NOTE
Sodium at Europa

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The observations of atomic sodium in Europa’s atmosphere (M. E. Brown and R. E. Hill 1996, Nature 380, 229–231, and an analytic model for the sputter-produced corona are used to estimate the Na loss rate from Europa. This loss rate appears to be larger than the rate of implantation of Iogenic Na into Europa’s surface when the local deflection of the incident ions is accounted for. Therefore, Europa’s surface, like that of the Moon, Mercury, and Io, may be a net source of Na. The required surface sputtering rate, derived for radiation-induced decomposition of hydrated minerals and for sputtering of Na in ice, is used to estimate the average Na concentration in Europa’s surface.

Key Words: Europa, atmospheres; composition, jupiter; magnetosphere.

1. Introduction. Although Na atoms are a trace species in most planetary atmospheres, they are easily seen via their resonance line near the peak of the solar spectrum. Therefore, the observation of Na near Io (Brown and Chaffee 1974) was the first indication that a moon of Jupiter had an escaping atmosphere. Subsequently, Na was seen at Mercury and the Moon. Here we examine the more recent observation by Brown and Hill (1996) that Europa, like Io, Mercury (Potter and Morgan 1985), and our Moon (Potter and Morgan 1988), has an atmosphere containing Na atoms which escape to space.

The observation of Na in the ambient gas at Europa preceeded the recent Galileo near-infrared observations (NIMS instrument) which suggested that Europa has hydrated Mg and Na-containing salts on its surface (e.g., McCord et al. 1998, 1999). This interpretation of the Galileo NIMS observations has generated considerable excitement because Europa is thought to have an underground ocean (Kuratana et al. 1998, Carr et al. 1998). Therefore, hydrated salts on the surface could indicate that material from this ocean has reached the surface sometime in the past. Since the presence of liquid water is thought to be a prerequisite for biologic activity, the possibility that we can study material from the putative ocean by remote sensing of gas-phase species sputtered from the surface is an exciting prospect (Johnson et al. 1998).

Recently, Carlson et al. (1999a) suggested that the hydrated minerals bands are consistent with frozen hydrated–sulfuric acid rather than hydrated salts. Therefore, it is important to obtain constraints on both the Mg and Na abundances in the surface. Here I use the atmospheric Na observations of Brown and Hill (1996) to examine the Na component. Before proceeding, it is important to remember that even the youngest surfaces suggested by Europa’s geology are much older than the time required to achieve equilibrium with the radiation environment. Therefore, the optical surface (<1 cm at unit density) is in sputter equilibrium everywhere on Europa (Cooper et al. 2000, Carlson et al. 1999b) and is not pristine.

The dominant species in Europa’s atmosphere is thought to be O 2 (Johnson et al. 1982, Johnson 1990, Hall et al. 1995), which comes from decomposition of water ice, a principal surface constituent. This decomposition is produced by charged-particle irradiation of Europa’s surface (Ip 1996, Ip et al. 1998, Cooper et al. 2000). Therefore, other products of sputter-induced decomposition of Europa’s surface will be present in the gas-phase (Johnson et al. 1998). One such element is Na, which is a radiation-induced decomposition product for a number of planetary materials (Maday et al. 1998, Johnson 2000). Iogenic sodium in the jovian plasma can also be implanted into Europa’s surface (Brown and Hill 1996). However, Brown (1999) recently showed the Na-to-K ratio differed from that at Io. Here I examine whether the sodium seen in Europa’s atmosphere is endogenic, consistent with an interpretation of the Galileo observations that a significant fraction of the surface consists of Na-containing hydrated minerals.

Because of the low surface temperatures the atmospheric sodium is produced by sputtering of the surface by the jovian plasma, whether the Na is implanted or endogenic. Therefore, the implantation rate for sodium is first estimated in Section 2, and then sputtering is reviewed in Section 3. Readers can, if they prefer, skip Section 3 and go directly to the estimates of the Na loss rate obtained from the Brown and Hill data. This is used to estimate the concentration of sodium in Europa’s surface. The implantation and loss rates are then compared suggesting that Europa is a net source of sodium.

