavy ions is species  
451 dependent, as listed in Table 5. Both the magnetic bubble and CME driver gas are highly  
452 enriched in heavy ions. Even in spite of the low density in the bubble, the sputter yield is  
453 substantially increased above that in the solar wind. The composition of the fast solar wind and  
454 slow wind are from vonSteiger et al. (2000) for south (fast wind) and minimum (slow wind).  
455 Abundance ratios were all given relative to O. The Ne/O and Mg/O ratios were found to vary

456 from 0.26 to 0.38 for Ne/O and from 0.23 to 0.36 for Mg/O for central events in ICMEs  
457 depending on whether the associated flare is none, C-flare, M-flare or X-flare, with X-flare being  
458 the most intense and having the most enhanced Ne and Mg abundances. The values in Table 5  
459 are for the M-flare associated ICME (Reinard, 2008). The values for S/O and Fe/O are from  
460 Wurz et al. (1997). Note that Carter et al. (2010) give the Si XIII/O VIII flux as 0.3 whereas the  
461 Si XIV/O VIII flux is given as 0.15. We have used the intermediate value of 0.18 consistent with  
462 the Wurz et al. (2000) report that Si/O is elevated by a factor of 1.55 in the January 6, 1997,  
463 CME. Although Gloeckler et al. (1999) report that the Si/O and Mg/O ratios in the May 1998  
464 CME were consistent with those typical of the slow solar wind, the more usual state is for these  
465 ions to be elevated by up to a factor of two in CMEs. We did not find information on the  
466 composition of the shock and magnetic bubble except for the alpha/proton and O/He. Therefore  
467 we used the same composition for the heavier ions for the three components of the CME.

468       Kinetic sputtering, a process in which kinetic energy is transferred from the incoming  
469 ions to the substrate, resulting in the ejection of atoms and ions, is relatively well understood.  
470 This is the dominant sputtering mechanism for metals and semiconductors. However, on  
471 insulating surfaces such as oxides an additional mechanism is important in removal of atoms and  
472 ions from surfaces: potential sputtering is attributed to ejection due to the potential energy of  
473 ionization carried by ions, and is the dominant sputtering process on insulating surfaces for

474 highly charged ions impacting with kinetic energies  $< 25$  keV/amu (Barghouthy et al., 2011).  
475 Barghouthy et al. (2011) calculated the kinetic sputter yield in atoms/ion by solar wind protons  
476 and heavy ions at 1 keV/amu as simulated by the SRIM/TRIM code. They then calculated the  
477 enhanced sputtering due to the potential energy of ionization. This potential energy of ionization  
478 was found to increase the yield by a factor of 1.3 to 1.9 depending on the species. Because the  
479 yield depends on both the incoming ion and outgoing ion, we have taken the kinetic yield of a  
480 given species by heavy ions in the solar wind to be the average of the yield of that species from  
481 all heavy ion species in the table. We used equation 2 from Barghouthy et al., 2011 to calculate  
482 the potential sputter yield, except that we assumed the same alpha and beta for all elements. We  
483 added the potential yield thus calculated to the kinetic sputter yield. The results are consistent  
484 with the average potential yield + kinetic yield of about 1.4 times the kinetic sputter yield alone.  
485 For  $\text{He}^{++}$  the potential sputter yield is slightly larger than the kinetic sputter yield. The increase in  
486 the sputter yield due to potential energy assumed in this paper is thus very modest and is less  
487 than a factor of 2 for all elements. Table 6 lists the sputter yield of neutrals (atom/ion) by  
488 protons, and by  $\text{He}^{++}$  and heavy ions weighted by the proton yield. Table 7 gives the flux ( $\text{cm}^{-2} \text{s}^{-1}$ )  
489 of neutral elements resulting from kinetic plus potential sputtering of a KREEP soil for slow  
490 wind, fast wind, and the 3 CME components as listed in Table 4; while Table 8 gives the  
491 corresponding flux for kinetic sputtering only.

