Effect of the Magnetospheric Plasma Interaction and Solar Illumination on Ion Sputtering of Europa's Surface Ice

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Key Points:

- Magnetic field-line draping partially protects Europa's upstream hemisphere from ion erosion, but causes substantial sputtering downstream
- If Europa's oxygen-bearing surface layer is thin compared to the ion penetration depth, maximum sputtering occurs near the upstream apex
- For a thick oxygen-bearing layer, two oxygen sputtering maxima form: one near the sub-solar point, and a weaker one near the upstream apex

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Abstract

For the entire ion energy range observed at Europa, we calculate spatially-resolved maps of the surface sputtering rates of H_2O, O_2, and H_2 from impacts by magnetospheric ions. We use the perturbed electromagnetic fields from a hybrid model of Europa's plasma interaction, along with a particle-tracing tool, to calculate the trajectories of magnetospheric ions impinging onto the surface and their resultant sputtering yields. We examine how the distribution of the sputtering rates depends on the electromagnetic field perturbations, the angle between the solar radiation and the corotating plasma flow, and the thickness of the oxygen-bearing layer within Europa's surface. Our major findings are: (a) Magnetic field-line draping partially diverts the impinging ions around Europa, reducing the sputtering rates on the upstream hemisphere, but allowing for substantial sputtering from the downstream hemisphere. In contrast, zero sputtering occurs in much of the downstream hemisphere with uniform electromagnetic fields. (b) If the oxygen-bearing surface layer is thin compared to the penetration depth of magnetospheric ions, thermal ions dominate the O_2 sputtering rates, and the region of strongest sputtering is persistently located near the upstream apex. However, if the oxygen-bearing layer is thick compared to the penetration depth, energetic ions sputter the most O_2, and the location of maximum sputtering follows the sub-solar point as Europa orbits Jupiter. (c) The global production rate of O_2 from Europa's surface varies by a factor of three depending upon the moon's orbital position, with the maximum particle release occurring when Europa's sun-lit and upstream hemispheres coincide.

1 Introduction

The icy moon Europa (radius $R_E = 1560.8$ km) is the smallest of the four Galilean moons of Jupiter, and possesses one of the youngest surfaces of any solar system object (about 50 million years, e.g., Bierhaus et al., 2009). The youth of Europa's surface is the result of continuous resurfacing processes, such as past tectonic activity (e.g., Kattenhorn & Hurford, 2009), meteorite impacts (e.g., Schenk et al., 2007), and sputtering by magnetospheric particles (e.g., Johnson et al., 2009). Neutral particles ejected from Europa's surface via sputtering form a dilute exosphere surrounding the moon (e.g., Hall et al., 1995; Johnson et al., 2009; Plainaki et al., 2018). Radiolysis via charged particle impacts is also hypothesized to be the source of the non-uniform coloration and brightness patterns across the moon's surface ice (McEwen, 1986; Hendrix et al., 2011). Eu-

ropa's differentiated structure includes a subsurface liquid water ocean (Kivelson et al., 2000), which may interact with the surface through plume activity (Roth et al., 2014; Jia et al., 2018; Arnold et al., 2019; Paganini et al., 2020).

Europa's orbital distance of 9.4 R_J (Jupiter radius $R_J = 71,492$ km) places the moon in the giant planet's inner magnetosphere. As such, it is exposed to a dynamic environment of strong electromagnetic fields and dense magnetospheric plasma. The 9.6° tilt between Jupiter's rotational and magnetic axes causes periodic variations in the strength and direction of the Jovian magnetic field as well as the plasma density at Europa's orbit (e.g., Kivelson et al., 1999; Seufert et al., 2011; Bagenal & Dols, 2020). This oscillation induces currents in Europa's conducting subsurface ocean, which in turn generate a secondary, quasi-dipolar magnetic field outside the moon (Kivelson et al., 2000; Zimmer et al., 2000; Vance et al., 2021). Such an induction signal has been detected by the Galileo spacecraft during several targeted flybys of Europa (e.g., Kivelson et al., 2000).

Europa's location within the inner magnetosphere also portends that the moon is exposed to a diverse range of plasma species. Neutral matter emitted by Europa's volcanically active neighbor, Io, is ionized via electron impacts and photoionization (Saur et al., 2003), and transported radially outward to Europa's orbit, forming a plasma sheet centered near the Jovian magnetic equator (e.g., Bagenal et al., 2016; Pensionerov et al., 2019). The thermal ion population in this sheet consists mainly of hydrogen, oxygen, and sulfur ions with energies of approximately 1 keV, and follows a Maxwellian distribution (Bagenal & Delamere, 2011; Bagenal & Dols, 2020; Kim et al., 2020). Since Jupiter's rotation period is only one-eighth of Europa's orbital period, the sub-alfvénic, (partially) corotating plasma overtakes the moon with a relative velocity of ≈100 km/s (Kivelson et al., 2009). As the magnetospheric plasma impinges onto Europa, electrons ionize neutral gas in the exosphere, creating an ionosphere that envelops the moon (Saur et al., 1998). The injection of slow-moving, newly-generated ionospheric ions into the magnetospheric flow drains momentum from the upstream plasma, causing it to slow and accumulate above the moon's upstream face. The magnetic field, which is frozen into the plasma, piles up in this region of enhanced plasma density and drapes around the moon (e.g., Rubin et al., 2015; Arnold, Liuzzo, & Simon, 2020).

The ion population near Europa also features a high-energy component, containing ions with energies E from several keV to tens of MeV (e.g., Cooper et al., 2001; Mauk

et al., 2004; Paranicas et al., 2009; Clark et al., 2020). The high energies of these ions allow them to travel along Jupiter's magnetic field lines all the way to the planet's poles, where they are mirrored back toward Europa's orbital plane. As such, energetic ions continually intercept the moon's orbit. Europa does not possess a sufficiently dense gas envelope for collisions to protect its surface from ion irradiation (Shematovich et al., 2005; Coustenis et al., 2010). Most magnetospheric ions can penetrate directly to the surface without encountering an exospheric molecule, although recent studies by Huybrighs et al. (2020) and Addison et al. (2021) suggest that charge exchange with exospheric neutrals may partially shield the moon's surface from low energy ($E \leq 200$ keV) proton bombardment. However, charge exchange reactions produce energetic neutral atoms (ENAs), which may still impact and erode the surface. As such, Europa's surface ice is continually abraded by corotating thermal ions ($E \approx 1$ keV), fast-moving energetic ions (5 keV $< E < 10$ MeV), and (to a minor extent) ENAs. Slow-moving ionospheric ions weather the surface, however their contribution to erosion is several orders of magnitude weaker than that of magnetospheric ions (Saur et al., 1998). The surface also faces irradiation by galactic cosmic rays, but their influx is dwarfed by magnetospheric ions in the upper reaches of the ice (first $\sim$ tens of centimeters, Nordheim et al., 2019), the realm typically sampled by optical instruments. In addition, thermal and energetic electrons contribute to surface modification (e.g., Vorburger & Wurz, 2018; Davis et al., 2021). However, this study focuses on the irradiation of the surface by magnetospheric ions only.

Magnetospheric ion irradiation has been identified as a critical agent in the weathering of Europa's surface (Cassidy et al., 2013; Dalton et al., 2013; Breer et al., 2019; Addison et al., 2021). The Photopolarimeter-Radiometer (PPR) aboard Galileo observed the upstream/orbital trailing hemisphere of Europa to be noticeably dark, with a bolometric albedo roughly thirty percent lower than that of the downstream hemisphere (Rathbun et al., 2010). Several studies have hypothesized that this hemispheric darkening is due to the presence of sulfur-containing compounds, which are formed when magnetospheric sulfur ions implant into surface ice (McEwen, 1986; Hendrix et al., 2011; Dalton et al., 2013). Measurements by the Galileo Near-Infrared Mapping Spectrometer (NIMS) also indicate a "bullseye" distribution of the sulfuric acid concentration on the surface, i.e., the sulfuric acid concentration maximizes near the upstream apex, and decreases with distance away from it (Carlson et al., 2005). Such a bullseye-like pattern is consistent with the spatial distribution of sulfur ion flux predicted by some models (Cassidy et al.,

111   2013; Dalton et al., 2013), reinforcing the idea that ion influx is the mechanism behind

112   surface darkening.

113   Magnetospheric ions that impact Europa's surface may directly eject H_2O from the

114   ice, or radiolytically dissociate H_2O into H_2, O_2, and a number of other trace species,

115   which can then be ejected by further particle impacts (Plainaki et al., 2013; Teolis et al.,

116   2017; Vorburger & Wurz, 2018). The Jeans parameter, i.e., the ratio between a parti-

117   cle's gravitational potential energy and its kinetic energy, is 0.25 for sputtered H_2 (Roth

118   et al., 2017), while for sputtered O_2 and H_2O it is approximately 10 (Saur et al., 1998).

119   Therefore, O_2 and H_2O remain gravitationally bound to Europa, while a large fraction

120   of the sputtered H_2 molecules are transported outward and escape Europa's Hill sphere,

121   populating the neutral torus along Europa's orbit (see, e.g., Lagg et al., 2003; Kollmann

122   et al., 2016). This escaping hydrogen has been detected by both the Hubble Space Tele-

123   scope (HST) in the form of a global H_2 corona (Roth et al., 2017) and by the Galileo En-

124   ergetic Particles Detector (EPD, see Nénon & André, 2019). Since both O_2 and H_2O re-

125   main gravitationally bound to Europa, molecules of both types may re-encounter Eu-

126   ropa's surface. The sticking coefficient (the likelihood that a molecule will re-freeze to

127   Europa's surface upon contact) of H_2O is approximately 1, while for O_2 it is approxi-

128   mately 10^{-3} (Eviatar et al., 1985). Refreezing therefore removes much of the sputtered

129   H_2O from the exosphere, but does not constitute a significant loss mechanism for O_2.

130   Despite this, a persistent, highly-localized H_2O exosphere has recently been detected above

131   Europa's upstream apex (Roth, 2021), suggesting that H_2O is not entirely lost to refreez-

132   ing. Molecular oxygen is removed from the exosphere mainly though ionization, with a

133   minor contribution from plasma-neutral collisions that eject molecules (Saur et al., 1998).

134   These two loss processes, along with O_2 production via ion impacts and radiolysis, al-

135   low O_2 to maintain mass balance within a near-surface exosphere approximately 300 km

136   in height (e.g., Vorburger & Wurz, 2018). Sputtering of neutral ice particles is therefore

137   the main source of Europa's predominantly O_2 exosphere (Plainaki et al., 2013; Teolis

138   et al., 2017), with an additional, minor contribution from sublimation.

139   The amount of neutral matter produced per area and time via ion sputtering at

140   a given surface location is dependent upon two factors: the differential ion surface flux

141   $j(E, \theta)$ reaching that location, i.e., how many ions of a specific energy E and incidence

142   angle θ hit a given surface area per unit time, and the sputtering yield $Y(E, \theta, T)$, i.e.,

143   how many neutral particles are released from a surface element of temperature T by each

impinging ion. The total sputtering *rate* of a given ion species, R, is the number of surface particles ejected at that location per unit area per unit time. The sputtering rate is determined by multiplying the differential ion flux $j(E, \theta)$ with the sputtering yield $Y(E, \theta, T)$ at each incident ion energy and impact angle, and integrating over the entire energy range and all impact angles. In sections 1.1 and 1.2, the current state of knowledge on the ion surface fluxes at Europa and sputtering yields is discussed.

1.1 Ion Surface Fluxes

The spatial distribution of the ion flux incident on Europa's surface has been investigated by a number of previous studies. Pospieszalska and Johnson (1989) modeled the trajectories of 30-140 keV sulfur ions near Europa and found that the surface flux of these ions maximizes near the moon's orbital trailing (upstream to the plasma flow) apex. These authors also found that sulfur ions at higher energies ($E \geq 140$ keV), which possess a gyroradius of roughly 0.25 R_E, can reach almost all locations on Europa's surface. Therefore, even the moon's downstream hemisphere is not entirely protected from ion irradiation at energies above approximately 100 keV. Cassidy et al. (2013) calculated the surface fluxes of hydrogen, oxygen, and sulfur ions from 1 keV to 10 MeV, thereby covering the energy range where Galileo detected significant ion fluxes outside of Europa's interaction region (e.g., Paranicas et al., 2009). Cassidy et al. (2013) found that the total ion flux onto Europa (taking into account all species and energies) is distributed in a bullseye-like pattern centered at the trailing hemisphere apex, consistent with the distribution of surface sulfuric acid concentration measured by the NIMS instrument (Carlson et al., 2005). Ions with energies above 100 keV were found to impact primarily Europa's polar regions, a result of high field-aligned (i.e., north-south) velocities relative to the corotation velocity. However, both Pospieszalska and Johnson (1989) and Cassidy et al. (2013) treated the electromagnetic fields near Europa as uniform, that is, the perturbations to the fields introduced by the induced dipole and the sub-Alfvénic plasma interaction were not taken into account. We note that the presence of the induced field was not known at the time of the Pospieszalska and Johnson (1989) study.

All eight targeted flybys of Europa performed by the Galileo spacecraft showed perturbations to the local magnetic field components of up to 100% of their background values (see review by Kivelson et al., 2009). Magnetometer data from several flybys (most notably E4 and E11) even revealed a local reversal in the sign of the horizontal (i.e., par-

allel to Europa's orbital plane) field components compared to their measured upstream values. Investigations of induction at Europa (e.g., Zimmer et al., 2000; Vance et al., 2021) have shown that the induced field alone may reach a strength near the moon's surface of approximately half ($\approx$ 210 nT) of the Jovian background field ($\approx$ 400 − 450 nT). Numerous modeling studies (e.g., Rubin et al., 2015; Arnold et al., 2019; Arnold, Liuzzo, & Simon, 2020; Harris et al., 2021) have reproduced the observed magnetic signatures by simulating the interaction between the upstream magnetospheric plasma, Europa's exosphere, and the moon's induced field. The draping and pileup of the magnetospheric field, as well as the non-linear coupling of the induced field to the sub-alfvénic interaction (Neubauer, 1999), significantly modify ion trajectories in Europa's vicinity (Breer et al., 2019; Addison et al., 2021). Accurate modeling of the ion fluxes incident upon Europa's surface therefore requires inclusion of the field perturbations generated by the plasma interaction with Europa's exosphere and induced field.

Several recent studies have modeled the spatial distribution ion flux onto Europa while including the deformation of the local electromagnetic fields by magnetospheric plasma deflection and induction. Breer et al. (2019) used the AIKEF hybrid model (kinetic ions, fluid electrons) to compute the perturbations to the electromagnetic fields near Europa. They then calculated spatially resolved maps of the accessibility—defined as the percentage of upstream ions that reach a given surface location—of Europa's surface to upstream magnetospheric ions. On the basis of Galileo measurements of the ion species and energies present near Europa, these authors traced H^+, O^{2+}, and S^{3+} ions at discrete energies ranging from 1 keV to 5 MeV. To establish a "baseline" for the identification of modifications in the accessibility patterns caused by the field perturbations, they also calculated maps of the ion irradiation of Europa's surface for uniform fields (similar to Pospieszalska and Johnson (1989) and Cassidy et al. (2013)). For the case of uniform fields, Breer et al. (2019) showed that Europa's surface is highly accessible to upstream ions of all energies, with accessibilities near 90% in all regions except for a narrow "belt" near the moon's equator, where the accessibility drops to 0-40% for ion energies below 1 MeV. This equatorial depletion belt results from the tendency of ions following magnetic field lines near Europa to gyrate into the moon's surface at high northern and southern latitudes before reaching the equatorial region. At MeV energies, even the protection of Europa's equatorial region from magnetospheric ions was found to largely

208 disappear, since MeV ions possess gyroradii of roughly 1 R_E, and can therefore gyrate

209 around Europa and impact any point on the surface.

210 However, Breer et al. (2019) also found that the draping and pileup of the mag-

211 netic field near Europa deflect a significant portion of the impinging ions around the moon,

212 reducing the accessibility by up nearly a factor of two at almost all surface locations. At

213 ion energies below 100 keV, only several small "islands", located mainly on the anti-Jovian

214 hemisphere, were found to remain accessible to more than 80% of upstream ions. Only

215 at MeV energies does the pattern of surface accessibility become qualitatively similar to

216 that produced with uniform electromagnetic fields, although the accessibility was still

217 five times smaller. Even the inclusion of the induced dipole field alone was found to make

218 the surface accessibilities five to ten times smaller at most energies. Thus, Breer et al.

219 (2019) found the perturbations to the electromagnetic fields near Europa to be critical

220 in modifying ion dynamics near the moon at all energies. Therefore, the plasma inter-

221 action must be taken into account by any reasonable model of ion surface fluxes.

222 A synodic rotation period of Jupiter at Europa is approximately ten hours, and on

223 this time scale both the Jovian magnetic equator and the magnetospheric plasma sheet

224 continuously sweep over the moon. Therefore, both the Jovian background field and the

225 ambient plasma density near Europa periodically vary. Not only does this variation af-

226 fect the strength and orientation of the moon's induced secondary field, but it also con-

227 tinually changes the Alfvénic Mach number M_A of the upstream flow, altering the tilt

228 of the Alfvén wings and the strength of the plasma interaction (Neubauer, 1980, 1998).

229 This oscillation results in drastically different magnitudes and spatial distributions of ion

230 flux onto Europa's surface at different locations along a synodic rotation, as magneto-

231 spheric ions navigate starkly different electromagnetic field configurations. Breer et al.

232 (2019) calculated the accessibility of Europa's surface to magnetospheric ions for a few

233 select sets of ambient electromagnetic field conditions, placing emphasis on the role of

234 water vapor plumes in locally protecting the surface from ion irradiation. However, these

235 authors did not systematically examine the evolution of these accessibility patterns as

236 Jupiter completes a synodic rotation; only several "snapshots" along a rotation were in-

237 vestigated. Furthermore, their study did not quantify ion surface *fluxes* based on the energy-

238 dependent upstream ion distributions measured by the Galileo spacecraft, but only the

239 accessibility of Europa's surface to upstream ions. In other words, the ion macroparticles—

240 conglomerate particles, representative of many actual ions, but with the same mass-to-

charge ratio—in the model of Breer et al. (2019) were all weighted equally, regardless
of their energy. Their approach did not take into account that, for the energetic ion dis-
tributions measured near Europa by Galileo (Paranicas et al., 2009), modeled ion macropar-
ticles at energies in the keV regime represent *several orders of magnitude* more real-world
particles than in the MeV regime. Converting surface accessibilities into realistic ion sur-
face flux maps requires taking into account the dependence of the upstream ion distri-
bution on ion energy and pitch angle, as observed by the Galileo EPD (Paranicas et al.,
2002; Nénon & André, 2019). The surface fluxes from such an approach may then be ap-
plied to inform studies of surface modification and sputtering.

Building upon the model of Breer et al. (2019), Addison et al. (2021) recently con-
strained the magnitude and spatial distribution of ion surface flux at Europa for differ-
ent sets of magnetospheric conditions encompassing an entire synodic rotation of Jupiter:
namely when Europa is located at the center of the Jovian plasma sheet, as well as at
maximum elongation north or south of the sheet. At each location, the AIKEF hybrid
code was used to calculate the moon's perturbed electromagnetic environment. Addison
et al. (2021) then combined a particle-tracing tool with the upstream energy and pitch
angle distributions of the ions, as measured by Galileo, to calculate ion surface fluxes.
Their model incorporated upstream plasma densities and temperatures derived from Galileo
observations (Paranicas et al., 2002; Kivelson et al., 2009; Bagenal & Delamere, 2011),
as well as the latest information on energetic ion charge states obtained by the Juno space-
craft (Clark et al., 2020; Kim et al., 2020). By averaging the flux maps obtained for the
three distances between Europa and the center of the Jovian plasma sheet, Addison et
al. (2021) then obtained average surface flux maps of magnetospheric oxygen, sulfur and
hydrogen ions over an entire synodic rotation. Their averaged flux maps consider con-
tributions of ions from the entire energy range (5 keV up to 10 MeV) where significant
ambient fluxes were observed near Europa.

The study of Addison et al. (2021) found that inclusion of the plasma interaction
results in drastically different patterns of ion surface flux compared to the case of uni-
form electromagnetic fields. Although the total ion flux in their model still maximizes
near the upstream apex, deflection of thermal ions around Europa's Alfvén wings was
shown to reduce ion flux onto the upstream hemisphere by two orders of magnitude com-
pared to predictions for uniform fields. Most surprisingly, the draped field geometry near
the moon was found to divert thermal ions from the "edges" of the Maxwellian distri-

bution onto Europa's polar regions, as well as onto its *downstream* hemisphere, result-

ing in a flux there of only one order of magnitude less than in the upstream hemisphere.

Using a fluid model and considering the forces generated by local pressure gradients, Harris

et al. (2021) identified a similar flow pattern in the thermal ion population near Europa.

In contrast to this, without plasma currents the thermal ion fluxes are zero in large seg-

ments of the downstream hemisphere.

Addison et al. (2021) showed the surface flux pattern of energetic ions ($E \geq 5$ keV)

to be considerably modified by the plasma interaction. A large, quasi-elliptical deple-

tion region was found to form around the upstream apex and extend approximately $\pm 60°$

in both latitude and longitude. The field draping enhances the distance that an ion trav-

eling along a magnetic field line is within one gyroradius of the moon's surface. This mech-

anism causes a significant fraction of the incoming energetic ions to gyrate into the moon's

surface at high latitudes before they can reach the upstream apex, resulting in this el-

liptical depletion region. This "inverted bullseye" feature is not predicted by a model

that treats the fields as uniform. The results of Addison et al. (2021) therefore show that

the inclusion of the sub-alfvénic plasma interaction is imperative to explain a number

of observations from both in-situ spacecraft and ground-based telescope observations,

such as the non-uniform surface distribution of sulfuric acid concentrations (Ligier et al.,

2016), and a drop in the upstream ion flux seen during several close Galileo flybys of Eu-

ropa (Paranicas et al., 2000).

1.2 Sputtering Yields

Once a magnetospheric ion impacts Europa's surface, the amount of neutral mat-

ter ejected is determined by the ion's sputtering yield $Y(E, \theta, T)$. Many laboratory ex-

periments have measured sputtering yields from water ice (see reviews by Johnson (1996),

Johnson et al. (2009), and references therein). Surface particles may be released from

the ice at any depth to which an impinging ion penetrates ($\approx 10^1 - 10^7$Å, e.g., Teolis

et al., 2017). However, the greater the depth at which a neutral particle is ejected, the

larger the chance that it will stick to another surface grain before escaping into the ex-

osphere (Cassidy & Johnson, 2005).

For projectile ion energies below approximately 100 keV, molecules are directly ejected

from the surface ice via momentum transfer (elastic) collisions (Sigmund, 1969). At higher

305   projectile energies, incident ions excite electrons in surface molecules, breaking covalent

306   bonds and causing the dissociation of constituent species, thereby facilitating neutral mat-

307   ter release from the surface (Brown et al., 1978; Sieger et al., 1998). Laboratory data has

308   shown that sputtering yields from water ice increase with energy in the momentum-transfer

309   regime, then rapidly grow in the electronic excitation regime, before dropping off at ex-

310   tremely high projectile energies (Johnson et al., 2009). The sputtering yields of the dom-

311   inant ion species at Europa (hydrogen, oxygen, and sulfur ions) therefore reach a max-

312   imum in the $E \approx 100$ keV–5 MeV range (depending upon the projectile species), and

313   then drop precipitously at higher energies. This non-monotonic energy dependence of

314   the sputtering yield seen in laboratory experiments has been fit with analytical forms

315   by, e.g., Famá et al. (2008). Their fits have shown that, due to their large masses and

316   atomic numbers, oxygen and sulfur ions possess the greatest sputtering yields: up to 5000

317   neutral particles are released per incident projectile. The analysis of laboratory data by

318   Famá et al. (2008) also revealed that ions which impact the surface at grazing angles $\theta \approx$

319    $90°$ against the surface normal sputter up to 100 times more neutral particles than ions

320   which impact normal to the surface ($\theta \approx 0°$), since grazing projectiles deposit more en-

321   ergy at shallower depths.

322   In addition to projectile properties, sputtering yields also depend on the proper-

323   ties of the surface that is impacted. The porosity of Europa's surface regolith may limit

324   sputtering yields to 25% of their values measured in the laboratory using "smooth" sur-

325   faces, as particles that are initially ejected may hit and stick to other grains rather than

326   escape into the exosphere (Cassidy & Johnson, 2005). Furthermore, sputtering yields in-

327   crease monotonically with temperature (Brown et al., 1982) in the range of surface tem-

328   peratures observed at Europa ($\approx 60 - 140$ K, Spencer et al., 1999). This temperature

329   dependence mainly affects the sputtering yields of O_2, which is radiolytically dissociated

330   from ice within the first ≈ 28 Å of the surface (Teolis et al., 2005, 2017). Increased sur-

331   face temperature facilitates the transformation of dissociated oxygen radicals into sta-

332   ble O_2 (Teolis et al., 2017), which may be sputtered by subsequent projectile impacts.

333   The surface temperature profile at Europa is determined by its orientation with respect

334   to the Sun, as well as the thermal inertia of its surface ice. Therefore, sputtering rates

335   may vary over the course of a Europan rotation as the sub-solar point moves along the

336   equator relative to the upstream apex, where the influx of magnetospheric ions peaks

337   (Addison et al., 2021).

