



## Exospheric signatures of alkali abundances in Europa's regolith

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[1] The sodium and potassium exospheres of Europa are described as well as the variations of the Na/K ratio from Europa's surface up to about 20 Europa radii. Observations carried out by M. E. Brown (2001) are used to constrain the Na and K source terms. We find that an average source rates ratio of  $17 \pm 2$  at the surface and loss rates ratio of  $26 \pm 2$  reproduce well the observations. These values are consistent with the conclusions by R. E. Johnson et al. (2002) on its most probable origin. Moreover, we here show that a local increase of the surface Na/K ratio by a factor 2 in a  $20^\circ \times 30^\circ$  wide region should induce an observable exospheric signature between 80 and 300 km above the surface. Therefore simultaneous observations of sodium and potassium from an Europa orbiter would allow one to derive important properties of the surface and subsurface of the Galilean moon. **Citation:** Cipriani, F., F. Leblanc, O. Witasse, and R. E. Johnson (2009), Exospheric signatures of alkali abundances in Europa's regolith, *Geophys. Res. Lett.*, 36, L12202, doi:10.1029/2009GL038636.

### 1. Introduction

[2] Brown [2001] observed simultaneously sodium and potassium at Io and Europa using the HIRES Echelle spectrograph at the Keck telescope. He derived a Na/K line-of-sight density ratio close to 25 at radial distances between 5 and 15 Europa radii ( $R_E$ ) from Europa center and a ratio close to 10 from 10 to 20 Io radii from Io center. Considering the possible channels of sodium and potassium transport from Io to Europa, he concluded that Io cannot be the primary source of the alkalis observed at Europa. Johnson et al. [2002] carried out Monte Carlo modelling of sodium and potassium sputtered from Europa's surface and used Na/K observations to constrain Na and K surface source rate (model sources supplied to the surface from below and above, hereafter noted  $\Phi_S$ ) and global loss rate (hereafter noted  $\Phi_L$ ) at Europa. A surface source rate ratio of  $20 \pm 4$  was estimated, corresponding to a concentration ratio for Na/K (hereafter noted  $R_C$ ) close to 27 at a depth below the charged particles penetration depth at the surface.

[3] In the present study, we use a refined 3D model of Europa's exosphere initially developed by Leblanc et al. [2002, 2005] and recently improved by Cipriani et al. [2008]. This model accounts for non-uniform sources of alkalis at Europa's surface and allows us to describe the relation between exospheric and surface densities of the

ejected material. In the present paper, the exospheres of sodium and potassium are built and compared to observations by Brown [2001] in order to better constrain the Na/K source rates ratio  $\Phi_S$  at the surface and to analyze possible signatures of the Na/K surface distribution in Europa's exosphere.

### 2. Model's Description

[4] The model used to simulate Europa's sodium exosphere was described by Cipriani et al. [2008]. In the present study, we also simulate the ejection of potassium atoms from Europa's regolith due to sputtering of the surface material by magnetospheric ions and electrons, and due to photo-stimulated desorption by UV solar photons (hereafter noted PSD). The flux of magnetospheric particles able to sputter Europa's surface is composed of hot electrons [Paranicas et al., 2002] and cold ions (with small gyroradius so that they impact Europa's surface with a globally trailing/leading asymmetry [see Popieszalska and Johnson, 1989]) and of energetic ions (with large gyroradius and therefore with a globally uniform flux at the surface [see Cooper et al., 2001; Paranicas et al., 2002]). Ejected atoms are followed until they are lost when they impact either Europa or Jupiter's surfaces, reach the limit of the calculation domain (at  $1000 R_E$  from Europa's center), or are ionized and swept away by Jupiter's magnetospheric plasma. The fraction of the ionized population which re-impact the surface is neglected here. As was done by Johnson et al. [2002], the time and space averaged electron impact ionization rate of potassium is about 1.2 times the rate for sodium. We also use the energy distribution of potassium atoms sputtered from an icy regolith published by Johnson et al. [2002]. The potassium energy distribution peaks at a slightly lower value (0.5 eV) than the sodium energy distribution (0.8 eV) and its tail decreases slightly faster. As was done by Cipriani et al. [2008], we use energy distributions for sodium and potassium ejected by PSD similar to the sputtering energy distributions. The surface sputtering yield is taken as a weighted function of sputtering yields for pure ice and non-ice bearing materials present at the surface, assuming a non-ice fraction distribution derived from New Horizons/LEISA measurements by Grundy et al. [2007].

