Interaction of the Jovian magnetosphere with Europa: Constraints on the neutral atmosphere

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Abstract. A three-dimensional plasma model was developed to understand the sources and sinks that maintain Europa’s neutral atmosphere and to study the interaction of the Jovian magnetosphere with this atmosphere and the formation of an ionosphere. The model includes self-consistently the feedback of the plasma action on the atmosphere through mass balance. Suprathermal torus ions with a contribution from thermal ions sputter O₂ from the water ice surface, and thermal torus ions remove the O₂ atmosphere by sputtering. For an oxygen column density of $5 \times 10^{18} \text{ m}^{-2}$ the calculated intensities of the oxygen lines OI 130.4 nm and 135.6 nm produced by electron impact dissociation agree with observations by the Hubble Space Telescope [Hall et al., 1995]. Mass balance is also consistent with this column density, with a net atmospheric mass loss of 50 kg s⁻¹. For a given neutral atmosphere and magnetospheric conditions, the electrodynamic model computes self-consistently plasma density, plasma velocity, electron temperature of the thermal and the suprathermal population, electric current and electric field in the vicinity of Europa, with the assumption of a constant homogeneous Jovian magnetic field. Europa’s ionosphere is created by electron impact ionization where the coupling of the ionosphere with the energy reservoir of the plasma torus by electron heat conduction supplies the energy to maintain ionization. The calculated distribution of electron densities with a maximum value of nearly $10^4 \text{ cm}^{-3}$ is in general agreement with densities derived by Kliore et al. [1997] from the Galileo spacecraft radio occultations. The Alfvénic current system closed by the ionospheric Hall and Pedersen conductivities carries a total current of $7 \times 10^5 \text{ A}$ in each Alfvén wing.

1. Introduction

The Galilean satellites are exposed to the harsh radiation environment of the inner Jovian magnetosphere also known as the Io plasma torus. The torus is characterized by plasma densities, ion temperatures, and electron temperatures in the range of $10^7 - 10^9 \text{ m}^{-3}$, 0.1 - 1 keV, and 5 - 50 eV, respectively. The collisional impact of magnetospheric ions with the Galilean satellites erodes their surfaces and sputters atoms and molecules to create tenuous atmospheres. Around the time of the Voyager 1 encounter with Jupiter, significant advances in our understanding of sputtering processes occurred from laboratory studies [Lanzerotti et al., 1978; Brown et al., 1980; Johnson et al., 1983] and from theoretical/modeling investigations [Johnson et al., 1982; Wolff and Mendis, 1983]. Reviews on this subject may be found by Cheng et al. [1986], Cheng and Johnson [1989], and Johnson [1990], where the interested reader can find a more extensive list of references to the literature.

The early report of an approximately 1 μbar atmosphere on Ganymede from a stellar occultation measurement [Carlson et al., 1973] motivated Yung and McElroy [1977] to develop a photochemical model of an H₂O atmosphere evolving into a stable molecular oxygen atmosphere. Prior to the appreciation of the importance...
of sputter-generated atmospheres/exospheres, they hypothesized that sublimation of water ice was the source of the inferred atmosphere and H2O molecules were converted by photolysis to O2, H2, O, and H. The hydrogen escaped thermally, leaving behind a predominantly molecular oxygen atmosphere. Nonthermal escape of O atoms balanced the production of oxygen, and their calculations yielded a surface pressure of ~1 mbar as purportedly observed. Kumar and Hunten [1982] pointed out that the Yang and McKelroy [1977] model also had a stable low surface pressure solution of ~10^-5 mbar. During the Voyager 1 encounter a stellar occultation by Ganymede yielded from Voyager Ultraviolet Spectrometer (UVS) measurements an upper limit on the surface pressure of 10^-5 mbar [Broadfoot et al., 1979]. Thus only the low-pressure solution could be compatible with these data.

The mean ice temperatures on Ganymede and Europa are ~103 and 95 K, respectively [Fink and Larson, 1975], whereas their respective disk brightness temperatures are larger: 135 and 124 K [Morrison, 1977]. Johnson et al. [1982] estimated O2 sputtered from water ice on Europa could yield a bound atmosphere with a column density ~2 - 3 x 10^19 m^-2. In a subsequent paper, Johnson et al. [1983] gave another estimate for the atmospheric column density on Europa of 2 x 10^17 m^-2, specifically for O atoms in the form of either H2O or O2 molecules. They considered only the direct sputtering fluxes, ignored thermally reemitted molecules, and assumed a sticking coefficient of unity. Eviatar et al. [1985] calculated that the exobase was on Europa's surface and that the atmosphere was a sputtered O2 exosphere with column density ~1 x 10^18 m^-2. They assumed a sticking coefficient of 1.5 x 10^-3 for O2 which if used in the Johnson et al. [1983] calculations would increase their net O2 column density to ~7 x 10^19 m^-2, approximately the value obtained by Johnson et al. [1982].

Hall et al. [1995] using the Goddard High-Resolution Spectrograph (G HRS) of the Hubble Space Telescope (HST) detected atomic oxygen emission from Europa. They observed an intensity ratio ~1.9:1 for the OI(55µ-3P)135.6 and OI(35ø - 3P)130.4 nm multiplets and interpreted this ratio as evidence for electron impact dissociative excitation of O2 as the dominant excitation mechanism. The absolute intensities implied the existence of a molecular oxygen atmosphere with column density (1.5 ± 0.5) x10^19 m^-2 on Europa. Their inferred column density is consistent with the early estimate of a bound atmosphere by Johnson et al. [1982] and the low-pressure limit given by Kumar and Hunten [1982] but inconsistent with the exospheric predictions of Johnson et al. [1983] and Eviatar et al. [1985]. In deriving the O2 column density, Hall et al. [1995] assumed that the spatial distribution of Europa's atmosphere was confined to the geometric cross section of the observed hemisphere, i.e., that the scale height of the atmosphere was significantly smaller than the radius of Europa and that a negligible contribution to the observed flux was emitted above the limb. Also the Io plasma torus electrons responsible for exciting the observed emissions were assumed to penetrate the atmosphere and exit without energy degradation. No electrodynamical interactions were considered such as the sub-Alfvénic interaction observed by Voyager at Io [e.g., Ness et al., 1979; Neubauer, 1980].

The discovery of an atmosphere on Europa was confirmed with further HST observations during the summer of 1996; in addition, UV atomic oxygen emission lines were detected from Ganymede [Hall et al., 1998]. The more recent analysis yields molecular oxygen column densities in the range of ~ (2 - 14) x 10^18 m^-2, on Europa and Ganymede [Hall et al., 1998].

Ip [1996] published an exospheric model for Europa generated by magnetospheric sputtering of O2 from water ice predominantly by thermal torus ions. His calculated exospheric column density failed by more than a factor of 1000 to account for the HST inferred O2 column density, and he invoked additional surface sputtering by new ionized O2 molecules accelerated by the corotational electric field and convected back into Europa's surface from which they had only recently been sputtered. This "resputtering" mechanism according to Ip is sufficient to raise the density of the gravitationally bound O2 molecules past the threshold value that defines the transition from an exosphere to an atmosphere.

From the Galileo spacecraft's first Europa pass in December 1996, Kivelson et al. [1997] inferred a maximum surface magnetic field strength of ~240 nT from a depression in B ~ 50 nT in the presence of Jupiter's larger magnetic field ~450 nT, assuming the absence of currents from electrodynamical interaction of Io torus plasma with Europa's ionosphere. But more important, Kivelson et al. [1997] expected, on the basis of scaling arguments, a magnetic field perturbation of ~100 nT from an Alfvénic interaction. Thus the observations at Europa do not necessarily require an intrinsic magnetic field. As Neubauer [this issue] has argued, even if Europa had a magnetic field of the above magnitude, it would only affect the quantitative details of an Alfvénic interaction with Europa and not invalidate any of the essential aspects of that interaction. In contrast, it is almost certain that Ganymede has an intrinsic magnetic field of maximum field strength ~1500 nT that is generated most probably by a core dynamo [Kivelson et al., 1996].

