ICARUS 120, 317–325 (1996)
ARTICLE NO. 0052

Europa's Oxygen Exosphere and Its Magnetospheric Interaction

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Received April 17, 1995; revised November 13, 1995

The newly detected oxygen atmosphere of Europa is modeled by invoking charged particle sputtering with H_2O and O_2 molecules as the main ejecta. The magnetospheric corotating ions could provide the required source strength (~3 × 10^{26} sec^{-1}) of O_2 molecules if a fraction (~20%) of the exospheric ions were recycled to Europa's surface where they produce additional sputtering product. Two exospheric components are expected to form: an extended corona with a size of a few satellite radii which is composed of sputtered molecules in ballistic motion, and a thermal population with a surface density of 10^8–10^9 cm^{-3} and a scale height of about 20 km. The electron impact ionization of this exosphere would lead to an Io-like interaction with the jovian magnetosphere with a field-aligned Birkeland current of about 5 × 10^5 A. © 1996 Academic Press, Inc.

1. INTRODUCTION

After Io, the next most enigmatic satellite in the jovian system is undoubtedly Europa. Its very high albedo and relatively smooth surface suggest that it might have a recent history of resurfacing by liquid water (Smith *et al.* 1979). Cassen *et al.* (1979) and Squyres *et al.* (1983) made the interesting suggestions that a liquid ocean covered by a thin (<30 km) shell of ice crust could exist and act as an intermittent source for the observed surface frost. The recent HST detection of an oxygen atmosphere in the near-proximity of Europa has further underlined this satellites' scientific importance (Hall *et al.* 1995).

The first indication of the existence of a neutral cloud of hydrogen and/or oxygen atoms surrounding Europa came from the UV photometer observations on Pioneer 10 at Jupiter (Wu *et al.* 1978). An emission brightness of $4\pi I \approx 10$ Rayleighs was inferred amounting to a column density of 10^{13} O-atoms cm^{-2} over an integration path of about 1.5 R_J. It is interesting to note that the column density of the OI atoms as estimated from the HST measurements at 1304 and 1356 A is about 5×10^{13} cm^{-2} (see Hall *et al.* 1995). However, because the UV photometric observations from Pioneer 10 might have been contaminated by the EUV emission from the Io plasma torus, no definite conclusion could be drawn at that time. The electrostatic analyzer experiment on Pioneer 10 detected an increase in ion density as the spacecraft crossed the L shell of Europa (Intriligator and Miller 1982). This feature might be associated with the formation of a Europa plasma torus as a result of mass injection from this icy satellite. This issue was followed up recently by Bagenal (1994), who showed that the O^+ density observed by Voyager 1 increases suddenly at radial distances $\gtrsim 7.5$ R_J.

Using a plasma chemical model, Schreier *et al.* (1993) investigated how the local increase of the number density of the O^+ ions could be related to the ionization of Europa's neutral oxygen atomic cloud. From parameter fittings, these authors found that the number density of the neutral oxygen atoms should be on the order of 3–7 atoms cm^{-3} while the corresponding source strength should be as much as $Q \sim 2 \times 10^{27}$ atoms sec^{-1}. [In comparison, the total SO_2 gas emission rate from Io was estimated to be on the order of 5×10^{28} molecules sec^{-1} (Broadfoot *et al.* 1979, Dessler 1980)]. A very strong dynamical coupling between the Europa neutral cloud and the jovian magnetosphere is implied if its Q value is indeed this large.

Because of the exciting discovery by Hall *et al.* (1995) and the pending commencement of the Galileo observations in the jovian system with Europa as an object of special interest, an exospheric model is constructed in this paper to facilitate planning of observations by Galileo. Special emphasis will be given to the bombardment effect of the magnetospheric ions on the satellite surface which was first investigated by Johnson *et al.* (1982). As will be discussed in the following sections, the mass loading effect as a result of electron impact ionization of the exospheric neutrals could lead to an Io-like magnetospheric interaction characterized by a field-aligned Birkeland current system.