492           These results are more conservative than those from Meyer et al. (2011) based on sputter  
493 yield of O from JSC-1A AGGL lunar simulant. They obtained an 80-fold increase in sputter  
494 yield of O by  $\text{Ar}^+$  over that from production by protons, and an additional factor of two for  
495 incident  $\text{Ar}^{+9}$ . The measurements were obtained for a pressed sample. The sputter yield of O by  
496 4 keV  $\text{He}^+$  ions was given by Dukes et al. (2011) as 0.37. This is roughly an order of magnitude  
497 larger than the sputter yield of O by protons. Our yields for  $\text{He}^{++}$  as a fraction of proton yields  
498 range from 12.9 to 14.9 and our yields for heavy ions as a fraction of proton yields range from 61  
499 to 83.

500           The calculated sputter yields for the impact of ions onto leaded glass by Shemansky  
501 (2003) are much greater than those used here. The sputter yield of  $\text{O}^{+7}$  given by Shemansky is  
502 about two orders of magnitude greater than that of  $\text{O}^+$ ; thus the calculated yield of  $\text{O}^{+7}$  relative to  
503 the yield of  $\text{H}^+$  is about 2500 for 1 keV/amu ions. He calculates that the relative sputtering yield  
504 of solar wind ions onto leaded glass is heavily weighted by the heavy ions, which are twice as  
505 efficient as protons even when weighted by their relative abundance in the solar wind.

506           The flux of neutral elements resulting from sputtering of a KREEP soil for slow wind,  
507 fast wind, shock, magnetic bubble gas and CME driver gas are listed in Table 8. The yields have  
508 been weighted by the yield per incident ion type and the fraction of that ion in the solar wind as  
509 listed in Table 5. The  $\text{yield}/\text{H}^+$  is the yield for sputtering by protons and is taken from Barghouty

510 et al. (2011, Table 3). The yield ( $\text{He}^{++}/\text{H}$ ) is the relative yield of each species from the  $\text{He}^{++}$  ion  
511 in the solar wind, and the yield ( $\text{Heavy}/\text{H}$ ) is the weighted yield from all ions heavier than He for  
512 the designated species. The yields differ because they are weighted by the composition.

513         The sputter yield of secondary ions by protons is taken from Elphic et al. (1991). The  
514 yield from  $\text{He}^{++}$  is taken to be a factor of 10 higher than that for protons, and that for heavy ions  
515 is taken to be a factor of 160 over that for protons. These yields are multiplied by the solar wind  
516 flux to obtain the flux of secondary ions by sputtering of the five solar wind types (Table 9).  
517 These values are not used in our simulations since we only simulate the neutral exosphere, but  
518 they are used in the accompanying papers (Krauss-Varben et al.; Travnicek et al., this issue). The  
519 sputter yield of secondary ions by  $\text{He}^{++}$  is taken to be a factor of ten times that for  $\text{H}^+$ ; however  
520 the secondary ion flux for incident  $\text{H}^+$  and for incident  $\text{He}^+$  appear to be similar even though  
521 secondary ion yields for other elements lie on a power law curve as a function of nuclear  
522 stopping power (Elphic et al., 1991). Oxygen is not listed in Table 4 because there is not a  
523 measurable flux of  $\text{O}^+$  secondary ions. Because the O ionization energy is relatively large, 13.6  
524 eV, and the ionization probability depends exponentially on ionization energy, we expect the  
525 relative secondary ion yield for  $\text{O}^+/\text{Na}^+$  to be on the order of  $10^{-7}$ , extending the curve in Elphic  
526 et al. (1991, Figure 3). It is likely that the copious amounts of  $\text{O}^+$  observed near the Moon  
527 originated at the Earth.

528

## 529 **4. Simulations**

530

531 To investigate the effect of a CME passage at the moon we ran simulations for an ion-  
532 sputtering source, impact vaporization source, and PSD source. We considered models for Na, K,  
533 Ca and Mg, elements predicted to be observable in the lunar exosphere by instruments on the  
534 LADEE spacecraft (Sarantos et al., 2011).

535

### 536 *4.1 Sodium*

537 The Na exosphere has been observed at the moon and has been shown to be variable. Our  
538 simulations for the lunar sodium exosphere are shown in Figure 1, due to sputtering by a CME  
539 (left) and slow solar wind (right). Figure 1 assumes that the atmosphere is in steady state. Both  
540 left and right sides contain the same steady state PSD and impact vaporization background  
541 sodium atmospheres in addition to the different sputtered components. The source rates are  
542 listed in Table 9. The upper panels show density as a function of longitude and distance from the  
543 moon with the Sun at the right. The lower panels show column abundance projected onto the  
544 surface with the subsolar point at the center. We assumed that Na atoms stick for  $T < 200$  K, and



545 otherwise are re-emitted. Of the particles that stick, 50% of the atoms are re-emitted when the  
546 surface warms up to 200 K again.