### 3. Model Simulation of the Na/K Surface and Exospheric Ratio

#### 3.1. Altitude Variation of the Exospheric Na/K Ratio

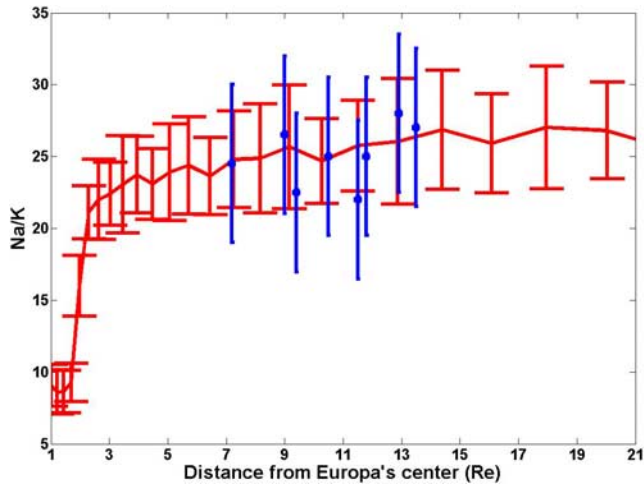
[5] Brown [2001] observations of the Na/K exospheric ratio (hereafter noted  $\Phi_E$ ) were carried out with a slit parallel to the rotational pole of Jupiter and placed at various distances from Europa's center along an east/west axis. Variations of the average simulated ratio of the line of sight

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**Figure 1.** Dependence of the Na/K column density ratio on the radial distance from Europa's center, along an east/west axis in Europa equatorial plane. The red line shows the simulated ratio averaged along Europa's orbit, with error bars corresponding to 1 standard deviation along an orbit. Blue squares with error bars show observed ratio by *Brown* [2001].

column densities of Na and K along an east/west axis and as a function of the distance from Europa's surface are shown in Figure 1 (red line). The mean standard deviation of this ratio along Europa's orbit is  $\pm 15\%$ . The numerical uncertainty on the average value is  $\pm 5\%$  (we estimate that numerical noise in our simulation is responsible for about 30% of the observed variability of the ratio of the Na/K source rates  $\Phi_S$  and of the Na/K loss rates  $\Phi_L$  over Europa's orbit around Jupiter). This uncertainty has been minimized by adding outputs from 10 separate runs involving each about  $3 \times 10^6$  representative test-particles ejected from the surface (with an average of  $2 \times 10^4$  exospheric test particles during the whole simulation). An intrinsic variability between 5% and 15% of the Na/K ratio  $\Phi_E$  is therefore observed along the orbit.

[6] The Na/K ratio  $\Phi_E$  appears as nearly independent of the radial distance from Europa beyond  $3 R_E$  from its centre. Between 1 and  $1.5 R_E$ , the ratio is roughly constant and close to Europa's average surface ratio value of 7 (ratio of surface densities, hereafter noted  $R_D$ , see section 3.2). It then increases steeply from  $1.5 R_E$  up to  $2 R_E$  up to values between 20 and 25. The closest region to Europa's surface is therefore the best place where to derive information on the concentration of Na and K in the surface. The size of this region is directly dependent on the energy distributions with which these species are ejected. The second region with a steep gradient is also essentially dependent on the energy distributions. The minimal energy required for a Na atom to reach  $3 R_E$  is close to 0.11 eV (that is about three times the peak energy of the Na distribution), whereas it is close to 0.2 eV (that is about six to seven times the peak energy of the K distribution) for a K atom. The variation of the Na/K exospheric ratio  $\Phi_E$  from  $1.5 R_E$  to  $2 R_E$  is, therefore, associated with the depletion of the K atoms with increasing altitude. Beyond  $2 R_E$ , few measurements of the Na and K exospheric densities should provide crucial information on

their relative abundances below the radiation's penetration depth [*Johnson et al.*, 2002]. Good agreement with *Brown* [2001] observations is obtained by adjusting the average surface source rates of potassium and sodium. Using the average sodium source rate of  $3 \times 10^6 \text{ cm}^{-2} \cdot \text{s}^{-1}$  constrained from the observed exospheric emission brightness of the sodium cloud [*Cipriani et al.*, 2008], we derive an average ratio of the source rates of sodium to potassium at the surface  $\Phi_S$  equal to  $17 \pm 2$  and an average surface source rate for potassium close to  $1.8 \times 10^5 \text{ cm}^{-2} \cdot \text{s}^{-1}$ . The average ratio  $\Phi_S$  of the surface source rates of  $17 \pm 2$  value is in the lower range estimated by *Johnson et al.* [2002], a source rate ratio of  $20 \pm 4$ , but is still significantly larger than the ratio measured at Io by *Brown* [2001].