2. SPUTTERING PROCESS

Because of the low surface temperature ($T \approx 120$ K), the ice sublimation rate is extremely low at Europa. Meteoroid impact may be able to generate vapor clouds at impact sites and its contribution could be significant if the corresponding gas mass production rate exceeds the meteoroid

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mass flux by a factor of 10–100. There is, however, a strong argument in favor of a third process, namely, impact bombardment by the magnetospheric ion population. The albedo variation across Europa shows a minimum at the pole ($\theta = 0$) of the trailing hemisphere and a maximum at the pole ($\theta = 180°$) of the leading hemisphere (McEwen 1986) which is consistent with the angular pattern expected of collisional interaction with the corotating plasma (Eviatar *et al.* 1981, Sieveka and Johnson 1982, Pospieszalska and Johnson 1989, Sack *et al.* 1992). There are also good reasons to believe that magnetospheric ion bombardment is an important source mechanism in view of the large yields of heavy ions on water ice (Johnson *et al.* 1982, 1983, Brown *et al.* 1984, Reimann *et al.* 1984, Bar-Nun *et al.* 1985, Eviatar *et al.* 1985, Cheng *et al.* 1986, Johnson 1990). As a matter of fact, in their pioneering work on the applications of the laboratory data on ion sputtering effects on condensed ices, Johnson *et al.* (1982) made the interesting point that the sputtered surface flux of O_2 molecules at Europa could be on the order of $\approx 10^9$ molecules cm^{-2} sec^{-1} and that an exosphere with an atmospheric column density of $\sim 2–3 \times 10^{15}$ O_2 cm^{-2} could form. This theoretical estimate is remarkably close to the observational value of $1.5 \pm 0.5 \times 10^{15}$ cm^{-2} obtained from the HST measurements (Hall *et al.* 1995). In this early work the assumption was made that the energetic ($\approx$MeV) ions in the jovian magnetosphere are dominated by oxygen and sulfur ions. There are, however, still uncertainties in the relative abundances of the MeV heavy ions, and the energy spectra of the suprathermal ions were not measured by Voyager. It is therefore useful to examine the potential contribution from the corotating plasma population of which we have detailed information from the PLS observations (Belcher 1983, Bagenal 1994). Our approach here is to investigate the advantages and limitations on scenarios of ion sputtering on Europa by different plasma populations, namely (a) corotating thermal plasma, (b) suprathermal ions, and (c) MeV ions.

2.1. Corotating Thermal Plasma

In the following we will expand on the discussion of Eviatar *et al.* (1985) by developing a scenario to show that the oxygen atmosphere (or exosphere) observed by Hall *et al.* (1995) could in principle be maintained by the sputtering effect of the corotating thermal ions. According to Bagenal (1994), the total number density of thermal ions at the centrifugal plane near Europa's orbit is on the order of $n_i \approx 80$ cm^{-3} (and $n_e \approx 130$ cm^{-3}) with 50% in O^+, 25% in O^{++}, and 8% each in S^{++} and S^{+++}. This composition is consistent with the scenario that an additional contribution could result from sputtering processes at Europa. As illustrated in Fig. 1, if the gyroradii of the corotating ions are small compared with the size of Europa, the incoming ion flux on the satellite surface will follow a cosine law. This is a valid approximation since the ion temperature was determined to be $T_i \approx 300$ eV (Bagenal 1994) so the gyroradius of O^+ is about 20 km. The magnetospheric plasma at $L \approx 9.3$ is in partial corotation with the azimuthal flow velocity lagging the full corotation value by about 20% (Belcher 1983). The local plasma flow speed is therefore $v_i \approx 95$ km sec^{-1} and the impact energy of oxygen ions would be $E_i \approx 800$ eV (and 1.6 keV for sulfur ions).