2. Implantation rate. In addition to possible endogenic sources of sodium discussed above, Na + ions from the jovian torus are implanted into Europa’s surface as described by Brown and Hill (1996). However, in their estimates of the implantation rate they did not account for the deflection of the plasma by the ionospheric fields. Saur et al. (1998) recently calculated a reduction factor, f i, for deflection of the bulk of the plasma by induced fields. They find significant reductions, f i ≈ 0.1–0.2 for atmospheric columns ~1.5–0.5 × 10 18 O 2 /cm 2, respectively. The flux of torus ions to Europa’s surface is written \( \Phi_i = \Phi_i^p \cdot \Phi_i^a \), where \( \Phi_i^p \) is the undeflected flux in the Europa plasma torus. There is an additional flux of local pick-up ions (Ip 1996), which will affect the sputter rate discussed below but not the implantation of Iogenic Na. The globally averaged implantation source rate can be written \( \Phi_i = \Phi_i^p \cdot \Phi_i^a \), where \( \Phi_i^a \) is the concentration of Na in the plasma which is not a well-known quantity. The factor, \( \Phi_i^a \), accounts for preferential impact of the bulk of the plasma on the trailing hemisphere. Brown and Hill used an undeflected flux of \( \Phi_i^p = 8 \times 10^8 \text{ions/cm}^2/\text{s} \), with \( \Phi_i^a = 0.01 \). However, a range of concentrations, \( \Phi_i^a = 0.01–0.02 \), may be more reasonable (Bagenal 1994). This gives an implantation flux \( \sim 0.2–0.8 \times 10^8 \text{Na/cm}^2/\text{s} \). These ions are implanted into both ice and sulfur-rich regions of Europa’s surface as discussed below.

3. Sputtering of sodium. Laboratory measurements are available for energetic ion sputtering of Na 2 SO 4 (Wiens et al. 1997) and Na 2 S 8 (Chrisey et al. 1988). These two species, in addition to SO 2 and S 8, are the Na-containing materials that have been proposed are hydrated salts, Na 2 SO 4, H 2 O and Na 2 CO 3, H 2 O with X = 6–10 (Fanele et al. 1974; Kargel 1991; McLeod et al. 1998, 1999).
Irradiation of salts was extensively studied ~30 to ~40 years ago because of the need for storing radioactive wastes (Hennig et al. 1953). Recently, Madey et al. (1998) reviewed the literature on the desorption of Na from various materials by incident radiation. However, the gaps in our knowledge are significant.

Since the principal atmospheric species at Europa, O$_2$, is a product of the decomposition of H$_2$O, it is presumed here that the atmospheric Na is a decomposition product of a surface mineral (Johnson et al. 1998, Johnson 2000). Under lightly ionizing radiation, such as the protons and electrons in the energetic particle flux seen by Galileo (Cooper et al. 2000), sulfate salts are remarkably stable, whereas nitrates (Hennig et al. 1953, Knutson and Orlando 1997) and carbonates such as Na$_2$CO$_3$ are much less stable. The stable species is the sulfate anion, SO$_4^{2-}$, but Na is readily desorbed and the hydrated minerals can lose their water of hydration (Johnson 2000). Therefore, one might expect that the surface minerals are dehydrated and depleted in Na if exposed to extensive irradiation. Indeed, hydrated copper sulfate changes color under heavy ion bombardment consistent with losing its water of hydration. But P. Williams (private communication, 1998) showed that on subsequent exposure to water vapor the irradiated crystal is quickly restored to its earlier state. Therefore, the regions of hydrated surface minerals on Europa will exist in a particular level of hydration that is in equilibrium with neighboring regions of surface ice. Similarly, Na will also exist in the surface in some global equilibrium.

A. Sputtering of minerals. Secondary ion mass spectrometry (e.g., Bennigshoven 1969) on alkali-containing salts clearly indicates that loss of Na and decomposition occur under heavy ion bombardment. Wiens et al. (1997) and Chrisey et al. (1988) showed that Na atoms were the dominant form of ejected sodium from both Na$_2$SO$_4$ and Na$_2$S$_2$, by an order of magnitude. Recently, Yakshinskiy and Madey (1999) showed that Na atoms are also desorbed electronically from minerals by electrons and UV irradiation. Therefore, although the sulfate is radiation resistant, Na will be preferentially desorbed by both heavy ions and by the lightly ionizing radiations. In addition, penetrating radiation and surface charging can cause Na to diffuse efficiently through many materials, as discussed for the Moon (Johnson and Baragili 1991) and Mercury (McGrath et al. 1986). In this way Na, a trace element can persist in the surface.