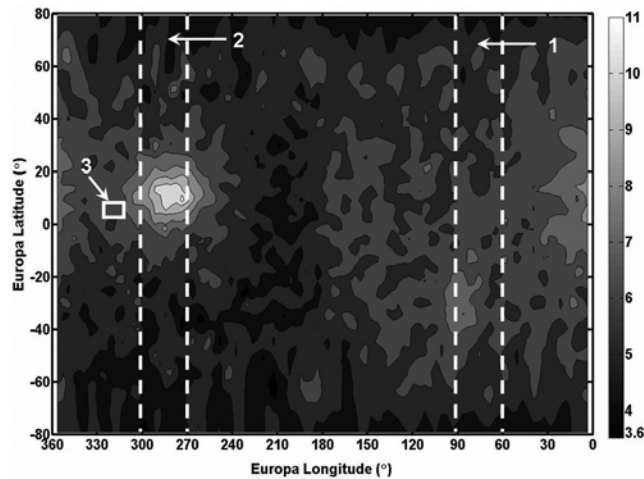
[7] Our estimate of the ratio of the loss rates  $\Phi_L$  is  $26 \pm 2$ , very close to *Johnson et al.* [2002] estimate of 27. As shown in Figure 1, this ratio of the loss rates  $\Phi_L$  can be estimated by measuring the ratio of the Na/K densities  $\Phi_E$  at distance larger than  $5 R_E$  (that is, all particles reaching distances larger than  $5 R_E$  escape Europa). The calculated value does not account for the ionic fraction of Na and K returning to the surface. The mean altitude of ionization of Na is 230 km and the mean altitude for K is 200 km. The component that becomes ionized represents about 16% of the ejected Na atoms and only 4.5% of the ejected K, whereas the fraction of neutral component escaping is about 5% for Na and only 1% for K. Therefore, the proportion of  $\text{Na}^+$  ions with respect to Na atoms returning to the surface is probably larger than the  $\text{K}^+/\text{K}$  ratio. As a consequence, the actual Na/K surface source term ratio  $\Phi_S$  (which is the sum of endogenic and exogenic terms) is probably slightly larger than the  $17 \pm 2$  ratio calculated here.

[8] Following the analysis by *Johnson et al.* [2002], the ratio of the loss rates  $\Phi_L$  of Na and K  $26 \pm 2$  is roughly representative of the ratio of the Na and K concentrations below the radiation penetration depth  $R_C$ . For comparison, *Zolotov and Shock* [2001] derived a range of oceanic Na/K ratios  $R_O$  between 14 and 19 from chemical and thermodynamic models of oceanic waters resulting from chondritic rock/water equilibrium. However, as emphasized by *Johnson et al.* [2002], this ratio should be smaller than the actual Na/K surface ratio  $R_D$  because of fractional crystallization of oceanic water during upwelling in the icy shell.

### 3.2. Possible Relations Between Surface and Exospheric Na/K Ratios

[9] As reported by *Cipriani et al.* [2008], at low altitudes in the exosphere (typically  $< 500$  km) sodium density asymmetries between trailing and leading hemispheres can appear as signatures of minor ejection processes, such as PSD, or signatures of non uniform surface distribution of the sodium source. The detection of such signatures at various Europa local times and from a low periapsis orbiter can give important clues on the origin of the associated surface features. In the following, we investigate how surface inhomogeneities in the alkali content give rise to detectable exospheric signatures. In this section, we consider the position of Europa during *Brown* [2001] observations in order to simplify our discussion.