In this paper we develop a comprehensive self-consistent framework and model to interpret the Hall et al. [1995, 1998] HST observations and accurately derive the average O2 column density. Specifically, we investigate a variety of torus plasma sputter-generated, extended atmospheres with exobases ranging from 0 to 200 km above the surface, and develop a model of Europa's ionosphere created by torus electron impact and its electrodynamical interaction with torus plasma as a tightly coupled system governed by the essential phys-
ichal feedback mechanisms. From consideration of (a) O$_2$ mass balance with sputtering of O$_2$ molecules from the surface as the source and loss by thermal ion sputtering of O$_2$ molecules, and by ionization and convection out of the atmosphere or into Europa's surface and (b) atomic oxygen emission intensities, we derived a radial O$_2$ column density of $\sim 5 \times 10^{18}$ m$^{-2}$. We show that the resputtering mechanism is ineffective due to the large electrodynamic reduction in the corotational electric field that penetrates into the ionosphere. Our predicted electron density distribution exhibits the essential large-scale properties of the six inferred electron density profiles from the Galileo spacecraft radio occultation measurements [Kliore et al., 1997]. An Alfvén current system closed by ionospheric Hall and Pedersen conductivities is predicted to carry a total electric current of $\sim 7 \times 10^6$ A in each wing and probably sufficient in magnitude to account for most, if not all, of the magnetic field perturbation observed by the Galileo spacecraft near Europa [Kivelson et al., 1997].

2. Model

Any model for Europa’s atmosphere/ionosphere and magnetospheric interaction must satisfy two basic constraints: (a) the observational constraint of Hall et al. [1995] for oxygen line intensities: OI($^{5}S - ^{3}P$)135.6 nm: $I = 69 \pm 13$ R and OI($^{5}S - ^{3}P$)130.4: $I = 37 \pm 15$ R for a total measured intensity of 106 R and (b) mass balance between the net surface sputtered O$_2$ flux by observed magnetospheric ion fluxes with correction for the electrodynamic interaction and the total loss flux from neutral sputtering and ionization followed by convection.

2.1. Neutral Atmosphere

The atmosphere is treated as a single fluid of O$_2$ molecules on the basis that, although the sputtered flux of H$_2$O may be a factor of 10 greater than the sputtered flux of O$_2$, the sticking coefficient of O$_2$ is probably $\sim 10^{-3}$. As Johnson et al. [1982] have shown, the approximate column densities of H$_2$O and O$_2$ vary linearly with flux and inversely with sticking coefficient. Thus O$_2$ should be the dominant molecular species.

The radial variation of O$_2$ density in Europa’s atmosphere will be governed by the equations of continuity and motion or momentum. From standard books on fluid dynamics, the momentum equation in the radial direction can be written as

$$\frac{\partial}{\partial r} \left( \frac{1}{2} r^2 \nu \right) - \frac{1}{\rho} \frac{\partial p}{\partial r} + g = 0 \tag{1}$$

where $p$ is pressure, $\rho$ is mass density, $w$ is radial bulk velocity, $r$ is radial distance from center of Europa, and $g$ is gravitational acceleration. By the usual scaling arguments, the first term is negligible for low Mach flow. For O$_2$ the Jeans $\lambda$ parameter is $\sim 10$ for 1000 K; thus O$_2$ is gravitationally bound to Europa and radial outflow will be at low Mach number. The thermal speed $v_{th}$ and sound speed $c$ of O$_2$ are $\sim 1$ km s$^{-1}$, and the time constant to establish hydrostatic equilibrium of a bound atmosphere is $\sim H/c$. If the atmospheric scale height $H$ is $\sim 150$ km, then $H/c \sim 150$ s. This time constant is short in comparison to the O$_2$ atmospheric loss time of $\sim 1 \times 10^6$ by torus ion neutral sputtering, ionization and $E \times B$ convection out of the atmosphere, dissociation, and charge exchange processes.

The viscous term may be compared with gravitational acceleration

$$\nu \frac{\partial r}{\partial t} \frac{r^2 \nu}{g} \sim \frac{1}{2} v_{th} \frac{w}{l} \sim \frac{w}{0.3 \text{ km s}^{-1}}$$

where $l$ is the mean free path and $w$ is in km s$^{-1}$. For low Mach number flow the viscous term is small and to zeroth order may be neglected.

On the basis of the discussion so far, one would conclude that a hydrostatic atmosphere would be a good approximation to Europa’s atmosphere. The origin of the atmosphere is almost certainly due to sputtering by magnetospheric ions [Johnson et al., 1982] because the mean ice temperature of $\sim 95$ K [Fink and Larson, 1979] and the brightness temperature of $\sim 124$ K [Morrison, 1977] are sufficiently cold to render sublimation ineffective as a competing source [cf. Shi et al., 1995, Figure 8]. According to Johnson et al. [1983], the mean energy of sputtered, gravitationally bound O$_2$ molecules is $\sim 0.1$ eV. We conducted one-dimensional (1-D) calculations of the vertical temperature profile with Joule heating and heating due to electron impact associated processes and heat conduction down to the surface and found temperatures also of the order of 750 – 1000 K for a range of plausible O$_2$ column densities with associated scale heights $\sim 150 – 200$ km.

As an alternative to a hydrostatic atmosphere, we adopt the coronal model of Summers et al. [1989] for reasons discussed below, where one solves the spherical continuity equation for radial outflow in the presence of O$_2$ loss processes, $L_2$:

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 n_{O_2} w \right) = -L_2 n_{O_2} \tag{2}$$

$$L_2 = L_s + L_e + L_d + L_{chex}$$

where $n_{O_2}$ is the O$_2$ number density, $L_s$ is the thermal ion sputtering rate of the neutral atmosphere, $L_e$ is the electron impact ionization rate, $L_d$ is the electron impact dissociation rate of O$_2$, and $L_{chex}$ is the charge exchange rate. If $w$ is a constant $= w_0$ and an appropriate value is adopted for $L_2 = \langle L_2 \rangle$ which may be regarded as the globally (altitude, latitude, longitude) averaged loss rate, then the solution to (2) is

$$n_{O_2} = n_{20} \left( \frac{R_E}{R_E + h} \right)^2 \exp \left[ - \left( \frac{\langle L_2 \rangle}{w_0} \right) h \right] \tag{3}$$
where $R_E$ is the radius of Europa and $h$ is the height above the surface. One can define a depletion length scale or scale height associated with this coronal model as

$$H_d = \left( \frac{-1}{n_{O_2}} \right) \left( \frac{dn_{O_2}}{dz} \right) \approx \frac{w_0}{\langle L_2 \rangle}$$

By a suitable choice of $w_0$, one can for a given value of $\langle L_2 \rangle$ achieve a value for $H_d \sim H \sim 150$ km and alter $w_0$ to obtain any desired choice of $H_d$. Associated with this choice of $w_0$ is a surface flux of O$_2$ molecules equal to $\phi_0 = n_{20}w_0$, which, in principle, can be equated to the surface sputtered flux rate of O$_2$ molecules. Although Brown and Hill [1996] reported an extended sodium corona around Europa with a depletion length scale of the order of $R_E$, we do not regard the sodium density distribution around Europa as compelling evidence on the O$_2$ density distribution any more than the sodium density distribution around Io [Schneider et al., 1991] reveals the SO$_2$ scale height in Io's atmosphere.

To connect the surface sputtered flux of O$_2$ with the atmosphere over a broad range of conditions, it would be best to construct a boundary layer model that self-consistently generates the surface atmospheric density $n_{20}$ and the vertical velocity at the surface $w(h = 0)$ such that $n_{20}w(h = 0) = \text{sputtered O}_2$ surface flux at any point on Europa's surface. For surface densities of interest the mean free path of a sputtered O$_2$ molecule could be $\sim 10^{-20}$ km. A low Mach number solution of (1)-(2), where the first term in (1) is neglected, would allow matching the vertical velocity at the surface $w(h = 0)$ with the vertical velocity required above the boundary layer of thickness $\Delta r$ to quasi-conserve the O$_2$ flux because $(L_2)\Delta r/c \ll 1$. However, our numerical model for electrodynamic effects developed below cannot resolve structure on the scale of this boundary layer. Accordingly, we adopt the approximate solution (3) to represent the large-scale radial structure of the atmosphere. This yields the additional benefit of an explicit upward flux of O$_2$ in the model consistent with the continuity equation (2), which would not be possible if we adopted a hydrostatic atmosphere. Note that in the limit when $H_d \rightarrow \infty$, the radial density profile yields the radial outflow solution for a coma of a comet, whereas in the limit of $H_d/R_E \ll 1$, the radial density profile corresponds to an isothermal atmosphere with constant gravitational acceleration.