338   The effect of solar orientation relative to the plasma flow direction on sputtering

339   rates at Europa has been studied by Plainaki et al. (2013), who modeled the generation

340   of the exosphere at four different locations of the moon relative to the Sun: with the sub-

341   solar point located at the sub-Jovian, downstream, anti-Jovian, and upstream apices (0:00,

342   6:00, 12:00, 18:00 local time (LT), respectively). These authors characterized the ion in-

343   flux pattern with an analytical profile, which combined a spatially homogeneous component—

344   representing an assumed isotropic influx of energetic ions—with a bullseye-like enhance-

345   ment centered at the upstream apex and suggested to be representative of the thermal

346   ion contribution. They then modeled the sputtering rates and subsequent exospheric dy-

347   namics for different orientations between the incoming solar radiation and the corota-

348   tional plasma flow. Plainaki et al. (2013) found that the exospheric column density is

349   greater by a factor of three when the sub-solar point and upstream apex are colocated,

350   compared to when the sub-solar point is located at the downstream apex. These authors

351   also suggested that the region where the largest amount of neutral matter is sputtered

352   follows the sub-solar point as it moves across Europa's surface, and does not remain fixed

353   at the upstream apex. However, laboratory measurements indicate that O_2 sputtering

354   from an icy surface has a delayed response to changes in surface temperature (Teolis et

355   al., 2005) as surface radicals require time to accumulate into O_2. Since this delay is po-

356   tentially comparable to a Europan day, the sputtering rate of O_2 may not have time to

357   adjust to changes in surface temperature following Europa's orbital motion (Teolis et al.,

358   2017).

359   In contrast to Plainaki et al. (2013)—who used an analytical profile to describe ion

360   surface flux—the study of Cassidy et al. (2013) combined *modeled* ion surface fluxes, fits

361   to laboratory data of sputtering yields, and a thermophysical surface temperature model

362   (Spencer et al., 1989) to calculate the spatial distribution of ion sputtering rates at Eu-

363   ropa. Adopting the notion of a delayed O_2 sputtering response to changes in surface tem-

364   perature (Teolis et al., 2005), Cassidy et al. (2013) applied a diurnally-averaged (i.e., av-

365   eraged over a full orbit) profile of Europa's surface temperature. These authors found

366   that Europa's surface is preferentially sputtered on the upstream hemisphere, with the

367   neutral production in that region exceeding that of the downstream hemisphere by a fac-

368   tor of three. Neutral particles ejected by thermal oxygen ions and energetic sulfur ions

369   were found to dominate the sputtering rate. The strong contribution of the thermal oxy-

370   gen ions in the model of Cassidy et al. (2013) arose from their high surface flux, which

was found to exceed that of any other species by roughly an order of magnitude. We note that the modeled surface fluxes of Cassidy et al. (2013) are not consistent with those of Addison et al. (2021), who found that—when field line draping is taken into account— magnetospheric hydrogen (*not* oxygen) makes the largest contribution of any ion species to surface flux. The large contribution of energetic sulfur ions to the sputtering rate calculated by Cassidy et al. (2013) arose mainly from their respective sputtering yield, which is roughly a factor of five greater than that of oxygen in the energetic regime, and orders of magnitude greater than the sputtering yield of hydrogen at all energies. Cassidy et al. (2013) found that nearly zero O_2 is produced on the downstream hemisphere, since in their model O_2 is sputtered almost entirely by the thermal heavy ions. Under the assumption of uniform fields, these ions only precipitate onto the upstream hemisphere. Vorburger and Wurz (2018) utilized a spatially homogeneous magnetospheric ion flux across Europa's surface in their calculation of sputtering rates, although they did approximate the deflection of thermal upstream ions in the perturbed fields near Europa by uniformly reducing their respective flux by a factor of 5. These authors confirmed that thermal oxygen and energetic sulfur ions are the most significant contributors to ion sputtering at Europa.

Although Plainaki et al. (2013), Cassidy et al. (2013), and Vorburger and Wurz (2018) have modeled neutral production via magnetospheric ion sputtering at Europa, no study to date has investigated how the spatial distribution of surface sputtering is modified when a realistic model of incident ion deflection in the draped electromagnetic fields is taken into account. The ion-tracing model of Cassidy et al. (2013) assumed the fields to be spatially uniform, an assumption also implicit in the ion influx pattern utilized by Plainaki et al. (2013). Vorburger and Wurz (2018) treated the ion influx as uniform at all points on Europa's surface.

However, (Addison et al., 2021) found not only that the shielding of Europa's upstream hemisphere from magnetospheric ion impacts due to field line draping is orders of magnitude stronger than assumed by Vorburger and Wurz (2018), but that it varies strongly with surface latitude and longitude. In addition, Addison et al. (2021) demonstrated that the downstream hemisphere of Europa receives only an order of magnitude less thermal ion flux than the upstream hemisphere. They also showed that, in draped fields, the influx of energetic ions *minimizes* near the upstream apex, exactly opposite to what is predicted for uniform fields. None of the available sputtering rate models take

into account these important aspects of ion precipitation onto Europa. Therefore, ion sputtering rates at Europa must be reexamined with the influence of the field perturbations included.

This study is the first to model the sputtering of Europa's surface ice via magnetospheric ion impacts while incorporating a realistic picture of the field perturbations generated by the moon's sub-alfvénic plasma interaction. We use the AIKEF hybrid model (e.g., Arnold et al., 2019; Arnold, Liuzzo, & Simon, 2020; Arnold, Simon, & Liuzzo, 2020) to calculate the perturbations to Europa's local electromagnetic environment. The electromagnetic fields from AIKEF are combined with the GENTOo particle-tracing tool (e.g., Addison et al., 2021) to calculate the trajectories of magnetospheric ions in Europa's perturbed electromagnetic environment, from the thermal energy regime up to 10 MeV. We then use established fits to laboratory data of ion sputtering yields to obtain spatially resolved maps of ion sputtering rates across Europa's surface. We examine the influence of projectile species, energy, incidence angle, as well as the orientation of the Sun relative to the plasma flow direction and the electromagnetic field perturbations on surface sputtering rates.

A description of the AIKEF and GENTOo models, as well as all input parameters, is provided in section 2. The modeled electromagnetic field configuration, as calculated by the AIKEF model, is presented in section 3.1. The corresponding modeled ion surface fluxes from GENTOo along with our modeled H_2O sputtering rate maps for uniform and perturbed fields are presented in 3.2. In section 3.3 we calculate maps of the O_2 and H_2 sputtering rates, while examining the role of Europa's orbital position and the thickness of the oxygen-bearing surface layer in modifying O_2 sputtering. The paper concludes with a summary of our main findings in section 4.

2 Model Description

We use a multifaceted approach in order to calculate maps of the magnetospheric ion sputtering rates at Europa. First, we model the perturbed electromagnetic environment near the moon using the AIKEF hybrid code. The AIKEF model has been extensively applied to Europa in five preceding publications (Arnold et al., 2019; Arnold, Liuzzo, & Simon, 2020; Arnold, Simon, & Liuzzo, 2020; Breer et al., 2019; Addison et al., 2021), as well as the Jovian moon Callisto (Liuzzo et al., 2015, 2016, 2017, 2018, 2019a,

2019b). In addition, AIKEF has been used to study plasma interactions at the terrestrial Moon (Wiehle et al., 2011; Liuzzo, Poppe, et al., 2021), the Saturnian moons Titan (e.g., Regoli et al., 2016; Feyerabend et al., 2015, 2016), Tethys (Simon et al., 2009), Rhea (Simon et al., 2012), and Dione (Krupp et al., 2020), as well as Neptune's moon Triton (Liuzzo, Paty, et al., 2021; Simon et al., 2022).

Secondly, we calculate the spatial distribution of ion flux onto Europa's surface with the GENTOo particle tracing code, which solves the equations of motion for ions moving through the draped fields near Europa. GENTOo has been applied to Europa in two preceding studies (Breer et al., 2019; Addison et al., 2021), as well as to Callisto (Liuzzo et al., 2019a, 2019b), and Ganymede (Liuzzo et al., 2020). Finally, we combine our modeled ion surface flux patterns with empirical models of the sputtering yields from water ice (Johnson et al., 2004; Famá et al., 2008; Teolis et al., 2017), along with a thermophysical model for Europa's surface temperature profile (Spencer et al., 1989, 1999). In this way, we calculate spatially resolved maps of the surface sputtering rate at Europa. The AIKEF and GENTOo models have been extensively described in our previous publications. We therefore provide only a brief discussion of these two models here, and refer the reader to these prior publications for more information.

2.1 Model of Europa's Electromagnetic Environment

To calculate the three-dimensional structure of the perturbed magnetospheric environment near Europa, we apply the AIKEF hybrid model (kinetic ions, fluid electrons) originally developed by Müller et al. (2011). Unlike a single-fluid MHD model (e.g., Kabin et al., 1999), the hybrid approach is able to capture the dynamics of individual ion macroparticles, some of which possess velocity vectors far from the peak of the Maxwellian upstream distribution. Such ions impinge onto Europa along highly inclined trajectories (with respect to the corotation direction) and substantially contribute to the irradiation of the moon's polar caps and downstream hemisphere (Addison et al., 2021). AIKEF has achieved excellent quantitative agreement with the magnetic field signatures measured near Europa during the E26 flyby of Galileo (Arnold et al., 2019), as well as plasma and magnetic field observations from several Callisto flybys (Liuzzo et al., 2015, 2016, 2017). Thus, AIKEF is highly suited for our study of magnetospheric ion sputtering of Europa's surface.

466   Throughout this paper we will use the Cartesian, Europa-centered "EPhiO" co-

467 ordinate system. In this system, the x axis points in the direction of corotation, the z

468 axis points northward (i.e., parallel to Jupiter's spin axis), and the y axis completes the

469 right-handed system, pointing toward the giant planet. The basis vectors along these three

470 axes are denoted $\hat{\mathbf{x}}, \hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$, respectively. In agreement with Galileo plasma observa-

471 tions (e.g., Kivelson et al., 2009; Bagenal et al., 2015; Bagenal & Dols, 2020), for the AIKEF

472 model we assume the corotating, thermal plasma to consist of a singly-charged, compos-

473 ite species of mass $m_0 = 18.5$ amu, with ion and electron temperatures $k_B T_0 = 100$ eV,

474 and bulk velocity $\mathbf{u}_0 = 100$ km/s $\hat{\mathbf{x}}$. Galileo Plasma Subsystem (PLS) measurements

475 have also shown the bulk plasma velocity to have radial (i.e., in the $\pm y$ direction) and

476 polar (i.e., in the $\pm z$ direction) components near Europa's orbit (Bagenal et al., 2016).

477 However, these components are, at most, $\approx 5\%$ of the azimuthal (corotational, i.e., along

478 $+x$) component. The radial and polar components also have been observed to have dif-

479 ferent directions during different crossings of Europa's orbit, revealing that there is no

480 consistent behavior of the radial or polar flow components near Europa (see Figure 7b

481 of Bagenal et al., 2016). However, such weak radial and polar plasma velocity compo-

482 nents would only cause a very subtle rotation of our surface flux patterns around the z

483 and y axes, respectively, and as such we do not consider them here.

484   Europa's exosphere is treated as consisting entirely of O_2 (Plainaki et al., 2018),

485 with a scale height of 100 km (Arnold et al., 2019; Arnold, Liuzzo, & Simon, 2020). Sim-

486 ilar to Rubin et al. (2015), Arnold et al. (2019), and Harris et al. (2021), the exosphere

487 in our model possesses an upstream-downstream asymmetry. In the moon's orbital lead-

488 ing (downstream) hemisphere ($x > 0$), the exospheric density depends only on the ra-

489 dial distance to the surface and includes no latitudinal or longitudinal variations. Above

490 the moon's orbital trailing (upstream) hemisphere, the exospheric density profile is ax-

491 isymmetric around the x axis and decreases with radial distance to the surface. How-

492 ever, it also drops with angular distance from the moon's upstream apex (see equation

493 (2) of Arnold, Liuzzo, & Simon, 2020). The exosphere is mainly ionized through elec-

494 tron impacts, which dominate the ionization rate at Europa by over an order of mag-

495 nitude compared to photoionization (Saur et al., 1998). The AIKEF simulation domain

496 covers the volume bounded by $-9R_E \leq x \leq 21R_E$, $-10R_E \leq y \leq 10R_E$, and $-30R_E \leq$

497 $z \leq 30R_E$. In order to achieve a high resolution near the moon, AIKEF uses a hier-

498   archical Cartesian grid, with a cell size of 0.02 R_E for the domain $|x|, |y|, |z| \leq 1.5$ R_E,

499   0.04 R_E for $1.5R_E < |x|, |y|, |z| \leq 3$ R_E, and 0.08 R_E for $|x|, |y|, |z| > 3$ R_E.

500   While the southward ($B_{0,z} < 0$) component of the Jovian background magnetic

501   field $\mathbf{B}_0$ near Europa remains nearly constant as the plasma sheet sweeps over the moon

502   (Kivelson et al., 1999), the $B_{0,x}$ and $B_{0,y}$ components exhibit oscillations in their strength

503   and orientation on the scales of 20% and 50% of the background field magnitude, respec-

504   tively (e.g., Schilling et al., 2007). Sweepback of the magnetic field lines within the plasma

505   sheet causes the magnetic field to bulge toward upstream (Khurana & Kivelson, 1993).

506   Therefore, the $B_{0,x}$ component oscillates near Europa as the center of the sheet passes

507   above and below the moon. The oscillation in the $B_{0,y}$ component arises from Europa's

508   excursions away from Jupiter's magnetic equator. North of the magnetic equator, the

509   Jovian magnetic field lines point away from Jupiter (i.e., in the $-y$ direction), whereas

510   south of the magnetic equator the field lines point toward Jupiter ($+y$ direction). Since

511   the plasma number density within the sheet follows a Gaussian profile with distance to

512   the sheet's center (Hill & Michel, 1976; Bagenal & Delamere, 2011), the thermal plasma

513   impinging onto Europa periodically varies in density over a synodic rotation. The plasma

514   density is maximized at the center of the sheet, while at maximum elongation north or

515   south the plasma is more dilute by a factor of ~ 5 (Bagenal & Delamere, 2011; Roth et

516   al., 2014). Data from the Galileo PLS show no significant variation in plasma sheet den-

517   sity at Europa's orbit with local time (see Figure 1 of Bagenal & Delamere, 2011). The

518   magnetopause of Jupiter is located more than 40 R_J outside of Europa's orbit, so the

519   plasma density at Europa is not significantly affected by the moon's orbital position with

520   respect to the magnetopause. For this reason, the empirical models of the plasma den-

521   sity along Europa's orbit provided by, e.g., Bagenal et al. (2015), include only dependen-

522   cies on the radial distance to Jupiter and vertical distance to the center of the sheet, but

523   not on local time. The number density of the thermal plasma within the sheet does ex-

524   hibit a local time dependence. However, this dependence becomes important only at ra-

525   dial distances far outside the orbit of Europa (Bagenal et al., 2016).

526   Addison et al. (2021) calculated the structure of the perturbed electromagnetic fields

527   near Europa at three equally-spaced points in time along a synodic rotation, namely when

528   the moon is located at (1) the center, (2) maximum elongation north, and (3) maximum

529   elongation south of the plasma sheet. They then determined the spatial distribution of

530   magnetospheric ion flux onto Europa's surface at each of these three locations. Finally,

531 Addison et al. (2021) averaged these three flux maps across a synodic rotation, and com-

532 pared the resulting map to the spatial distribution of ion flux calculated at the center

533 of the plasma sheet (case (1)). These authors showed that the surface flux patterns from

534 both scenarios possessed significant similarities. In both cases, the distribution of the

535 total flux onto the surface was dominated by the contribution of the thermal ions, which

536 were able to reach nearly every location on the surface, with the highest irradiation oc-

537 curring near the upstream apex (see Figures 4(g) and 8(f) of Addison et al., 2021). Only

538 in a narrow band near Europa's geographic equator was the thermal ion flux reduced by

539 3–4 orders of magnitude compared to the poles or the upstream apex. The surface flux

540 pattern of energetic ions was also nearly identical in both scenarios (Figures 4(h) and

541 8(e), Addison et al., 2021). While the spatial distribution of energetic ion influx was more

542 uniform across the surface than that of the thermal ions, the energetic ions were found

543 to preferentially impact Europa's high-latitude regions. In both cases, a circular deple-

544 tion in the energetic ion flux by roughly an order of magnitude was identified near Eu-

545 ropa's upstream apex. At no location on Europa's surface was the ion flux averaged over

546 an entire synodic rotation different by more than a factor of five from the ion flux cal-

547 culated near the center of the plasma sheet. Addison et al. (2021) therefore concluded

548 that the distribution of ion surface flux onto Europa near the center of the plasma sheet

549 is an excellent approximation of the averaged ion flux pattern onto the moon over an en-

550 tire synodic rotation.

551 Therefore, our study of surface sputtering is based on a single configuration of the

552 ambient environment near Europa, namely one that is representative of the magneto-

553 spheric conditions near the center of the plasma sheet. The Jovian background magnetic

554 field $\mathbf{B}_0$ for this model setup is determined by averaging the time-dependent magneto-

555 spheric field at Europa's position (given in equation (17) of Schilling et al., 2007) over

556 an entire synodic period, which yields a background magnetic field of $\mathbf{B}_0 = -410\,\text{nT}\,\hat{\mathbf{z}}$.

557 We note that, with such a purely southward magnetic field, the induced dipole moment

558 at Europa disappears (Zimmer et al., 2000). We set the upstream plasma density to n_0

559 = 200 cm^{-3}, the same value utilized by Addison et al. (2021) to simulate Europa's con-

560 ditions near the center of the plasma sheet. This value is in agreement with the upstream

561 plasma density near the center of the plasma sheet as measured by the Galileo Plasma

562 Wave Subsystem (PWS), see Roth et al. (2014). Such a density is also approximately

563 in the middle of the range of densities derived by Bagenal et al. (2015), based upon com-

564 prehensive analysis of PWS data from Europa's orbit. The Alfvén speed $v_{A,0} = \frac{|\mathbf{B}_0|}{\sqrt{\mu_0\, n_0\, m_0}}$

565 in this configuration is 147 km/s, and the Alfvénic Mach number of the upstream plasma

566 $M_{A,0} = \frac{|\mathbf{u}_0|}{v_{A,0}}$ is approximately 0.68. The choice of this single electromagnetic field con-

567 figuration facilitates the analysis of the influence of other important variables on surface

568 sputtering rates. The role of factors such as the impact angles of impinging ions and the

569 time-varying surface temperature profile can be studied in isolation from the changing

570 electromagnetic fields.

571 ## 2.2 Model of Magnetospheric Ion Surface Flux

572 To calculate the spatial distribution of the magnetospheric ion flux onto Europa's

573 surface, we use the GENTOo particle-tracing code (Liuzzo et al., 2019a, 2019b; Addi-

574 son et al., 2021). GENTOo calculates the trajectories of individual macroparticles when

575 moving through the perturbed electromagnetic fields from AIKEF. The GENTOo model

576 utilizes a backtracing approach, that is, ion macroparticles are initialized on a grid across

577 Europa's surface (which is equidistant in latitude and longitude) and traced *backwards*

578 in time (model time step $\Delta t < 0$). At each grid point on the surface, particles are launched

579 at equal angular increments across a half-sphere in velocity space, thereby encompass-

580 ing all possible incident velocity vectors. Backtraced macroparticles whose trajectories

581 re-intersect Europa's surface after launch are deleted from the simulation. In a forward-

582 tracing approach, such an ion would have to pass through Europa's solid body in order

583 to reach its starting location on the moon's surface. Macroparticles whose trajectories

584 do not re-encounter Europa's surface, but reach the unperturbed magnetospheric envi-

585 ronment, are considered to have "allowed" trajectories. Since the bounce times of mag-

586 netospheric ions are larger than the convection time of the plasma through Europa's in-

587 teraction region, an ion with an allowed trajectory cannot make a second attempt to im-

588 pact Europa's surface and become forbidden (Breer et al., 2019; Addison et al., 2021).

589 In the forward-tracing picture, allowed particles are able to precipitate from Jupiter's

590 magnetosphere onto Europa's surface, and thus contribute to surface flux.

591 We initialize ions on Europa's surface at discrete energies ranging from $E = \frac{1}{2}m(u_0 -$

592 $v_{th})^2$ to $E = 10$ MeV. Here m is the mass of each ion, $u_0 = |\mathbf{u}_0|$ denotes the corota-

593 tion speed, and $v_{th} = \sqrt{2k_B T/m}$ (where $k_B T$: ion temperature) is the thermal speed

594 of the respective ion species. We choose intermediate energies at $E = \frac{1}{2}mu_0^2$, $\frac{1}{2}m(u_0 +$

595 $v_{th})^2$, 5 keV, 10 keV, 50 keV, 100 keV, 500 keV, 1 MeV, and 5 MeV. The three lowest

596 energies allow adequate coverage of the thermal ion regime, where the upstream distri-

597 bution changes rapidly as a function of energy (see Figure 2 of Addison et al., 2021). In

598 agreement with, e.g., Mauk et al. (2004), ions traced by the GENTOo model are con-

599 sidered test particles, that is, they do not alter their local electromagnetic environment.

600 We calculate the trajectories of thermal and energetic sulfur, oxygen, and hydro-

601 gen ions, the dominant ion species near Europa as measured by the Galileo and Juno

602 spacecraft (Cooper et al., 2001; Mauk et al., 2004; Kim et al., 2020; Clark et al., 2020).

603 While the surface flux of the thermal plasma could in principle be calculated with the

604 AIKEF hybrid code, this approach would yield maps with a four times lower resolution

605 than the GENTOo model. The currents carried by the thermal ions (and their influence

606 on the electromagnetic fields) are already taken into account in the AIKEF model and

607 in the resulting field cubes provided to GENTOo. Therefore, the feedback of the ther-

608 mal ions onto the fields does not need to be taken into account (a second time) in GEN-

609 TOo. Each ion with an allowed trajectory in GENTOo possesses a counterpart within

610 the framework of the hybrid model. Similar to Addison et al. (2021), the thermal plasma

611 is modeled as consisting of H^+, O^+, and S^{2+}, while the energetic plasma is modeled as

612 consisting of H^+, O^{2+}, and S^{3+}. This approach is in agreement with data on charge states

613 gathered by the Juno spacecraft (Kim et al., 2020; Clark et al., 2020). The thermal hy-

614 drogen has a temperature $k_B T_{\mathrm{H}} = 20$ eV (Paterson et al., 1999; Bagenal et al., 2015),

615 while the thermal oxygen and sulfur ions have a temperature of $k_B T_{\mathrm{O,S}} = 100$ eV (Kivelson

616 et al., 2009; Bagenal et al., 2015). Thus, the thermal velocities of the three ion species

617 read $v_{th,\mathrm{H}^+} = 63\,\mathrm{km/s}$, $v_{th,\mathrm{O}^+} = 34\,\mathrm{km/s}$, and $v_{th,\mathrm{S}^{2+}} = 24\,\mathrm{km/s}$ for hydrogen, oxy-

618 gen, and sulfur ions, respectively. The total thermal plasma density of $n_0 = 200$ cm^{-3}

619 is divided amongst the three three species (hydrogen, oxygen, and sulfur) using mixing

620 ratios derived by Bagenal et al. (2015). The resulting densities of thermal sulfur, oxy-

621 gen, and hydrogen ions are 112 cm^{-3}, 60 cm^{-3}, and 28 cm^{-3}, respectively (Addison et

622 al., 2021).

623 Once a backtraced ion macroparticle of a given energy with an "allowed" trajec-

624 tory escapes into the ambient magnetospheric plasma, its contribution to the surface flux

625 is calculated from measured upstream distributions. To do this, GENTOo invokes Li-

626 ouville's Theorem, which states that, in the absence of collisions or other loss/production

627 processes, the phase space density is conserved along each ion's trajectory. This allows

628 the flux represented by an ion macroparticle in the upstream plasma to be related to the

flux it carries onto Europa's surface. The energetic ion distributions outside of Europa's local interaction region are shaped by a multitude of magnetospheric processes, such as radial transport of charged particles within the Jovian magnetosphere and dissociation of sulfur dioxide from Io's volcanoes. To calculate the surface flux represented by each backtraced particle in GENTOo, we apply the ion distributions observed by Galileo in the vicinity of Europa's interaction region. In this way, we ensure that all of the above processes are properly accounted for when modeling ion precipitation onto Europa. Details of this procedure are discussed in section 2.2 of Addison et al. (2021). A detailed justification for the applicability of Liouville's Theorem at Europa is also provided in section 2.2 of Addison et al. (2021).

We utilize a drifting Maxwellian upstream distribution to calculate the surface flux of the (thermal) corotating plasma. The upstream energy distributions of energetic ions used in our model are a fit to EPD data taken during the E12 flyby of Galileo (Paranicas et al., 2002), which occurred when the moon was located near the center of the Jovian plasma sheet (see Figure 2 of Addison et al., 2021). The energetic ion distributions measured by the Galileo spacecraft changed by less than an order of magnitude as a result of Europa's variable proximity to the center of the plasma sheet. Thus, applying the E12 distribution in our model setups does not introduce any significant uncertainties into our results. While Mauk et al. (2004) suggest the pitch angle distribution (PAD) of energetic ions near Europa to be isotropic to within 25%, subsequent analysis by Kollmann et al. (2016) and Nénon and André (2019) has revealed that the energetic ion PAD may in fact be "pancake-shaped", with a depletion of particles possessing pitch angles near 0°. However, for this study we assume the PAD of the energetic ions near Europa to be isotropic, as Addison et al. (2021) found that the inclusion of an anisotropic PAD has only a minimal, quantitative effect on the surface flux pattern. These authors showed that inclusion of a pancake-shaped PAD causes a discernible reduction of the surface fluxes only in the MeV regime, where the energetic ion upstream distribution is only sparsely populated (see Figure 2 of Addison et al., 2021). At each latitude λ and longitude ϕ point on the GENTOo grid, the differential flux $\mathrm{d}J(E, \lambda, \phi)$ is calculated by summing the flux contributions of each macroparticle of a given energy with an allowed trajectory which was launched from that point.