[10] The spatial distribution of the Na/K surface density ratio  $R_D$  is shown in Figure 2. This distribution was obtained by taking the ratio of the calculated steady state



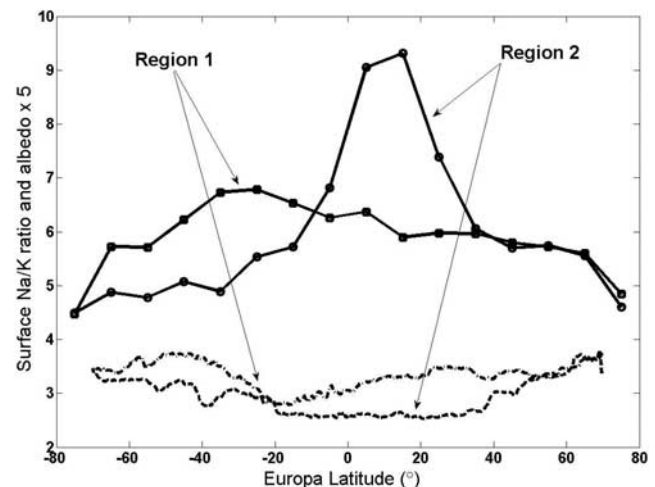
**Figure 2.** Simulated surface distribution of the Na/K ratio  $R_D$  at the date of *Brown* [2001] observations (Jovian local time angle of  $234^\circ$ ). Areas labelled 1, 2, and 3 correspond to the three regions discussed in the text (1 and 2 are described in Figure 3). The longitude system is such that  $0^\circ$  corresponds to the sub-Jupiter meridian, and  $90^\circ$  corresponds to the leading hemisphere apex. At this particular position of Europa, the leading apex was at  $75^\circ$  and the trailing apex at  $255^\circ$ . This distribution was obtained by taking the ratio of the calculated steady state sodium surface density to the potassium density in each cell of the surface grid.

sodium surface density to the potassium density in each cell of the surface grid, and is seen to be closely related to spatial distributions of the surface albedo and of the fraction of non-ice materials using a simulation like that described by *Cipriani et al.* [2008].

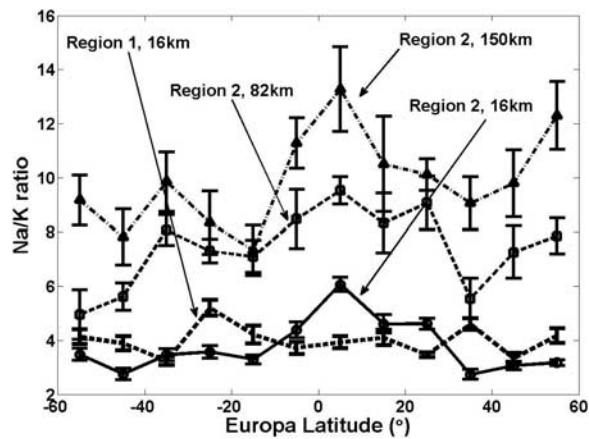
[11] The average surface density ratio  $R_D$  is close to 7. Therefore, the surface is, on average, significantly enriched in potassium with respect to Europa's atmosphere. This enrichment results from the preferential loss of sodium as discussed above. In Figure 2, the surface distribution of the Na/K ratio  $R_D$  peaks to values close to 10 at  $270^\circ$ W in longitude. This region matches the low albedo regions bearing the largest fraction of non-ice materials observed by *Grundy et al.* [2007]. Since the sputtering yield is lower in those regions than in the rest of Europa's surface (see *Cipriani et al.* [2008] for further explanations), the mass fractionation induced by the ejection is less efficient (the surface ratio is, therefore, assumed to be closer to the underground surface abundance ratio of  $26 \pm 2$ ).

[12] In Figure 2, we examine three particular areas of Europa's surface. The first case labelled (1) is a  $30^\circ$  wide longitude band between  $60^\circ$ W and  $90^\circ$ W. Such area corresponds to the low albedo surface features observed between latitudes  $-40^\circ$ S and  $10^\circ$ N and associated with an area of large mottled terrains next to bright plains [*Greeley et al.*, 1998]. In Figure 3, we plotted for comparison the variation of the average blue filter albedo (magnified by a factor of 5 in order to ease multiple plotting) in the same longitude band (dashed-dotted line). This albedo was derived from *McEwen* [1986] albedo maps. A longitudinally averaged surface ratio profile extracted from the surface map of Figure 2 is also shown in Figure 3 (solid line with squares