547 For the slow solar wind case (right side of Figure 1), the steady state distribution for  
548 sputtering using the slow solar wind source rate is included. For the CME case (left side), the  
549 steady state distribution from sputtering using the peak CME sputtering yields is added to the  
550 PSD and impact vaporization background. The increased sputtering yield from the ICME has  
551 two effects. First, the total Na atmospheric content is increased 6.9 times the ambient  
552 atmosphere. Second, the scale height of the atmosphere increases owing to the increase in higher  
553 energy sodium atoms from sputtering relative to PSD.

554

555 CME conditions typically persist for a few days when and ICME encounters the moon. Thus we  
556 investigate a time dependent case that shows how the exosphere evolves from the slow solar  
557 wind state to the enhanced CME state. In these time-dependent runs, the source rate is elevated  
558 for a 2-day duration to approximate the passage of the ICME. Figure 2 shows the total  
559 atmospheric mass of sodium (and other constituents discussed later) as a function of time during  
560 the passage of the 48-hour ICME. Because it takes longer than 2 days for all sputtered sodium  
561 atoms to be removed from the lunar system, the total sodium mass continues to increase  
562 throughout the event, although it does not increase much after the first several hours. If CME

563 conditions had a longer duration, the exosphere would continue to approach the steady-state  
564 ICME simulation on the left side of Figure 1. As the ICME turns off, there is a rapid decline in  
565 the sodium atmosphere.

566

567 The Auxiliary Material contains movies of the time-evolution of the atmospheric enhancement  
568 for the passing ICME. Movies of the time-dependent runs for Na, K, Ca and Mg, both for the  
569 sputter component alone (Movies 1, 2, 3, and 4) and for the sum of all components including  
570 sputter, PSD, and impact vaporization (Movies 5, 6, 7, and 8), are provided. The color scale is  
571 the same for each movie, and is identical to the color scale in Figure 1. The movies show the  
572 density averaged over latitude as a function of longitude and distance from the center of the  
573 Moon, with the Sun on the right (identical to the top row of Figure 1).

574 Because sputtering is an energetic process, >95% of the sodium ejected by the CME escapes  
575 the Moon or is photoionized. At the Hill radius, 84% reaches that distance without being  
576 photoionized, and 11% is photoionized before reaching the Hill radius. Some (<5%) recycling  
577 within the regolith occurs with the sticking and re-release selected for these runs, as likely occurs  
578 on the Moon.

579

580

581 *4.2 Potassium*

582 Simulations for the lunar potassium exosphere due to sputtering in steady-state by a CME  
583 (left) and slow solar wind (right), are plotted in Figure 3. The coordinate systems and the color  
584 bar are the same as described above for sodium (Figure 1). We assumed that K atoms stick for  
585  $T < 200$  K and that 100% of the atoms that stick to the surface are re-emitted. This assumption of  
586 sticking and re-emission causes the dawnside enhancement (left side of bottom panels above, at -  
587 90 longitude), which would occur for Na under the same assumptions. Under steady-state CME  
588 conditions, the total atmospheric content is 9.3 times that of the ambient K atmosphere.

589 For the 2-day CME run, the total mass of K in the atmosphere follows a pattern similar to  
590 Na (Figure 2.) For both Na and K, the decline in atmospheric mass takes longer than the ramp-  
591 up due to the recycling in the regolith included in the simulations. See also Ancillary Material,  
592 movies 1 and 5 (Na) and 2 and 6 (K).

593 The photoionization rate for K is much faster than for Na. In addition, the heavier mass  
594 of K makes ejected atoms slower than Na. Together, this causes a much greater portion, 45% of  
595 K, to be photoionized before reaching the Hill sphere. These ions subsequently are picked up by  
596 the solar wind. Some are driven back to the surface, depending on the location of ionization and  
597 the direction of the motional electric field.