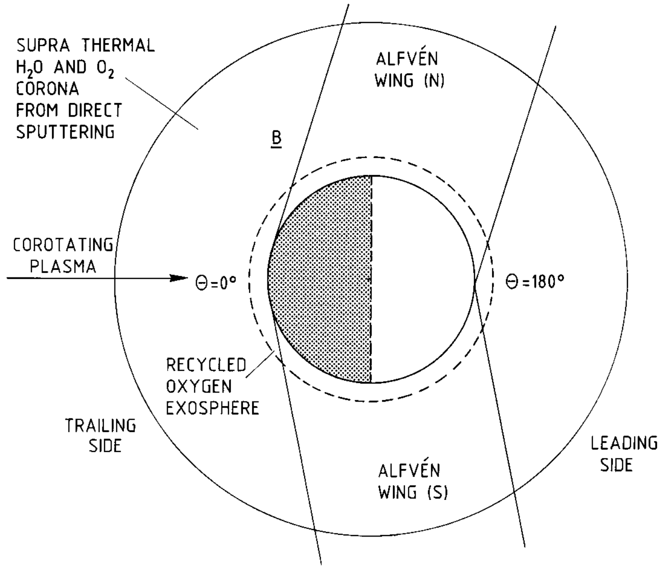

FIG. 1. A schematic view of the collisional impact of the corotating thermal ions with Europa which results in the formation of a two-component exospheric structure: (a) the extended corona from ballistic particles and (b) the thin layer of oxygen molecules after surface recycling. The Alfvén wings from magnetospheric interaction are also depicted.

The ejection yields of heavy (Ar or Ne) ion sputtering on water ice as functions of ion energy and ice temperature have been investigated by a number of research groups (see Bar-Nun *et al.* 1984, Brown *et al.* 1984, Reimann *et al.* 1984). The laboratory results of special interest to us here are (a) copious amounts of oxygen and hydrogen molecules could be ejected among the sputtered neutrals and (b) the sputter yields of H_2O and H remain nearly constant within the temperature range $T_{ice} \approx 54–140$ K while those of H_2 and O_2 increase with increasing values of the ice temperature. At $T_{ice} \approx 100$ K and $E_i \approx 1$ keV, the yield for H_2O is $Y_{H_2O} \approx 9$ and that for O_2 is $Y_{O_2} \approx 5$. Thus with a total cross section of $A \approx \alpha \cdot 7 \times 10^{16}$ cm^{-2}, where α is a parameter accounting for the magnetospheric interaction, and an ion flux of $f_i (= \langle n_i \rangle v_i) \sim 3.8 \times 10^8$ ions cm^{-2} ($\langle n_i \rangle \approx 40$ cm^{-3}), the production rates of H_2O and O_2 molecules are consequently

$$Q(H_2O) \approx \alpha A f_i Y(H_2O) \approx 2.8 \times 10^{26} \cdot \alpha \text{ molecules sec}^{-1} \quad (1)$$

and

$$Q(O_2) \sim \alpha A f_i Y(O_2) \approx 1.4 \times 10^{26} \cdot \alpha \text{ molecules sec}^{-1} \quad (2)$$

Note that in numerical simulations of the magnetospheric ion bombardment effects on planetary satellites, Pospieszalska and Johnson (1989) estimated that $\alpha \approx 1.2$ if there was no diversion of the plasma flow around Europa because of the finite gyroradius of the corotating thermal ions.

2.2. Suprathermal and Energetic Ions

Because of the gap in the energy coverages of the LECP and the PLS experiments on Voyager, no precise information was obtained on the suprathermal ions with energies between 6 and 20 keV in the inner jovian magnetosphere near Europa's orbit. From extrapolation of the LECP measurements, Smith *et al.* (1988) suggested that the ($E > 500$ keV) ion omnidirectional flux at $L \approx 8$ can be approximated to be $dj/dE = 5.8 \times 10^4[E(\text{keV})/1020]^{-1.8}$ cm^{-2} sec^{-1} keV$^{-1.}$