Pospieszalska and Johnson [1989] showed that sputtering is not uniform over the surface of Europa. Their calculations show a factor of 1.4 - 3 decrease from pole to pole of trailing hemisphere ($\Theta = 0^\circ$) to the pole of the leading hemisphere ($\Theta = 180^\circ$) in the sputtered flux due to the inability of cold torus ions to isotropically impact the surface. We assume in our model that the surface density $n_{20} \equiv n_{20}(\theta)$ varies in direct proportion to the normalized flux variation calculated by Pospieszalska and Johnson [1989] for 90% cold ions at 1 keV and 10% hot ions at 30 - 140 keV. Specifically, the surface density has the following spatial dependence:

$$n_{20}(\theta) = n_{20}(\theta = 0) \left[ 1.08 H \left( \frac{\pi}{2} - \theta \right) \cos \theta + 0.885 \left( \cos \frac{\theta}{2} + 1.675 \right) \right]$$

where $H(\pi/2 - \theta)$ is the Heaviside step function. In this model the ratio of $n_{20}(\theta = 0)/n_{20}(\theta = \pi) \sim 2.3$. Hence the hot ions cause considerable sputtering on the leading hemisphere. In the absence of any electrodynamic interaction, Shi et al. [1995] calculated an integrated sputtering rate over the surface of $(1-4) \times 120 \times 10^{26}$ molecules s$^{-1}$. The factor of $(1-4)$ originates from uncertainties in the porosity of Europa's surface. Based on the discussions by Johnson et al. [1983] and Johnson [1990], the fraction of sputtered O$_2$ molecules was taken as 0.15. Thus the maximum sputtered source rate of O$_2$ is $(1.8-7.2) \times 10^{27}$ s$^{-1}$.

2.2. Electron Impact Cross Sections and Rates

For the calculation of electron impact rates by torus plasma, we adopted the same plasma densities and temperatures that Hall et al. [1995] derived from Voyager 1 plasma science (PLS) measurements analyzed by Sittler and Strobel [1987] and Bagenal [1994]. These electron properties at Europa's orbital distance are a Maxwellian electron distribution core with density $N_{pt} = 38$ cm$^{-3}$ and temperature $T_{e,pt} = 20$ eV, and a suprathermal tail with density $N_{ps} = 2$ cm$^{-3}$ and temperature $T_{e,ps} = 250$ eV (subscript "pt" denotes "primary thermal" and "ps" "primary suprathermal"). With cross sections from Kanik et al. [1993] for electron impact ionization and dissociation, the ionization rate is $1.9 \times 10^{-6}$ s$^{-1}$ and the dissociation rate is $3.8 \times 10^{-7}$ s$^{-1}$, at the top of the atmosphere. The electron impact dissociative excitation rate for OI(3S$^0$ - $^3P$)130.4 nm is based on the cross section measurements by Zipf [1986] and is equal to $2.6 \times 10^{-8}$ s$^{-1}$. The electron impact dissociative excitation cross section for OI(3S$^0$ - $^3P$)135.6 nm is (a) normalized at 100 eV to $7 \times 10^{-22}$ m$^2$ [Itikawa et al., 1989], (b) varies in shape from 20 to 100 eV based on Wells et al. [1971], and (c) above 100 eV as Erdmann and Zipf [1987]. The electron impact cross section measured by Erdmann and Zipf [1987] for excitation of the OI(3S$^0$ - $^3P$)135.6 nm multiplet provides a lower limit to the OI(3S$^0$3S$^0$3p$^5$; $\lambda$774.7 nm) multiplet's cross section as it radiatively decays to the upper term of the 135.6 nm multiplet. The calculated emission rate is $4.7 \times 10^{-8}$ s$^{-1}$. For completeness, inelastic cross sections for various electronic states and vibrational levels of O$_2$ were included to adequately calculate the cooling of torus electrons by O$_2$ collisions (Itikawa et al. [1989]; details available on request).
2.3. Charge Exchange

Charge exchange enters our model in two important ways: (a) its contribution to the momentum transfer collision frequency and (b) as a mechanism to convert a collision pair of a hot ion – cold neutral into a cold ion – hot neutral with the subsequent escape of the hot neutral if it does not traverse the exobase. Momentum transfer collision frequencies for ion–neutral collisions have been discussed by Banks [1966]. The momentum transfer cross section at low energies is dominated by ion-induced dipole attraction and polarization of the neutral partner and by charge exchange at the higher energies characteristic of torus ions. At higher energies the momentum transfer cross section is twice the charge exchange cross section. The torus ions are primarily O⁺, S+++, and S+, whereas the ionospheric plasma is mostly O₂⁺. However, our model is for a single ion fluid, and we chose an effective charge exchange cross-section at 60 km s⁻¹ of 2.6 × 10⁻¹⁹ m² and assume that the cross section energy dependence is the same as for O⁺ + O collisions. At low energies our momentum transfer collision frequency becomes the standard Langevin expression with the polarizability of O₂ and the reduced mass of O₂⁺ – O₂ partners. Charge exchange contributes to atmospheric sputtering as discussed below.

2.4. Plasma Interaction Model

The plasma interaction model is a steady state, three-dimensional two-fluid plasma model, which is self-consistent with the exception of the magnetic field, which is assumed to be the constant, homogeneous Jovian background field B₀. This model is described in much greater detail by Neubauer [this issue], except for the aspects on energy balance. We will thus describe in the following sections the merits of this model briefly, referring the reader to Neubauer [this issue] and focusing mainly on the special features regarding Europa and energy balance.

We use a coordinate system, where the x direction is oriented along the undisturbed corotating plasma flow, the z direction is in the opposite direction to the Jovian background magnetic field at the location of Europa, and the y axis completes the right-handed coordinate system. This is shown in Figure 1. Note, the y axis does not, in general, point exactly toward Jupiter, and thus the xy plane is, in general, not exactly the equatorial plane, since spin axis and magnetic field direction at the location of Europa are, in general, not parallel.

Plasma from the Jovian magnetosphere convecting past Europa interacts with the atmosphere of Europa and creates by electron impact ionization an ionosphere with large electrical conductivity, thus enabling an electric current to flow, which short-circuits the undisturbed electric field seen by an observer on Europa. The electric current through Europa’s ionosphere feeds into the northern and southern Alfvén wing. The electrodynamic interaction also affects the plasma flow, by deflection around Europa, deceleration in the close vicinity of the upstream side of the satellite and reacceleration in the wake region. The electron impact ionization process would, however, come to a halt very rapidly if there were...
no additional energy source, since the energy of the local torus electrons swept into Europa's atmosphere is very limited. However, the plasma torus embedding Europa provides an extensive energy reservoir, which enhances the available energy via electron heat conduction along the magnetic field lines. This mechanism is very effective for maintenance of the ionization process.

2.4.1. Electron density. As described earlier, electrons in the Jovian magnetosphere at the location of Europa are divided basically in two populations, the thermal and the suprathermal population with a density of $N_{\text{pt}} = 38 \text{ cm}^{-3}$ and temperature $T_{\text{e,pt}} = 20 \text{ eV}$, and with $N_{\text{ps}} = 2 \text{ cm}^{-3}$ at $T_{\text{e,ps}} = 250 \text{ eV}$ [Sittler and Strobel, 1987]. These electrons are convected into the atmosphere of Europa, and by impact ionization, they are the main source of the ionospheric plasma population. Photoionization of $O_2$ at Europa is over an order of magnitude smaller, with a diurnally averaged value at solar maximum of $3 \times 10^{-8} \text{ s}^{-1}$ and a factor of 3 lower at solar minimum [Torr et al., 1979].