598

599 4.3 Calcium

600 Figure 4 shows the simulations for the lunar calcium exosphere for the CME (left) and  
601 slow solar wind (right) plotted as for sodium. We assumed that any Ca atom that reencounters  
602 the surface sticks to the surface with unit efficiency. Note that in comparing CME sputtering and  
603 nominal solar wind sputtering, this choice was not very important because <1% of the sputtered  
604 particles actually returned to the surface. However, the Ca released by impact vaporization is not  
605 energetic enough to escape the Moon. Therefore the choice of sticking affects the background  
606 atmosphere substantially. The CME causes a much more extended and denser exosphere than  
607 the slow solar wind. The high sputtering yields for Ca produce an atmospheric enhancement of  
608 36 times the nominal mass of Ca during a prolonged sputtering event on the Moon, based on the  
609 calculated sputtering yield enhancements from the energetic component of the ICME flux.

610 For the time dependent case, the ramp up and ramp down times are much shorter for Ca  
611 than for Na and K. Na and K are less strongly bound to the surface than Ca and Mg. Thus the  
612 energy of sputtered Ca and Mg is greater than sputtered Na and K (eq. 3). It only takes 38  
613 minutes for half of the Ca particles to reach  $10 R_{\text{moon}}$ , compared to 67 minutes for Na. In  
614 contrast to Na and K, the total amount of Ca in the exosphere is back down to the background  
615 level within a few hours of the end of CME conditions (see the Ancillary Material, movies 3 and  
616 7).

617           The effect of the CME on the total mass of Ca in the exosphere is greater than for Na and  
618 K by a factor of a few. This is because there is no PSD component of Ca in the exosphere. PSD  
619 is the dominant source in steady state conditions for Na and K. Thus, the sputtered component is  
620 a greater percentage of the total exosphere for Ca, and its resulting increase during a CME has a  
621 greater relative effect.

622

#### 623 *4.4 Magnesium*

624           Simulations for the lunar magnesium exosphere for the CME (left) and slow solar wind  
625 (right) are plotted in Figure 5. We assumed that 100% of Mg atoms that reencounter the surface  
626 stick are not re-emitted. The magnesium exosphere is more extended than sodium due to its  
627 larger binding energy with the surface. The CME causes a much more extended exosphere than  
628 the slow solar wind, and a factor of 15 increase in the number of magnesium atoms in the  
629 exosphere. The magnesium is similar to calcium due to its similar binding energy with the  
630 surface, but its scale height is larger due to its lesser mass. The time evolution of the Mg content  
631 of the atmosphere during the time dependent run is also similar to Ca, owing to the high velocity  
632 of the sputtered atoms, but it takes the longest to decay owing to its low mass, high velocity and  
633 very long photoionization lifetime (see the Ancillary Material, movies 4 and 8). Like Ca, Mg  
634 lacks a PSD component to the exosphere, which lends a greater relative contribution from the

635 sputtered component. The lifetime of Mg due to photoionization is 204 days, thus  
636 photoionization can be neglected for this species.

637

## 638 **5. Discussion**

639       Using observations of the lunar atmosphere when the Moon is inside and outside of the  
640 Earth's magnetosphere, respectively, Mendillo et al. (1999) concluded that solar wind sputtering  
641 is not a significant source of the Na atmosphere of the moon. Using estimates of the solar wind  
642 density, velocity and composition in the slow solar wind and a CME, we have estimated that a  
643 ~10 fold increase in the lunar exospheric density due to sputtering alone could result from a  
644 CME passage through the influence of sputtering by highly charged ions, including He<sup>++</sup> that  
645 may be highly enriched in the CME plasma. Wurz et al. (2007) argue that the potential sputter  
646 enhancement is strongly dependent upon the ion dose and, after a removal of about a monolayer  
647 from the oxide surface, the sputter yield for highly charged ions drops to about the values for  
648 singly charged ions. As discussed by Barghouty et al. (2011), there was no metalization effect  
649 observed in their measurements of sputtering by highly charged ions, thus the preferential  
650 removal of oxygen from a surface monolayer is most likely not occurring on the lunar surface as  
651 proposed by Wurz et al. (2007). Also, as discussed by Killen et al. (2004) ion-enhanced diffusion  
652 will act to replenish the surface monolayer. The characteristic timescale for an element to reach

653 steady state in a normal solar wind is about 1200 years, which is the timescale for a 1  $\mu\text{m}$  layer to  
654 be overturned on the lunar surface. Thus fresh material is exposed by gardening, and brought to  
655 the surface by diffusion on timescales shorter than timescales on which the elemental abundance  
656 reaches its yield-weighted fractional abundance. Observations of the lunar exosphere during an  
657 extended period of time, especially during solar maximum, could be of use in testing this  
658 hypothesis.