line). The peak observed close to  $-25^\circ$ S corresponds to an increase by less than 10% of the Na/K ratio  $R_D$  in a region  $20^\circ$  large in latitude, and matches the transition region between high and low albedo regions over the surface. The second area (case 2 in Figure 2) is a  $30^\circ$  wide longitude band between  $270^\circ$ W and  $300^\circ$ W. This band contains a higher percentage of lineas features and mottled terrains compared to the previous case, and no bright plain [*Greeley et al.*, 1998]. As shown in Figure 3, the Na/K ratio  $R_D$  is found to vary between values of 4.5 and 9 and displays a significant maximum in a region  $20^\circ$  large in latitude and centered around  $10^\circ$ N (solid line with disks). Such peak matches well the corresponding low albedo region (dashed line). The third area (case 3), a rectangle centred on  $6^\circ$ N,  $322^\circ$ W about 500 km by 300 km wide, corresponds to the so called hummocky (mottled) terrains observed by Galileo [see *Greeley et al.*, 1998, Figure 10], where endogenic processes associated with magmatic intrusion, diapirs, thermally driven convection and surface flow have been proposed as being responsible for the observed surface morphology. Resurfacing events as warm ice/water emplacement, such as those modelled by *Abramov and Spencer* [2008] may typically take place in such area. As mentioned by *Brown* [2001], trace elements intrinsic in the ice and deposited in such liquid water resurfacing events may be enriched or depleted depending on their solubility. For instance sodium sulfates have a solubility more than four times larger than that of potassium sulfates. To study if such inhomogeneities may have significant signatures in the exosphere we assumed a source term ratio constantly enhanced by a factor of 4 in this area as compared to neighbouring areas during our simulation. The time scale of such event may vary significantly, but *Abramov and Spencer* [2008] showed that a 10 km sized



**Figure 3.** Variations within the surface region between longitude  $60^\circ$ W and  $90^\circ$ W (region 1 from Figure 2, solid line with squares) and between  $270^\circ$ W and  $300^\circ$ W (region 2 from Figure 2, solid line with circles) of the Na/K ratios  $R_D$  with respect to latitude. For comparison the averaged surface albedos (magnified by a factor of 5) derived from *McEwen* [1986] maps computed from Voyager imaging data are shown in dash-dotted line (region 1) and dashed line (region 2).



**Figure 4.** Dependence on latitude of the average atmospheric Na/K ratio  $\Phi_E$  located between  $60^\circ\text{W}$  and  $90^\circ\text{W}$  longitude (above region 1, dashed line) and between  $270^\circ\text{W}$  and  $300^\circ\text{W}$  (above region 2, solid line with circles, dashed line with squares, dash-dotted line with triangles correspond to 16, 82, and 150 km in altitude above the surface, respectively). Error bars show the numerical noise associated with the computed ratio.

freshly formed chaos region would remain above the freezing temperature during more than 100 Earth days, meaning that such localized enhancement could persist over the surface for a significant amount of time. With the above assumption, we observe that the Na/K ratio  $R_D$  peaks at a value of 13.6 near  $6^\circ\text{N}$  (not shown in Figure 3 because of the low resolution of such a plot). Such a peak corresponds to an increase of the ratio by 60% with respect to regions of longitude close to  $320^\circ\text{W}$  and latitudes typically higher than  $25^\circ\text{N}$  or lower than  $-5^\circ\text{S}$ .

[13] In Figure 4, the exospheric Na/K ratio  $\Phi_E$  at different altitudes over the surface is displayed. In case 1, a small Na/K peak at  $-25^\circ\text{S}$  appears at 16 km (dashed line without symbol in Figure 4) but is no more observed at higher altitudes. A small surface increase of the Na/K of less than 10% in a  $20^\circ$  wide region can therefore not be observed above few tens of kilometres altitude. Case 2 corresponds to an area with less albedo difference but is located in a region where the non-ice fraction, hence the sputtering yield, are the lowest. In this case the high Na/K surface ratio  $R_D$  generates exospheric Na/K signatures increasing with increasing altitudes up to an altitude around  $\sim 300$  km where it disappears. Therefore, surface inhomogeneity of the Na/K ratio in a  $30^\circ$  wide region should be easily observed in the exosphere. Its interpretation in term of surface concentration will need profiles in longitude, latitude and altitude of the Na/K exospheric ratio. The last case, case 3, corresponding to a very localized Na/K surface inhomogeneity, displays an enhancement by about 20% of the Na/K ratio up to a few tenths of km above the surface (not shown). Such a signature should in principle be observable from an orbiter at 100 km in altitude using remote sensing instruments.