In the collisional ionization process, from a quantum-mechanical point of view, one cannot distinguish between the originally impacting electron and the newly created electron after the collision. However, from laboratory plasma experiments it is known [McDaniel, 1993] that the energy distribution of the electrons after the collision is a "$U$" distribution with maximum probability at 0 eV and at the maximum available energy $E_d$, which is the energy of the impacting electron minus the ionization potential. For this model we assume an idealized U distribution, i.e., one electron comes off cold with nearly no energy and the other electron with the maximum available energy $E_d$. Without this assumption, the model would require a kinetic description, which is beyond the scope of this work. With the above treatment we generate a "secondary cold" population of electrons and add the other electrons with energy $E_d$ as belonging to the original primary population, which however, reduces the temperature of this population due to energy loss in the ionization process. In this way, we describe the electrons by three different populations: the primary thermal and suprathermal population which do not change density, but which change temperature, and a third population, the secondary cold electrons at about $T_e \approx 0 \text{ eV}$, which does not change temperature but has strong density variations.

For the density $N_{\text{sc}}$ of the secondary cold population, we obtain

$$v_e \cdot \nabla N_{\text{sc}} = \sum_{j=\text{pt,ps}} f_{e,j}(T_{e,j}) N_j n_{O_2} - \alpha N_{\text{sc}}^2,$$  

where $n_{O_2}$ is the atmospheric oxygen density. The ionization rate by the electron population $j$ is given by

$$f_{e,j}(T_{e,j}) = \int d^3v_e f_{\text{Max},j}(E) v_e$$

with the Maxwell–Boltzmann distribution $f_{\text{Max},j}$, the electron impact ionization cross section $\sigma_e$ [Kanik et al., 1993], and $v_e$ the electron velocity with respect to the neutrals, which are assumed at rest in Europa's frame of reference. In this description an electron fluid with mean energy below the ionization potential can still contribute to the ionization process due to the high–energy tail in the Maxwell–Boltzmann distribution. Note also that the function $f_{e,j}$ depends very strongly on the electron temperature. For the dissociative recombination rate, we use the value for ionospheric modeling [Torr, 1985]

$$\alpha(T_e) = 2 \times 10^{-13} \frac{300}{T_e^{0.7}} \text{ m}^3/\text{s}$$

where we used for the recombination rate an approximate temperature for the secondary cold electrons of 0.5 eV.

In (6) we assumed that the velocity field is divergence free, which will be discussed in the next subsection, where we consider the electron velocity equation.

2.4.2. Electron velocity. The general form of the velocity equation for the electrons is given by Newbauer [this issue, equation (7)]. Scaling this equation for typical conditions at Europa, we find that perpendicular to the magnetic field the dominant contribution governing the electron velocity is the Lorenz force. We obtain for the electron velocity

$$v_e = \frac{E \times B_0}{B_0^2} + v_{\parallel} \frac{B_0}{B_0}$$

The parallel velocity component is given by the small electric field, collisional forces, and electron pressure gradients parallel to $B_0$. It is related to the component of the current parallel to $B_0$. As a further simplification, we neglect the contribution of $v_{\parallel}$ to $v_e$ and obtain $\nabla \cdot \nabla v_e \approx 0$, because $B_0$ is assumed to be constant. Thus $v_{\parallel}$ is included only in $j_0$.

2.4.3. Electron temperatures. As mentioned above, the energy balance of the electrons is crucial for the electron density distribution because the ionization rate has a strong dependence on the electron temperature. The electron plasma convecting through the atmosphere suffers a series of inelastic collisions, which reduce the electron temperature. The amount of energy transported into the atmosphere via convection is insufficient to create a dense ionosphere. With given plasma parameters from section 2.4.1 and an ionization potential of 12.06 eV, a simple estimate gives an upper limit for the ionospheric electron density of a factor of 2.6 greater than the torus electron density. However, heat conduction along magnetic field lines is very effective and connects the plasma torus around Europa with the ionosphere of Europa. In this way, the plasma torus provides an extensive, but also limited, energy reservoir for maintenance of the ionization process and thus the generation of a dense ionosphere.
To derive the electron temperature equation, the plasma torus is assumed to extend a distance $L_{\text{Torus}}$ along the field lines with respect to Europa. Let us consider flux tubes/field lines with length $L_{\text{Torus}}$ of electrons with number density $N_j$ and temperature $T_{e,j}$, which have a column internal energy density $W_j = \frac{3}{2} k_B T_{e,j} N_j L_{\text{Torus}}$, where the index $j$ can stand either for the thermal or the suprathermal population. We assume these populations do not interact on electron convection timescales through the atmosphere of Europa. Heat conductivity along magnetic field lines is large in a hot, thin plasma [e.g., Banks and Kockarts, 1973]. Thus we assume for simplicity that heat conduction enforces instantaneously a uniform temperature for each electron population along the field lines. This implies that any change in the internal energy anywhere along a flux tube has a proportional, equal impact everywhere along the total flux tube. We include explicitly changes in $W_j$ due to inelastic collisions with the neutral atmosphere and a heat flux $F_{\text{surf}}$ into the cold, icy surface of Europa if a flux tube is in contact with the surface. This leads to the equation

\[
\nabla \cdot \left( \frac{3}{2} k_B T_{e,j} N_j L_{\text{Torus}} \right) V_e = - \sum_{\kappa} \int dz L_{\kappa,j} n_{\text{O}2} N_j - F_{\text{surf}} H_{\text{contact}}
\]

with the energy loss rate for the processes $\kappa$ given by

\[
L_{\kappa,j}(T_{e,j}) = \epsilon_\kappa \int dV_{\text{elec}} \sigma_{\text{inelast.},\kappa} v_{\text{e}}
\]

The inelastic processes $\kappa$ are described by the energy $\epsilon_\kappa$ and their respective energy dependent cross section $\sigma_{\text{inelast.},\kappa}$ and include ionization, dissociation, excitation of vibrational states, etc., which are described in detail in section 2.2. The switch function $H_{\text{contact}}$ in (10) is equal to 1 if a flux tube with a finite electron density at the surface is in contact with Europa’s solid surface; everywhere else, $H_{\text{contact}}$ is zero.

For the surface heat flux, we use as a crude approximation:

\[
F_{\text{surf}} = \frac{3}{2} N_j k_B T_{e,j} |v_{||}|
\]

where we couple the internal energy flux into the surface with the ion-parallel velocity instead of the electron velocity. This treatment is motivated by the assumption that at the plasma surface boundaries polarization fields will be generated due to the higher mobility of the electrons, and hence transport processes will be controlled by the slower population, i.e., the ions, as in ambipolar diffusion.

2.4.4. Electric potential. After discussing the fluid equation, we come to the treatment of the electrodynamic fields. Only the electric field is calculated because we assume the constant homogeneous background magnetic field of Jupiter dominates any magnetic field relevant to the electrodynamic interaction. This is partly justified by the magnetic field observations of the Galileo spacecraft, which measured a magnetic field depression along its trajectory of 50 nT in a background field of 450 nT [Kivelson et al., 1997]. Though deviations of the undisturbed background field are probably greater closer to the satellite, even a superimposed dipole field with a magnitude of 240 nT at the surface, as suggested in Kivelson et al. [1997], will not change the physics qualitatively, but only (rather slightly) quantitatively [Neubauer, this issue].

Derivation of the equation for the electric potential is given by Neubauer [this issue], so we just briefly sketch the essential ideas here. We apply $\nabla \cdot j = 0$, which is a consequence of Ampère’s law for a steady state situation. The current system which has to obey this condition consists of the ionospheric currents and the Alfvénic current. The currents through Europa’s ionosphere are described by the anisotropic Ohm’s law characterized by the standard Pedersen, Hall, and longitudinal conductivities. The Alfvén wing current given by Neubauer [1980] is characterized by the Alfvén conductance

\[
\sigma_A = \frac{1}{\mu_0 V_{A0}}
\]

with the magnetic permeability $\mu_0$ and the Alfvén velocity $V_{A0}$. An additional important aspect of the model is based on the fact that the conductivity along the magnetic field, i.e., longitudinal conductivity, strongly exceeds the conductivities perpendicular to the magnetic field at the low neutral gas densities of Europa. Thus the parallel electric field is negligible and the 3-D problem is reduced to 2-D. The contribution of the conductivities is gathered by the integration along the field lines in the conductance functions

\[
\Sigma_i = \int dz \sigma_i(x, y, z) \quad i = 1, 2
\]

with $i = 1$ for the standard Pedersen and $i = 2$ for the standard Hall conductivity.