However, a smaller flux was given by Lanzerotti *et al.* (1982) with $dj/dE \sim 4 \times 10^3$ ions cm^{-2} sec^{-1} at particle energy $\approx$ 1 MeV; and in the same work the particle flux at $L \approx 9.5$ was estimated to be $dj/dE \approx 1.5 \times 10^3$ ions cm^{-2} sec^{-1} for the oxygen or sulfur ions (see Fig. 2). It is also likely that for $E < 1$ MeV the energy spectra will become harder such that the corresponding particle flux would be limited by a certain plateau. If so, this would mean a flux of heavy ions of $f(10\text{–}100 \text{ keV}) \approx 4 \times 10^6$ ions cm^{-2} sec^{-1} and a corresponding flux of sputtered O_2 molecules of $f(O_2) \approx Y(O_2) f(10\text{–}100 \text{ keV}) \approx 8 \times 10^7$ molecules cm^{-2} sec^{-1} (for $Y \approx 20$ and $\alpha \approx 4$). The total production rate due to suprathermal ion sputtering is thus $Q(O_2) \approx 2 \times 10^{25}$ molecules sec^{-1}. This value is only about 15% of the sputter production rate from the corotating plasma given in Eq. (2). This exercise suggests that the suprathermal ion population is not likely to be the dominant contributor to the oxygen atmosphere of Europa, taking into account the observational data available at the present time.

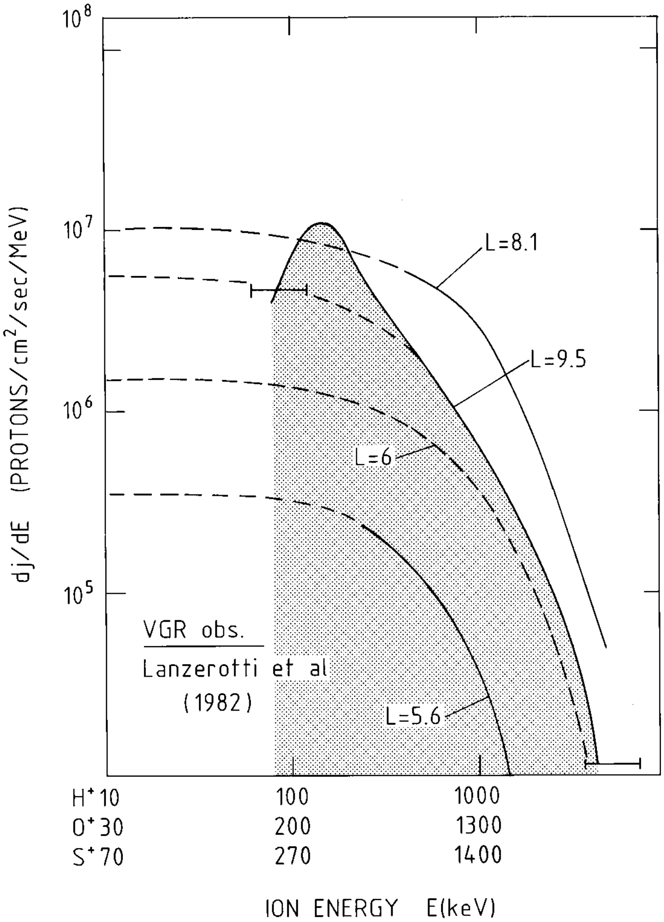

FIG. 2. A comparison of the ion energy spectra (thick lines) obtained by the LECP experiment on Voyager (Lanzerotti *et al.* 1982) and the extrapolated theoretical curves (dashed curves).

How about energetic ions? Cheng *et al.* (1986) estimated that if the composition of the MeV ions detected by the LECP instrument on Voyager were dominated by oxygen, the escape flux of the sputtered H_2O molecules at the surface of Europa would be as high as 2×10^9 cm^{-2} sec^{-1}. If protons were the major component, however, the H_2O escape rate would be only 5×10^6 cm^{-2} sec^{-1}.