We do not consider charge exchange reactions between magnetospheric ions and exospheric neutrals. Addison et al. (2021) found that these reactions only affect the sur-

face flux of protons with energies below ~ 50 keV, which have negligible sputtering yields (Johnson et al. (2009) and section 2.3 of this study).

2.3 Sputtering Yields of Magnetospheric Ions

Based upon laboratory experiments, several empirical models have been developed for the sputtering yields Y of ions impinging onto water ice (e.g., Famá et al., 2008; Johnson et al., 2009; Teolis et al., 2017). Sputtering yields depend upon projectile species, energy, and impact angle, as well as the temperature and composition of the surface. Different surface species may be sputtered in varying amounts based upon the extent to which dissociative chemical processes have caused different molecules to accumulate in layers close to the surface. Each of the available sputtering yield models (e.g., Famá et al., 2008; Johnson et al., 2009; Teolis et al., 2017) matches laboratory data best only in a specific projectile energy window, or for a certain sputtered species. Therefore, calculation of sputtering rates across the range of incident magnetospheric ion energies observed at Europa requires a combination of yields from several models. Sputtering yields are expressed in units of molecules released per incident particle. In sections 2.3.1 and 2.3.2 we describe our approach to calculate the surface sputtering rates of H_2O, O_2, and H_2 at Europa from the surface flux maps of magnetospheric ions provided by GENTOo.

2.3.1 Sputtering Yields of H_2O

Europa's surface consists primarily of water ice, which may be chemically decomposed into constituent atoms via ion and electron impacts (Bar-Nun et al., 1985; Johnson et al., 2005). However, intact H_2O may be directly sputtered from the surface prior to any chemical decomposition. Data on sputtering yields generated by laboratory experiments has been fit with analytical forms by both Famá et al. (2008) and Johnson et al. (2009). Cassidy et al. (2013) showed that the model of Famá et al. (2008) matches the laboratory data for projectile energies below $E \approx 100$ keV, while that of Johnson et al. (2009) matches the data more closely above 100 keV. Since Europa's regolith is approximately 1 m deep (Carlson et al., 2009), water ice is present well beyond the depth to which a magnetospheric ion may penetrate (≈ 1 mm at most, Teolis et al., 2017). As such, the source of sputterable H_2O may be considered unlimited on short time scales. Over geologic timescales, sputtering may locally lead to lowered water ice concentrations (e.g., Ligier et al., 2016), gradually reducing H_2O yields from areas of consistently high

693   bombardment. However, quantitative constraints on this thinning of the ice layer are yet

694   to be determined through observations or modeling.

695   The sputtering yields of H_2O molecules are independent of surface temperature be-

696   low 140 K (Baragiola et al., 2003), which is approximately the maximum surface tem-

697   perature at Europa (Spencer et al., 1999). Hence, for the calculation of H_2O sputtering

698   yields, we can omit the temperature-dependent term in the yield expressions of both Famá

699   et al. (2008) and Johnson et al. (2009). The H_2O sputtering yields in our model are there-

700   fore given by

$$
Y_{H_2O}(m, Z, E, \theta) = \begin{cases} \left\{ A(m)\, S_n(m, Z, E) + B(Z)\, S_e^2(m, Z, E) \right\} \cos^{-f(m)}(\theta) & ; \quad E \leq E_T(m, Z) \\ \left\{ \left[C_1 \left(\frac{v}{Z^{\frac{1}{3}}} \right)^{C_2} \right]^{-1} + \left[D_1 \left(\frac{v}{Z^{\frac{1}{3}}} \right)^{D_2} \right]^{-1} \right\}^{-1} \cos^{-f(m)}(\theta) & ; \quad E > E_T(m, Z) \end{cases} ,
$$

(1)

701   where the top equation is that of Famá et al. (2008), the bottom equation is from Johnson

702   et al. (2009), and $E_T(m, Z)$ is a "transition energy" at which we switch between the two

703   models (see discussion below). The mass, atomic number, and incidence angle (measured

704   against the local surface normal) of the projectile ion are given by m, Z and θ, respec-

705   tively, while v is the velocity of the particle divided by 2.19×10^6 m/s (Johnson et al.,

706   2009). The factors $A(m)$, $B(Z)$, and $f(m)$ are functions of projectile mass and atomic

707   number and are given by Famá et al. (2008), while the constants $C_1 = 4.2$, $C_2 = 2.16$,

708    $D_1 = 11.22$, and $D_2 = -2.24$ do *not* depend on projectile species and are provided

709   by Johnson et al. (2009). The factor $f(m)$ controls the sensitivity of Y for each species

710   to varying incidence angles, and reads $f(m) = 1.3$, $f(m) = 1.66$, $f(m) = 1.75$ for hy-

711   drogen, oxygen, and sulfur ions, respectively. In addition, the yields calculated from equa-

712   tion (1) are subsequently multiplied by a factor of 0.3 to account for the sticking of ejected

713   H_2O within Europa's surface regolith (Cassidy & Johnson, 2005; Cassidy et al., 2008;

714   Teolis et al., 2017). A similar combination of sputtering yield models has been imple-

715   mented by, e.g., Cassidy et al. (2013) and Vorburger and Wurz (2018) in order to study

716   exospheric generation at Europa.

717   Cassidy et al. (2013) suggested that the a suitable fit to laboratory data on sput-

718   tering yields can be accomplished by transitioning from the model of Famá et al. (2008)

719   to that of Johnson et al. (2009) at $E \approx 100$ keV. However, such a procedure results in

720   discontinuities of the sputtering yield profiles of all three ion species. Attempting to avoid

721   such jumps in the sputtering yield profiles, we define a transition energy, $E_T(m, Z)$, for

722   each species at which we switch from the yield profiles of Famá et al. (2008) at $E \leq E_T(m, Z)$

723   to Johnson et al. (2009) at $E > E_T(m, Z)$. We set the transition energy of hydrogen

724   and sulfur ions to the energy at which yield curves from the two models intersect, roughly

725    $E_T = 30$ keV and $E_T = 50$ keV, respectively. Not only does this choice ensure continu-

726   ity of the sputtering yield profiles for these two species, but the values of E_T are also close

727   to the value of $E_T \approx 100$ keV suggested by Cassidy et al. (2013). Since the starting en-

728   ergies of the ions modeled here are discrete, the shift of the transition energy from the

729   100 keV value suggested by Cassidy et al. (2013) to our proposed values only affects the

730   calculation of sputtering yields at two energies (50 keV and 100 keV) for sulfur, and one

731   energy (100 keV) for hydrogen. At these energy values, the yields from the empirical mod-

732   els of Johnson et al. (2009) and Famá et al. (2008) do not differ by more than a factor

733   of three. As such, the shift of the transition energy from 100 keV to 50 keV (hydrogen)

734   and 30 keV (sulfur) does not substantially affect our results. The models of the sput-

735   tering yields from *oxygen* ions presented by Famá et al. (2008) and Johnson et al. (2009)

736   do not intersect, thus the occurrence of a discontinuity in the yield curve for oxygen can

737   not be avoided. We therefore set the transition energy for sputtering by oxygen ions to

738    $E_T = 100$ keV, in agreement with the method of Cassidy et al. (2013). This approach

739   results in a jump in the sputtering yields by a factor of approximately 1.5 at $E_T = 100$

740   keV.

741   The expression presented by Famá et al. (2008) for the H_2O sputtering yield is writ-

742   ten in terms of the nuclear and electronic stopping powers of incident ions ($S_n(m, Z, E)$

743   and $S_e(m, Z, E)$, respectively), for which those authors provide empirical fits. These stop-

744   ping powers represent the rate at which an incident ion loses its energy with depth in

745   the surface, either by nuclear/momentum transfer (elastic) collisions ($S_n(m, Z, E)$) or

746   electronic excitation of surface molecules ($S_e(m, Z, E)$). Nuclear collisions dominate the

747   yields at projectile energies below ≈ 50 keV, while electronic excitation reactions become

748   predominant at higher energies. The expression provided by Johnson et al. (2009) is a

749   fit to laboratory data gathered in the electronic regime. Therefore, while this expression

750   is not written in terms of the electronic stopping power S_e, it still describes yields Y as-

751   sociated with electronic sputtering.

752   Figure 1(a) displays the sputtering yields of H_2O as a function of projectile energy

753   from 10 eV (approximately the corotation energy of protons) to 10 MeV, calculated from

754   equation (1). We do not consider "secondary" sputtering of the surface by ionospheric
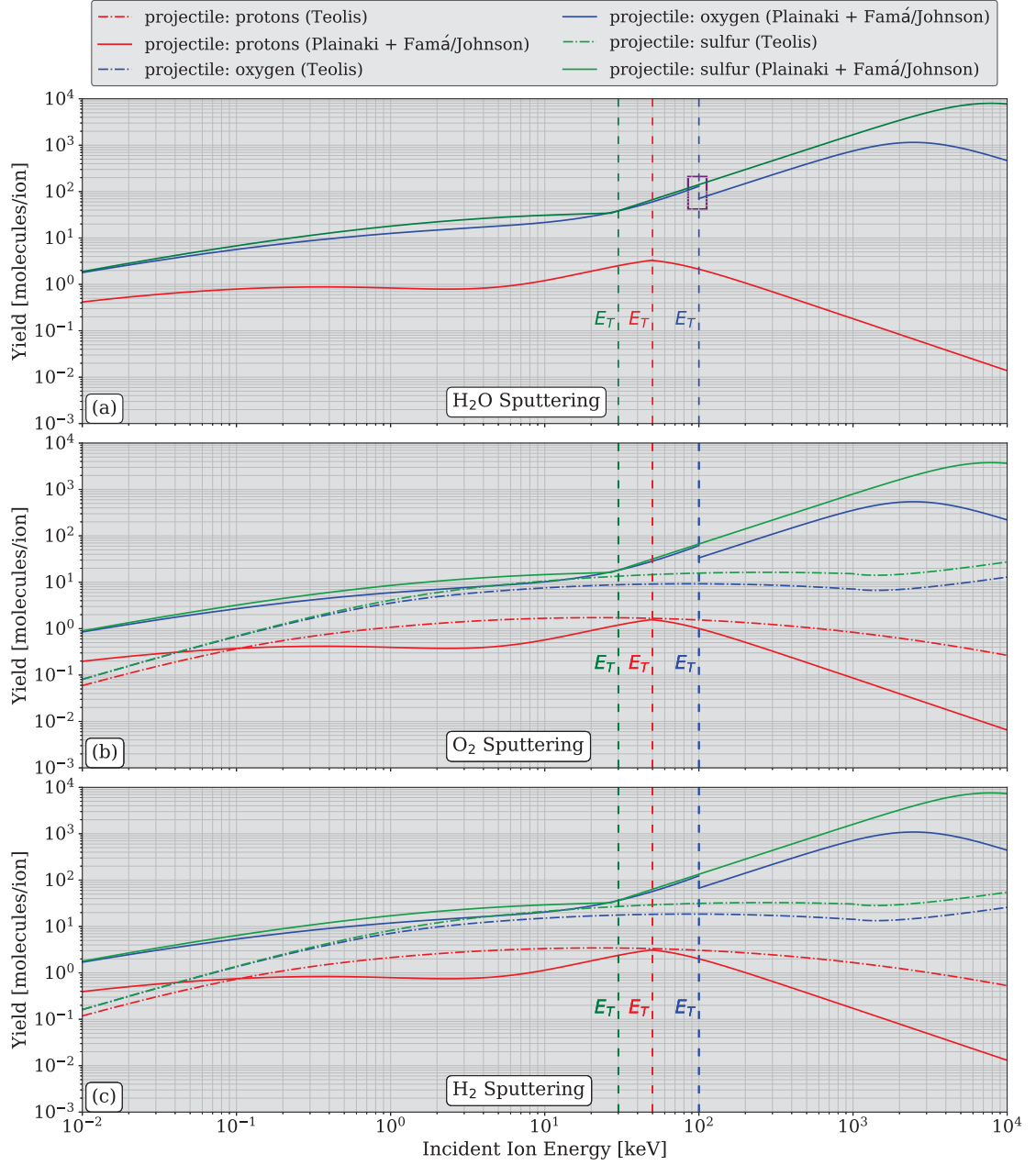
Figure 1. Sputtering yields in molecules/ion of H_2O (panel (a)), O_2 (panel (b)), and H_2 (panel (c)) via impacts by normally-incident ($\theta = 0°$) hydrogen (red), oxygen (blue), and sulfur (green) ions with energies from 10 eV-10 MeV onto water ice at 100 K. Yields derived via the models of Plainaki et al. (2013), Famá et al. (2008) and Johnson et al. (2009) are shown as solid lines, while yields from Teolis et al. (2017) are shown as dash-dotted lines. The transition energy E_T is denoted with a vertical dashed line in the color corresponding to each species. The model of Famá et al. (2008) is applied for energies below the transition energy E_T, while the model Johnson et al. (2009) is used above E_T. The purple box near 100 keV in panel (a) highlights the unavoidable jump between the sputtering yields from oxygen ions of the two models. Yields derived with the model of Teolis et al. (2017) are valid across the entire energy range considered, i.e., we do not have to switch between different models at the transition energy.

755   pickup ions ($E \ll 10$ eV), as the contribution of this process to atmospheric genera-

756   tion has been found to be a factor of 100 weaker than sputtering by magnetospheric ions

757   (Saur et al., 1998). We note that sputtering by ionospheric ions may play an important

758   role at Ganymede (Carnielli et al., 2020). In Figure 1(a) we discriminate between the

759   three projectile ion species most prevalent along Europa's orbit, with the yields from hy-

760   drogen, oxygen, and sulfur impacts shown in red, blue, and green, respectively. The tran-

761   sition energy E_T for each species is marked with a vertical, dashed line of correspond-

762   ing color. Due to their similar atomic numbers, the H_2O sputtering yields of incident oxy-

763   gen and sulfur ions (blue and green curves) have very similar values over a wide range

764   of energies; only at the very top of the energy range considered ($E \approx 10$ MeV) do they

765   differ by over an order of magnitude. The yield of incident hydrogen ions (red) is con-

766   sistently smaller than that of the two heavy ion species, due to their small mass and atomic

767   number. This difference in the H_2O sputtering yields between hydrogen and oxygen/sulfur

768   varies from a factor of approximately three at 10 eV to almost six orders of magnitude

769   at 10 MeV (see Figure 1(a)). In general, the sputtering yields increase gradually with

770   energy in the nuclear collision regime (below ≈ 50 keV), before growing rapidly above

771   this energy due to the onset of electronic excitations. The sputtering yields of heavy ions

772   maximize in the MeV regime, while the yields of protons maximize near 50 keV.

773   Laboratory experiments by Gibbs et al. (1988) and Vidal et al. (2005) revealed that

774   sputtering yields follow a $\cos^{-f(m)}(\theta)$ dependence on incidence angle in the electronic

775   sputtering regime. Standard linear cascade theory predicts a similar dependence on in-

776   cidence angle for nuclear sputtering yields (Famá et al., 2008). The form of $f(m)$ for H_2O

777   sputtering is provided by Famá et al. (2008) based upon laboratory data, and ranges from

778   $f(m) \approx 1.3 - 1.8$ depending upon the projectile species. Therefore, sputtering yields

779   can grow sharply with increasing incidence angle. For example, an impinging sulfur ion

780   with an incidence angle of $\theta = 80°$ sputters up to twenty times more H_2O than a sul-

781   fur ion with $\theta = 0°$. This form of the angular dependence exhibits a singularity at $\theta =$

782   $90°$, which would inflate the modeled sputtering yield to infinity. To avoid this, GEN-

783   TOo does not initialize backtraced macroparticles exactly tangential to the surface, rather,

784   only at angles of $\theta \leq 87°$.

785   Previous studies of magnetospheric ion sputtering at Jupiter's icy moons have typ-

786   ically assumed that all impinging ions hit the surface at the same incidence angle θ. This

787   assumption accounts for the fact that, in the absence of a detailed, high-resolution to-

788   pographical surface map (down to centimeter-scale), it is not feasible to precisely deter-

789   mine the incidence angle of an impinging ion. An ion may impact a crack or crevice on

790   the moon's surface and therefore impinge at a completely different angle than if it had

791   hit a perfectly smooth sphere. Therefore, particle-tracing models often assume that the

792   incidence angles of impacting ions average to a certain value within each cell of the grid

793   used to discretize the surface. Cassidy et al. (2013) assumed a normal angle of incidence

794   ($\theta = 0°$) for all impinging ions at Europa, while Carnielli et al. (2020) modeled ion sput-

795   tering at Ganymede with $\theta = 45°$. So far, only Plainaki et al. (2015) studied ion sput-

796   tering at Ganymede without assuming a single, average incidence angle: their model con-

797   siders the actual incidence angles of the ions onto a smooth sphere. Therefore, in order

798   to constrain the uncertainties associated with the treatment of the incidence angle we

799   will calculate H_2O sputtering rates with (i) all ions treated as impacting normally (similar

800   to Cassidy et al., 2013), and (ii) using the actual incidence angles onto a perfectly smooth

801   sphere as obtained from GENTOo.

802   ### 2.3.2 Sputtering Yields of O_2 and H_2

803   Sputtering of O_2 and H_2 from Europa's surface is the result of radiolysis and sub-

804   sequent buildup of each type of molecule in the upper layers of the ice (e.g., Teolis et al.,

805   2005, 2017). The sputtering of O_2 at Europa is of particular interest, as this process con-

806   stitutes the main source of the moon's near-surface (altitude < 300 km) exosphere. Within

807   much of this region O_2 dominates the number density by up to two orders of magnitude,

808   compared to H_2O, H_2, or other trace species (Plainaki et al., 2018; Vorburger & Wurz,

809   2018). However, the abundance of H_2O has been found to exceed that of O_2 by an or-

810   der of magnitude in a localized region above the central trailing hemisphere (Roth, 2021).

811   At the time of this study, two conceptually different models of O_2 sputtering have

812   been applied in order to calculate the source rate of O_2 via magnetospheric ion sputter-

813   ing at Europa. Plainaki et al. (2013) modeled the O_2 sputtering yield by using the temperature-

814   dependent term in the equation for Y provided by Famá et al. (2008). They judged this

815   approach to be accurate to within one order of magnitude. The sputtering yield of O_2

816   in this formulation (see, e.g, Plainaki et al., 2015) is given by

$$Y_{O_2}(m, Z, E, \theta, T) = \frac{1}{2} Y_{H_2O}(m, Z, E, \theta) \, \Phi(T) \qquad , \qquad (2)$$

where T is the temperature of the surface element from which material is sputtered, and $Y_{\mathrm{H_2O}}$ is given in equation (1). The temperature dependence of the sputtering yield,

$$\Phi(T) = q_0 \, \exp\left[-\frac{E_A}{k_B T}\right] \qquad , \qquad (3)$$

resembles that of a Maxwell-Boltzmann distribution (Famá et al., 2008; Johnson et al., 2009; Teolis et al., 2017). In equation (3), $q_0 = 1000$ is a scaling factor and $E_A = 0.06$ eV is the activation energy required for breakdown of surface constituents (Johnson et al., 2009). The factor of $\frac{1}{2}$ in equation (2) arises from the fact that two H_2O molecules must be decomposed in order for one O_2 to form (Cassidy et al., 2010). The sputtering yield of H_2 is therefore always twice that of O_2, i.e.,

$$Y_{\mathrm{H_2}}(m, Z, E, \theta, T) = 2\, Y_{\mathrm{O_2}}(m, Z, E, \theta, T) \qquad , \qquad (4)$$

which holds regardless of the formulation for $Y_{O_2}(m, Z, E, \theta, T)$. Figures 1(b) and 1(c) display the sputtering yields at $T = 100$ K (roughly the mean temperature of Europa's surface, e.g., Spencer et al., 1999) of O_2 and H_2, respectively. The factor $\Phi(T)$ becomes ranges from a value of 10^{-2} at 60 K to a value of 7 at 140 K, the approximate minimum and maximum surface temperatures at Europa (e.g., Spencer et al., 1999; Oza et al., 2019). Therefore, the O_2 and H_2 yields calculated via the model of Plainaki et al. (2013) follow from the H_2O yields (equation (1)) by multiplication with $\frac{1}{3}\Phi(T)$ for oxygen and $\frac{2}{3}\Phi(T)$ for hydrogen. In Figure 1, we calculate the yield curves assuming a constant surface temperature of $T = 100$ K.

The O_2 sputtering yield model of Plainaki et al. (2013) is based upon available sputtering models of H_2O. As such, it assumes that, like H_2O, substantial amounts of O_2 are present at any depth to which a magnetospheric ion may penetrate. Hence, their sputtering yield grows with energy, since higher energy ions penetrate deeper into the surface (up to 10^7 Å for 10 MeV protons, see, e.g., Teolis et al., 2017) and interact with more material than their lower energy counterparts.

An alternative method for calculating the sputtering yields of O_2 and H_2 is presented by Teolis et al. (2010, 2017). Based upon the findings of Petrik et al. (2006) and Teolis et al. (2005, 2009), these authors suggested that O_2 and H_2 molecules are mainly concentrated within the first ≈ 28 Å of Europa's surface, while their densities decrease sharply below this thin upper layer. Thus, penetration of projectile ions beyond this thin layer makes only a very minor additional contribution to the release of O_2 or H_2. Teolis

et al. (2010, 2017) formulate a novel method of calculating O_2 sputtering yields which considers this decreasing density of sputterable molecules at ion penetration depths greater than ≈ 28 Å. Their expression for O_2 sputtering yields reads

$$Y_{O_2}(E, \theta, T) = E \, g^0_{O_2} \, x_0 \left[1 - \exp\left(\frac{-r_0(E)\cos(\theta)}{x_0} \right) \right] \frac{1}{r_0(E)\cos(\theta)} \left(1 + \Phi(T) \right) \qquad , \quad (5)$$

where $g^0_{O_2} = 5 \times 10^{-3}$ eV^{-1} is the (constant) sputtering yield per energy when the surface temperature is below ≈ 80 K, $x_0 = 28$ Å is the thickness of the concentrated layer of O_2 and H_2 molecules directly beneath the surface, and $r_0(E)$ is the energy-dependent penetration range of the projectile (Ziegler & Manoyan, 1988; Teolis et al., 2017). The sputtering yields of H_2 are again twice the O_2 yields (equation (4)). The form of $\Phi(T)$ is the same as in equation (2). Values of $r_0(E)$ in our model are taken from a fit to the curve provided by Teolis et al. (2017) in their Figure 4. When the penetration depth $r_0(E)\cos(\theta)$ of the projectile, i.e., the penetration range $r_0(E)$ projected onto the local surface normal, greatly exceeds the O_2 layer depth x_0, the exponential term in equation (3) approaches zero. The sputtering yield of O_2 then becomes inversely proportional to the energy-dependent penetration depth. Note that the angular dependence of equation (5) is limited to the two occurrences of the penetration depth of the projectile, $r_0(E)\cos(\theta)$. At high penetration depths $(r_0(E)\cos(\theta) \gg x_0)$, the yield becomes proportional to $\cos^{-1}(\theta)$, similar to the angle dependence of equations (1) and (2) with $f(m) = 1$. Due to the negligible sticking coefficient of O_2 (Saur et al., 1998), it is not necessary to include a reduction factor in the O_2 yields to account for sticking within the regolith (as is done for H_2O).

Yields derived at $T = 100$ K with the formulation of Teolis et al. (2010, 2017) are shown in Figures 1(b) for O_2 and 1(c) for H_2 as dash-dotted lines. Only for oxygen and sulfur impacts between 1 keV and 30 keV do the O_2 yields calculated with the model of Teolis et al. (2017) approximately match those of Plainaki et al. (2012). The yields from the two models differ by up to an order of magnitude below this energy range, and by over two orders of magnitude above this range. For hydrogen impacts, sputtering yields calculated with the methods of Plainaki et al. (2012) and Teolis et al. (2017) are different by 1-2 orders of magnitude across the entire energy range considered, except in very narrow windows near 4×10^{-2} keV and 100 keV (see Figure 1(a)). The yields from the model of Teolis et al. (2017) initially grow with energy (and associated penetration depth), but level off near 10 keV as the ions pass deeper into surface layers where little O_2 or H_2 is present.

878   Observed sputtering yields of O_2 and H_2 increase exponentially with temperature

879   above ~ 70 K, while below 70 K they are roughly constant with temperature (Baragiola

880   et al., 2003). The models of Plainaki et al. (2012) and Teolis et al. (2017) each utilize

881   a slightly different form to emulate this temperature dependence: $Y \propto \Phi(T)$ and $Y \propto$

882    $[1 + \Phi(T)]$, respectively (see equations (2) and (5)). Therefore, while the O_2 sputter-

883   ing yields of Plainaki et al. (2012) approach a value of zero when the surface tempera-

884   ture decreases below 70 K, the yields of Teolis et al. (2017) level off at nonzero values

885   in this temperature regime, which more closely matches laboratory measurements (see

886   Figure 5 of that paper).

887   In addition, Teolis et al. (2005, 2010, 2017) suggest that a water ice surface requires

888   a minimum irradiation dosage of 10^{15} cm^{-2} before the O_2 sputtering yield displays a re-

889   sponse to changes in the surface temperature. At Europa, such a dosage from imping-

890   ing magnetospheric ions alone requires approximately three orbits around Jupiter to ac-

891   cumulate (Addison et al., 2021). Considering only magnetospheric ion bombardment,

892   a discernible reaction of the O_2 sputtering rate at Europa to varying solar orientation

893   (Plainaki et al., 2013) would therefore only occur on time scales far greater than the moon's

894   orbital period. In other words, the surface temperature profile would be "reset" before

895   the ice has adjusted to the change in temperature encountered along Europa's orbit. In

896   this picture, the sputtering yields can be calculated by considering a diurnally-averaged

897   temperature profile (i.e., averaged over an entire orbit).