659

## 660 **6. Conclusions**

661 Our simulations indicate that sputtering by the enhanced highly charged heavy ions in the  
662 plasma associated with a CME can enhance the lunar exosphere content due to sputtering by  
663 approximately a factor of  $\sim 10$ , depending on the species. The enhanced flux in the CME plasma  
664 is an additional important factor in enhancing the total sputter yield. The solar wind density and  
665 velocity are being monitored by the STEREO spacecraft, and the heliosphere can be modeled  
666 using the community model center at Goddard Space Flight Center. Future observations of the  
667 lunar exosphere can be used, along with measurements of the solar wind, to test these results.  
668 The Lyman Alpha Mapping Project (LAMP) onboard the Lunar Reconnaissance Orbiter is  
669 conducting observations of the atmosphere that will further constrain the amounts of Mg and Ca  
670 in the lunar atmosphere. LAMP observations in conjunction with these simulations can verify

671 the source rates for those species in the lunar exosphere. The Lunar Atmosphere and Dust  
672 Environment Explorer (LADEE) spacecraft will also observe the atmosphere of the Moon. Its  
673 planned launch in 2013 places the mission during solar maximum. Species expected to reside in  
674 the lunar exosphere normally just below levels of detectability for a 1-s integration by the  
675 LADEE UV spectrometer (Ca, Mg, and Al) (Sarantos et al., 2011) will be elevated above the  
676 limit of detectability during the passage of a CME. Provided that the instrument can operate with  
677 elevated particle fluxes, we will spatially resolve all of these species rather than just "smear"  
678 them spatially in order to detect them. Likewise, species predicted to normally exist in the lunar  
679 exosphere at levels just below detectability by the LADEE Neutral Mass Spectrometer (Si, O  
680 and Al) (Sarantos et al., 2011) should be elevated above minimum detectable limits during the  
681 CME passage. Thus LADEE will provide crucial data to test these predictions through the  
682 neutral mass spectrometer and the UV spectrometer. Furthermore, LADEE will likely observe  
683 the moon as it passes through a meteor shower, allowing it to quantify the contribution of impact  
684 vaporization to the exosphere by observing the enhancement from a sudden increase in the  
685 impact vaporization rate. This model can be used to simulate that process as well.

686         The enhanced exosphere from a CME increases the amount of photoions near the Moon.  
687 Additionally, sputtering ejects a small percentage of species as ions (Elphic et al., 1991). The  
688 results of this work feed into the hybrid plasma calculations of Krauss-Varben et al. (this issue).



689 Picked-up ions were detected downstream of the Moon by AMPTE and WIND (Hilchenbach et  
690 al., 1993; Mall et al., 1998). More recently, Yokota et al. (2009) have detected photoions and  
691 sputtered ions close to the Moon with Kaguya.

692

693 **Acknowledgments**

694

695 This work was supported by the National Aeronautics and Space Administration under  
696 Grants NNX09AH51G and NNG05GA80G issued through the Planetary Atmospheres  
697 Program and by cooperative agreement NNX09AH68A to the DREAM team of the NASA  
698 Lunar Science Institute. The work was facilitated by the SSLAM Lunar Extreme Workshop  
699 conducted by William Farrell and enhanced through the participation of the DREAM team.

700 We thank Walter Huebner for providing photoionization rates for calcium and magnesium.

701 We thank Kevin Tennyson for performing model runs.

702

703

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704

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933 **Figure Captions.**

934

935 Figure 1. Simulations for the composite lunar sodium exosphere due to sputtering by a CME  
936 (left) and slow solar wind (right). Both left and right sides contain the same steady state PSD and  
937 impact vaporization background sodium atmospheres in addition to the different sputtered  
938 components. We assumed that Na atoms stick for  $T < 200$  K, and otherwise are re-emitted. The  
939 upper panels show density, with the sun at the right. The average value over all latitudes is  
940 shown as a function of longitude and distance from the center of the Moon. Circles show the  
941 locations of 5 and 10  $R_{\text{Moon}}$ . The lower panels show column abundance projected onto the  
942 surface with the subsolar point at the center.