This leads to an equation for the electric potential $\Phi(x, y, z)$:

\[
(\Sigma_1 + \Sigma_A) \Delta \Phi + \left( \frac{\partial \Sigma_1}{\partial x} - \frac{\partial \Sigma_2}{\partial y} \right) \frac{\partial \Phi}{\partial x}
+ \left( \frac{\partial \Sigma_1}{\partial y} + \frac{\partial \Sigma_2}{\partial x} \right) \frac{\partial \Phi}{\partial y} = 0
\]

with the boundary condition that the perturbation vanishes at infinity, and the corotational electric field is obtained:

\[
\Phi = E_0 y \sqrt{(x^2 + y^2)} \to \infty
\]

(This is equation (40) of Neubauer [this issue].)
Pickup processes are incorporated with effective collision frequencies

$$\dot{\nu}_{in} = \nu_{in} + P/N_i$$

which include mass loading [Neubauer, this issue]; \(\nu_{in}\) is the total ion production rate, and \(N_i\) the total ion density, which are both equal to the electron rate and density.

The model is a two-fluid description where the physics of the ions is basically embedded in the potential equation (15) through the ionospheric conductivities. The velocity equation of the ions is contained in the derivation of the conductivities, which is subsequently used in the derivation of (15). The continuity equation of the ions is fulfilled automatically because of \(\nabla \cdot j = 0\) and equation (6).

For the ion temperature which is needed, for example, in the effective collision frequencies, we approximate this temperature based on the drift velocity \(\frac{1}{2} k_B T_i = \frac{1}{2} m_i v_i^2\), and thus neglect the finite equilibration time between ions and neutrals and the isotropization time of the ions.

This set of partial differential equation is solved numerically with a grid resolution for the Europa model of 20 km. The principal idea of the numerical scheme is to solve directly for the steady state solution using an iterative strategy. With given parameters at step \(i\), we solve the fluid equations in Lagrange’s description along the trajectories of the plasma flow to each grid point to get the plasma parameters at step \(i + 1\). With these parameters, we solve the potential equation in an iterative fashion, interpreting it as Laplace’s equation to get the electric potential at step \(i + 1\). We repeat iterations until convergence of the model parameters with iteration steps \(i\). The detailed numerical scheme is described in full by J. Saur et al. (Three dimensional plasma simulation of Io’s interaction with the Io plasma torus, submitted to Journal of Geophysical Research, 1998).

2.5. Neutral Atmosphere Mass Balance

Over suitably long timescales there should be a balanced budget in the neutral atmosphere mass flow. In particular, we demand that the total \(O_2\) production rate \(P_{O_2}\) and the total loss rate \(L_{O_2}\) be equal. For the production rate, we consider surface sputtering of \(H_2O\) ice by incident torus ions and by newly generated ionospheric ions, where we will call the former process “primary sputtering” \(F^P_{sput}\) and the latter “secondary sputtering” \(F^S_{sput}\). \(H_2O\) ice can be dissociated into \(H_2\) and \(O_2\), and subsequently, sputtered into the atmosphere, where the light hydrogen will escape easily and the heavier oxygen will be retained as an oxygen atmosphere. Loss is due to (a) newly generated ions, which are convected out of Europa’s atmosphere or which hit the solid surface of Europa and are therefore absorbed by the satellite, and (b) atmospheric sputtering.

2.5.1. Primary sputtering. We obtain the primary sputtering rate \(F^P_{sput}\) using the results of Shi et al. [1995], who found a total sputtering rate \(F_{O_2} = (1 - 4) \times 18 \times 10^{26} \text{ s}^{-1}\) for Europa with our assumed \(O_2\) fraction. They simulated the flux of incident torus ions hitting Europa and calculated the total sputtering flux using new laboratory measurements of sputtering yields from water ice. However, they did not correct the flux of the incident ions for the modified field conditions in the vicinity of Europa. Since the electric field is strongly reduced, the torus plasma is swept around Europa, decreasing the ion flux incident on Europa. We use the self-consistently calculated electric field to determine a reduction factor \(r_{Europa}\), which describes the reduced area given by plasma trajectories that still intersect with Europa (in units of the actual area of Europa). Thus we find for the primary sputtering flux

$$F^P_{sput} = F_{O_2} r_{Europa}$$

2.5.2. Secondary sputtering. A large number of ions newly created in the ionosphere of Europa collide with the surface and thus will also contribute to surface sputtering. These “secondary” ions, however, differ from the torus ions responsible for sputtering because of their much lower energy. In particular, torus ions contribute equally to surface sputtering through their thermal and suprathermal population in the thin atmosphere limit. For the secondary ions created in Europa’s atmosphere, we assume that there are no mechanisms to heat them to high temperatures during the short transit time through the ionosphere of Europa. We calculate the total secondary sputtering rate \(F^S_{sput}\) as follows:

$$F^S_{sput} \approx \int_{surface} d\mathbf{r} \cdot \mathbf{v}_i n_i \zeta(v_i)$$

where we have introduced an effective yield \(\zeta\) given by

$$\zeta(v_i) = \int du f_{Max}(u - v_i) Y\left(\frac{1}{2} m_i u^2\right)$$

with the ion temperature calculated with the drift velocity (see section 2.4). The sputtering yield \(Y\) is given by Shi et al. [1995] and depends strongly on the energy \(E_i\) of the incident ions. The effective yield takes into account the convected Maxwellian velocity distribution \(f_{Max}\) of the ions in the nonlinear relation of the yield \(Y\) upon the ion energy \(E_i\).

We would like to point out that there are additional effects which will influence the secondary sputtering rate. The detailed local velocity distribution of the ions near the surface will also modify the incident ion flux responsible for the sputtering yield and the finite gyroradius has to be taken into account too. However, since on average the expected gyroradii near the surface are less than \(~10\ \text{km}\), smaller than an atmospheric scale height \(~200\ \text{km}\), we neglect the finite gyroradius effect.
2.5.3. Pickup loss. We calculate the total loss of pickup particles as the total flux \( F_{\text{pick}} \) of the ions hitting the surface of Europa or being convected out of Europa’s atmosphere,

\[
F_{\text{pick}} = \int_{\text{surface+atmos}} df \cdot (v_1 n_i) \tag{21}
\]

2.5.4. Atmospheric sputtering. In this subsection we first describe the simplified method for calculating the atmospheric sputtering rate and afterward discuss the basic motivations underlying our method.

We assume atmospheric sputtering occurs by torus and ionospheric ions with velocity \( v_1 \) and mass \( m_i \), where we assume the mass of all of the atmospheric molecules are the same, i.e., mainly O\(_2\). Assuming purely head-on collisions, the molecules have velocity \( v_1 \) after the collision, whereas the ions are at rest. If the ion velocity is much larger than the escape velocity \( v_{\text{esc}} \), the trajectories of the sputtered molecules will be straight lines. All collisions above the exobase with trajectories that do not intersect the exobase will contribute to the total sputtering rate \( F_{\text{atmos}} \) given by

\[
F_{\text{atmos}} = \int_{\text{exobasis}} dV \left( \sigma_{\text{mt}} v_i n_i n_{\text{O}_2} \right) \text{Prob} \tag{22}
\]

with the cross sections for momentum transfer \( \sigma_{\text{mt}} \), which is 2 times the cross section for charge exchange \( \sigma_{\text{chex}} \) in the velocity range applicable for Europa, with the ion density \( n_i \) and the neutral oxygen density \( n_{\text{O}_2} \), and with the simplified escape probability \( \text{Prob} \)

\[
\text{Prob} = H (v_1^2 - v_{\text{esc}}^2) \{ H(x_0 \cdot v_1) H(x_0^2 - r_{\text{exo}}^2)
+ H(-x_0 \cdot v_1) H(x_{\text{min}}^2 - r_{\text{exo}}^2) \} \tag{23}
\]

for a collision to meet the above described conditions. Here \( H \) denotes the Heaviside function, \( x_0 \) is location of the collision, \( r_{\text{exo}} \) is the height of the exobase, and \( x_{\text{min}} \) is the closest radial distance from the origin of the coordinate system a particle can get after collision, which is given by

\[
x_{\text{min}}^2 = x_0^2 - \frac{(x \cdot v_1)^2}{v_1^2} \tag{24}
\]