898   However, magnetospheric electrons also impart a significant irradiation dosage onto

899   Europa's surface (e.g., Paranicas et al., 2001, 2007; Dalton et al., 2013). Indeed, recent

900   analysis by Davis et al. (2021) suggests that electrons may irradiate Europa's surface at

901   even higher levels than the ions, although their study did not take into account shield-

902   ing of the surface by the moon's plasma interaction. Such shielding has been found to

903   sharply reduce the precipitation of magnetospheric electrons onto Callisto (Liuzzo et al.,

904   2019a). Therefore, the magnetospheric electron fluxes onto Europa's surface calculated

905   by, e.g., Paranicas et al. (2001, 2007), Dalton et al. (2013), and Nordheim et al. (2018)

906   for uniform fields can be considered only an upper limit to electron surface irradiation.

907   However, modeling of magnetospheric electron bombardment at Europa is a non-trivial

908   task, requiring extensive modifications to the GENTOo framework. Electrons with en-

909   ergies greater than 50 keV display significant relativistic mass growth, changing the equa-

910   tion of motion that must be solved in order to determine their trajectories. Furthermore,

the bounce times of magnetospheric electrons can be smaller than the convection time

of the plasma through Europa's interaction region (Paranicas et al., 2009). Modeling of

electron bombardment therefore requires the implementation of a global model of Jupiter's

magnetosphere, and is beyond the scope of this study. However, if electrons contribute

to surface irradiation to the same extent (or greater) as the ions, the 10^{15} cm^{-2} irradi-

ation dose required for the ice to adapt to surface temperature changes (Teolis et al., 2017)

may be reached in far less than a Europan day. In that case, variations of the surface

temperature profile generated by Europa's changing orientation with respect to the Sun

need to be considered.

Our study will take into account the availability of two conceptually different mod-

els of O_2 and H_2 sputtering at Europa. In addition, we consider the uncertainty regard-

ing the response of surface sputtering to changes in the incident solar flux which results

from the moon's orbital motion. We shall compare maps of the O_2 and H_2 sputtering

rates utilizing the approaches of both Plainaki et al. (2013) and Teolis et al. (2017). In

addition, we will model the spatial distribution of O_2 and H_2 sputtering rates for four

different orientations of the Sun relative to the incident plasma flow, as well as for a tem-

perature profile averaged over a full Europan day. Specifically, we examine the O_2 and

H_2 sputtering rates at Europa while the moon is located at 06:00 LT, 12:00 LT, 18:00

LT, and 23:30 LT. We do not consider the scenario of exactly 00:00 LT, as in this con-

figuration Europa is in eclipse (see, e.g., Cassidy et al., 2008; Oza et al., 2019). The moon

only spends approximately 3% of its orbit in eclipse, and the surface temperature quickly

recovers (after approximately 6 hours, compared to an orbital period of 80 hours, see,

e.g., Oza et al., 2019). Since our priority is to systematically assess the role of chang-

ing solar orientation along a full orbital period (rather than the special case of eclipse),

we calculate maps of the O_2 and H_2 surface sputtering rate at 23:30 LT, just prior to

Europa entering Jupiter's optical shadow. In this case, the sub-solar point is located only

6° east of where it would be in the (hypothetical) case of a Sun-illuminated Europa at

00:00 LT.

A global illustration of Europa's orbit showing each of these four cases, along with

maps of the resultant surface temperature profiles, is displayed in Figure 2. Maps of the

surface temperature are displayed in the West Longitude system, where longitude ϕ in-

creases in a clockwise direction when viewed from the north ($z > 0$). In this system,

Europa's sub-Jovian, downstream, anti-Jovian, and upstream apices are located at $\phi =$

944 0°, 90°, 180°, and 270°, respectively. These maps range in latitude from $\lambda = -90°$ (de-

945 noting the south pole) to $\lambda = 90°$ (north pole).

946   For each of these four orbital positions, a map of the surface temperature profile

947 is calculated using the thermophysical model THERMPROJRS (Spencer et al., 1989,

948 1999). The THERMPROJRS model solves the conductive heat flow equation for a sur-

949 face layer of a given thermal inertia and bolometric albedo. A steady-state surface tem-

950 perature is then calculated assuming equilibrium between solar heat influx and thermal

951 emission from the moon. For our simulations, we utilize values of the emissivity and ther-

952 mal inertia at Europa of 0.9 and 7×10^4 erg cm^{-2} s$^{-1/2}$ K^{-1}, in agreement with Spencer

953 et al. (1999). Their thermophysical model assumes the albedo to be uniform across Eu-

954 ropa's surface. However, analysis of Galileo Photopolarimeter-Radiometer (PPR) data

955 by Rathbun et al. (2010) and Oza et al. (2019) has demonstrated that Europa's surface

956 albedo varies linearly with longitude from a minimum of 0.45 near the upstream apex

957 to a maximum of 0.65 near the downstream apex. In order to capture this upstream-downstream

958 asymmetry in Europa's surface brightness, we set the albedo to 0.45 at 18:00 LT (where

959 the moon's dayside and upstream hemispheres coincide), and to 0.65 at 06:00 LT (where

960 the dayside and downstream hemispheres coincide). At 12:00 and 23:30 LT, when Eu-

961 ropa's terminator plane is approximately aligned with the corotation direction, the albedo

962 is set to 0.55, i.e., we use the average of the upstream and downstream hemisphere val-

963 ues. The lower albedo at 18:00 LT in our model results in a slightly higher surface tem-

964 perature by approximately 15% compared to 06:00 LT, and 8% compared to 12:00 and

965 23:30 LT (Figure 2). The temperature maps in Figure 2 each display a bullseye-like en-

966 hancement around the apex of the dayside hemisphere, as well as a "tail" of increased

967 temperature extending eastward. This tail is a result of the thermal inertia of the sur-

968 face material, which partially retains the heat after a surface element has rotated out

969 of daylight.

970   The four surface temperature profiles shown in Figure 2 are averaged in order to

971 produce a map of the average temperature profile over a complete orbit ("diurnal-average",

972 see Figure 3). The diurnally-averaged temperature profile is *not* uniform in longitude,

973 since the sun-lit hemisphere heats to higher temperatures at 18:00 LT than at 06:00 LT.

974 Averaging the surface temperature over a full Europan orbit therefore results in a pro-

975 file which is hotter upstream and cooler downstream, albeit with a weaker upstream-downstream

976 discrepancy compared to 18:00 LT (≈ 45 K versus ≈ 60 K, see Figures 2 and 3). In re-
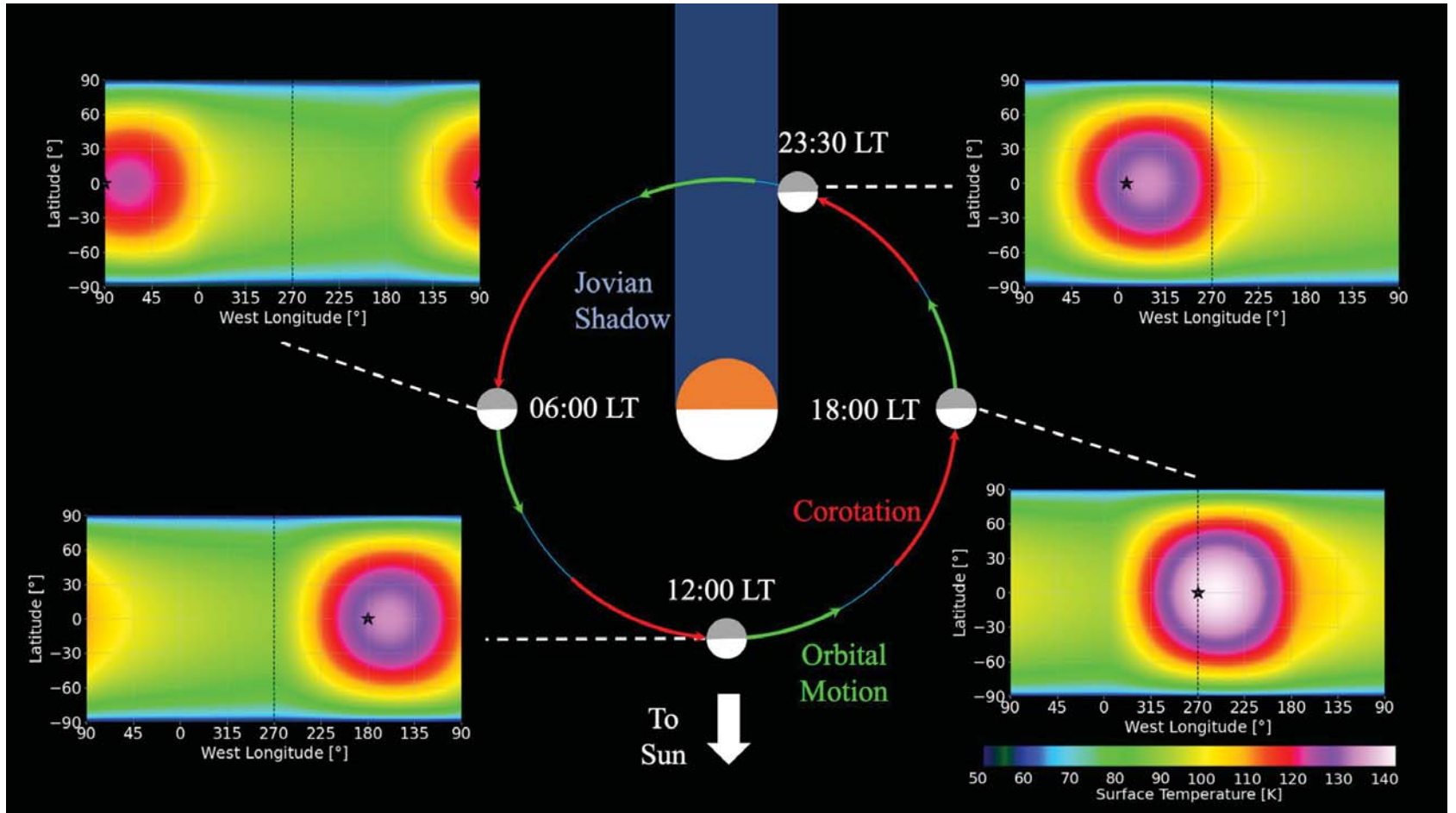
Figure 2. Orientation of Europa relative to Jupiter and the Sun for 06:00, 12:00, 18:00, and 23:30 LT, as described in section 2.3.2. Jupiter (orange nightside and white dayside) is located in the center of the figure. Red arrows indicate the direction of the corotating plasma flow, while green arrows indicate the direction of Europa's orbital motion. For each orbital position, Europa's nightside hemisphere is shown in gray, while the Sun-lit/dayside hemisphere is colored white. Next to each of the four orbital positions is a plot of the surface temperature profile in West Longitude coordinates, with Europa's sub-Jovian, downstream, anti-Jovian, and upstream apices located at longitudes of 0°, 90°, 180°, and 270°, respectively. The sub-solar point is marked with a black star, and a vertical dashed line marks a semi-meridian through the upstream apex. Note that at 06:00 LT, the black star is split between the left and right sides of the temperature map.
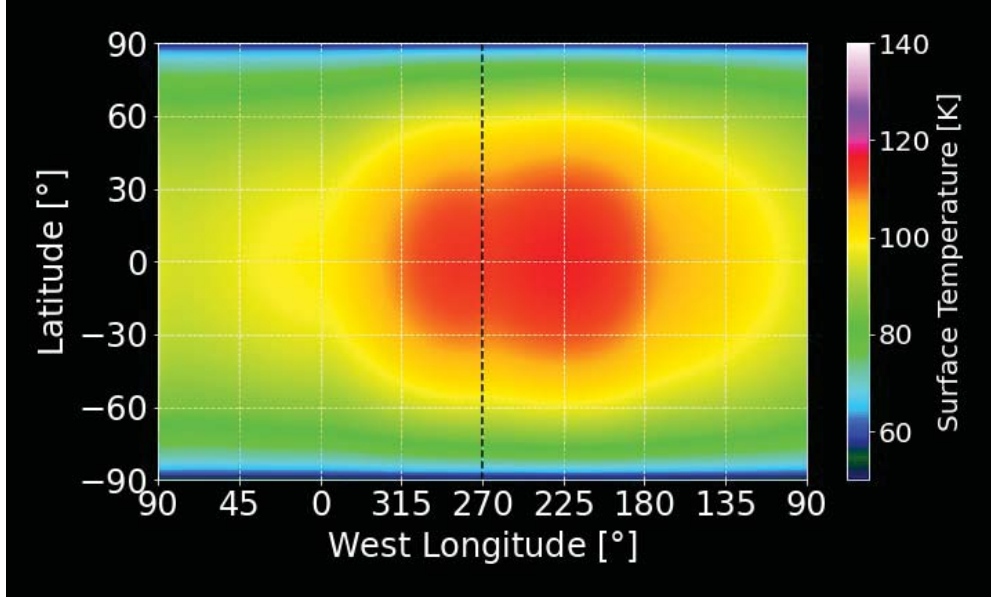
Figure 3. Diurnally-averaged surface temperature profile at Europa, calculated using the four temperature profiles shown in Figure 2.

977 ality, the diurnally-averaged temperature profile may be slightly cooler, since our model

978 does not consider the drop in surface temperature during and after eclipse. In each sce-

979 nario (the four local times and the diurnal average), the O_2 and H_2 sputtering yields are

980 calculated with the respective temperature profile and the temperature dependence $\Phi(T)$,

981 as given in equations (2) and (5).

3 Results

3.1 Hybrid Simulation of Europa's Electromagnetic Environment

984 Figure 4 displays the structure of Europa's perturbed electromagnetic and plasma

985 environment, as calculated by the AIKEF model. All quantities in Figure 4 are presented

986 in cuts through the three-dimensional simulation domain at $y = 0$, i.e., in the plane that

987 contains the corotational flow velocity $\mathbf{u}_0$, the background magnetic field $\mathbf{B}_0$, and the

988 center of the moon. The first row (panels 4(a) and 4(b)) displays the flow-aligned com-

989 ponent of the magnetic field, B_x, and the magnitude of the magnetic field, $|\mathbf{B}|$, respec-

990 tively. The magnitude of the electric field, $|\mathbf{E}|$, is shown in panel 4(c). Finally, the num-

991 ber density of the corotating plasma, n, is presented in panel 4(d).
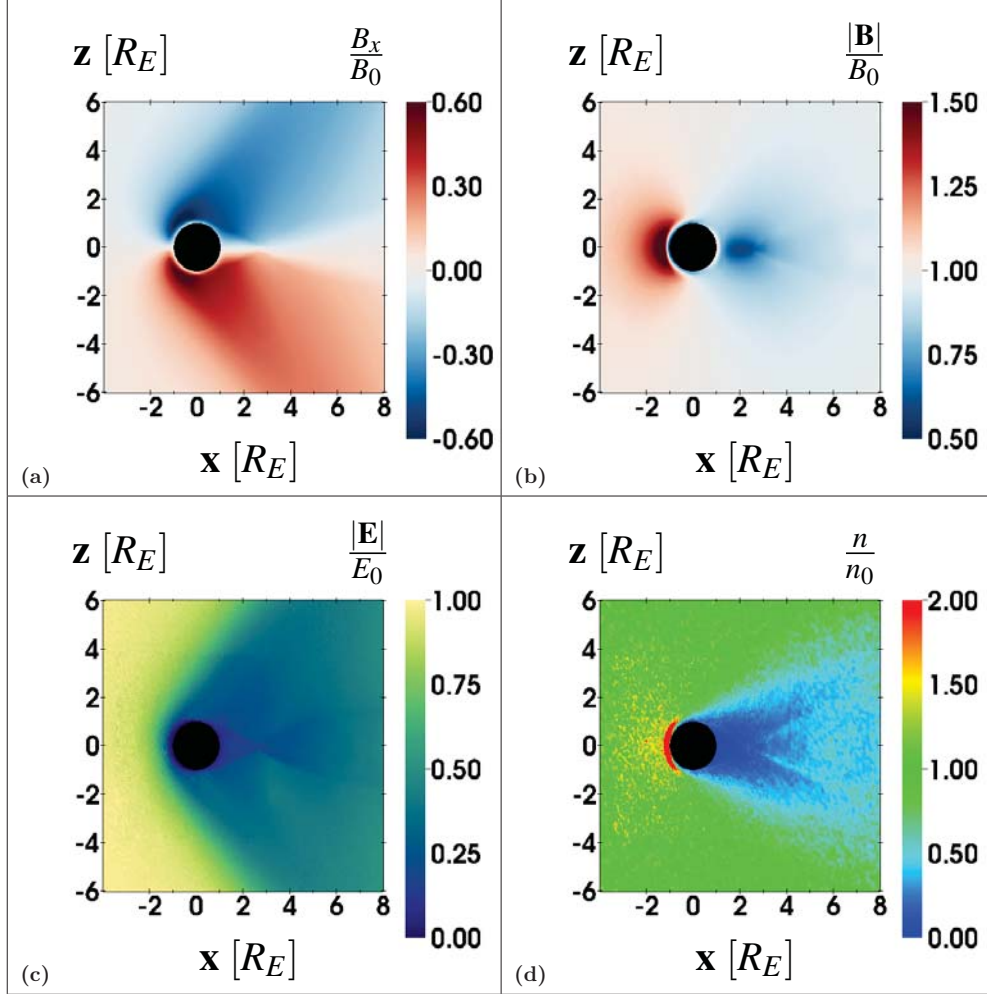
Figure 4. Electromagnetic and plasma environment near Europa, as calculated by the AIKEF model. All quantities are shown in cuts through the (x, z) plane, which contains the upstream flow velocity $\mathbf{u}_0$, the background magnetic field $\mathbf{B}_0$, and the center of Europa. Panels (a) and (b) display the B_x component and magnitude of the magnetic field, respectively, as a fraction of the background field magnitude $|\mathbf{B}_0| = B_0 = 410$ nT. Panel (c) displays the electric field magnitude, normalized to the background convective electric field strength $E_0 = u_0 B_0 = 41$ mV/m. Panel (d) displays the number density of the magnetospheric plasma, as a fraction of the upstream density $n_0 = 200$ cm^{-3}.

Ionization of Europa's exosphere drains momentum from the upstream plasma, caus-

ing the magnetospheric ion number density to grow to over twice the background value

$n_0 = 200 \, \text{cm}^{-3}$ above the moon's upstream hemisphere (Figure 4(d)). Ionospheric ions

are convected downstream, refilling the moon's magnetospheric plasma wake and main-

taining pressure balance with the adjacent flow (see Figure 3 of Addison et al., 2021).

The frozen-in magnetospheric field lines pile up above Europa's orbital trailing hemisphere,

leading to an enhancement in the magnetic field magnitude by 50% compared to the back-

ground value (red region in Figure 4(b)). This upstream pileup is accompanied by a weak-

ening of the magnetic field magnitude by 50% immediately downstream of the moon (blue

region in Figure 4(b)). The plasma interaction also generates a system of Alfvén wings

which extend north and south from Europa to Jupiter's polar ionosphere (Neubauer, 1980,

1998). The Alfvén wings are tilted against the z axis by an angle of $\arctan(M_A) = 34°$,

where $M_A = 0.68$ is the Alfvénic Mach number. Inside of the Alfvén wing tubes the

field possesses a flow-aligned component south of the moon ($B_x > 0$, red region in Fig-

ure 4(a)), and a component antiparallel to the flow direction north of the moon ($B_x <$

0, blue region in Figure 4(a)). The magnetospheric plasma slows within and downstream

of the Alfvén wings, causing the downstream reduction in the electric field seen in Fig-

ure 4(c).

For a more detailed discussion of the electromagnetic field perturbations near Eu-

ropa, the reader is referred to our numerous preceding publications that applied the same

model to this moon (Arnold et al., 2019; Arnold, Liuzzo, & Simon, 2020; Arnold, Simon,

& Liuzzo, 2020; Breer et al., 2019; Addison et al., 2021).

3.2 Magnetospheric Ion Surface Fluxes and Sputtering Rates of H_2O

In Figure 5 we present maps of the magnetospheric ion surface fluxes onto Europa

for both the thermal (panels 5(a) and 5(b)) and energetic (panels 5(c) and 5(d)) regime,

as calculated by the GENTOo model. The left column (panels 5(a) and 5(c)) displays

flux maps calculated with only the uniform Jovian magnetic field $\mathbf{B}_0$ and the undisturbed

convective electric field $\mathbf{E}_0$, while the right column displays flux maps determined with

the perturbed electromagnetic fields from AIKEF (see Figure 4). Figure 6 features maps

of the H_2O sputtering rates across Europa's surface from thermal ions (panels 6(a)–6(c)),

energetic ions (panels 6(d)–6(f)), and magnetospheric ions of all energies and species con-

sidered in this study (panels 6(g)–6(i)). The first column (panels 6(a), 6(d), and 6(g))
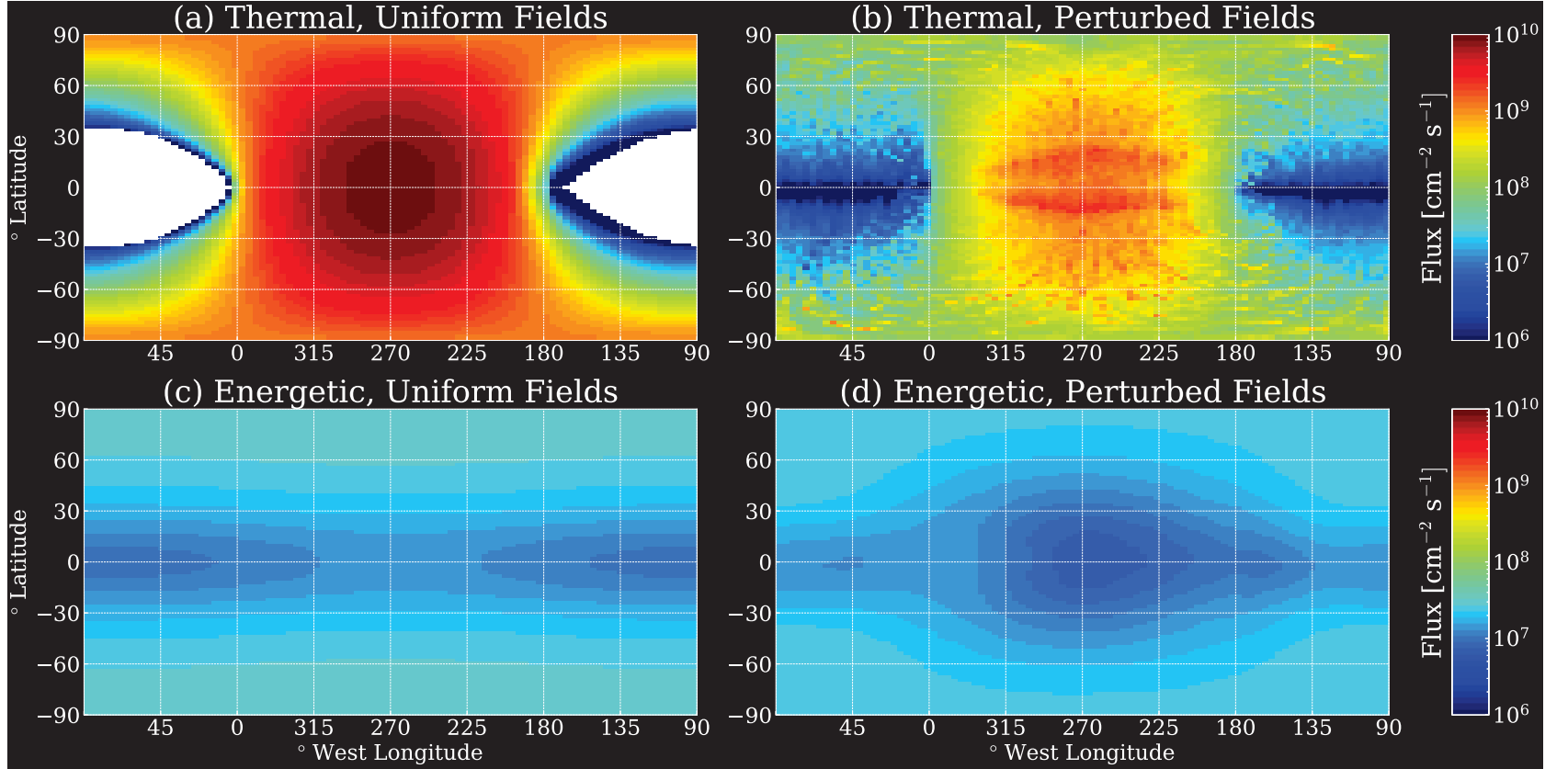
Figure 5. Surface flux maps of magnetospheric ions (hydrogen, oxygen, and sulfur) at Europa, calculated with the GENTOo model. The first row (panels (a) and (b)) displays the surface flux of the thermal ion population, while the second row (panels (c) and (d)) shows the flux from the energetic ion population (energies 5keV $\leq E \leq$ 10MeV). The left column (panels (a) and (c)) shows fluxes calculated with the uniform electromagnetic fields $\mathbf{B}_0$ and $\mathbf{E}_0$, while the right column (panels (b) and (d)) shows fluxes calculated with the perturbed fields determined by AIKEF. Each map is shown in the West Longitude system. The white region in panel (a) indicates areas in Europa's downstream hemisphere where the thermal ion surface flux is exactly zero.
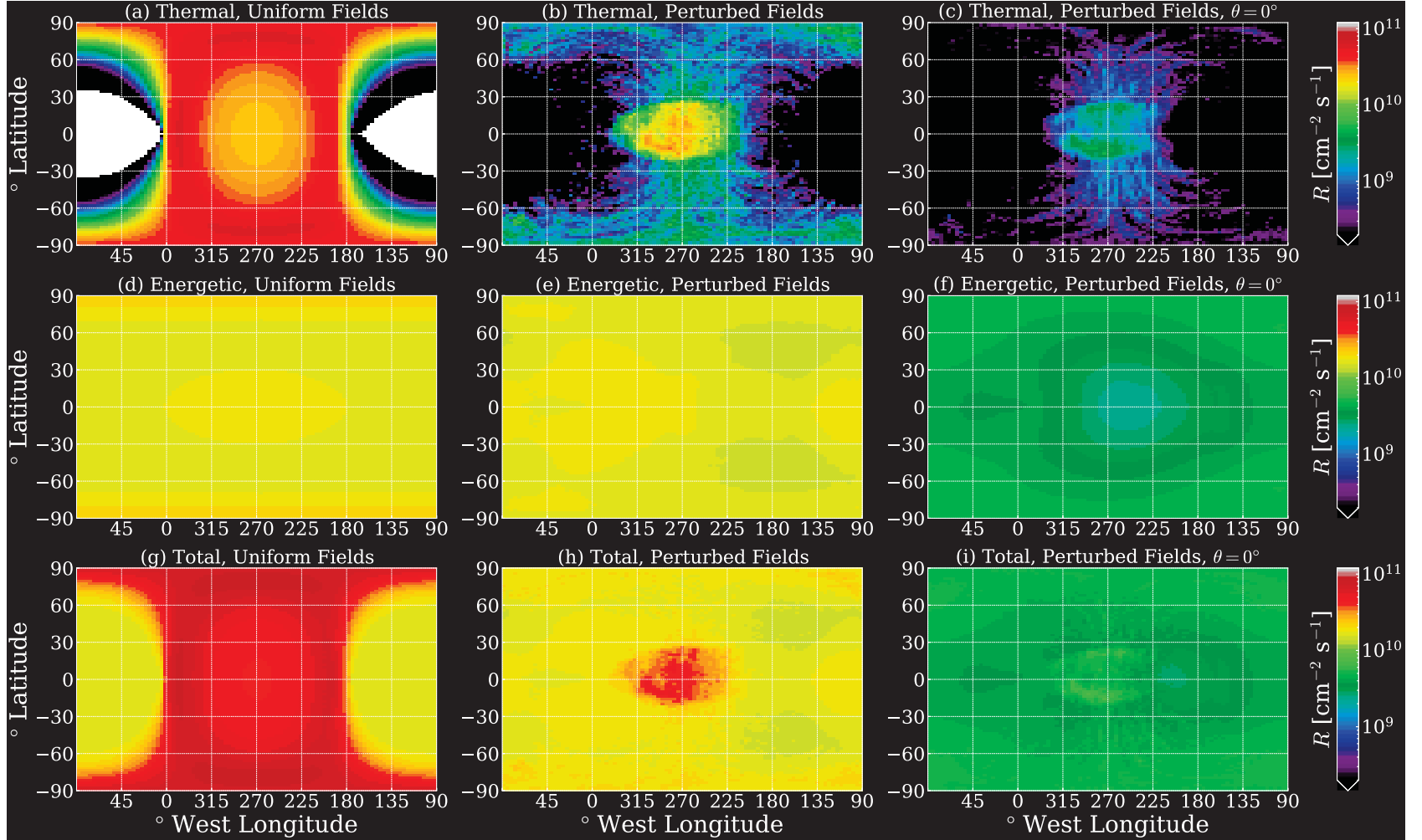
Figure 6. H$_2$O surface sputtering rates from impacts by all magnetospheric ion species (hydrogen, oxygen, and sulfur) considered in this study. Each map is displayed in the West Longitude system as described in the text. The first column (panels (a), (d), and (g)) shows H$_2$O sputtering rates calculated with only the uniform background electromagnetic fields $\mathbf{B}_0$ and $\mathbf{E}_0$ included, while the second column (panels (b), (e), and (h)) displays H$_2$O sputtering rates calculated using Europa's perturbed electromagnetic environment from the AIKEF model. Both the first and second columns utilize the actual incidence angles θ of the incoming ions in their calculation of the sputtering yields (equation (1)). The third column (panels (c), (f), and (i)) displays H$_2$O sputtering rates calculated with perturbed electromagnetic fields (as in the second column), but with the incidence angles of all impinging ions set to $\theta = 0°$ in equation (1). From top to bottom, the rows display H$_2$O sputtering rates of thermal ions (panels (a)–(c)), energetic ions with energies 5keV $\leq E \leq$ 10MeV (panels (d)–(f)), and the total sputtering rate of all magnetospheric ions (thermal and energetic, panels (g)–(i)). White regions in panel (a) indicate areas where the sputtering rate from thermal ion impacts is exactly zero.