943

944 Figure 2. Time-dependent simulations were performed for enhanced sputtering from a 2-day  
945 ICME. The shaded region shows when the sputtering source rate is enhanced. The mass of each  
946 constituent as a function of time is shown relative to its ambient exospheric mass. The time-  
947 dependent runs are illustrated in two-dimensional projection in the movies in the Ancillary  
948 Material. Movies 1, 2, 3 and 4 illustrate the time evolution of the sputter component of the Na,  
949 K, Ca and Mg exospheres, respectively. Movies 5, 6, 7 and 8 for Na, K, Ca and Mg, respectively,

950 illustrate the time dependent evolution of the exospheres including the steady-state background  
951 PSD (for Na and K only) and impact vaporization components with the time-dependent sputter  
952 component co-added.

953

954 Figure 3. Simulations for the lunar potassium exosphere due to sputtering by a CME (left) and  
955 slow solar wind (right), plotted as for sodium. We assumed that K atoms stick for  $T < 200$  K and  
956 that 100% of the atoms that stick to the surface are re-emitted. This assumption of sticking and  
957 re-emission causes the dawnside enhancement (left side of bottom panels above, at  $-90$   
958 longitude), which would occur for Na under the same assumptions.

959

960 Figure 4. Simulations for the lunar calcium exosphere for the CME (left) and slow solar wind  
961 (right) plotted as for sodium. We assumed that Ca atoms stick to the surface with unit efficiency.  
962 Photon-stimulated desorption is not energetic enough to eject calcium or magnesium, but impact  
963 vaporization is included. The CME produces a much denser exosphere than the slow solar wind.

964

965 Figure 5. Simulations for the lunar magnesium exosphere for the CME (left) and slow solar wind  
966 (right) plotted as for sodium. We assumed that Mg atoms stick to the surface with unit efficiency.  
967 The magnesium is more extended than sodium due to its larger binding energy with the surface,

968 which results in a higher ejection velocity. The CME causes a much denser exosphere than the  
969 slow solar wind. Note that there is little difference between the slow and fast solar wind in terms  
970 of sputtering efficiency. The magnesium is similar to calcium due to its similar binding energy  
971 with the surface, but its scale height is larger due to its lesser mass.

972

972 Table 1. Enthalpy of vaporization for various minerals, metals and oxides

973

Material	Enthalpy of vaporization (MJ/kg)
FeS	1.150
Fe	6.272
diabase	8.500
regolith	9.643
MgO	10.46
SiO <sub>2</sub>	20.93

974

975 Table 2. Parameters to fit the minimum impact velocity as a function of distention.

976

Mineral	a	b	c
Al - enstatite	21.014	-14.154	3.058
Al - dunite	28.214	-27.23	7.812
Fe - enstatite	16.657	-11.371	2.5
Fe - dunite	18.893	-17.034	4.866

977

978

978

979 Table 3. Physical parameters for the Moon and Mercury

980

Body	Moon	Mercury
vesc (km/s)	2.376	4.25
g (m/s <sup>2</sup> )	1.624	3.8
radius (km)	1738	2438
tphot (Na)	1.689E5	1.689E5 R <sub>orbit</sub> <sup>2</sup>
tphot (K)	4.510E4	4.510E4 R <sub>orbit</sub> <sup>2</sup>
tphot (Ca)	1.429E4	1.429E4 R <sub>orbit</sub> <sup>2</sup>
tphot (Mg)	1.770E6	1.770E6 R <sub>orbit</sub> <sup>2</sup>

981

982 Table 4. Density, velocity and He<sup>++</sup> fraction assumed for wind types

Wind type	f(He <sup>++</sup> )	density (cm <sup>-3</sup> )	velocity (Km/s)
fast	0.02	5	450
slow	0.04	5	450
shock	0.001	20	600
bubble	0.100	3	650
CME	0.300	70	500

983

984

985 Table 5. Composition of the solar wind, shock, magnetic bubble and driver gas assumed

species ratio	fast wind	slow wind	shock	magnetic bubble	driver gas
alpha/proton	0.02	0.04	0.001	0.10	0.30
O/He	0.0137	0.0119	0.0322	0.0322	0.0322
C/O	0.683	0.670	0.380	0.380	0.380
N/O	0.111	0.088	0.08	0.08	0.08
Ne/O	0.082	0.104	0.32	0.32	0.32
Mg/O	0.105	0.143	0.29	0.29	0.29
Si/O	0.115	0.132	0.18	0.18	0.18
S/O	0.056	0.051	0.122	0.122	0.122
Fe/O	0.092	0.106	0.73	0.73	0.73