Calculating the atmospheric sputtering rate in a totally realistic and self-consistent manner is beyond the scope of this work. Thus we use a simplified method which we think is still adequate to describe the principal physical process. The exobase is the boundary separating regions that are in collision dominated and collision free, so sputtered molecules intersecting regions below the exobase will be slowed by collisions. Additionally, it is probable that the mass of projectile and target are equal, since the main ionospheric ion species in the molecular oxygen atmosphere is O\(_2^+\), and also sulfur ions, a major fraction of the torus ions, have mass equal to O\(_2\). Neutralized ions created by charge exchange will essentially be forward scattered, whereas O\(_2\) molecules elastically scattered are directed mostly at right angles to the collision direction [Sieveka and Johnson, 1984]. We assume that charge exchange and elastic collision cross sections are comparable in magnitude and that all sputtered neutrals travel in the direction of the incident ion. The latter assumption is admittedly oversimplifying.

The above description of production and loss rate depends on the ion velocity. As an additional assumption, we replace in these calculations the ion velocity by the electron velocity (for computational simplicity). This assumption holds because in the relatively thin atmosphere of Europa the effective ion neutral collision frequency is less than the ion gyrofrequency.

2.6. Radiation

One of the strongest observational constraints on our model is the radiation of the two oxygen lines \( \lambda_1 = 135.6 \) nm and \( \lambda_2 = 130.4 \) nm observed by HST [Hall et al., 1995]. The dominant excitation mechanism is electron impact dissociation described by the production rates \( f_{\lambda_1} \) and \( f_{\lambda_2} \) (see section 2.2). The total emitted intensity \( I \) of the radiation in rayleighs is given by the integral over the radiation originating in the atmospheric domain \( V_{\text{HST}} \) visible to HST:

\[
I = \int_{V_{\text{HST}}} dV \frac{\sum f_{\lambda_j} (T_{e,i}) n_{\text{O}_2} N_i}{10^6 \pi R_E^2} \quad j = 1, 2 \tag{25}
\]

Index \( i \) denotes the thermal and the suprathermal population. Particularly important is the dependence of \( I \) upon electron temperature and upon neutral density. For a given neutral atmosphere and magnetospheric plasma parameters, our electrodynamic interaction model generates the spatial distribution of the electron temperature and thus \( I \). Because \( I \) is a function of the neutral atmosphere density distribution, the O\(_2\) column density can be inferred from the constraint \( I = 106 \) R, the combined disk-averaged OI 130.4 nm and OI 135.6 nm multiplet intensities observed by HST.

3. Results

3.1. Approach

We infer the average O\(_2\) column density of the neutral atmosphere by a balanced budget of neutral atmosphere gas flow, which is a consequence of mass conservation. We apply additionally the independent constraint that the atmosphere emits the radiation observed by HST [Hall et al., 1995]. The first constraint implies a nonstatic atmosphere and is the reason that we chose the coronal outflow model rather than the hydrostatic atmosphere model. The coronal outflow model has basically two free parameters, the surface density \( n_{2,0} \) and the depletion length scale \( H_d \). From the HST
point-spread-function broadening of the oxygen lines, we know that the radiation is emitted primarily from a disk with radius of $R_E + 300$ km and with a $2\sigma$ upper limit radius of $R_E + 900$ km [Hall et al., 1995]. This confinement of the UV radiation implies that the depletion length scale must be small. Assuming a constant electron temperature, we find for depletion length scales of 145 km, 500 km, and 1400 km that only with the first value is most of the radiation confined within the $2\sigma$ upper limit radius. For clarity, we use the column density $N_{\text{col}}$ as the free parameter rather than the surface density $n_{2,0}$. The two are equivalent for a fixed $H_d$. For the given neutral atmosphere model with a depletion length scale of $H_d = 145$ km, we explore the electromagnetic interaction as a function of column densities over the range 1.0 to $15.0 \times 10^{18}$ m$^{-2}$. For these models the location of the exobase ranges from the surface of Europa for a column density of $1.0 \times 10^{18}$ m$^{-2}$, to 71 km for $5 \times 10^{18}$ m$^{-2}$, and to 203 km for $15 \times 10^{18}$ m$^{-2}$. In Table 1 we give the other parameters used in our calculations.

### 3.2. Radiation

In our model, a molecular oxygen column density of $N_{\text{col}} = 5.0 \times 10^{18}$ m$^{-2}$ yields a calculated intensity of $I = 108$ R in excellent agreement with $I = 106$ R observed by HST. In Figure 2 (top) we show the radiation versus column density. Radiation increases with increasing column density, but more slowly for larger $N_{\text{col}}$, since the finite energy of the electrons in a flux tube is more strongly depleted in a denser atmosphere yielding lower temperatures and decreased locally emitted intensity. In Figure 2 we also display the measurement error of the HST observation [Hall et al., 1995]. These correspond to an uncertainty in the column density depicted in grey ranging from 3.4 to $7.2 \times 10^{18}$ m$^{-2}$. The most recent oxygen airglow observations of Europa by Hall et al. [1998] are basically identical to the spectrum ana-

---

**Table 1. Magnetospheric and Other Parameters Used in the Model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field $B_0$</td>
<td>$5.0 \times 10^{-7}$ T</td>
</tr>
<tr>
<td>Corotational plasma velocity $v$</td>
<td>104.3 km s$^{-1}$</td>
</tr>
<tr>
<td>Alfvén conductance $\Sigma_A$</td>
<td>1.69 S</td>
</tr>
<tr>
<td>Thermal electrons:</td>
<td></td>
</tr>
<tr>
<td>Density $N_{p_t}$</td>
<td>38 cm$^{-3}$</td>
</tr>
<tr>
<td>Temperature $T_{e,p_t}$</td>
<td>20 eV</td>
</tr>
<tr>
<td>Suprathermal electrons:</td>
<td></td>
</tr>
<tr>
<td>Density $N_{p_s}$</td>
<td>2 cm$^{-3}$</td>
</tr>
<tr>
<td>Temperature $T_{e,p_s}$</td>
<td>250 eV</td>
</tr>
<tr>
<td>Ion parallel velocity $v_{i,p}$</td>
<td>33.8 km s$^{-1}$</td>
</tr>
<tr>
<td>Radius of Europa $R_E$</td>
<td>1569 km</td>
</tr>
<tr>
<td>Extension of plasma torus $R_{\text{Torus}}$</td>
<td>$1.5 \times 7 \times 10^7$ m</td>
</tr>
</tbody>
</table>
alyzed by Hall et al. [1995], which confirms the existence of an oxygen atmosphere and the temporal stability of the airglow.

3.3. Mass Fluxes

A molecular oxygen column density of $N_{\text{col}} \sim 5 \times 10^{18} \text{ m}^{-2}$ is also consistent with a mass balanced neutral atmosphere. In Figure 2 (bottom) we show atmospheric fluxes, i.e., the atmospheric sputtering rate and the pickup loss, which together give the total loss, the total surface sputtering rate, and additionally, the secondary sputtering, all in units of $10^{26} \text{ s}^{-1}$. Loss rates and production rates balance within a range of $N_{\text{col}} \sim 3$ to $7 \times 10^{18} \text{ m}^{-2}$, depending on the precise value of the surface sputtering rate. This rate depends on the unknown porosity of Europa’s surface [Shi et al., 1995], and the associated uncertainty is shaded in Figure 2. For a column density of $N_{\text{col}} = 5.0 \times 10^{18} \text{ m}^{-2}$ the individual fluxes are given in Table 2 with a balanced mass budget at a total flux of $8.5 \times 10^{26} \text{ s}^{-1}$, which corresponds to a mass loss of $\sim 50 \text{ kg s}^{-1}$. Remarkably, atmospheric sputtering dominates pickup loss by about a factor of 10, and primary sputtering by torus ions exceeds respurting by about a factor of 100. For the former effect it is essential that an ion which was at rest immediately after a collision is then instantaneously accelerated to local convection velocity and thus available as a new projectile for further sputtering. The latter effect will be discussed below.