1024 displays H_2O sputtering rates calculated with a uniform field configuration, as well as

1025 with the modeled incidence angles from GENTOo used in equation (1). Sputtering rates

1026 calculated with the perturbed fields from AIKEF and the incidence angles from GEN-

1027 TOo are presented in the second column (panels 6(b), 6(e), and 6(h)).

1028 Finally, to isolate the influence of non-uniform ion incidence angles on the H_2O sput-

1029 tering rate, the third column (panels 6(c), 6(f), and 6(i)) displays H_2O sputtering rates

1030 determined with perturbed fields, but with the incidence angle of all impinging ions set

1031 to a constant value ($\theta = 0°$) in equation (1). This specific choice of incidence angle is

1032 consistent with the approach of Cassidy et al. (2013), but still somewhat arbitrary. Re-

1033 garding the angle dependence of the sputtering yields, the choice of $\theta = 0°$ gives equal

1034 weight to all three ion species ($\cos^{-f(m)}(0) = 1$), while a value of $\theta > 0°$ weights the

1035 three species differently (due to the mass dependence of $f(m)$). However, choosing a value

1036 of, e.g., $\theta = 45°$, as done at Ganymede by Carnielli et al. (2020), results in (at maxi-

1037 mum) a 14% enhancement of the H_2O sputtering yield of one ion species compared to

1038 another. Therefore, the choice of a constant incidence angle $\theta > 0°$ would only cause

1039 a minor, quantitative enhancement of the H_2O sputtering rate compared to when $\theta =$

1040 $0°$, and would not appreciably alter the spatial distribution of our modeled rates.

1041 When the electromagnetic fields near Europa are treated as uniform, the corotat-

1042 ing thermal plasma can impinge unimpeded onto the moon's upstream hemisphere. In

1043 this case, the spatial distribution of the thermal ion surface flux onto Europa's upstream

1044 hemisphere (180°–360° west longitude, Figure 5(a)) is mainly determined by the cosine

1045 of the angle between the normal vector at each surface location and the corotation di-

1046 rection ($+x$, see also equation (8) in Addison et al., 2021). This angle grows from 0° at

1047 the upstream apex to 90° at surface locations in the $x = 0$ plane (0° W and 180° W

1048 longitudes, at all latitudes), and is rotationally symmetric around the x axis. The sur-

1049 face flux of the impinging thermal ions therefore drops with distance from the upstream

1050 apex, as the angle between the corotation direction and the surface normal vector grows.

1051 This results in a bullseye-like flux pattern in the upstream hemisphere, as also found by

1052 Cassidy et al. (2013) and Addison et al. (2021).

1053 The downstream hemisphere between $\lambda = -30°$ and $\lambda = 30°$ latitude is mainly

1054 devoid of thermal ion influx, as many of the thermal ions are prevented access to this

1055 region by the solid body of Europa (Figure 5(a)). However, the thermal velocity of the

1056 corotating magnetospheric ions can achieve values of over 60% of the bulk speed u_0 (see

1057 section 2.2). Thus, the velocity vectors of a significant number of thermal ions near the

1058 moon are strongly inclined against the corotation direction. These ions are able to reach

1059 the high-latitude regions on Europa's downstream hemisphere without being intercepted

1060 by the moon's upstream surface.

1061 The sputtering rates R of thermal ions in uniform fields (Figure 6(a)) achieve their

1062 peak values (up to $R = 6 \times 10^{10} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) on the upstream hemisphere, but are zero

1063 on the downstream hemisphere equatorward of $\pm 30°$ latitude. However, unlike the ther-

1064 mal ion surface flux, the H_2O sputtering rate of thermal ions (Figure 6(a)) does *not* max-

1065 imize near the upstream apex. Rather, the H_2O sputtering rate from thermal ion im-

1066 pacts grows monotonically with distance from the upstream apex and maximizes in the

1067 region where the $x = 0$ plane intersects Europa (dark red in Figure 6(a)). To explain

1068 this behavior, we consider ions whose velocity vectors are nearly aligned with the coro-

1069 tation direction, i.e., ions which originate from the region of velocity space where the Maxwellian

1070 distribution peaks and the bulk of the upstream thermal population is concentrated. For

1071 such an ion, the impact angle θ in equation (1) is approximately given by the angle be-

1072 tween the corotation direction and the surface normal vector. The contribution that such

1073 an ion makes to the surface flux is proportional to $\cos(\theta)$, whereas the ion's sputtering

1074 yield is proportional to $\cos^{-f(m)}(\theta)$. The ion's contribution to the sputtering rate, which

1075 is the product of these two quantities, is therefore proportional to $\cos^{1-f(m)}(\theta)$. Since

1076 $f(m) > 1$ for all ion species (Famá et al., 2008), the sputtering rate of ions that move

1077 (nearly) along the corotation direction and impact the upstream hemisphere increases

1078 with distance from the upstream apex, i.e., as the angle between the ion's velocity vec-

1079 tor and the surface normal grows. This increase in sputtering rates with distance from

1080 the upstream apex is opposite to the pattern predicted by Cassidy et al. (2013) for uni-

1081 form fields, as those authors treated all thermal ions as impacting the surface with the

1082 same incidence angle ($\theta = 0°$) when calculating sputtering yields.

1083 Including the influence of Europa's plasma interaction on magnetospheric ion tra-

1084 jectories drastically alters the spatial distribution of the thermal ion surface flux (Fig-

1085 ure 5(b)). In this scenario, thermal ions no longer have unimpeded access to the moon's

1086 upstream hemisphere. Deflection of thermal ions in the magnetic pileup region is too weak

1087 to appreciably reduce ion flux onto Europa's upstream hemisphere (Addison et al., 2021).

1088 Deflection of thermal ions away from the moon is caused almost entirely by the Alfvén

wings, which encapsulate Europa and its exosphere. The bulk of the thermal ions which enter Europa's interaction region are diverted around the Alfvén wing tubes, and pass by the moon's sub-Jovian and anti-Jovian flanks (see also Figure 2 of Simon et al., 2021). Deflection of thermal ions around Europa's Alfvén wings reduces the ion surface flux by over an order of magnitude at nearly all locations on the upstream hemisphere (Addison et al., 2021). As shown by Simon et al. (2021), the small number of ions which penetrate the wing tubes move almost completely in the corotation direction, since the ionospheric Hall Effect is too weak at Europa to drastically break the symmetry of the ion flow pattern between the sub-Jovian and anti-Jovian hemispheres. In analogy to the case of uniform fields, the influx pattern of these ions onto the upstream hemisphere is therefore determined by the cosine of the angle between the corotation direction and the local surface normal. Hence, even when the field perturbations are taken into account, the spatial distribution of the thermal ion flux onto the upstream hemisphere retains something of the bullseye-like distribution seen in the case of uniform fields (Figure 5(a)). We note that the model of Simon et al. (2021) applies a fluid approach to describe ion dynamics. Hence, their model does not capture individual ions from the "edges" of the Maxwellian upstream distribution that impinge onto Europa at large angles against the corotation direction.

Although the bulk of the thermal ions move along the corotation direction, a non-negligible fraction of the upstream ions have velocity vectors which are significantly inclined against the corotation direction. These ions are deflected by the draped magnetic fields onto Europa's downstream and polar regions (Addison et al., 2021). The thermal ion flux onto the polar caps is therefore similar in magnitude to that at lower latitudes of the upstream hemisphere, except near the upstream apex where the thermal ion surface flux is higher by two orders of magnitude. The deflection of ions with highly-inclined trajectories against the corotation direction onto the high-latitude regions leaves an equatorial depletion in flux by up to three orders of magnitude compared to the polar and low-latitude upstream regions (dark blue region in Figure 5(b)). This is in contrast to a uniform field geometry, where *no* thermal ions can reach the downstream hemisphere between approximately $-30°$ and $30°$ latitude (white regions in Figure 5(a)).

The alterations to the thermal ion flux pattern brought on by the field perturbations carry over into the H_2O sputtering rates (Figure 6(b)). For perturbed fields, the spatial distribution of the rates from thermal ions sputtering is remarkably similar to the

1122 pattern seen in the thermal ion flux (Figure 5). Unlike in the case of uniform electro-

1123 magnetic fields (Figure 6(a)), the H_2O sputtering rate for perturbed fields (Figure 6(b))

1124 does indeed maximize near the trailing apex ($270°$ W) in an elliptically-shaped region

1125 which extends approximately $45°$ east and west of the upstream apex and $30°$ north and

1126 south. This elliptical region of enhanced H_2O sputtering corresponds to the ion surface

1127 flux enhancement centered near the upstream apex (Figure 5(b)). This enhancement pos-

1128 sesses a minor east-west asymmetry, which results from the (small) rotation of the elec-

1129 tric field against the $-\hat{\mathbf{y}}$ axis by the ionospheric Hall Effect. Simon et al. (2021) estimated

1130 that this angle of rotation may reach about $16°$, consistent with the rather subtle east-

1131 west asymmetry in Figure 6(b). The draping of the magnetic field lines allows thermal

1132 ions with a greater range of incidence angles to impinge upon each surface location on

1133 the upstream hemisphere, compared to when the fields are uniform. In particular, ions

1134 with grazing trajectories may impinge onto the surface near the upstream apex, while

1135 ions with trajectories normal to the surface may impact far from the upstream apex (see

1136 Figure 5 of Addison et al., 2021). As such, the increase in the H_2O sputtering rate with

1137 distance from the upstream apex seen in uniform fields (Figure 6a) does not occur when

1138 the field perturbations are included. In draped fields, the H_2O sputtering rate from ther-

1139 mal ions decreases with distance from the upstream apex, and falls off sharply upon en-

1140 tering the downstream hemisphere. The H_2O sputtering rate is 2-3 orders of magnitude

1141 lower on the downstream hemisphere than it is near the upstream apex. The near-equatorial

1142 depletion in thermal ion surface flux onto the downstream hemisphere (Figure 5(b)) causes

1143 a similar depletion in the H_2O sputtering rate at low latitudes. However, even near the

1144 downstream equator the sputtering rate obtained for perturbed fields still reaches $R \approx$

1145 $10^6 \, \text{cm}^{-2} \, \text{s}^{-1}$. This is in contrast to a uniform field configuration, where the sputtering

1146 rate in this region is exactly zero (Figure 6(a)). Setting $\theta = 0°$ in equation (1) further

1147 reduces the H_2O sputtering rate from thermal ions by up to an order of magnitude (Fig-

1148 ure 6(c)) to the minimum possible value. However, the spatial distribution largely re-

1149 mains unaffected compared to the rates obtained with the actual incidence angles (Fig-

1150 ure 6(b)).

1151 In a uniform field configuration, the surface flux of energetic ($5 \, \text{keV} \leq E \leq 10 \, \text{MeV}$)

1152 ions is nearly uniform across Europa's surface, differing between any two locations by

1153 no more than one order of magnitude (Figure 5(c)). The large gyroradii of energetic ions

1154 ($\approx 0.5 R_E$ for 1 MeV S^{3+}) allow them to impact every location on Europa's surface, in-

cluding the downstream hemisphere between -30° and 30° latitude which is inaccessible to the thermal ions in a uniform field setup (Figure 6(a) and Addison et al., 2021). The high field-aligned velocities of many energetic ions cause them to most heavily irradiate Europa's polar caps (Cassidy et al., 2013; Breer et al., 2019; Addison et al., 2021). As a result, the energetic ion surface flux monotonically decreases in the direction of descending latitude (Figure 5(c)), achieving a value at the equator that is roughly one order of magnitude lower than at the poles. A latitudinal decrease can also be seen in the H_2O sputtering rates of energetic ions in uniform fields (Figure 6(d)). Convection of energetic ions toward downstream leads to a slight enhancement in the energetic ion influx by approximately 20% near the upstream apex (Figure 5(c)) compared to the downstream equator. Thus, in the upstream hemisphere, the equatorial reduction in H_2O sputtering rate is interrupted by an elliptical enhancement of approximately 20% compared to the downstream equator.

Magnetic field line draping leads to a large, quasi-elliptical region of reduced energetic ion flux centered at Europa's upstream apex and covering much of the upstream hemisphere (see Figure 5(d), as well as Addison et al., 2021). The draping increases the latitudinal extent of the region near the moon where ions traveling along the field lines are within one gyroradius of the surface. Impinging ions can therefore gyrate into the moon at higher latitudes than in uniform fields (Addison et al., 2021), creating an influx depletion by approximately a factor of two near the upstream apex compared to the downstream equatorial region. Surprisingly, a similar depletion feature is *not* present in the energetic ion H_2O sputtering rate calculated with draped fields and the actual incidence angles from GENTOo (Figure 6(e)). Although the energetic ion flux is reduced near the upstream apex by a factor of three compared to the poles (Figure 5(d)), ions entering the interaction region along the draped field lines (mostly) encounter the near-equatorial surface with grazing trajectories, i.e., with incidence angles well over $\theta = 45°$ (Breer et al., 2019; Addison et al., 2021). Such grazing impacts result in substantial sputtering yields around the upstream apex (equation (1)), overcompensating the drop in incident ion flux and producing a slight enhancement of the H_2O sputtering rates in that region.

To further illustrate this mechanism, Figure 7 displays maps of the average incidence angles of impinging sulfur ions exposed to Europa's perturbed electromagnetic environment, with energies of 10 keV (panel (a)), 100 keV (panel (b)), and 1 MeV (panel
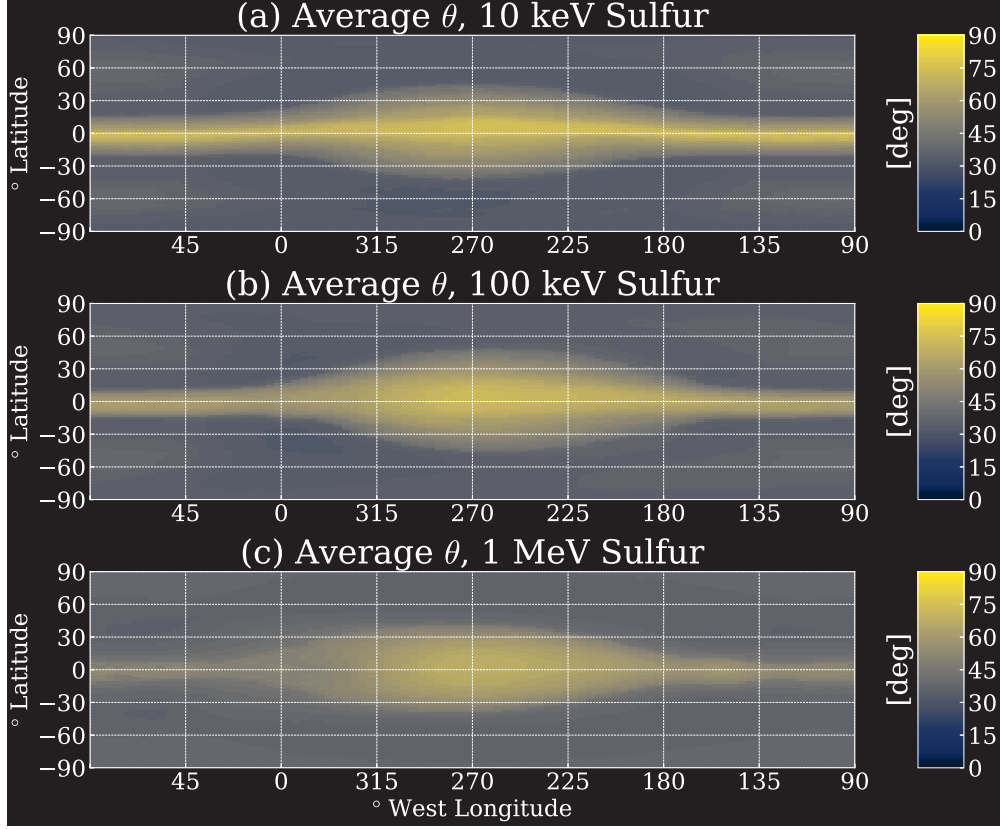
Figure 7. Maps of the average incidence angle $\langle\theta\rangle$ of (a) 10 keV, (b) 100 keV, and (c) 1 MeV S^{3+} ions with allowed trajectories, calculated with the perturbed electromagnetic fields from AIKEF.

(c)). It can be seen that these sulfur ions impact the surface with high incidence angles exactly in the regions where the ion influx is low (Figure 5(d)). The resultant high sputtering yields of these ions are able to replenish the upstream flux depletion revealed by Figure 5(d). The result is that the energetic ion H_2O sputtering rate in the upstream hemisphere is similar for uniform and perturbed fields. However, the mechanism behind this similarity is highly intricate. In the case of uniform fields, the drift motion of the energetic ions along the corotation direction causes the surface flux near the upstream apex to be roughly 20% higher than at the downstream equator, which leads to a sputtering rate around the upstream apex that is similarly enhanced. In contrast, field line draping *lowers* the flux near the upstream apex by a factor of two. However, the grazing trajectories of energetic ions which impact these regions generate substantial sputtering yields and compensate for the low surface flux.

When a constant impact angle of $\theta = 0°$ is used to calculate the H_2O sputtering yields (analogous to Cassidy et al., 2013), the depletion in energetic ion flux around the upstream apex (Figure 5(d)) maps into the H_2O sputtering rates (Figure 6(f)). In this case, the non-uniformity of ion incidence angles across Europa's surface is truncated, and the sputtering rates assume their minimum value (regarding the angle dependence) everywhere on the surface. Ions precipitating along grazing trajectories are thus not able to compensate for the upstream depletion in energetic ion flux. The result is an "inverted bullseye" distribution in the upstream hemisphere, where the sputtering rate grows with distance from the upstream apex (Figure 6(f)).

The H_2O sputtering rates of all ions and energies combined are shown in Figures 6(g)–6(i). In the case of uniform electromagnetic fields (Figure 6(g)), the spatial distribution of the total H_2O sputtering rate is nearly rotationally symmetric about the x axis, and maximizes near the $x = 0$ plane. The nearly homogeneous H_2O sputtering rate from energetic ions (second row of Figure 6) uniformly augments that from thermal ions at all locations. Without the field perturbations, energetic ions are the sole agents of H_2O sputtering on the downstream hemisphere between approximately $-30°$ and $30°$ latitude (which is inaccessible to upstream thermal ions in the case of uniform fields, see Figure 5(a)). The H_2O sputtering rate on the downstream hemisphere is a factor of 2-3 less than the maximum value on the upstream hemisphere. When the fields are treated as uniform, H_2O sputtering from thermal ions dominates at every point on the surface except mid-to-low latitudes on the downstream hemisphere (first column in Figure 6).
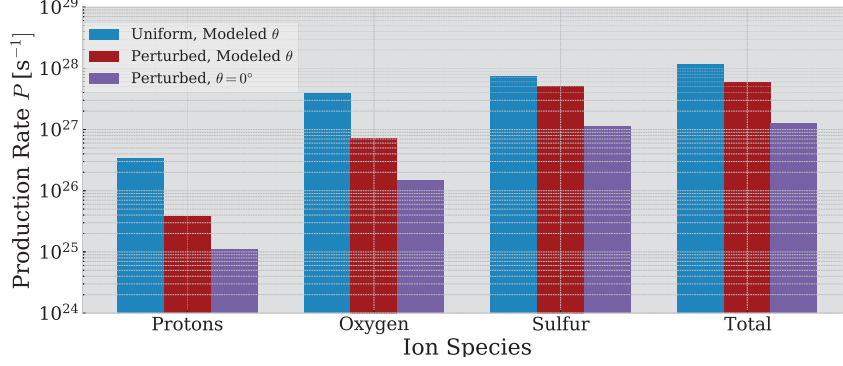
Figure 8. Total H$_2$O production rate P for all ion energies and species modeled in this study. From left to right, production rates of incident hydrogen, oxygen, sulfur, and the combined production rates of all ion species are shown. The production rates calculated with uniform and perturbed electromagnetic fields are displayed in blue and red, respectively, both with sputtering yields calculated using the actual incidence angles from GENTOo in equation (1). Purple bars indicate production rates calculated with perturbed fields and the incidence angles of all impinging ions set to $\theta = 0°$ in equation (1).

However, with perturbed fields, the quasi-uniform H$_2$O sputtering rate from energetic ions exceeds that from thermal ions at nearly every surface location except near the upstream apex (Figures 6(b) and 6(e)). The map of the total H$_2$O sputtering rate from all ions and energies combined (Figure 6(h)) therefore closely resembles the nearly featureless pattern caused by energetic ion sputtering alone (Figure 6(e)). Comparison of Figures 6(b) and 6(e) reveals that the contribution of thermal ions to the total H$_2$O sputtering rate equals that of the energetic ions only near the upstream apex, effectively doubling the energetic H$_2$O sputtering rate there (red region in Figure 6(h)). This preferential emission of H$_2$O molecules near the upstream apex agrees well with a recent study by Roth (2021), who used observed emission rates from HST to surmise the presence of a stable, localized H$_2$O component of the exosphere above Europa's central trailing hemisphere.