The compositional determinations by Hamilton *et al.* (1981) found that at $L \approx 10$, the abundance ratios of different magnetospheric ions with $E \approx 0.6$–1.15 MeV/nucl. are [O]/[He] ≈ 0.3, [S]/[He] ≈ 0.1, and [H]/[He] ≈ 50, respectively. The recent Ulysses ion composition measurements in the energy range between 0.45 and 1.6 MeV/nucl. in the inner jovian magnetosphere showed that [O]/[He] and [S]/[He] are 0.03 and 0.01, respectively (Keppler *et al.* 1992). These observations have therefore indicated that the oxygen and sulfur ions are minor species in the jovian magnetosphere (with [O]/[H] $\approx 6 \times 10^{-3}$ and [S]/[H] $\approx 2 \times 10^{-3}$) even though their relative abundances are significantly higher than the values defined by the cosmic abundances ([O]/[H] $\approx 6.6 \times 10^{-4}$ and [S]/[H] $\approx 1.6 \times 10^{-5}$). From this point of view, the effective escape flux of H_2O molecules (or O_2) from Europa due to the sputtering effect of MeV heavy ions should be below 10^7 cm^{-2} sec^{-1} with a total production rate of $Q_{\text{MeV}} \approx 3 \times 10^{24}$ molecules sec^{-1}.

The above consideration of the sputtering production rates of H_2O and O_2 molecules from the surface of Europa by ions in different energy ranges leads us to the interesting conclusion that most of the neutral atmosphere must have been created by the surface bombardment effect of the corotating thermal plasma. It is, of course, possible that physical parameters such as the sputtering yields and the magnetospheric energetic ion fluxes could eventually be revised upward because of new laboratory studies and the pending *in situ* plasma observations of the Galileo mission. With this caveat in mind, we will proceed to construct a ''minimum'' model of Europa's exosphere using the surface sputtering mechanism by the corotating thermal ions as the main source and investigate the physical implications.

3. EXOSPHERIC MODELS

The H_2O and O_2 molecules emitted from the surface will escape into circumplanetary orbits around Jupiter if the initial ejection velocity (v_e) is larger than the surface escape velocity of $v_s (= 2.04 \text{ km sec}^{-1})$. On the other hand, they will execute ballistic motion if $v_e < v_s$. If the molecules on ballistic orbits are not ionized by electron collisional impact or solar UV radiation, they will return to the satellite and be absorbed at its surface. The vertical distribution of the sputtered molecules is critically dependent on their energy spectra at production. Published results from laboratory experiments can be found in Reimann *et al.* (1984) for water molecules from ion bombardments (e.g., 1.5 MeV He^+, 1.5 MeV Ar^+, and 50 keV Ar^+) of low temperature ice ($T_{\text{ice}} = 12$ K or 25 K). The energy spectrum for the 50 keV Ar^+ data can be well fitted by a collision cascade curve defined as (Johnson *et al.* 1983, Johnson *et al.* 1989)

$$Y(E) = \frac{2UE}{(E+U)^3}, \qquad (3)$$

with $U \approx 0.05$ eV. In calculations in the next section we will assume that this expression can be applied to H_2O and O_2 yields from keV-heavy ion sputtering at Europa.

Two potential limitations to the above energy spectrum must be mentioned. First, this expression is derived from laboratory data relevant to heavy sputtering ions of impact energies > a few tens of keV. Its extrapolation to the keV energy regime might not be strictly applicable. Experimental work on low-energy heavy ion sputtering effects is therefore very interesting from this point of view. Second, since the O_2 molecules are created by direct sputtering and thermal ejection from the icy surface after reabsorption, a low-velocity component must be included in the emitted particle population. Such a two-component exospheric structure has been discussed in the context of the lunar exosphere and the exospheric models of Mercury (see McGrath *et al.* 1986, Ip 1990). It turns out that this feature is also characteristic of Europa's oxygen exosphere (Johnson *et al.* 1982, 1983, Eviatar *et al.* 1985, Johnson 1990).