The energy distribution of Na sputtered by heavy ions (Wiens et al. 1997) was found to be well fitted using the distribution for collision cascade sputtering, $f(E) = 2E(E + U)^{1/2}$ (e.g., Johnson 1990). In this expression, $E$ is the energy of the Na leaving the surface and $U$ is a parameter often related to the surface binding energy of the atom. For the Na$_2$SO$_4$ samples and incident ions studied $U \approx 0.27$ eV. This value of $U$ is very different from the material sublimation energy and gives a peak in the energy spectrum ($U/2$) similar in size to the peak in the energy spectra for electronic-stimulated desorption of alkalis (Madey et al. 1998, Yakshinskiy and Madey 1999). Therefore, electronic processes control the sodium sputtering efficiency (Johnson 1990, 1998). Here, this energy distribution will also be used for sputtering of sodium from hydrated Na$_2$SO$_4$.

The absolute yields for sputtering of Na$_2$SO$_4$ were estimated (Wiens et al. 1997) assuming that the average atomic ejection efficiency was roughly the same as that measured for Na$_2$S. Chrisey et al. (1988) measured the yields for sputtering of Na$_2$S by 34-keV Ne$^+$ and Ar$^+$ ions; these are representative of energetic O$^+$ and S$^+$ which are the dominant sputtering agents in the Europa torus. They obtained $Y \approx 0.25$ and 0.5 Na$_2$S/ion for incident O$^+$ and S$^+$ respectively. This would give $Y \approx (0.7 \pm 3.5) \times 10^{-6}$ Na$_2$S/ion, where c$_{Na}$ is the areal concentration of atomic Na in the surface. The yield, of course, should depend on the molecular environment of the sodium atom. After adjusting for the concentration, c$_{Na}$, the yield should be somewhat larger for the hydrated material. Also, the laboratory data give the yield after extensive irradiation. Since Na desorption is prompt, the removal from a fresh surface is more efficient. Therefore, the laboratory surfaces are depleted in Na after a short irradiation time, suggesting the yields for a fresh surface are larger. Finally, the recent discovery of Cl$^-$ in the Io plasma torus (Kueppers and Schneider 1999) means that chlorine is also an important satellite constituent. Therefore, frozen hydrated NaCl may be present in Europa’s surface. Na is also ejected efficiency from NaCl by an electronic process, (Madey et al. 1998), leading to a soft energy spectra.

B. Sputtering of sodium in ice. In addition to Na diffusing to the surface, Na$^+$ plasma ions from Io are implanted into Europa’s surface, as discussed above, and returning sputtered Na atoms are readsorbed on the surface. Implanta- tion or adsorption in a sulfur-rich region could produce sodium sulfates or sulfides. However, Europa’s icy surface is oxidizing due to preferential loss of hydrogen (Johnson and Quickenden 1997). This was confirmed by the presence of significant concentrations of H$_2$O$_2$ in the irradiated ice (Carlson et al. 1999b). Therefore, likely products are NaOH, NaO, and Na$_2$O (Johnson 2000), although NaOH not seen in the NIMS spectra at the few percent level (R. W. Carlson, private communication, 1999). Since NaOH is more volatile than Na$_2$SO$_4$ or Na$_2$S$_2$, it would be sputtered more efficiently. For this reason, and the fact that Na is efficiently desorbed from the sulfate, the yield given above is a lower bound for ejection of atomic Na from materials relevant to Europa’s surface.

Since the sputtering yields for ice-rich regions are large, implanted or adsorbed Na would be sputtered with the bulk material, independent of the its molecular state in the ice (Johnson et al. 1998). The sputtering yield for ice averaged over the fast and slow plasma is ~40 H$_2$O/ion, and the energy spectra is represented, roughly, by $U \approx 0.055$ eV (Reizmann et al. 1984), again indicative that electronic processes dominate. Weighting the yield by the Na content gives an upper bound to the Na sputtering yield.

C. Photon-stimulated desorption of Na. At Europa, the energetic plasma ions and electrons deposit a greater amount of energy than the UV photons, but this energy is distributed differently with depth into the surface (Cooper et al. 2000). Therefore, photo-induced desorption (McGrath et al. 1986) can be principal be important. The photo-desorption cross-section for Na absorbed on a silicate was recently measured to be $\sigma_{\text{Na}} \approx 3 \times 10^{-20}$ cm$^2$ and increases with photon energy (Yakshinskiy and Madey 1999). Using this cross-section and the flux of photons $\approx 5 \times 10^{-17}$ cm$^{-2}$ s$^{-1}$, a lower bound to the globally averaged UV desorption flux is $5 \times 10^{-19}$ cm$^{-2}$ s$^{-1}$ n$_i$. The size of the escape fraction and reasonable estimates of c$_{Na}$ suggest that UV desorption is not the controlling escape process.