For each species, the total amount of H$_2$O sputtered from Europa's surface per time via magnetospheric ion impacts at all energies, P, is given by

$$P(m, Z) = R_E^2 \int_{-\pi/2}^{\pi/2} \int_0^{2\pi} R(m, Z, \lambda, \phi) \cos(\lambda) \mathrm{d}\phi \, \mathrm{d}\lambda \qquad , \qquad (6)$$

1235   where $R(m, Z, \lambda, \phi)$ is the H_2O sputtering rate of a given species at a particular surface

1236   location (λ, ϕ). The resulting production rates from protons, oxygen ions, sulfur ions,

1237   and all ion species combined are displayed in Figure 8. Blue bars indicate production

1238   rates calculated with uniform electromagnetic fields and the incidence angles obtained

1239   from GENTOo, red bars indicate production rates calculated with perturbed fields and

1240   incidence angles from GENTOo, and purple bars show production rates calculated with

1241   perturbed fields and θ set to $0°$ in equation (1) for all precipitating ions.

1242   In all three setups presented in Figure 8, sulfur ions sputter the most H_2O per sec-

1243   ond, while oxygen ions and protons sputter successively less. This trend follows the hi-

1244   erarchy of the sputtering yield curves shown in Figure 1(a), revealing that the yields (not

1245   the surface fluxes) are the most important factor in determining the relative H_2O sput-

1246   tering rate contributions between ion species. As shown by Addison et al. (2021), the

1247   surface fluxes of hydrogen ions exceed those of the two heavy ion species by up to an or-

1248   der of magnitude. However, due to their low mass, hydrogen ions play a negligible role

1249   in the sputtering of H_2O from Europa's surface (see Figure 1(a)). The surface fluxes of

1250   sulfur and oxygen ions differ by no more than a factor of five (Addison et al., 2021). How-

1251   ever, since the sputtering yields of sulfur ions may exceed those of oxygen ions by over

1252   an order of magnitude (see Figure 1a), sulfur makes the largest contribution to the to-

1253   tal H_2O production rate. In the case of uniform fields (blue bars in Figure 8), sulfur ions

1254   sputter roughly twice as much H_2O per second as oxygen ions ($P \approx 7 \times 10^{27}\,\mathrm{s}^{-1}$ ver-

1255   sus $P \approx 4 \times 10^{27}\,\mathrm{s}^{-1}$, respectively). Hydrogen ions sputter an order of magnitude less

1256 H_2O than either of the heavy ion species. We calculate a total H_2O production rate (from

1257   all three species) of $P_T = 1.16 \times 10^{28}\,\mathrm{s}^{-1}$ in a uniform field configuration. Energetic

1258   sulfur ions generate the most H_2O per second (42% of P_T), while thermal oxygen ions

1259   generate the second most (31%). Cassidy et al. (2013) found the same hierarchy of sput-

1260   tering agents from their calculation of the total sputtering rates in uniform fields and

1261   with $\theta = 0°$ for all impinging ions (63% from energetic sulfur, 19% from thermal oxy-

1262   gen).

1263   The H_2O production rate from sulfur ion impacts is reduced by only 10% when the

1264   field perturbations are considered, while the production rates associated with oxygen and

1265   hydrogen ions each fall by almost an order of magnitude (red bars, Figure 8). This dis-

1266   crepancy can be understood by isolating the contribution of the thermal and energetic

1267   regimes to each species' sputtering rate with perturbed fields. The high sputtering yields

1268   of sulfur ions in the energetic regime (Figure 1(a)) allow the production rate from en-

1269   ergetic sulfur ions ($P = 4.9 \times 10^{27}\,\text{s}^{-1}$) to exceed that from the thermal sulfur ions ($P =$

1270 $2.5 \times 10^{26}\,\text{s}^{-1}$) by over an order of magnitude, despite the energetic sulfur ion surface

1271   flux being an order of magnitude lower (Addison et al., 2021). For oxygen, thermal ions

1272   produce 50% more H_2O per second than energetic ions ($P = 4.38 \times 10^{26}\,\text{s}^{-1}$ versus

1273 $P = 2.9 \times 10^{26}\,\text{s}^{-1}$, respectively). The discrepancy for hydrogen ions is even more stark:

1274   thermal protons produce $P = 3.58 \times 10^{25}\,\text{s}^{-1}$, while energetic protons produce only

1275 $P = 2.3 \times 10^{24}\,\text{s}^{-1}$. In other words, sulfur is the only ion species that causes higher

1276 H_2O production rates in the energetic regime than in the thermal regime. Since the sput-

1277   tering rates of energetic ions are much less affected by the perturbed fields (Figure 6),

1278   the sulfur ion contribution to the total production rate is much more "resilient" to the

1279   inclusion of the field perturbations than the contributions from hydrogen or oxygen, whose

1280   production rates are dominated by the thermal ions.

1281   Of the thermal ion contribution to the total H_2O production rate P_T in perturbed

1282   fields, sulfur ions constitute 35%, oxygen ions constitute 60%, and protons add 5%. These

1283   values are in rough agreement with the 21%, 78%, and $< 1\%$ contributions (for ther-

1284   mal sulfur, oxygen, and hydrogen ions, respectively) found by Cassidy et al. (2013) with

1285   uniform fields. The dominance of H_2O sputtering by thermal oxygen ions over the con-

1286   tribution from thermal sulfur stems from the slightly higher surface flux of oxygen (Addison

1287   et al., 2021). In the energetic regime, we find that sulfur ions contribute approximately

1288   94% of H_2O production in perturbed fields, while oxygen ions and protons add 6% and

1289 $< 1\%$, respectively. The total production rate from all ions falls by about 50% to a value

1290   of $P_T \approx 5.9 \times 10^{27}\,\text{s}^{-1}$ when the field perturbations are included (blue versus red bars

1291   in the right-most block of Figure 8). Setting the incidence angles of all impinging ions

1292   to $\theta = 0°$ in equation (1) further reduces the H_2O production rate by a factor of 2-5,

1293   depending upon the ion species (purple bars in Figure 8). The total H_2O production rate

1294   from all ion species in the case of perturbed fields and $\theta = 0°$ falls to $P_T = 1.27 \times$

1295 $10^{27}\,\text{s}^{-1}$, which is a factor of five smaller than the rate calculated with the actual inci-

1296   dence angles from GENTOo.

1297   Thus, inclusion of the perturbed fields reduces the total H_2O production rate at

1298   Europa by at least a factor of two compared to uniform fields (rightmost block in Fig-

1299   ure 8). In addition, the perturbed fields significantly modify the spatial distribution of

1300   the H_2O sputtering rates (Figure 6). When the electromagnetic fields near Europa are

treated as uniform, the corotating thermal plasma is unable to sputter material from the moon's low-latitude downstream hemisphere, and the H_2O sputtering rate maximizes near the meridian through the moon's sub-Jovian and anti-Jovian apices. With the inclusion of the magnetospheric field perturbations, the distribution of the H_2O sputtering rate becomes much more homogeneous, besides a localized enhancement by up to an order of magnitude near the upstream apex. Except for this narrow region, the quasi-uniform H_2O sputtering rate of the energetic ions exceeds that of the thermal ions at every surface location. Therefore, in draped fields the energetic ions are able to "smear out" many of the non-uniformities in the thermal ion H_2O sputtering rate pattern.

3.3 Sputtering Rates of O_2 and H_2

We now investigate the temperature-dependent sputtering rates of O_2 and H_2 over the course of a Europan day (≈ 80 hours), i.e., as the sub-solar point moves across the moon's surface. Maps of the H_2 sputtering rates will be qualitatively identical to those of O_2, since H_2 sputtering rates are twice those of O_2 (equation (4)). Therefore, for most of this section we will restrict our discussion to O_2 sputtering rates. In section 3.3.1 we present sputtering rates calculated with the O_2 sputtering yield model of Teolis et al. (2017), i.e., with the assumption that the O_2 is concentrated in a "thin layer" approximately 28 Å in depth (dash-dotted lines in Figures 1(b) and 1(c)). In section 3.3.2 we investigate O_2 sputtering rates calculated with a "thick layer" model, i.e., with the assumption that the O_2-bearing layer within Europa's surface extends to any depth to which a magnetospheric ion may penetrate. This model is shown as solid lines in Figures 1(b) and 1(c), and is adopted from Plainaki et al. (2013). In section 3.3.3 we compare the total production rates of O_2 from both models, and discuss their implications for the generation of Europa's exosphere.

3.3.1 *Contributions of Thermal and Energetic Ions in a "Thin Layer" Model*

Figure 9 shows O_2 sputtering rates from thermal (first column) and energetic (second column) ions impinging upon a thin O_2 layer, i.e., calculated with equations (3) and (5). To isolate the effect of a non-uniform temperature profile on the O_2 sputtering rates, the first row in Figure 9 (panels (a)–(b)) displays the spatial distribution of the O_2 sputtering rates calculated with a uniform surface temperature of $T = 93$ K. This value of

1332 T was derived by averaging the diurnal temperature profile shown in Figure 3. In the

1333   case of a uniform surface temperature, $\Phi(T)$ in equation (5) assumes the same constant

1334   value at all surface locations, i.e., the temperature dependence of the sputtering yields

1335   does not generate any changes to the spatial distribution of the O_2 and H_2 sputtering

1336   rates. The middle four rows (panels 9(c)–(j)) present maps of the O_2 sputtering rates

1337   at the four local times for which temperature maps have been provided in Figure 2. The

1338   final row (panels 9(k) and 9(l)) shows O_2 sputtering rates calculated with the diurnally-

1339   averaged temperature profile presented in Figure 3.

1340   All sputtering rates shown in Figure 9 were calculated with the perturbed fields

1341   from AIKEF: the necessity to include these perturbations has been demonstrated in sec-

1342   tion 3.2 and numerous preceding publications. The angular dependence for O_2 in a thin

1343   layer model (Teolis et al., 2017) is given by $(1 - \exp[-r_0(E)\cos(\theta)/x_0)]) \cos^{-1}(\theta)$, see

1344   equation (5). Within the range of $r_0(E)$ values used in our study, this term always re-

1345   sults in an increase in O_2 sputtering yields with increasing incidence angle, similar to

1346 H_2O. Therefore, in analogy to H_2O (middle vs. right columns of Figure 6), inclusion of

1347   the incidence angles from GENTOo (instead of a constant value) is expected to cause

1348   cause only subtle differences in the spatial distribution of the O_2 sputtering rates, and

1349   will not alter the relative contributions of thermal and energetic ions. Hence, for our cal-

1350   culation of O_2 sputtering rates we utilize the modeled incidence angles from GENTOo

1351   in equation (5).

1352   The first column of Figure 9 reveals that the O_2 sputtering rate from thermal ions

1353   peaks near the upstream apex, where the thermal ion flux is largest, and decreases with

1354   distance from the upstream apex as the surface influx drops (Figure 5(b)). The down-

1355   stream hemisphere at low latitudes experiences substantially less O_2 sputtering from ther-

1356   mal ions, with a sputtering rate 3-4 orders of magnitude lower than on the upstream hemi-

1357   sphere. Since the sputtering yields of H_2O and O_2 both grow monotonically with increas-

1358   ing incidence angle, the O_2 sputtering rate pattern from thermal ions resembles that of

1359 H_2O (Figure 6).

1360   Changes in the orientation between the incoming solar radiation (and thus the sur-

1361   face temperature profile) and the upstream plasma flow cause slight qualitative modi-

1362   fications to the spatial distribution of the O_2 sputtering rate from thermal ions (Figures

1363   9(c), 9(e), 9(g), and 9(i)), compared to the "baseline" case of a constant surface temper-
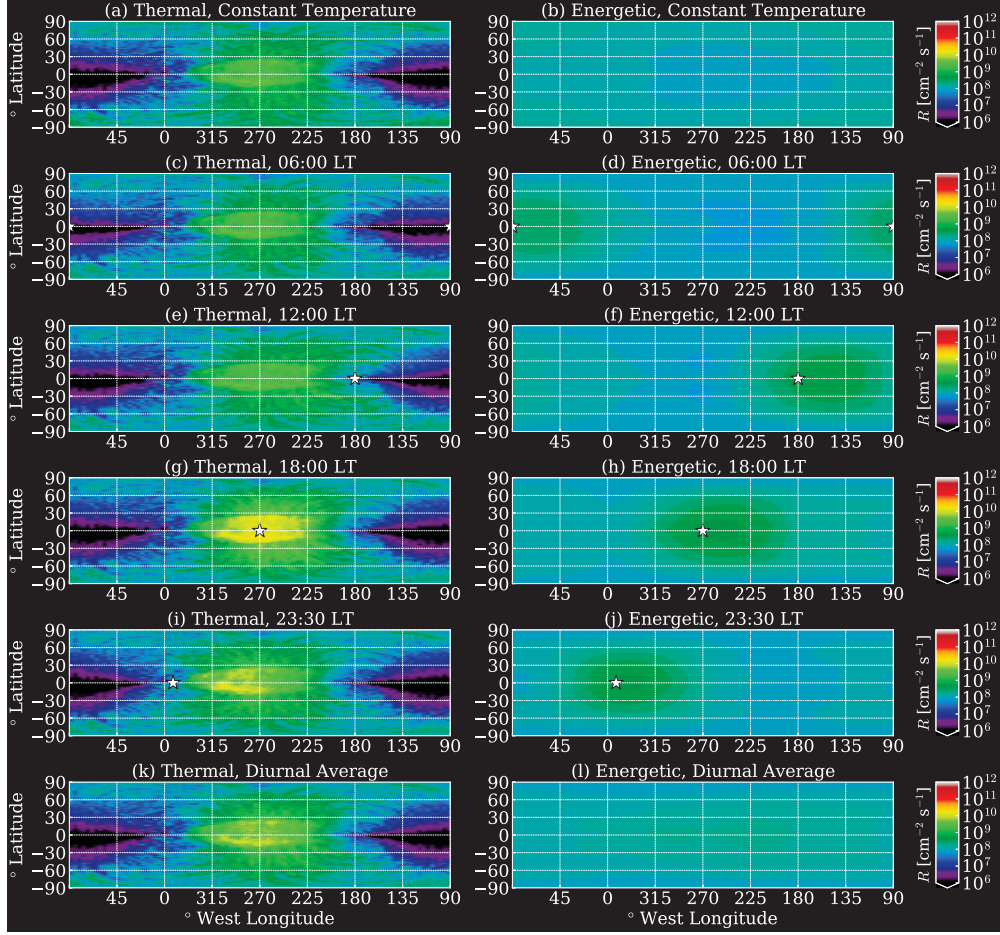
Figure 9. Maps of the O_2 sputtering rates from all ion species considered in this study, calculated with the perturbed electromagnetic fields from AIKEF and the actual incidence angles from GENTOo. The sputtering yields were calculated with a "thin layer" model of the oxygen-bearing surface layer (Teolis et al., 2017), i.e., with equation (5). The first column (panels (a), (c), (e), (g), (i), and (k)) displays the O_2 sputtering rates from thermal ion impacts, while the second column (panels (b), (d), (f), (h), (j), and (l)) shows O_2 sputtering rates from energetic ion impacts. To establish a "baseline" for our analysis, the first row (panels (a) and (b)) presents O_2 sputtering rates calculated with a uniform surface temperature of $T = 93$ K. The next four rows show maps of the sputtering rates for different orbital positions of Europa, as illustrated in Figure 2: 06:00 LT (panels (c) and (d)), 12:00 LT (panels (e) and (f)), 18:00 LT (panels (g) and (h)), and 23:30 LT (panels (i) and (j)). In the plots which depict a specific local time (panels (c)–(j)), a white star is shown to denote the sub-solar point on Europa's surface. Note that in panels (c) and (d), the star is divided between the leftmost and rightmost edges of the surface maps. The final row (panels (k) and (l)) presents maps of the O_2 sputtering rates calculated with a diurnally-averaged temperature profile (see Figure 3)

.

ature (Figure 9(a)). Within the range of surface temperatures present at Europa ($\approx 60-$ 140 K, see Figure 2), the temperature-dependent term $\Phi(T)$ in equation (5) ranges from approximately 10^{-2} to 7 . As such, variations in the surface temperature profile along Europa's orbit can (at most) enhance the O_2 sputtering rate at a given point by a factor of eight. Since the thermal ion surface flux varies by more than three orders of magnitude between surface locations, the shifting of the surface temperature profile along Europa's orbit is not sufficient to qualitatively alter the O_2 sputtering rate maps from thermal ions when the oxygen-bearing surface layer is thin.

For each of the orbital positions shown in Figure 9, the O_2 sputtering rates drop slightly with increasing latitude, since Europa's polar caps are consistently cold (Figures 2 and 3). Movement of the sub-solar point (denoted by a star in the plots) across Europa's surface quantitatively enhances the sputtering rate by a factor of 4-7, which is insufficient to noticeably alter the spatial distribution (left column of Figure 9). When the upstream apex and sub-solar point are coincident at 18:00 LT, the O_2 sputtering rate from thermal ions near the upstream apex maximizes, as the thermal plasma directly impinges upon the hottest region of the moon's surface (see also Figure 2). The surface near the sub-solar point in this configuration is hotter than at any other local time, since the low albedo at 18:00 LT causes it to heat to a maximum temperature that is roughly 15% higher than when the sub-solar point is located on the downstream hemisphere (06:00 LT). At 12:00 LT and 23:30 LT the sub-solar point is located near the moon's anti-Jovian and sub-Jovian apices, respectively (Figures 9(e) and 9(i)), and the upstream enhancement in O_2 sputtering rates is slightly "pulled" toward the sub-solar point, where the temperature and the resultant sputtering yields maximize. At these two orbital positions, the sub-solar enhancement in surface temperature, and therefore the enhancement in O_2 sputtering rates, is roughly a factor of two less than at 18:00 LT (Figure 9(g)).

Figure 9(k) displays the O_2 sputtering rate from thermal ions calculated with a diurnally averaged surface temperature profile (shown in Figure 3). The dichotomy in the surface temperatures between the upstream and downstream hemisphere in this case causes the map of the thermal ion O_2 sputtering rate to qualitatively resemble that at 18:00 LT (Figure 9(g)), although the upstream enhancement is a factor of two weaker. When the oxygen-bearing surface layer is thin, the chosen surface temperature profile does not significantly alter the map of the O_2 sputtering rate from thermal ions. Regardless of

the temperature profile, the maps of the sputtering rates display similar patterns as the influx map for thermal magnetospheric ions (Figure 5(b)).

In contrast, the spatial distribution of the O_2 sputtering rate from energetic ion impacts is largely determined by the surface temperature profile, i.e., by the orientation of the Sun relative to Europa. The energetic ion sputtering rate for a constant surface temperature (Figure 9(b)) is nearly homogeneous, never varying between any two surface locations by more than a factor of two. A global minimum in the O_2 sputtering rate from energetic ions is present near the upstream apex, with the rate reduced by 35% compared to that near the poles (Figure 9(b)). Above incident ion energies of $E = 10$ keV, the penetration depths of the ions are greater than the O_2 layer depth ($x_0 = 28$ Å) even at an extreme grazing incidence of $\theta = 80°$ (Ziegler & Manoyan, 1988; Teolis et al., 2017). The angle-dependent exponential term in equation (5) is therefore nearly zero, and the sputtering yield is proportional to $\cos^{-1}(\theta)$. Hence, the O_2 sputtering yields around the upstream apex are less amplified by high incidence angles compared to the H_2O yields, which are proportional to $\cos^{-f(m)}(\theta)$ with $f(m) > 1$ for all ion species. For example, the H_2O sputtering yield of a $\theta = 80°$ incident sulfur ion is enhanced by a factor of $\approx$ 21 compared to normal incidence ($\theta = 0°$), while the O_2 yield of the same projectile would only be enhanced by a factor of ≈ 6. As a result, the sputtering yields due to grazing impacts of energetic ions near the upstream apex are no longer able to compensate for the upstream flux depletion (Figure 5(d)), resulting in a net drop of the sputtering rate around the upstream apex. However, this upstream drop in the energetic ion O_2 sputtering rates is much smaller than the variability associated with the range of Europan surface temperatures.

At all four local times considered (Figures 9(d), 9(f), 9(h), and 9(j)), a quasi-elliptical enhancement in the O_2 sputtering rate forms near the sub-solar point. In each case, the maximum of the O_2 sputtering rate from energetic ions is displaced somewhat to the east of the sub-solar point, since the thermal inertia of Europa's surface slightly delays the surface heating. With a diurnally-averaged temperature profile, the map of the O_2 sputtering rates from energetic ions (Figure 9(l)) is nearly homogeneous, since the temperature enhancement covers a wider range of surface longitudes on the upstream hemisphere (see Figure 3).

In contrast to the case of sputtered H_2O, thermal ions dominate the O_2 sputtering rate at almost every location on Europa's upstream hemisphere ($180-360°$ W longitude), regardless of the surface temperature profile (Figure 9). While the H_2O sputtering yields of heavy ions grow by 3-4 orders of magnitude in the energetic regime compared to the thermal regime (equation (1) and Figure 1(a)), the respective O_2 yields increase by no more than two orders of magnitude. The energetic ions still penetrate more deeply into the surface than thermal ions. However, this increased penetration is largely ineffective at producing additional O_2 in the "thin layer" picture of Teolis et al. (2017), since the O_2 surface concentration quickly drops at greater depths. Thus, the O_2 sputtering yields of the energetic ions are insufficient for their sputtering rates to overcome those of the thermal ions on the upstream hemisphere, and the thermal ion O_2 sputtering rate dominates. This does not hold for the downstream hemisphere, however, where the thermal ion surface flux and the associated sputtering rates are several orders of magnitude lower than those of energetic ions. However, the energetic ion sputtering rate on the downstream hemisphere is still 1-2 orders of magnitude weaker than the upstream maximum.

3.3.2 Contributions of Thermal and Energetic Ions in a "Thick Layer" model

Figure 10 displays O_2 sputtering rates calculated with a "thick layer" model of the sputtering yields (Plainaki et al., 2013), i.e., with the assumption that the thickness of the O_2-bearing layer within Europa's surface exceeds the penetration depth of any incident magnetospheric ion. The associated yields are given in equation (2) and shown as solid lines in Figure 1(b).

The assumption of a thick oxygen-bearing surface layer does not significantly alter the qualitative distribution of the O_2 sputtering rates from thermal (left column of Figure 10) or energetic (right column of Figure 10) ions compared to when a thin layer is assumed (Figure 9). Recall that O_2 yields in a both a thick-layer model and a thin-layer model grow with incidence angle, similar to the yields of H_2O. Therefore, the quantitative behavior of the O_2 sputtering rates with respect to incidence angle is the same as for the H_2O rates, regardless of O_2 layer thickness.
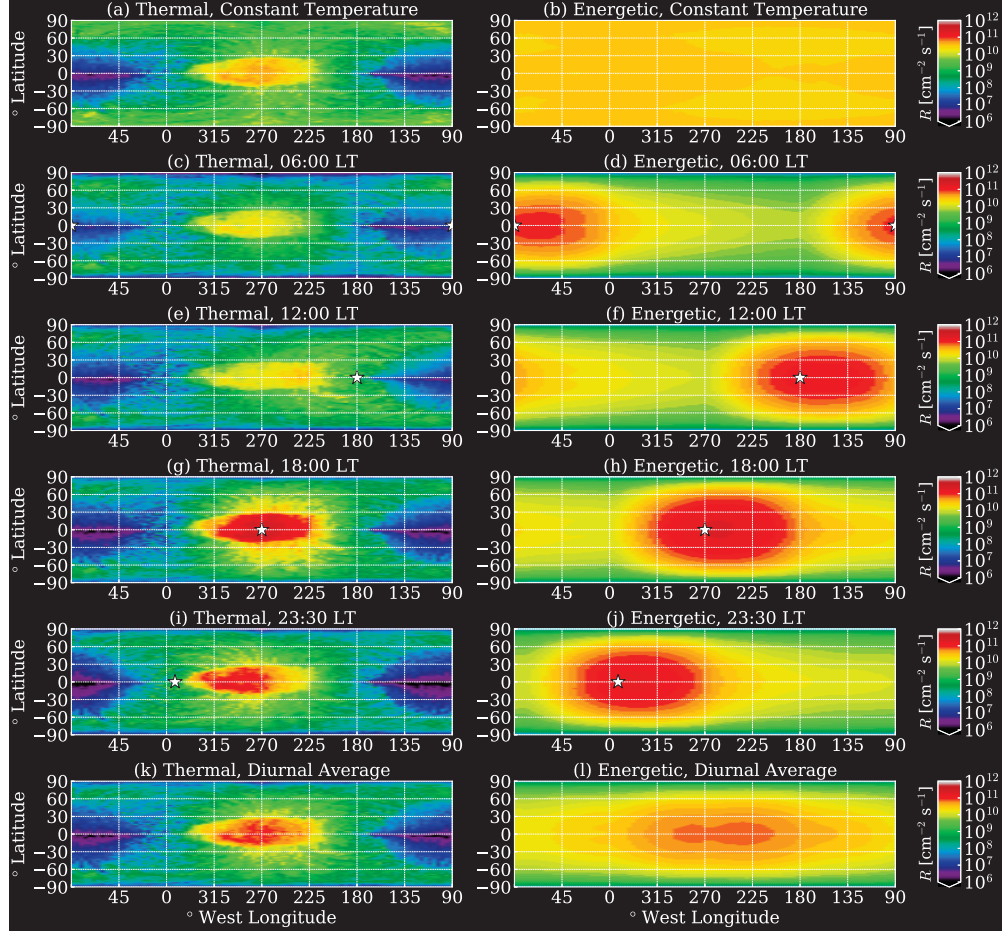
Figure 10. Maps of the O_2 sputtering rates from all ion species considered in this study, calculated with the perturbed electromagnetic fields from AIKEF and the actual incidence angles from GENTOo. The sputtering yields were calculated with a "thick layer" model of the surface oxygen (Plainaki et al., 2013), i.e., with equation (2), depicted as solid lines in Figure 1(b). The layout of the panels is identical to Figure 9.