Each contributor to the total loss rate increases with column density, but more slowly with larger $N_{\text{col}}$, since the finite supply of energy from the torus reservoir is more depleted for a denser atmosphere. This finite power reservoir produces only a finite amount of newly created plasma in the ionosphere of Europa and yields a corresponding limited amount of pickup plasma and of projectiles responsible for neutral sputtering. The total surface sputtering rate decreases with increasing $N_{\text{col}}$ due to the reduction factor $r_{\text{Europa}}$, which is a measure of the disturbance of the velocity field and the shielding of the plasma flow around Europa. The values of the reduction factor $r_{\text{Europa}}$ upon column density are shown in Figure 3. Increasing atmospheric density enhances plasma effects that result in increased electric currents and modified and strongly reduced electric fields in the vicinity of Europa. These effects create strong shielding of torus plasma from Europa and deceleration of the plasma near Europa (see Figure 4). We find that secondary sputtering through newly created ionospheric ions does not provide the major source of the atmosphere, primarily because of the reduced electric field and convection plasma velocity. Consequently, ionospheric ions have very little energy and low sputtering yield because of the very strong dependence upon energy of the incident ions [Shi et al., 1995]. This is in contrast to Ip [1996], who concluded respurting was the major source of Europa’s atmosphere.

### Table 2. Flux Budget of the Molecular Oxygen Atmosphere for a Column Density of $5.0 \times 10^{18} \text{ m}^{-2}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Flux, $10^{26} \text{ s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss</td>
<td>1.2</td>
</tr>
<tr>
<td>Pickup-loss</td>
<td></td>
</tr>
<tr>
<td>Atmospheric sputtering</td>
<td>7.3</td>
</tr>
<tr>
<td>Total loss</td>
<td>8.5</td>
</tr>
<tr>
<td>Gain</td>
<td></td>
</tr>
<tr>
<td>Surface sputtering by torus ions</td>
<td>8.42</td>
</tr>
<tr>
<td>Surface sputtering by secondary ions</td>
<td>0.04</td>
</tr>
<tr>
<td>Total gain</td>
<td>8.5</td>
</tr>
</tbody>
</table>

For this column density the mass budget is balanced within the uncertainties of the input parameters. Surface sputtering by torus ions is calculated as product of the reduction factor $r_{\text{Europa}} = 0.195$ and the undisturbed sputtering rate $F_0 = 2.4 \times 18 \times 10^{26} \text{ s}^{-1}$. The factor of 2.4 is chosen within the range of 1 to 4 due to the uncertainties in the porosity of Europa’s surface given by Shi et al. [1995]; see also (18). For further explanations, see text.

3.4. Comparison of Both Constraints

Both constraints on the neutral atmosphere, i.e., radiated intensities, and mass conservation are totally independent, yet yield consistent column densities. In addition to stated uncertainties, i.e., the measurement error of HST observations and the unknown porosity of Europa’s surface, there are additional uncertainties in the other input parameters and the simplifying assumptions underlying our model.

A completely rigorous calculation of atmospheric sputtering is exceedingly complex because it would demand a kinetic approach, considering the actual trajectories of the projectiles, angular and energy dependent collision cross sections for energy transfer based on applicable atomic collision physics, and escape probabilities for neutrals with escape energy created below the exobase. Such a calculation is beyond the scope of this work. In
our study we have calculated with energy dependent
cross sections reasonably accurate atmospheric sputtering
rates by charge exchange. Our principal approximations were (a)
neglect of the precise kinetics, with pure head-on collisions
with velocity given by the, however, self-consistently calculated plasma bulk velocity,
(b) zero escape probability below the exobase. Neither of
these assumptions severely compromises calculated
charge exchange sputtering rates.

Elastic collisions transfer preferentially most of the
available kinetic energy in small fractional amounts
with recoil at right angles to the impacting ion in con-
trast to forward scattering by charge exchange. Because
we assumed a hard sphere elastic collision cross section
identical in value to the charge exchange cross section
with all of the available kinetic energy transferred to the
target particle, which is forward scattered, our treat-
ment of elastic collisions is admittedly very crude.

Consequently, we compare our method with a dif-
f erent approach [Haff and Watson, 1979] to estimate
the removal rate of Europa's oxygen atmosphere due
to elastic collisions of torus ions with O₂ molecules.
Their sputtering treatment, which is significantly dif-
ferent from ours, is based on rigorous atomic collision
physics, on a collisionally thick atmospheric target
to impacting ions, and unit atmospheric escape probabil-
ity for primary recoiling atoms. For the column densi-
ties that we derived for Europa's atmosphere (5 x 10^{18}
 m⁻²), neither of the latter two approximations is valid
and imply that their treatment would yield overesti-
mates of sputtering rates. Specifically, the atmosphere
is not collisionally thick at the upstream/trailing hemi-
sphere nose, whereas on the flanks ions only traverse

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{Lines of equal electric potential (in V),
which are also trajectories of the electrons. The electric
field is decreased and modified in the close vicinity of
Europa in a way that the electrons are slowed down and
mostly swept around Europa.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{Integrated Pedersen conductivity Σ₁ in S.}
\end{figure}

a collisionally thick column density near the surface
but with an escape probability considerably less than
1. Thus the sputtered flux of 10^{27} O₂ molecules s⁻¹ ob-
tained with their expressions is an upper limit for elastic
collisions to be compared to our calculated atmospheric
sputtering rate due to elastic collisions of 3.65 x 10^{26} O₂
molecules s⁻¹. Our calculation includes one additional
physical process not considered by Haff and Watson
[1979], namely, atmospheric sputtering by newly cre-
ated ionospheric ions accelerated by the reduced iono-
spheric electric field. Note, in our calculation we include
self-consistently the impact of atmospheric sputtering,
i.e., acceleration of the newborn ions, on the modifica-
tion of the plasma flow and the electric field by using
effective collision frequencies (see (17)). This indepen-
dent calculation confirms that our simplified approach
for atmospheric sputtering yields satisfactory results.

Thus within the uncertainties, our preferred atmo-
spheric O₂ column density satisfies mass balance when
it yields precisely the observed atomic oxygen line emis-
sion intensities.

3.5. Output of the Model

The above results yield a satisfactory neutral atmo-
sphere with a column density N_{col} = 5 \times 10^{18} m⁻² and
a scale height H = 145 km that is consistent with mass
balance, and one observational constraint, although it is
probably not a unique solution. Our electrodynamic
model generates predictions of the plasma environment
near Europa which can be compared with the recent
observations of the Galileo spacecraft.

In Figure 4 we show lines of constant electric field
potential. These lines are also the trajectories of the
electrons at constant z. Plasma is streaming from left
to right in Figure 4. Since the divergence of the ve-
locity field is zero, the spacing of trajectories is a mea-
sure for the flow velocity. Where equipotential lines are
squeezed together, plasma flows faster and vice versa. In the vicinity of Europa the electric field is disturbed relatively strongly due to the ionospheric conductivities. The integrated Pedersen and Hall conductivities along the magnetic field lines, i.e., the conductance functions, play an essential role in our model and are displayed in Figures 5 and 6. A general feature of these conductance functions is a local maximum on a circle with radius $R_E$ around the center of the coordinate system with a hole on the downstream direction. The reason for the special location of the maximum is due to a reduced path length of the integration if a flux tube intersects Europa, whereas for nonintersecting flux tubes the conductance functions basically decrease with increasing distance from Europa (see Neubauer [this issue] for further explanation). On the flanks are the highest values of the conductances, since the electron density maximizes there. In the actual wake we have a hole, since in our model no electrons can be convected into the wake because they intersect Europa’s solid surface. The atmospheric densities are relatively low, and thus the Pedersen conductivity dominates the Hall conductivity because the ion cyclotron frequency is larger than the effective ion-neutral collision frequency. The Hall conductivity is the origin of the loss of symmetry with respect to the $y$ axis (see (15)). The small contribution due to the Hall effect thus slightly disturbs the symmetry of the plasma flow with respect to the $y$ axis. Far from Europa the undisturbed corotational flow is obtained because the disturbance of the electric field fades away. On the flanks there are regions of increased velocity, which can be understood by regarding the electric field disturbance outside the current carrying region to first order as the field of an electric dipole in two dimensions [Neubauer, 1980].