#### 4. Conclusion

[14] In this paper we investigate the possible simultaneous variations of the Na/K ratios in the exosphere and

surface of Europa. Our results are constrained by observations of the Na/K exospheric ratio carried out by *Brown* [2001]. The average exospheric ratio  $\Phi_E$  of  $26 \pm 2$  (in good agreement with *Johnson et al.* [2002]) beyond 2 Europa radii should be directly related to the average ratio of the Na/K loss rates  $\Phi_L$ , and the average Na/K concentration of Europa underground  $R_C$ . The corresponding surface source rate ratio of Na and K is  $17 \pm 2$  and the averaged surface ratio  $R_D$  is close to 7. This indicates a pronounced preferential enrichment of the surface in potassium with respect to sodium. Interestingly, we observed a steep variation of the average exospheric Na/K ratio in a few hundred kilometres range of altitudes which suggests that direct constraints on the energy distributions of the ejected species could be derived from in situ measurements.

[15] We also studied the effect of surface inhomogeneities in this ratio and found that significant low altitude exospheric signatures could be easily detectable above 100 km in altitude if the surface ratio  $R_D$  is two times larger in a  $20^\circ$  width region than the surrounding regions. Such regions could correspond to areas having a high non-ice fraction and/or were altered by warm ice/water resurfacing events. Therefore, in situ measurements of the exospheric composition, complemented by ionospheric measurements, should allow one to retrieve crucial information on the variations in the surface composition a possibility also considered by *Cassidy et al.* [2009].

#### References

- Abramov, O., and J. R. Spencer (2008), Numerical modelling of endogenic thermal anomalies on Europa, *Icarus*, *195*, 378–385.
- Brown, M. E. (2001), Potassium in Europa's atmosphere, *Icarus*, *151*, 190–195.
- Cassidy, T. A., R. E. Johnson, and O. J. Tucker (2009), Trace constituents of Europa's atmosphere, *Icarus*, *201*, 182–190, doi:10.1016/j.icarus.2008.12.033.
- Cipriani, F., F. Leblanc, O. Witasse, and R. E. Johnson (2008), Sodium recycling at Europa: What do we learn from the sodium cloud variability?, *Geophys. Res. Lett.*, *35*, L19201, doi:10.1029/2008GL035061.
- Cooper, J. F., et al. (2001), Energetic ion and electron irradiation of the icy Galilean satellites, *Icarus*, *149*, 133–159.
- Greeley, R., et al. (1998), Europa: Initial Galileo geological observations, *Icarus*, *135*, 4–24.
- Grundy, W. M., et al. (2007), New Horizons mapping of Europa and Ganymede, *Science*, *318*, 234–237.
- Johnson, R. E., F. Leblanc, B. V. Yakshinskiy, and T. E. Madey (2002), Energy distributions for desorption of sodium and potassium from ice: The Na/K ratio at Europa, *Icarus*, *156*, 136–142.
- Leblanc, F., R. E. Johnson, and M. Brown (2002), Europa's sodium atmosphere: An ocean source?, *Icarus*, *159*, 132–144.
- Leblanc, F., A. E. Potter, R. M. Killen, and R. E. Johnson (2005), Origins of Europa Na cloud and torus, *Icarus*, *178*, 367–385.
- McEwen, A. (1986), Exogenic and endogenic albedo and color patterns on Europa, *J. Geophys. Res.*, *91*, 8077–8097.
- Paranicas, C., J. M. Ratliff, B. H. Mauk, C. Cohen, and R. E. Johnson (2002), The ion environment near Europa and its role in surface energetics, *Geophys. Res. Lett.*, *29*(5), 1074, doi:10.1029/2001GL014127.
- Popieszalska, M. K., and R. E. Johnson (1989), Magnetospheric ion bombardment profiles of satellites: Europa and Dione, *Icarus*, *78*, 1–13.
- Zolotov, M. Y., and E. L. Shock (2001), Composition and stability of salts on the surface of Europa and their oceanic origin, *J. Geophys. Res.*, *106*, 32,815–32,828.

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