D. Summary. When applying laboratory sputtering yields to a satellite surface a reduction factor is needed to account for the presence of the regolith. Hapke (1986) suggested a factor of 10 for collisional sputtering of refractory solids, and Johnson (1989) suggested a factor of ~4 net reduction for electronic sputtering. There is also an enhancement factor due to nonnormal incident (Jurac et al. 2000) for the dominant sputtering agents giving a net reduction ~1–5. For these materials I reduce the yields by a net factor of 2. Therefore, a very rough lower bound to the Na sputtering yield is obtained for sputtering from the hydrated minerals, $Y > \approx 0.5$ c$_{Na}$ Na/ion using about half-energetic S and O in the heavy ion plasma (Bagental 1994, Cooper et al. 2000). A very rough upper bound is obtained considering Na in ice, giving $Y < \approx 0.2$ c$_{Na}$ Na/ion.

4. Na loss rate from Europa. The observations of Brown and Hill (1996) describe the Na column well above the atmospheric exobase. Since the surface of Europa is the source of atmospheric sodium, the thickness of the ambient gas controls the escape process. The column density of Europa’s O$_2$ atmosphere formed by decomposition of ice was estimated to be $\approx 3 \times 10^{13}$ O$_2$/cm$^2$ (Johnson 1990). This consisted of a relatively small, directly sputtered, energetic component (Johnson et al. 1983) and a much larger, thermally accommodated component (Johnson et al. 1982). The observation of excited atomic O formed from O$_2$ dissociated by electron impact (Hall et al. 1995) also suggested $\approx 2 \times 10^{12}$ O$_2$/cm$^2$, in which case Europa would have more than an exospheric component of gas. Therefore, Na sputtered from the surface would collide with the ambient O$_2$ so that a process-like atmospheric sputtering would determine the loss rate. Recently, Saur et al. (1998) estimated that the O$_2$ observations are more consistent with $\approx 0.6 \times 10^{13}$ O$_2$/cm$^2$. This is less than or on the order of an exospheric component for Na escaping through O$_2$. Therefore, direct sputtering from the surface to space is possible and is used to determine a rough lower bound to the surface source rate and column density. Knowledge of the sputtering efficiency can then be used to give an upper bound to the Na concentration on the surface. The Na observations are evaluated both for directly escaping, sputtered Na and for atmospheric sputtering. The sputtered-atom energy and angular distribution, $f(E, \theta)$, determines the density of the ballistic atmosphere with distance from the surface, $n(r)$. 
The atmospheric structure in the region observed by Brown and Hill is only weakly dependent on the type of nonthermal Na escape process (Johnson 1994). That is, Na may be sputtered from the surface, as discussed, or if there is a thick enough atmosphere, Na populates the corona by either atmospheric sputtering or a molecular dissociation process. If the loss of Na is driven by atmospheric sputtering, then a fit to the atmospheric corona data in Fig. 1 is again obtained and a rough upper bound to the Na escape flux can be calculated using the analytic expressions in Johnson (1990). Assuming an “incomplete” collision cascade energy spectra associated with escaping particles, \( f(E) \approx A/E^{1.5} \) (Smyth and Combi 1988, Johnson et al. 2000), the column density in the region of interest is \( N(b) \approx \pi \Phi_\text{esc} \langle R_\text{c}^2 \rangle /b \), where \( \Phi_\text{esc} \) is the escape speed. Matching to the data in Fig. 1 gives \( \Phi_\text{esc} \approx 4 \times 10^6 \text{Na/cm}^2 \text{s} \). These bounds place reasonably tight constraints on the escape flux.

Because the Na column observed over the two hemispheres of Europa was nearly the same, these are, roughly, globally averaged escape fluxes. Since the plasma ions and the energetic ions exhibit different spatial bombardment profiles (Pospieszalska and Johnson 1989), this suggests that electronic sputtering by the energetic ions with large gyro-radius is the dominant erosion process. Note that the Na escape flux is only about 0.1% of the total atmospheric oxygen loss rate (Saur et al. 1998).