We display in Figure 7 the electron density in the $xy$ plane, which is perpendicular to the magnetic field $B_0$.

![Figure 7. Equatorial electron density in units of $N_0 = 40 \text{ cm}^{-3}$](image)

In this plot and subsequent plots with plasma results, torus plasma flows from left to right. As plasma is convected through the atmosphere of Europa, electron impact ionization creates new secondary cold electrons which also drift along the trajectories shown in Figure 4. As long as recombination is not dominant, the electron density increases monotonically along each trajectory. Thus there is a local maximum of the density of about $1000 \text{ cm}^{-3}$ at the upstream surface of Europa. Along the inside of the flanks the electron density has its global maximum, reaching values of nearly $9000 \text{ cm}^{-3}$ because of the much longer transport time for a plasma fluid element through the dense part of the atmosphere. Further downstream the electron density starts to decrease again, since no ionization, only recombination, in the plasma-loaded flow occurs. In the model wake, no electrons are present, since we only solve the velocity equation just perpendicular to $B_0$, which is a shortcoming of our model. Thus plasma hitting Europa will be removed by the satellite and form a wake. However, primarily due to plasma pressure gradients, plasma will be forced mainly along the field lines into the wake. Our results are in reasonably good agreement with the very recent observation by Kliore et al. [1997], who obtained ionospheric electron densities from the Galileo spacecraft radio occultation measurements. They derived comparable maximum electron densities of $10,000 \text{ cm}^{-3}$, but with a somewhat larger electron scale height of $240 \text{ km}$. Our model generates electron densities which are not spherically symmetric with maximum density on the flanks, minimum density in the wake, and intermediate density on the upstream side, in essential agreement with the features observed by Kliore et al. [1997] at different occultation points. Note that Kliore et al. [1997] assumed a spherical symmetric ionosphere to derive their observational electron densi-
ties, which is a very simplifying assumption according to our model results in Figure 7.

We show in Figure 8 the temperature of the thermal electrons (the temperature of the suprathermals exhibit similar behavior). Because infinite heat conductivity was assumed for electrons along the magnetic field lines, the electron temperature distribution is two-dimensional. Torus electrons are convected into Europa's atmosphere, and by ionization and other inelastic collision processes their temperature is reduced, so deep in the ionosphere and along the flanks the electron temperature reaches its lowest values, with a global minimum of about 8 eV. The characteristics of the electron density distribution matches those of the electron temperature; basically, regions with high electron density can be mapped to regions with low electron temperature. Heat conduction is the only mechanism in our model providing energy locally. Since we assume an infinite conductivity along the field lines, electron temperature decreases monotonically along each trajectory and is therefore lowest on the downstream side. Note, recombination does not modify the electron temperature. Here again it should be pointed out that heat conduction of torus energy into the ionosphere enables ongoing ionization. Without this energy reservoir, all the energy of the electrons which are convected into the atmosphere and collisionally interact with it would be used up very quickly without creating a significant ionosphere.

Applying Ohm's law $J_\perp = \Sigma_l E + \Sigma_B B_0 \times E/B_0$, we can calculate for a given electric field and given integrated conductivities the overall current $J_\perp$ through Europa's ionosphere, i.e., the electric current perpendicular to the magnetic field integrated along a field line. This ionospheric electric current is connected to the Alfvén wing tube, which continues the current via Alfvén currents $j_z \approx \Sigma_A \nabla \cdot E$ [Neubauer, 1980] above the atmosphere. In Figure 9 we show the ionospheric current $J_\perp$, and in Figure 10 the Alfvénic current $j_z$. Both plots together yield a good picture of the current system. The current flows down in the northern Alfvén wing (and up in the southern) on the side facing Jupiter. In the ionosphere this current continues as Pedersen and Hall currents mainly in the direction away from Jupiter. On the side opposite to Jupiter the currents again escape into the Alfvén wings. The two little spots on the downstream side where field reversal occurs are most likely an effect of our simplifying assumption in the velocity equation. This effect would probably vanish when the velocity equation is also solved in direction along the magnetic field lines. This becomes noticeable in the tail region, where a strict boundary between regions with and without electrons are created by the model assumption. For the conductances at this location, it leads to an artificial large gradient with a decrease to zero, which prohibits an electric current in the wake to flow across the wake. Because of the divergence free nature of the current in steady state conditions, current has to be supplied from or fed into the Alfvén wings. In reality, due to the field-aligned component of plasma flow, there will be an ionosphere and therefore also closure currents in the wake region. We obtain in our model a total current $J_{\text{tot}} = 7 \times 10^5$ A fed into the northern Alfvén wing. This is sufficiently large to generate a significant perturbation to the ambient background magnetic field which is not included in our calculations. However, we suggest that this current and the associated closure currents could contribute to a large extent, if not completely, to the magnetic field disturbances observed by the Galileo spacecraft [Kivelson et al., 1997].

![Figure 8. Electron temperature of the thermal population in eV.](image)

![Figure 9. Ionospheric electric current $J_\perp$. The longest arrow corresponds to 0.42 A/m.](image)
the mass balance of the neutral atmosphere, which we employ simplifying assumptions, our model includes the processes governing the overall content of Europa’s atmosphere. Although we use for a self–consistent treatment of the feedback of the plasma action on the atmosphere and vice versa, since both are very strongly coupled. The neutral atmosphere is generated, removed, and maintained by sputtering processes, which strongly depend on the electrodynamic conditions at Europa. Suprathermal torus ions with a contribution from thermal ions sputter O2 from the surface water ice. Europa’s atmosphere is lost primarily by thermal torus ion sputtering. Thus the properties of the Jovian magnetospheric plasma control the thickness of Europa’s atmosphere.

In our model, an oxygen column density of $5 \times 10^{18}$ m$^{-2}$ produces a radiative output in atomic oxygen line emission in agreement with the HST observations of Hall et al. [1995]. This column density is also consistent with mass balance between production and loss processes governing the overall content of Europa’s atmosphere.

The plasma interaction strongly depends on the neutral atmosphere. Our electrodynamic model is self–consistent with the exception of an assumed homogeneous Jovian magnetic field. It predicts plasma density, plasma velocity, and electron temperature as well as the ionospheric conductivities, the electric currents, and the electric field given the density and energy distribution of the impacting torus plasma and the corotating magnetic field. Basic ideas are that the ionosphere is created by electron impact ionization by the thermal and suprathermal populations of the torus electrons. The ionospheric electrons are presumed cold, whereas the temperature of the ionizing primary electrons is computed as they convect through the ionosphere. It is crucial that the ionosphere is coupled via heat conduction to tap the extensive energy reservoir of the plasma torus to attain the distribution of high electron densities of nearly 10,000 cm$^{-3}$ in general agreement with those derived by Kliore et al. [1997].

The Alfvén current system closed by the ionospheric Hall and Pedersen conductivities carries in our model a total electric current of $7 \times 10^5$ A in each wing. The large current derived in our analysis will produce also a distinct magnetic signature which could contribute to a large extent, if not all, to the magnetic field disturbances observed by the Galileo spacecraft [Kivelson et al., 1997].

The large Alfvénic currents could reach Jupiter’s ionosphere generating a Europa footprint. Thus there might be additional acceleration mechanisms yielding high electron energies possibly contributing to ionization, dissociation, and excitation.

The mass loss from Europa’s surface by ion sputtering and subsequently from Europa’s atmosphere also mainly by ion sputtering corresponds to a mass loss of 50 kg s$^{-1}$, which would erode the surface of Europa by 1 m in 20 Myr.

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