Europa's exosphere can thus be divided into two components: (a) the suprathermal population from direct ion bombardment and (b) the thermal population generated by the surface recycling of the sputtered neutrals at their reimpacts. The first exospheric component can be simulated by following the numerical procedure used in previous kinetic calculations (Ip 1995). The basic scheme is to launch test particles from Europa randomly according to the cosine law of surface emission. That is, on the trailing side with θ between 0° and 90° the particle emission rate is described by $F(\theta)\ \alpha \cos(\theta)$ while $F = 0$ on the leading side where the corotating thermal ions could not reach. At emission the initial velocities of the test particles are chosen according to the energy spectrum given in Eq. (3). Furthermore, the angular distribution of the velocity vectors is assumed to be isotropic. The trajectories of the emitted particles are followed at each time step so that their contributions to the density distribution can be binned in different grid points.

We limit our calculations to within six satellite radii (R_{E}) of Europe where the gravitational effect of Jupiter on the particle motion is still small . (The radius of the Hill sphere of Europa is 8.7 R_{E}.) Trajectory calculations for particles exiting this boundary will be terminated. The number of escaping particles accounts for about 13% of the total population emitted by direct sputtering. Because the outbound trajectories of the escaping particles are counted in our algorithm, the numerical error caused by the omission of the ''downward legs'' is therefore small.

In our calculations for the oxygen exosphere we have also included loss due to electron impact dissociation

$$O_2 + e \rightarrow O + O + e, \qquad (4)$$

and electron impact ionization

$$O_2 + e \rightarrow O_2^+ + 2e. \qquad (5)$$

Belcher (1983) reported that the electron distributions near Europa's orbit are characterized by a cold core component with a temperature of $T_{e,c} = 26$ eV and a hot component with $T_{e,h} = 1.2$ keV constituting about 10% of the total electron population. From Schreier *et al.* (1993), the electron impact rates (in units of $\text{cm}^3 \text{ sec}^{-1}$) for the two processes in Eq. (4) and (5) are $k_{4,c} = 2.45 \times 10^{-8}$, $k_{4,h} = 2.02 \times 10^{-7}$, $k_{5,c} = 2.0 \times 10^{-8}$, and $k_{5,h} = 1.6 \times 10^{-7}$, respectively. To estimate the loss time scale of the O_2 molecules, we must take into consideration the excursion of Europa above and below the centrifugal plane of the jovian plasmasphere. This means that the average value of the electron number density $\langle n_e \rangle$ would be on the order of 60 cm^{-3}. The corresponding electron impact ionization time scale hence would be $t_i(O_2) \approx 6.7 \times 10^5$ sec and the electron impact dissociation time scale would be $t_d(O_2) \approx 8.6 \times 10^5$ sec. Collisional interaction between the O_2 molecules and O^+ ions could lead to charge exchange loss, but with a rate coefficient of 1.9×10^{-11} cm^3

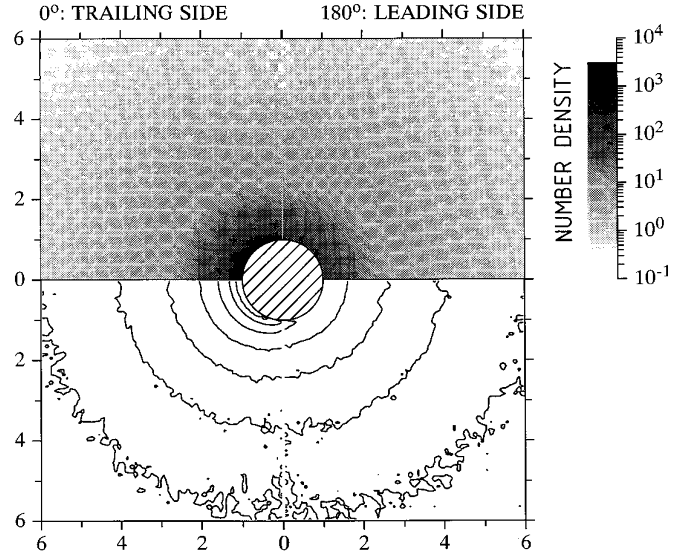

FIG. 3. The density variation of the oxygen corona computed by assuming a cosine emission law and an isotropic ejection velocity distribution. The source strength of the oxygen molecules is assumed to be $Q(O_2) = 10^{26}$ sec^{-1}.

sec^{-1} (Schreier *et al.* 1993) and $n(O^+) \approx 40$ cm^{-3} the corresponding loss time scale is as large as 1.3×10^9 sec. The effective loss time scale can hence be approximated as $t_e(O_2) = (1/t_i(O_2) + 1/t_d(O_2))^{-1} \approx 3.8 \times 10^5$ sec. In spite of this relatively short electron loss time, the O_2 molecules in ballistic orbits would suffer no more than a 5% reduction of number density.