The difference between the temperature-dependent terms of the two O_2 sputtering models (thin layer and thick layer) becomes significant in regions of low surface temperatures, especially the polar caps. With a thin oxygen-bearing layer (Teolis et al., 2017), the temperature dependence takes the form of $1+\Phi(T)$, while with a thick layer (Plainaki et al., 2013) the dependence is given by only $\Phi(T)$. Thus, in both models the O_2 yields are independent of temperature below approximately 70 K, grow monotonically with temperature above 70 K, and eventually stagnate at very high temperatures. At the hottest regions of Europa's surface, the temperature dependencies of both models augment the sputtering yields by nearly the same factor. However, at low temperatures ($\Phi(T) \approx 0$), the O_2 sputtering yields of Plainaki et al. (2013) approach a value of zero, while those of Teolis et al. (2017) approach a nonzero value. This discrepancy at low temperatures causes the two models to produce vastly different sputtering rates in cold surface regions (below 70 K). Since Europa's surface temperature (Figures 2 and 3) drops by a factor of two from the equator (100-140 K) to the poles ($\approx$60 K), the O_2 sputtering rates from thermal ions calculated with a thick oxygen-bearing layer fall by up to five orders of magnitude from the upstream equator to the poles (Figures 10(c), 10(e), 10(g), 10(i), 10(k)). In contrast, with a thin oxygen-bearing layer (Figure 9) the difference between the O_2 sputtering rates of thermal ions at the equator and the poles at any local time is limited to around three orders of magnitude. In the (hypothetical) case of a constant, averaged surface temperature the O_2 sputtering rates of thermal ions fall by at most two orders of magnitude from the equator to the poles (Figure 10(a)), and this decrease is caused purely by non-uniformities in the ion influx pattern. O_2 sputtering rates from energetic ions feature a similar behavior, falling by up to four orders of magnitude from the equator to the poles when a non-uniform temperature profile is included (Figures 10(d), 10(f), 10(h), 10(j), 10(l)). In contrast, the O_2 sputtering rates of energetic ions calculated with a constant temperature profile (Figure 10) do not decrease with increasing latitude. The consistently low temperatures of Europa's polar caps are therefore crucial to understanding exospheric generation at high latitudes.

In contrast to the thin layer model (Teolis et al., 2017), energetic ions in the thick layer model (Plainaki et al., 2013) can eject O_2 along their entire trajectory through the surface ice. As such, the O_2 sputtering yields of these ions dwarf those of the thermal ions by up to three orders of magnitude (Figure 1(b)). Hence, the O_2 sputtering rates of energetic ions in the picture of Plainaki et al. (2013) exceed those of the thermal ions

at nearly every surface location, regardless of the temperature profile (Figure 10). When the thick layer approach is used, the "roving" enhancement in energetic ion sputtering rates which follows the sub-solar point slightly exceeds that due to preferential thermal ion bombardment at the upstream apex.

The sputtering yields of thermal heavy ions in a thick layer approach exceed those in a thin layer approach by nearly an order of magnitude (solid vs. dash-dotted lines, Figure 1(b)). As can be seen from the left columns in Figures 9 and 10, this leads to the O_2 sputtering rates of thermal ions in a thick layer model surpassing those in a thin layer model by roughly an order of magnitude at almost every surface location. The deviation in the O_2 sputtering yields and rates of energetic ions between the two models is much more drastic, with the rates in a thick layer model typically exceeding those in a thin layer model by 2-3 orders of magnitude.

3.3.3 *Total Sputtering and Neutral Gas Production Rates*

Presented in Figure 11 are maps of the total O_2 sputtering rates from ions of all species and energies considered in this study. Rates calculated with the thin layer model of the O_2 sputtering yields (Teolis et al., 2017) are displayed in the first column, while results from the thick layer model (Plainaki et al., 2013) are shown in the second column. Similar to Figures 9 and 10, each row corresponds to a specific surface temperature profile, with the first row representing a constant, averaged temperature of $T = 93$ K at all surface points, the next four rows corresponding to specific local times, and the final row denoting rates calculated with a diurnally-averaged temperature profile (Figure 3).

In the upstream hemisphere, the total O_2 sputtering rates calculated with a thin oxygen-bearing layer (left column of Figure 11) closely resemble the thermal ion rates (left column of Figure 9). The downstream depletion in the thermal ion sputtering rate is "filled in" by the energetic ion contribution (right column of Figure 9 and left column of Figure 11). Thus, the thermal ion contribution to O_2 sputtering dominates that of energetic ions on the upstream hemisphere, while the energetic ion contribution exceeds that of the thermal ions on much of the downstream hemisphere. This is in contrast to the H_2O sputtering rate pattern, where the nearly homogeneous energetic ion sputtering rate dominates the thermal ion contribution at all surface locations except for a nar-
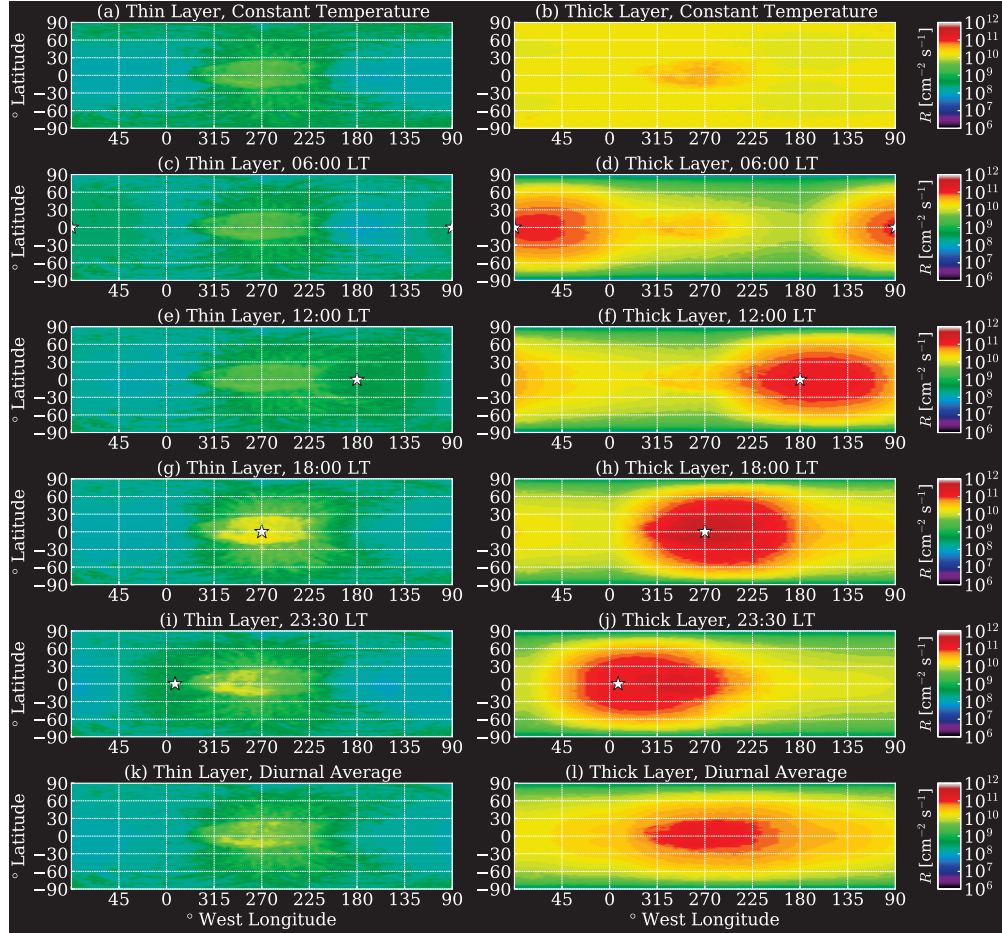
Figure 11. Maps of the total O_2 sputtering rates from all ion species and energies considered in this study, calculated with the perturbed electromagnetic fields from AIKEF and the actual incidence angles from GENTOo. In the first column (panels (a), (c), (e), (g), (i), and (k)) are presented the O_2 sputtering rates calculated with a "thin layer" model of the surface oxygen (equation (5)), while the second column (panels (b), (d), (f), (h), (j), and (l)) shows O_2 sputtering rates from a "thick layer" model (equation (2)). The rows represent different surface temperature profiles, following the layout of Figures 9 and 10.

row region near the upstream apex (Figure 6(h)), since for H_2O the energetic ion sputtering yields exceed those of thermal ions by several orders of magnitude.

The region of maximum O_2 generation in the thin layer approach is always located near the upstream apex, regardless of the solar orientation. Depending on the local time, the center of this enhancement is slightly displaced in longitude toward the sub-solar point (Figures 11(e) and 11(i)), as long as the sub-solar point is not located on the downstream side of the moon (Figure 11(c)). The maximum O_2 sputtering rate in the upstream hemisphere calculated with a thin oxygen-bearing layer ranges from $R = 5.1 \times 10^9 \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$ at 06:00 LT to $R = 2.5 \times 10^{10} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$ at 18:00 LT.

For a thin layer model, the diurnally-averaged temperature profile yields a maximum O_2 sputtering rate (reached near the upstream apex) of approximately $R = 1.1 \times 10^{10} \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$, a factor of four lower than predicted for uniform fields by Cassidy et al. (2013). These authors also utilized a diurnally-averaged temperature profile and a thin O_2-bearing layer. However, Cassidy et al. (2013) treated all impinging ions as impacting normal to the surface ($\theta = 0°$). Therefore, these authors' sputtering rates constitute the minimum value possible with their choice of magnetospheric parameters (see also equation (5)). If Cassidy et al. (2013) had utilized actual incidence angles instead, their sputtering rates would be higher, and the discrepancy between their rates for uniform fields and those calculated here for draped fields would be even greater. The low sputtering rates obtained for draped fields in our model are consistent with the idea that the perturbations to the electromagnetic fields partially shield Europa's surface from magnetospheric ion bombardment (Breer et al., 2019; Addison et al., 2021; Harris et al., 2021; Simon et al., 2021).

Using a thin layer, our model predicts a minimum O_2 sputtering rate near the downstream apex (90° W) of $R \approx 10^8 \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$. While this value is roughly two orders of magnitude lower than the peak value near the upstream apex, the occurrence of such substantial surface erosion in Europa's downstream hemisphere is in stark contrast to the results of Cassidy et al. (2013). Using uniform fields, these authors predicted a minimum sputtering rate of nearly zero on almost the *entire* downstream hemisphere (see Figure 9 of that paper). Therefore, if Europa's electromagnetic environment were perfectly uniform, any O_2 gas located above the downstream hemisphere would have to be transported there from the upstream hemisphere through, e.g., Coriolis or centrifugal

forces (Oza et al., 2019). However, with the inclusion of the perturbed fields in our model, O_2 gas can be produced directly in the downstream hemisphere. As can be seen from the right column of Figure 11, this effect is amplified when the surface oxygen is assumed to occupy a thick layer (Plainaki et al., 2013).

In the thick layer picture, the energetic ions have substantial sputtering yields compared to a thin layer approach (right columns of Figures 9 and 10). This allows the energetic ions to become the dominant agents in determining the spatial distribution of the O_2 source rate at Europa. When the surface temperature is treated as constant (Figure 11(b)), the O_2 yields in a thick layer approach are simply the H_2O yields multiplied by the same, constant coefficient at every surface location (equation (2)). Therefore, if the surface temperature were uniform, the spatial distribution of the O_2 sputtering rate would be largely homogeneous across Europa's surface, with the bullseye-like "surplus" of thermal ion influx near the upstream apex (red in Figure 5(b)) generating the only significant local enhancement.

When a non-uniform temperature profile is used to calculate the O_2 sputtering yields for a thick oxygen-bearing layer, the spatial distribution of the energetic ion O_2 sputtering rate demonstrates a quasi-elliptical enhancement by a factor of five around the sub-solar point (Figures 10(d), 10(f), 10(h), and 10(j)). Since in this case the O_2 sputtering rates from energetic ions exceed those from thermal ions at nearly every surface point, this sub-solar augmentation is also clearly visible in the total O_2 rate maps (right column of Figure 11). At 06:00 LT (Figure 11(d)), this results in two distinct O_2 sputtering maxima on Europa's surface: the more pronounced one is centered near the sub-solar point at 90° W, whereas the fainter one (originating from the preferential precipitation of thermal ions near the upstream apex) is located near the upstream apex at 270° W. These two enhancements are still discernible, but also have substantial overlap at 12:00 LT and 23:30 LT (red regions in Figures 11(f) and 11(j)), since the sub-solar point is located only approximately 90° in longitude from the upstream apex. At 18:00 LT, the sub-plasma and sub-solar points are coincident, resulting in a single, quasi-elliptical enhancement by approximately an order of magnitude compared to the downstream apex. This enhancement ($R \approx 5 \times 10^{11} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$) is over an order of magnitude greater than the maximum sputtering rate calculated with a thin layer at 18:00 LT, and marks the maximum O_2 sputtering rate at any point along Europa's orbit.

If the sputtering maxima from a thick layer model directly translated into local enhancements of the exospheric column density, this would imply that there may be two distinct "bulges" in Europa's neutral gas envelope: a minor enhancement persistently located near the upstream apex, and a more pronounced increase that follows the region of greatest solar irradiation. This is in contrast to the results for a thin oxygen-bearing layer model, which predicts only one emission maximum for O_2 molecules, consistently located near the upstream apex. However, investigating any potential exospheric asymmetries requires to take into account all relevant influences on the dynamics of the emitted gas molecules (e.g., gravitational and fictitious forces, collisions, ionization). Such an effort is beyond the scope of this study.

The total O_2 production rates P from ions of all species and energies considered in this study are presented in Figure 12 for each of the five non-uniform temperature profiles shown in Figure 11. We do not include the case of a uniform surface temperature profile, as we do not expect this approach to generate accurate sputtering rates for Europa's nightside hemisphere. Figure 12(a) displays production rates calculated with a thin O_2-bearing surface layer (equation (5)). Averaged across all four local times shown in Figure 12(a), oxygen ions produce roughly the same amount of O_2 as sulfur ions (the averaged rates differ by only $\approx 30\%$), whereas sulfur ions sputter nearly seven times more H_2O than oxygen ions (Figure 8). Regardless of the chosen sputtering model, the surface flux and O_2 sputtering yields of the two heavy ion species are very similar in the thermal regime. Since thermal ions dominate the O_2 sputtering rate in a thin layer model, the contributions of the two heavy ion species are nearly the same.

However, if the O_2-bearing surface layer is assumed to be thick (Figure 10), energetic ions make the greatest contribution to the total O_2 sputtering rates at nearly every location on the surface. Hence, sulfur ions, which dominate the O_2 sputtering yields in the energetic regime by up to an order of magnitude over oxygen ions (solid lines in Figure 1(b)), surpass the production rates of oxygen ions by at least an order of magnitude regardless of the temperature profile (second vs. third block in Figure 12(b)). Sulfur ions in a thick layer configuration (Figure 12(b)) produce approximately two orders of magnitude more O_2 per second than when the O_2-bearing layer is thin (Figure 12(a)), while the discrepancies for oxygen and hydrogen ions are roughly an order of magnitude and a factor of 2-5, respectively. Thus, the thickness of the oxygen-bearing layer beneath
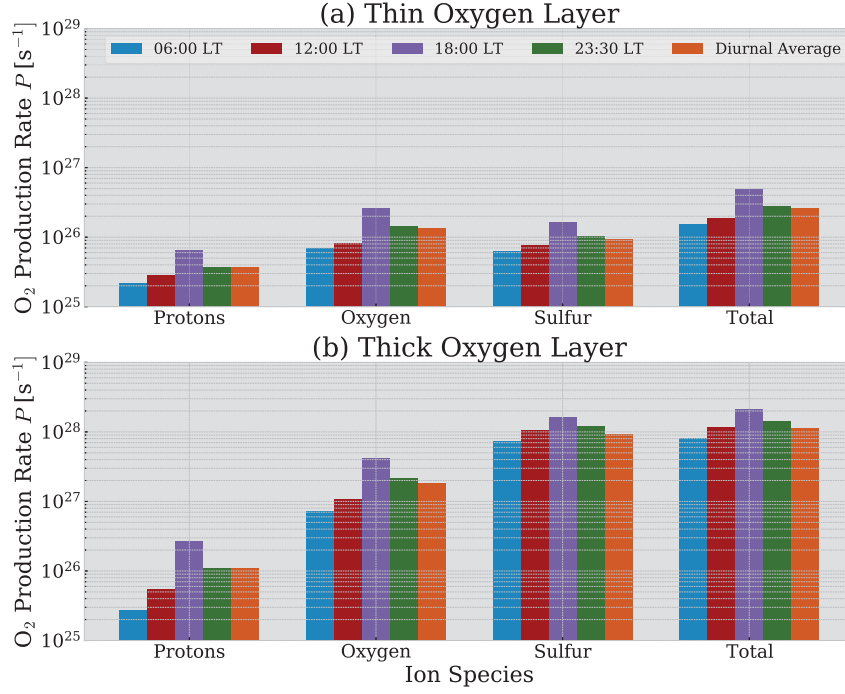
Figure 12. O$_2$ production rates from impinging magnetospheric protons, oxygen ions, sulfur ions, and all species combined at all energies, calculated with a thin layer model (panel (a)), and a thick layer model (panel (b)) of the oxygen concentration within Europa's surface. The different colors denote different orbital positions: 06:00 LT (blue), 12:00 LT (red), 18:00 LT (purple), and 23:30 LT (green). Rates calculated with a diurnally-averaged temperature profile are shown in orange. The production rates of H$_2$ are exactly twice those of O$_2$ (see equation (4)).

1617 Europa's surface has a measurable impact on the production, and likely the resulting den-

1618 sity, of the moon's neutral gas envelope and the torus formed along its orbit.

1619 This effect is particularly visible in the total O_2 production rates (rightmost blocks

1620 of Figures 12(a) and 12(b)), which differ drastically based upon the assumed thickness

1621 of the surface O_2-bearing layer. For all five temperature profiles shown, the production

1622 rate calculated with a thick layer is nearly two orders of magnitude greater than that

1623 calculated with a thin layer. Depending upon the temperature profile used, the total O_2

1624 production rate for a thin layer ranges from $P_T = (1.5 \times 10^{26} - 4.9 \times 10^{26})\, s^{-1}$, while

1625 the thick layer estimate ranges from $P_T = (8.1 \times 10^{27} - 2.1 \times 10^{28})\, s^{-1}$. Our modeled

1626 production rate for a thin layer agrees well with published estimates of the global neu-

1627 tral *escape* rate at Europa of $\approx 1 \times 10^{26}\, s^{-1}$ (Vorburger & Wurz, 2018) and $\approx 2.7 \times$

1628 $10^{26}\, s^{-1}$ (Smyth & Marconi, 2006), which must be true for the exosphere to be in hy-

1629 drostatic equilibrium. Dols et al. (2016) suggested that symmetric charge exchange re-

1630 actions between picked-up O_2^+ ions and exospheric O_2 neutrals may increase the O_2 es-

1631 cape rate by up to an order of magnitude, arriving at a figure of $P \approx 4 \times 10^{27}\, s^{-1}$.

1632 This value edges slightly closer to our thick layer estimate.

1633 Cassidy et al. (2013) reported a global O_2 production rate of $P_T = 1.0 \times 10^{26}\, s^{-1}$

1634 using uniform electromagnetic fields and the same thin oxygen layer model applied here.

1635 Thus, the combination of the field perturbations (which reduce the surface flux) and the

1636 actual incidence angles (which enhance the sputtering yields) in our model results in a

1637 similar estimate of P as a model setup that treats the fields as uniform and assumes a

1638 constant incidence angle of $\theta = 0°$ (Cassidy et al., 2013). When the field perturbations

1639 are included, the chosen treatment of the incidence angles does not substantially alter

1640 the *spatial distribution* of the sputtering rates. However, assuming normal incidence does

1641 reduce the rates to their minimum possible values at all surface locations (see also sec-

1642 ond vs. third column of Figure 6). Therefore, if our model was to utilize a constant in-

1643 cidence angle of $\theta = 0°$ for all impinging ions, our estimate of the total O_2 production

1644 rate would fall below that of Cassidy et al. (2013), due to the shielding effect of the elec-

1645 tromagnetic field perturbations. Regardless of the integrated production rates, using uni-

1646 form electromagnetic fields (Cassidy et al., 2013) leads to vastly different estimates as

1647 to where the most exospheric material is being ejected compared to perturbed fields. In

1648 other words, careful treatment of Europa's perturbed electromagnetic environment is manda-

1649 tory to constrain, e.g., the location and extent of large-scale inhomogeneities in the moon's

exosphere. Precise knowledge on the properties of such exospheric inhomogeneities is critical for the ongoing search for transient water vapor plumes in plasma and magnetic field data (Jia et al., 2018; Arnold et al., 2019).

For both a thick and a thin oxygen-bearing layer the total production rate is affected by less than a factor of five when the surface temperature profile is altered (rightmost blocks of Figures 12(a) and 12(b)). In both cases, the O_2 production maximizes at 18:00 LT, when the surface temperature reaches its maximum and the sub-plasma point coincides with the sub-solar point. The minimum production rate occurs at 06:00 LT for both sputtering yield models, since the surface is at its coolest and the dayside hemisphere is downstream (i.e., it is only weakly irradiated). For either model of the O_2-bearing surface layer thickness, the production rate at 18:00 LT exceeds that at 06:00 LT by a factor of approximately three. Therefore, while the assumption of a thick O_2-bearing layer markedly increases the O_2 source rate compared to a thin layer, both assumptions result in a similar dependence of P on Europa's orbital position.

Sputtered O_2 remains in Europa's exosphere for only a finite residence time before it is lost due to ionization or Jeans escape into the neutral torus (Smith et al., 2019). The average residence time of sputtered O_2 in Europa's exosphere ($\approx 1.4 \times 10^5$ s, Smyth and Marconi (2006)) allows for an estimation of the globally-averaged O_2 column density, namely by multiplying the production rate P with the residence time and dividing by Europa's surface area $4\pi R_E^2$. Using this method we estimate an O_2 column density of $(6.9 \times 10^{13} - 2.2 \times 10^{14})\,\mathrm{cm}^{-2}$ in a thin layer model, and $(7.6 \times 10^{15} - 1.9 \times 10^{16})\,\mathrm{cm}^{-2}$ for a thick layer. HST observations have assessed the column density of Europa's exosphere to be $(2 \times 10^{14} - 6 \times 10^{14})\,\mathrm{cm}^{-2}$ (Hall et al., 1998; Saur et al., 2011; Roth et al., 2016). Thus, our model indicates that a thick oxygen layer approach to O_2 sputtering overestimates the observed O_2 content of Europa's exosphere, whereas a thin oxygen layer approach is consistent with the observed exospheric column densities.

Since the sputtering yields (and resultant rates) of H_2 are exactly twice those of O_2 (equation (4)), the spatial distribution of the H_2 sputtering rates is the same as that of O_2, regardless of the surface layer thickness. The production rates of H_2 in a thin layer approach range from $P_T = (3.0 \times 10^{26} - 9.8 \times 10^{26})\,\mathrm{s}^{-1}$, depending upon the local time, while those in a thick layer approach vary from $P_T = (1.6 \times 10^{28} - 6.3 \times 10^{28})\,\mathrm{s}^{-1}$. Again combining our modeled production rates with the exospheric residence time of H_2

1682 $(1.2 \times 10^4 \, \mathrm{s}$, Smyth & Marconi, 2006), we estimate an H_2 column density of $(2.9 \times 10^{12} -$

1683 $9.6 \times 10^{12}) \, \mathrm{cm}^{-2}$ with a thin layer, and $(1.6 \times 10^{14} - 3.9 \times 10^{14}) \, \mathrm{cm}^{-2}$ with a thick layer.

1684   Although the column density of molecular hydrogen in Europa's exosphere has not yet

1685   been constrained through observations, our estimated H_2 column density calculated with

1686   a thin layer is in good agreement with exospheric modeling by Vorburger and Wurz (2018).

1687   These authors calculated a value of $\approx 2.0 \times 10^{12} \, \mathrm{cm}^{-2}$.

4 Summary and Concluding Remarks

1689   In this study, we have presented the first model of magnetospheric ion sputtering

1690   at Europa which takes into account the perturbations to the electromagnetic fields near

1691   the moon. To accomplish this, we have combined the electromagnetic fields from the AIKEF

1692   hybrid model (Arnold et al., 2019; Arnold, Liuzzo, & Simon, 2020; Arnold, Simon, & Li-

1693   uzzo, 2020; Breer et al., 2019; Addison et al., 2021) with a variant of the GENTOo par-

1694   ticle tracing model (Liuzzo et al., 2019a, 2019b, 2020; Breer et al., 2019; Addison et al.,

1695   2021) which has been expanded to calculate the contribution of impinging magnetospheric

1696   ions to surface sputtering. We have calculated maps of the sputtering rates of H_2O, O_2,

1697   and H_2, the major exospheric constituents at Europa (e.g., Vorburger & Wurz, 2018; Roth

1698   et al., 2016; Roth, 2021) from the three dominant ion species in the moon's magneto-

1699   spheric environment. To constrain the variations in the surface sputtering rate with so-

1700   lar orientation (Europan local time), we have examined the temperature-dependent O_2

1701   and H_2 sputtering rates at four (near) equally-spaced locations of Europa along its or-

1702   bit, as well as with a diurnally-averaged temperature profile. In addition, we have in-

1703   vestigated how the thickness of the O_2-bearing layer within Europa's surface (Plainaki

1704   et al., 2013; Teolis et al., 2017) affects the spatial distribution of the sputtering rates.

1705   Finally, we have calculated the total H_2O, O_2, and H_2 production rates at Europa, as

1706   well as estimations of the corresponding exospheric O_2 column densities, which agree well

1707   with observations by HST and the Galileo spacecraft.