986

987 Table 6. Sputter yield of neutrals (atom/ion) of a KREEP surface by solar wind protons, helium

988 and heavy ions

element	Na	Mg	Al	Si	K	Ca	Ti	Fe	Mn	O
yield(H <sup>+</sup> )	2.6E-4	2.4E-3	1.7E-3	3.9E-3	8.6E-5	2.9E-3	5.4E-4	1.3E-3	4.3E-5	2.4E-2
yield(He <sup>++</sup> /H <sup>+</sup> )	13.1	12.8	14.2	14.5	14.9	12.7	14.4	13.6	14.5	12.9
yield(heavy/H <sup>+</sup> )	73	71	79	80	77	74	83	70	61.5	80

989

990

991

992 Table 7. Flux ( $\text{cm}^{-2} \text{s}^{-1}$ ) of neutral elements resulting from kinetic plus potential sputtering of a  
993 KREEP soil for slow wind, fast wind, and the 3 CME components

994

<b>species</b>	<b>slow wind</b>	<b>fast wind</b>	<b>shock</b>	<b>mag. bubble</b>	<b>CME</b>
Na	9.0E4	7.5E4	3.2E5	1.4E5	4.9E6
Mg	8.2E5	6.9E5	2.9E6	1.3E6	4.4E7
Al	6.1E5	5.0E5	2.1E6	9.7E5	3.5E7
Si	1.4E6	1.1E6	4.7E6	2.2E6	7.9E7
K	3.1E4	2.6E4	1.0E5	4.9E4	1.8E6
Ca	9.8E5	8.2E5	3.5E6	1.5E6	5.3E7
Ti	2.0E5	1.6E5	6.7E5	3.1E5	1.1E7
Fe	4.7E5	3.9E5	1.6E6	7.2E5	2.5E7
Mn	1.5E4	1.3E4	5.3E4	2.3E4	8.2E5

995

996 Table 8. Flux ( $\text{cm}^{-2} \text{s}^{-1}$ ) of neutral elements resulting from kinetic sputtering only for a KREEP  
997 soil for slow wind, fast wind, and the 3 CME components

998

999

species	slow wind	fast wind	shock	mag. bubble	CME
Na	7.3E4	6.6E4	3.2E5	1.0E5	3.2E6
Mg	6.7E5	6.1E5	2.9E6	9.3E5	2.9E7
Al	4.8E5	4.4E5	2.1E6	6.6E5	2.1E7
Si	1.1E6	9.8E5	4.7E6	1.5E6	4.7E7
K	2.4E4	2.2E4	1.0E5	3.3E4	1.0E6
Ca	8.0E5	7.3E5	3.5E6	1.1E6	3.5E7
Ti	1.5E5	1.4E5	6.6E5	2.1E5	6.6E6
Fe	3.8E5	3.4E5	1.6E6	5.2E5	1.6E7
Mn	1.2E4	1.1E4	5.2E4	1.7E4	5.2E5

1000

1001 Table 9. Sputter yield of secondary ions (ion/proton) of a KREEP surface by solar wind protons  
 1002 and ratio of yield from He<sup>++</sup> and heavy ions to proton yield

1003

element	Na	Mg	Al	Si	K	Ca	Ti	Fe	Mn	O
yield/H <sup>+</sup>	8E-6	1E-5	2E-5	6E-5	3E-6	2.E-5	1.E-6	3.E-6	2.E-7	-
yield(He <sup>++</sup> /H <sup>+</sup> )	10	10	10	10	10	10	10	10	10	-
yield(heavy/H <sup>+</sup> )	160	160	160	160	160	160	160	160	160	-

1004

1005



1006 Table 10. Source rate ( $s^{-1}$ ) for each species and process included in the simulations presented in

1007 Figures 1-5.

1008

<b>species</b>	<b>PSD</b>	<b>Impact vaporization</b>	<b>Slow SW</b>	<b>CME</b>
Na	9.49E21	1.79E21	8.54E21	4.65E23
K	3.80E21	2.81E20	2.94E21	1.71E23
Ca		2.95E22	9.30E22	5.03E24
Mg		3.08E22	7.78E22	4.18E24

1009

1010