The above considerations permit the step-by-step construction of an axially symmetric model for the suprathermal oxygen exosphere assuming a source strength of $Q(O_2) \approx 1.0 \times 10^{26}$ sec^{-1}. As shown in Fig. 3, the maximum number density at the pole of the trailing hemisphere ($\theta = 0$) is $n(O_2) \approx 3 \times 10^3$ cm^{-3}. The number density decreases to a value of about 100 cm^{-3} at a vertical height $\approx 1\ R_E$. Because of the assumption of a cosine emission law, a strong asymmetry in the number density exists near the satellite surface. The maximum value of the integrated column density is $N_{max}(O_2) \approx n_{max}(O_2)(2\pi H R_E)^{0.5}$; we have therefore $N_{max}(O_2) \approx 5 \times 10^{11}$ cm^{-2} with $H \approx 300$ km. In comparison, Hall *et al.* (1995) derived a value of $1.5 \pm 0.5 \times 10^{15}$ cm^{-2} for the detected oxygen atmosphere. This means that the UV emissions of OI must have come from a different source, namely, the thermal component of the oxygen exosphere. The question is then whether there are enough oxygen molecules in this component.

4. THE RESPUTTERING MECHANISM

In order to estimate the content of the recycled population of the O_2 molecules we must make two other assumptions (see Eviatar *et al.* 1985). The first is that O_2 molecules will not recondense when they hit the satellite surface. The H_2O molecules probably will be trapped and bound to the surface ice. The second is that the O_2 molecules will be thermally coupled to the surface temperature so that they will be reemitted into ballistic motion across Europa's surface with thermal velocity determined by the local value of T_{ice}. As a first approximation, the surface of Europa is assumed to be isothermal with $T_{ice} \sim 100$ K. The equivalent scale height is hence $h \approx 20$ km. Under the steady state condition, the loss of the atmosphere due to electron impact ionization and dissociation must be balanced by the influx of the recycled O_2 molecules. The average oxygen number density can be written as:

$$\langle n'(O_2)\rangle \approx 2.7 \times 10^7 \left(\frac{\alpha \cdot \gamma}{0.5}\right)\left(\frac{Q(O_2)}{10^{26}\ \text{sec}^{-1}}\right) \cdot \left(\frac{t_e}{3.8 \times 10^5\ \text{sec}}\right) \cdot \left(\frac{20\ \text{km}}{h}\right)\ \text{cm}^{-3}. \quad (6)$$

In the above equation, γ is the numerical factor accounting for the electron impact (ionization and dissociation) loss of the suprathermal corona ($\gamma = 1 \rightarrow$ no loss). As will be discussed below, because of the modification of the convection electric field in the vicinity of Europa, the corotating plasma flow would be partially diverted around it leading to $\alpha \approx 0.9$. We have assigned the product of α and γ to be ≈ 0.5 in Eq. (6).

While the number density of oxygen molecules given above is comparable to the value obtained by Eviatar *et al.* (1985), it is a factor of 10 too small to explain the HST observations. The scenario we would like to explore is related to the resputtering of Europa's surface by the new O_2^+ ions created in its thin exosphere. Because of the small scale height ($h \approx 20$ km), most of the O_2^+ ions produced on the trailing side will be able to hit the solid surface again. Such a recapture effect will imply a reduction of the electron impact ionization loss. (In fact, a fraction of the dissociated oxygen atoms could also be returned to Europa's surface.) Assuming that 50% of the oxygen ions created on the trailing side will be recycled, we have $t''_e(O_2) = (0.5/t_i(O_2) + 1/t_d(O_2))^{-1} \approx 5.2 \times 10^5$ sec.