5. Discussion and conclusions. The optical surface of Europa is in radiation-induced, chemical equilibrium (Carlson et al. 1999a,b; Cooper et al. 2000). For sodium this involves implantation and sputter removal competing with possible endogenic sources. Sputtering is, of course, the ultimate source of atmospheric sodium. The escape rate of sodium extracted from the observations of Brown and Hill requires a surface sputter flux of \( \Phi_\text{s} \approx 5 \times 10^6 \text{Na/cm}^2 \text{s} \) if the refractory regions dominate on Europa’s surface. This escape flux and the corresponding energy distribution imply a minimum atmospheric density at the surface of \( \approx 90 \text{Na/cm}^3 \) using the expressions in Johnson (1990), Appendix 4.D. The plasma reduction factor applies to the lower energy ions and gives \( \Phi_\text{s} \approx 0.8–1.6 \times 10^6 \text{ions/cm}^2 \text{s} \). The flux of high energy ions (>10 keV) have an enhancement factor of about 1.5 due to gyro motion (Pospieszalska and Johnson 1989), contributing \( \approx 0.7 \times 10^6 \text{ions/cm}^2 \text{s} \) (Cooper et al. 2000), so that \( \langle Y \rangle \approx 0.02–0.03 \). Applying the sputtering yield derived above for the refractory regions, \( \langle Y \rangle \approx 0.5 \text{Na} \), then the required surface concentration of Na is \( c_{\text{Na}} \approx 0.04–0.06 \). This concentration is probably too large. Even in the regions thought to be dominated by hydrated salts, the best fit in McCord et al. (1999) to the NIMS spectra of the hydrated minerals containing Na requires \( c_{\text{Na}} \approx 0.08 \) weighting the H’s by a half. If hydrated sulfatic acid dominates (Carlson et al. 1999a), then much smaller concentrations are expected. Therefore, sputtering is likely more efficient than estimated, as discussed earlier.

Using the sputtering estimate for sodium in ice and the appropriate velocity distribution, the atmospheric density of Na near the surface is \( \approx 600 \text{Na/cm}^3 \). Assuming the same ion flux as above and using a yield of \( \langle Y \rangle \approx 0.8 \text{Na}, \text{ion} \), the global average concentration required is \( c_{\text{Na}} \approx 0.004–0.007 \). This is closer to what one might expect in Europa’s surface layer. Therefore, although more efficient sputtering than estimated here must occur in the refractory regions, the supply to the atmosphere is dominated by sputtering from the icy regions, as is the case with atmospheric O\(_2\). This suggests a globally averaged surface Na concentration of 0.5%.

It is seen above that a reasonably well-constrained estimate of the Na loss rate is \( \approx 2–4 \times 10^3 \text{Na/cm}^2 \text{s} \). This is larger than the estimate of the Iogenic implantation rate, \( \approx 0.2–0.8 \times 10^6 \text{Na/cm}^2 \text{s} \). Although there are considerable uncertainties in both estimates, this comparison implies that Europa is likely a net source of Na, as is the case for the Moon, Mercury, and Io. In a recent paper Brown (1999) showed that the Na-to-K ratio in Europa’s atmosphere differs from that at Io, also suggesting that observed sodium is endogenic. The largest uncertainty in the estimate presented here is in the flux of Na implanted into the surface. This is determined using an estimate of the plasma flow to the surface and a very rough estimate of the Na\(^+\) concentration in the Europa torus. Although the modeling of the total flux will improve rapidly, better estimates for the Na ion concentration are not likely in the near future. However, even using the maximum concentration \( c_{\text{Na}} \approx 0.03 \) (Bagenal 1994) does not change this conclusion. In addition, I think the O\(_2\) observations support the thicker atmospheric model which gives the lowest implantation rate (largest plasma.

FIG. 1. Line of sight column abundance, \( N \), of sodium atoms vs distance, \( b \), from Europa given in Europa radii, \( R_E \). Diamonds are the data of Brown and Hill (1996). The solid curve is for sputtered Na atoms calculated from Eqs. 4.D.1 and 4.D.2 in Johnson (1990) with satellite escape energy 0.48 eV and using collision cascade energy distribution \( f(E) \), described in text with \( U = 0.27 \text{eV} \) with a solid angle distribution (cos \( \theta/\pi \)). This calculation is then fitted to the observations in order to obtain the surface sputter flux \( \Phi_{\text{surf}} \approx \langle Y \rangle \Phi_i = 5.1 \times 10^8 \text{Na/cm}^2 \text{s} \). The dashed line is the nesconesizing contribution for this energy and angular distribution: the escape flux is \( \Phi_{\text{esc}} \approx 3 \times 10^8 \text{Na/cm}^2 \text{s} \) if the refractory material dominates the surface, and \( \Phi_{\text{esc}} \approx 2 \times 10^6 \text{Na/cm}^2 \text{s} \) for an ice-rich surface.