1708   Our major results are as follows:

1709   1. The inclusion of the electromagnetic field perturbations near Europa substantially

1710   modifies the spatial distribution of H_2O sputtering rates across the surface. Com-

1711   pared to a uniform field model, the deflection of the impinging ions by the draped

1712   fields reduces the sputtering rate by up to two orders of magnitude across much

1713 of the upstream hemisphere. Furthermore, substantial amounts of H_2O, O_2, and
1714 H_2 are sputtered from the downstream hemisphere when the field perturbations
1715 are taken into account, in contrast to a uniform field model which predicts zero
1716 sputtering in this region (Cassidy et al., 2013). Therefore, while a uniform field
1717 model would require redistribution of the sputtered gas in order to explain any
1718 substantial column density above the downstream hemisphere, deflection of the
1719 projectile ions by the perturbed fields allows for the direct generation of exospheric
1720 neutrals in this region. Thus, not only are the field perturbations affected by any
1721 asymmetries in Europa's neutral gas envelope (e.g., Arnold et al., 2019), but—due
1722 to their influence on the trajectories of projectile ions—the field perturbations in
1723 turn play a key role in determining where such "bulges" in the moon's exosphere
1724 are located.

2. The spatial distribution of the temperature-dependent O_2 and H_2 sputtering rates
1726 is largely determined by the thickness of the oxygen-bearing layer within Europa's
1727 surface. If the oxygen-bearing layer is thin compared to the penetration depths
1728 of energetic ions, thermal ions dominate the O_2 and H_2 sputtering rates everywhere
1729 except low latitudes on the downstream hemisphere. Thus, the highest sputter-
1730 ing rates with a thin layer are persistently located near Europa's upstream apex,
1731 regardless of the moon's orbital position. However, if the oxygen-bearing surface
1732 layer is thick, the sputtering efficiency of energetic ions does not decrease with pen-
1733 etration depth, and energetic ions make the greatest contribution to the sputter-
1734 ing rate. The spatial distribution of the energetic ion sputtering rate is then de-
1735 termined almost exclusively by the surface temperature profile. Hence, with a thick
1736 oxygen-bearing layer the region of maximum O_2 and H_2 sputtering follows the sub-
1737 solar point as Europa orbits Jupiter. Therefore, depending on the moon's orbital
1738 position, two enhancements in the sputtering rates may be present if the O_2-bearing
1739 surface layer is thick: one located near the sub-solar point (which moves along Eu-
1740 ropa's equator as the moon orbits Jupiter), and a persistent, weaker enhancement
1741 near the upstream apex.

3. The total production rates of O_2 and H_2 vary as a function of Europa's orbital
1743 position. The O_2 production rate maximizes at 18:00 LT, when the Sun is illu-
1744 minating the moon's low-albedo, upstream hemisphere. The O_2 production rate
1745 minimizes at 06:00 LT, when the dayside hemisphere is located on the moon's brighter,

downstream face. Regardless of the thickness of the oxygen-bearing surface layer, the production rate at 18:00 LT exceeds that at 06:00 LT by a factor of approximately three.

4. Assuming the oxygen-bearing surface layer to be thin compared to the penetration depth of energetic ions reproduces the values of Europa's exospheric column density, as observed by HST and the Galileo spacecraft. However, our estimated column densities do not take into account the redistribution of newly-sputtered molecules due to, e.g., gravitational and fictitious forces, nor the contribution of magnetospheric electrons to surface erosion.

5. The preferential ejection of H_2O molecules from a narrow region near the upstream apex, as revealed by our model, correlates well with the recent detection of a localized, persistent H_2O exosphere above Europa's upstream apex by Roth (2021) using HST observations. In addition, particularly intense weathering of the upstream hemisphere in a quasi-ellipse centered near the upstream apex (see section 3.2) matches the low concentrations of H_2O ice observed in that region by the Earth-based *Very Large Telescope* (Ligier et al., 2016).

The analytical exosphere model used in AIKEF to determine the field perturbations near Europa includes a upstream-downstream asymmetry (see section 2.1 and, e.g., Addison et al., 2021). The upstream "bulge" in this model exosphere has a clearly discernible impact on the field perturbations near the moon (Arnold et al., 2019). However, our results for the sputtering rates suggest that the draped fields themselves play a critical role in determining the regions on Europa's surface that are exposed to particularly intense erosion by magnetospheric ions. To achieve self-consistency, it would therefore be necessary to develop an improved exosphere model based on our calculated maps of the sputtering rates, subsequently use AIKEF to assess the influence of this modified neutral gas envelope on the electromagnetic fields, and then again update the ion surface fluxes and sputtering rates with GENTOo. This cycle would have to be repeated until convergence is achieved. However, such an exhaustive modeling effort is beyond the scope of the present study. In addition, our model has not considered the contribution of magnetospheric electrons to surface sputtering, which was recently suggested to be equal to, or even exceed, that of the ions (Vorburger & Wurz, 2018; Davis et al., 2021). Modeling of electron surface bombardment requires treatment of the bounce motion of electrons between Europa's local interaction region and Jupiter's polar ionosphere (Paranicas

et al., 2009), as well as inclusion of relativistic mass growth of the electrons. This effort will be the subject of a future publication.

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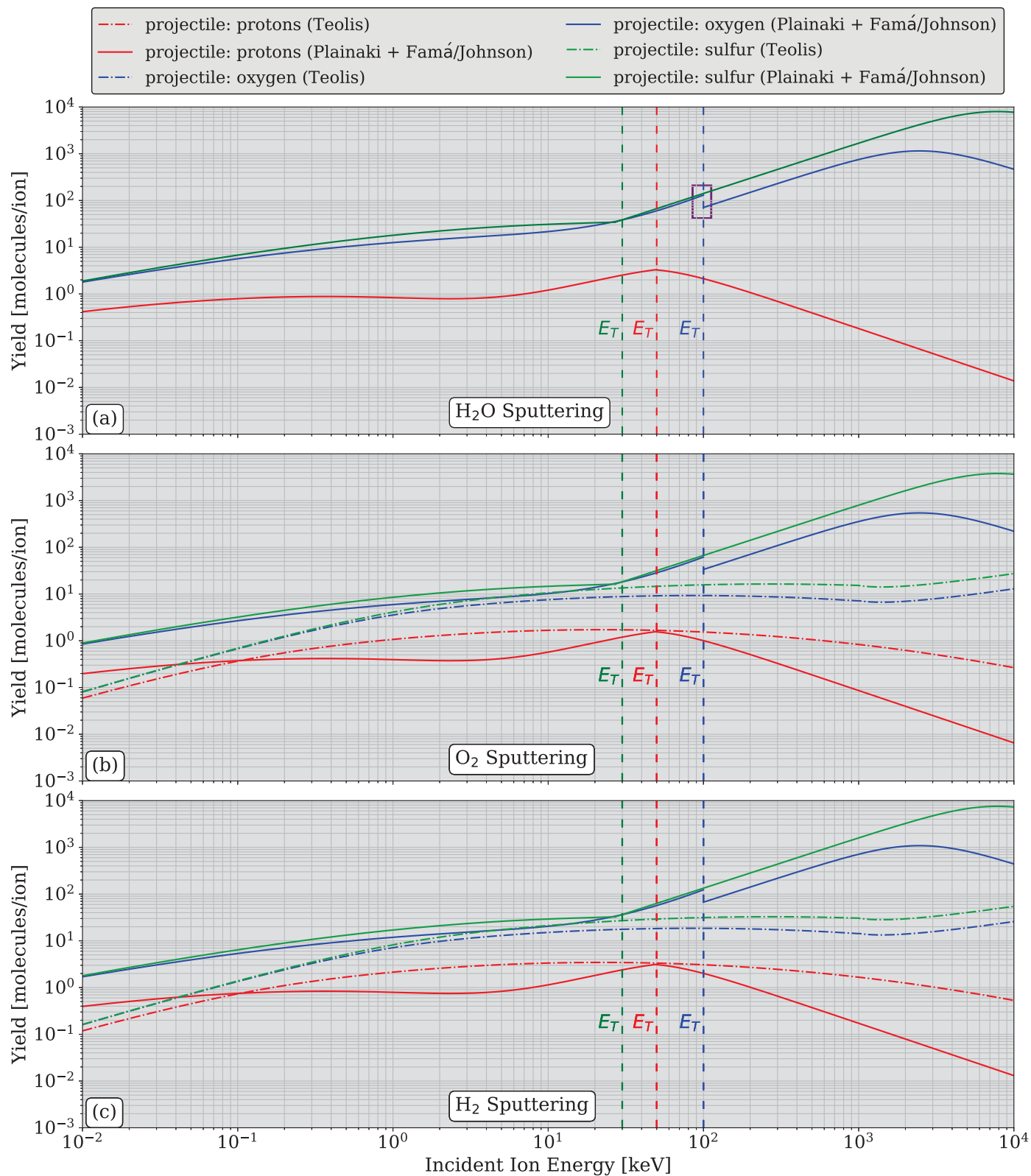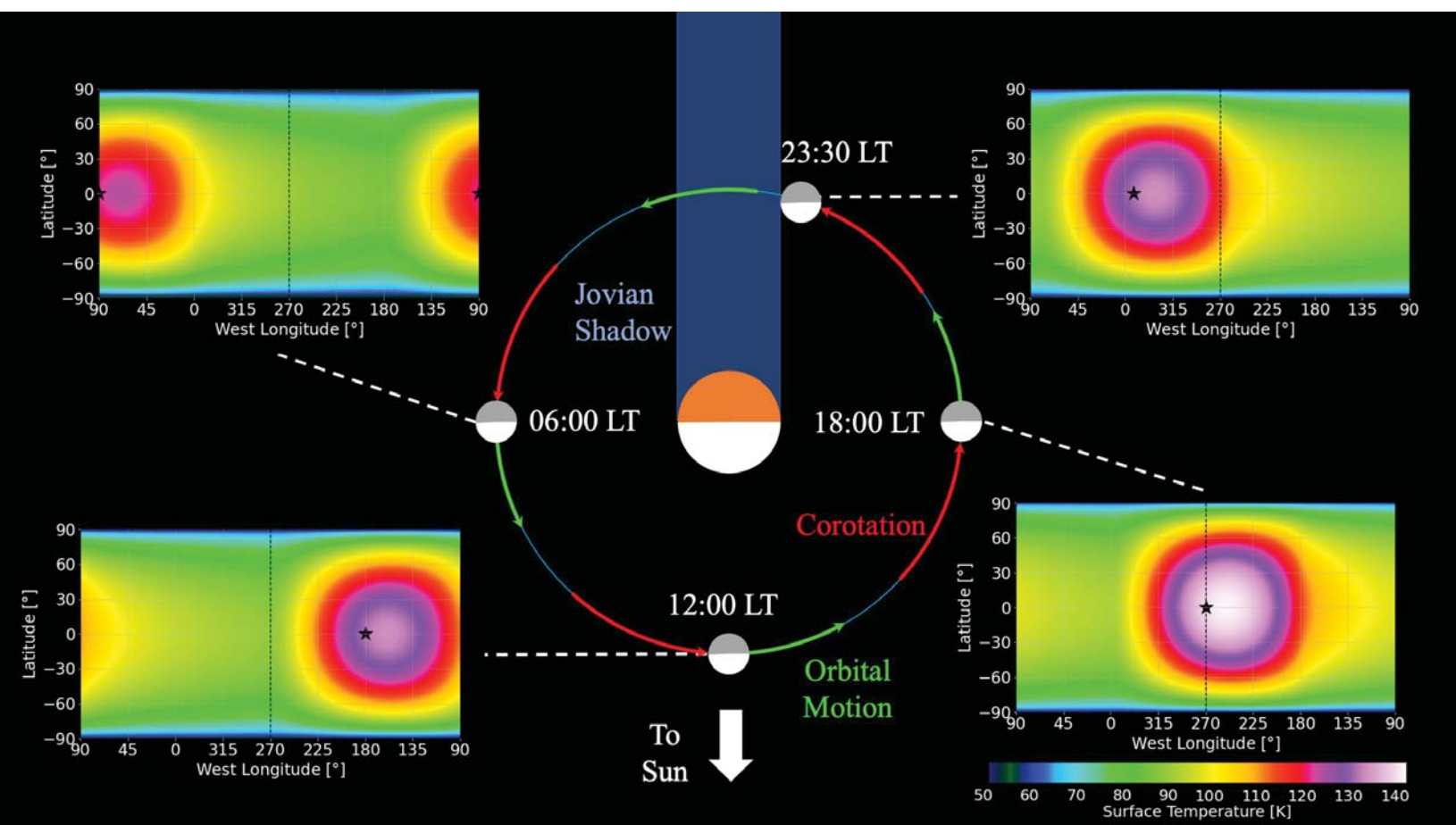
Figure 1.

Legend:
- projectile: protons (Teolis) — red dash-dot
- projectile: protons (Plainaki + Famá/Johnson) — red solid
- projectile: oxygen (Teolis) — blue dash-dot
- projectile: oxygen (Plainaki + Famá/Johnson) — blue solid
- projectile: sulfur (Teolis) — green dash-dot
- projectile: sulfur (Plainaki + Famá/Johnson) — green solid

(a) H_2O Sputtering

(b) O_2 Sputtering

(c) H_2 Sputtering

Yield [molecules/ion]

Incident Ion Energy [keV]

E_T E_T E_T

Figure 2.

Figure 3.

Figure 4.

(a) $z\ [R_E]$, $\dfrac{B_x}{B_0}$

(b) $z\ [R_E]$, $\dfrac{|\mathbf{B}|}{B_0}$

(c) $z\ [R_E]$, $\dfrac{|\mathbf{E}|}{E_0}$

(d) $z\ [R_E]$, $\dfrac{n}{n_0}$

Figure 5.

(a) Thermal, Uniform Fields

(b) Thermal, Perturbed Fields

(c) Energetic, Uniform Fields

(d) Energetic, Perturbed Fields

Figure 6.

(a) Thermal, Uniform Fields
(b) Thermal, Perturbed Fields
(c) Thermal, Perturbed Fields, $\theta = 0°$
(d) Energetic, Uniform Fields
(e) Energetic, Perturbed Fields
(f) Energetic, Perturbed Fields, $\theta = 0°$
(g) Total, Uniform Fields
(h) Total, Perturbed Fields
(i) Total, Perturbed Fields, $\theta = 0°$

R [cm^{-2} s^{-1}]

Figure 7.

(a) Average θ, 10 keV Sulfur

(b) Average θ, 100 keV Sulfur

(c) Average θ, 1 MeV Sulfur

Figure 8.

Figure 9.

(a) Thermal, Constant Temperature | (b) Energetic, Constant Temperature

(c) Thermal, 06:00 LT | (d) Energetic, 06:00 LT

(e) Thermal, 12:00 LT | (f) Energetic, 12:00 LT

(g) Thermal, 18:00 LT | (h) Energetic, 18:00 LT

(i) Thermal, 23:30 LT | (j) Energetic, 23:30 LT

(k) Thermal, Diurnal Average | (l) Energetic, Diurnal Average

° West Longitude

R [cm^{-2} s^{-1}]

Figure 10.

(a) Thermal, Constant Temperature
(b) Energetic, Constant Temperature
(c) Thermal, 06:00 LT
(d) Energetic, 06:00 LT
(e) Thermal, 12:00 LT
(f) Energetic, 12:00 LT
(g) Thermal, 18:00 LT
(h) Energetic, 18:00 LT
(i) Thermal, 23:30 LT
(j) Energetic, 23:30 LT
(k) Thermal, Diurnal Average
(l) Energetic, Diurnal Average

Figure 11.

(a) Thin Layer, Constant Temperature
(b) Thick Layer, Constant Temperature
(c) Thin Layer, 06:00 LT
(d) Thick Layer, 06:00 LT
(e) Thin Layer, 12:00 LT
(f) Thick Layer, 12:00 LT
(g) Thin Layer, 18:00 LT
(h) Thick Layer, 18:00 LT
(i) Thin Layer, 23:30 LT
(j) Thick Layer, 23:30 LT
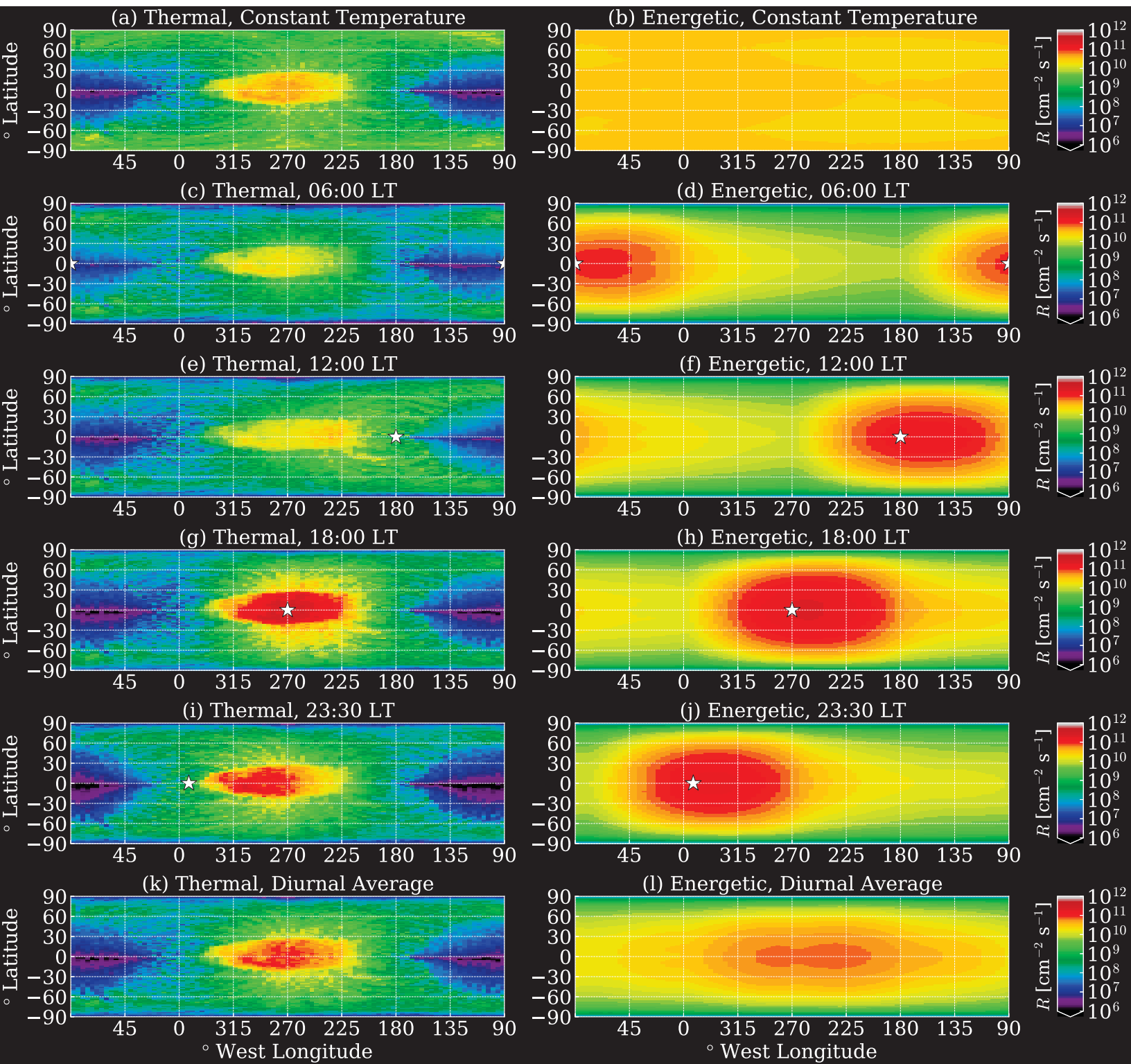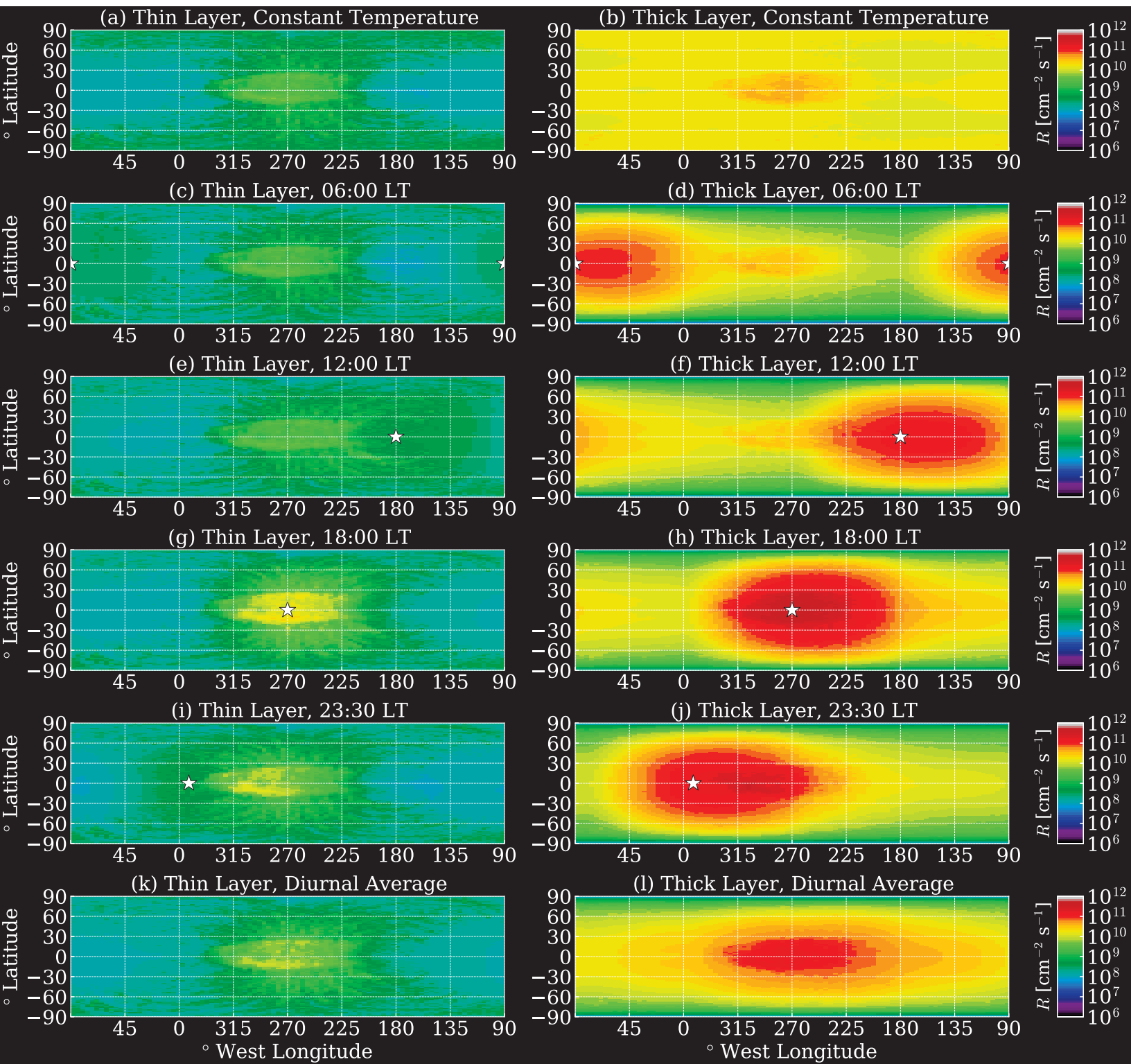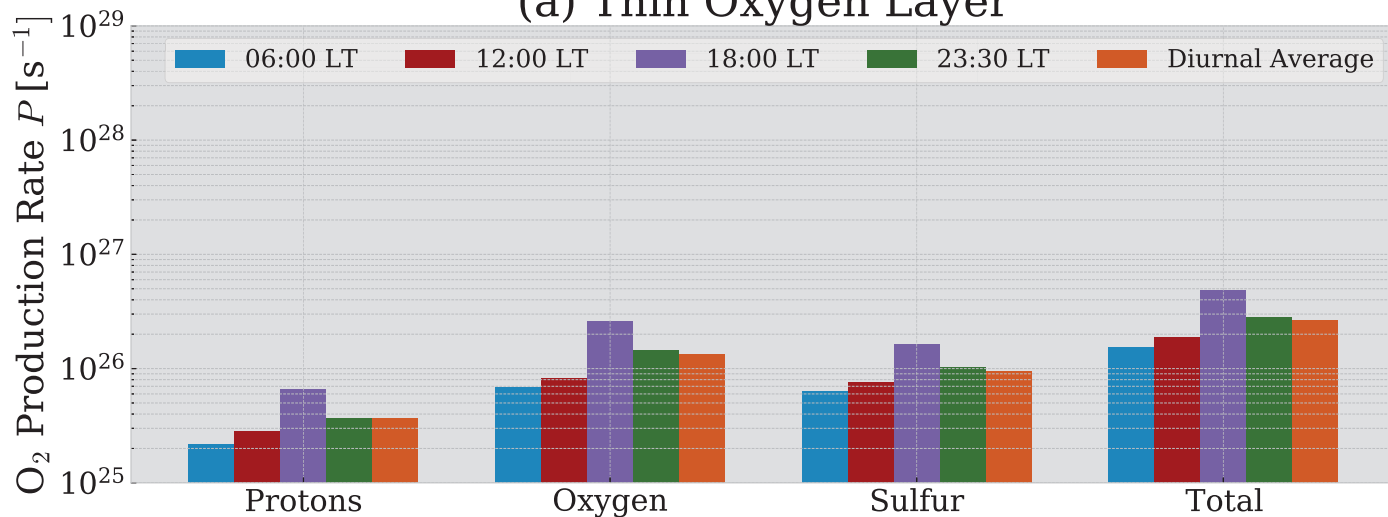(k) Thin Layer, Diurnal Average
(l) Thick Layer, Diurnal Average

Figure 12.

(a) Thin Oxygen Layer

(b) Thick Oxygen Layer