From the energy distribution discussed above and a simple angular distribution, \( f(E, \theta) = [2U E/(E + U)] \text{cos} \theta/\pi \) is the normalized distribution per energy interval per unit solid angle, with \( \theta \) being the angle relative to the surface normal. This is used in Eqs. 4.D.1 and 4.D.2 in Johnson (1990) to obtain an analytic expression for \( n(r) \), which is assumed to be isotropic to first order (Johnson 1990, Eqs. 4.D.1 and 4.D.2). It consists of two components, one of which consists of gravitationally bound atoms and the other escaping atoms. To obtain the line-of-sight column density, \( N(b) \), integrate the density, \( n(r) \), over the straight-line path defined by \( b \) which is the closest distance to the Moon. At large \( b \) this results in the form \( N(b) = \langle R_\text{c}^2 \rangle /b \) (Johnson 1990), where \( R_E \) is the radius of Europa. This is the dependence seen in the data in Fig. 1 from about 5–13 \( R_E \).

The full expression for the sputter-produced column density obtained using \( U = 0.27 \text{eV} \) is matched to the measured column density in Fig. 1 by choosing the surface flux \( \Phi_{\text{surf}} \approx 5.1 \times 10^8 \text{Na/cm}^2 \text{s} \). This flux is written as \( \Phi_{\text{surf}} = \langle Y \rangle \Phi_i \), where \( \Phi_i \) is the ion flux to the surface and \( \langle Y \rangle \) is the average sputtering yield. \( \langle Y \rangle \) must account for the average surface concentration of Na. Both the total column and the contribution from bound trajectories are shown in Fig. 1. It is seen that the fit is good over a broad range of \( b \) and that the atmosphere in the region observed is dominated by escape. It is also seen that the observed column falls off faster with \( b \) at large \( b \) consistent with an ionization lifetime of Na in the plasma \( \approx 10 \text{h} \). If the same procedure is used for implanted or adsorbed Na carried off with ice then the values \( U \approx 0.055 \text{eV} \) and \( \Phi_{\text{surf}} = \langle Y \rangle \Phi_i \approx 2 \times 10^7 \text{Na/cm}^2 \text{s} \) are required to match the data in Fig. 1.

A lower bound to the escape flux for direct sputtering of Na is now obtained from the fit in Fig. 1. The escape flux is \( \Phi_{\text{esc}} = f_d \langle Y \rangle \Phi_i \), where \( f_d \) is the escape fraction (Johnson 1990). Using the energy distribution above, this is \( f_d = U/[2U_i + U]/[U_i + U]^2 \approx 0.6 \) when \( U = 0.27 \text{eV} \), and \( f_d = 0.1 \) when \( U = 0.055 \text{eV} \). Here \( U_i = 0.48 \text{eV} \) is the gravitational binding energy for sodium at Europa. Therefore, the escape flux is \( \Phi_{\text{esc}} \approx 3 \times 10^8 \text{Na/cm}^2 \text{s} \) if the refractory material dominates the surface, and \( \Phi_{\text{esc}} \approx 2 \times 10^6 \text{Na/cm}^2 \text{s} \) for an ice-rich surface.
Evolution of lineaments on Europa: Clues

Cooper, J. H., R. E. Johnson, B. H. Mauk, and N. Gehrels 2000. Energetic ion


Carlson, R. W., R. E. Johnson, and M. S. Anderson 1999a. Sulfuric acid in the

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Cooper et al. 1999, Geissler et al. 1999, the sodium in the source region must be replenished from below. This is accomplished, as stated earlier, by enhanced sodium diffusion produced by the highly penetrating ions and electrons (~1 gm/cm²; Cooper et al. 2000) and by meteoritic mixing of the surface. However, a fresh surface area containing a hydrated sodium sulfate or carbonate will rapidly lose much of its surface-layer sodium. Since the sulfate is relatively stable, the Na is replaced by H, forming hydrated H 2 SO 4 (Carlson et al. 1999a) as well as hydrated NaHSO 4 . Therefore, although there appears to be evidence for endogenic Na, its surface manifestation will be very indirectly related to the nature of its source. Mg on the other hand is not sputterred efficiently, and therefore, if it is a constituent of a “fresh” surface it should be seen in an oxidized form (Johnson et al. 1998, Johnson 2000).

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