Another important byproduct of this recycling process is that some of these reimpacting O_2^+ ions will be accelerated to keV energies by the convection electric field, so that they will sputter additional O_2 molecules from Europa's surface. If the production rate of this secondary generation of sputtered molecules can be approximated as $\varepsilon Y(O_2) \cdot (\alpha Q)$ where ε is the fraction of returned O_2^+ ions at keV energies, the effective value of the average oxygen number density can be expressed as

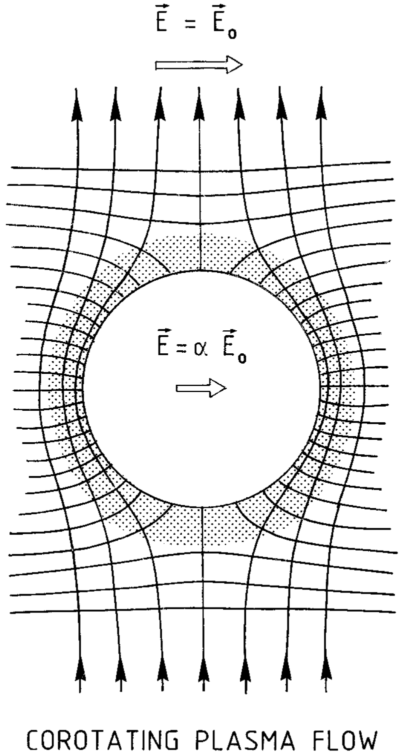

FIG. 4. A schematic view of the flow pattern of the corotating plasma around Europa. The thermal component of the oxygen exosphere (not to scale) is represented by the shaded region. The new oxygen molecular ions created in the ram direction of the exosphere will be accelerated to a range of velocities at surface reimpact.

$$\langle n''(O_2)\rangle \approx 4.2\times 10^7\left(\frac{\alpha\gamma}{0.5}\right)\cdot\left(\frac{Q}{10^{26}\,\mathrm{sec}^{-1}}\right)\cdot\left(\frac{1}{1-\varepsilon Y(O_2)}\right)\cdot\left(\frac{t''_e}{5.2\times 10^5}\right)\left(\frac{20\,\mathrm{km}}{h}\right)\mathrm{cm}^{-3}. \tag{7}$$

Thus $\langle n''\rangle \approx 3.8\times 10^8\ \mathrm{cm}^{-3}$ if $\varepsilon Y \approx 0.9$ or $\varepsilon \approx 0.2$, in case the observed oxygen atmosphere is to be maintained by the resputtering effect. It should be mentioned here that a similar resputtering process was first discussed by Matson *et al.* (1974) in the context of the emission of neutral sodium atoms from Io [see also Sieveka and Johnson (1985)].

In order to test this hypothesis, we have constructed a simple Monte Carlo model to simulate the reimpact effect of the exospheric O_2^+ ions. The starting point of the calculation is to apply the two-dimensional MHD model developed for Io's electrodynamical interaction by Schulz and Eviatar (1977), Neubauer (1980), and Ip (1982) to the Europa problem. As illustrated in Fig. 4, if the ionosphere of Europa is partially conducting the local electric field distribution will be modified and the corotating plasma flow would be diverted around it. Inside the current-carrying flux tube of radius R_c, the components of the flow velocity can be written as

$$V_x = 0$$
$$V_y = \alpha V_o \text{ for } r < R_c \tag{8}$$

and the external flow field is described by

$$V_x = -2(1-\alpha)V_o(R_c/r)^2 xy/r^2$$
$$V_y = V_o + (1-\alpha)V_o(R_c/r)^2(1-2y^2/r^2) \text{ for } r > R_c. \tag{9}$$

In the above equations, α is the interaction parameter (i.e., no MHD interaction if $\alpha = 1$), V_o is the upstream value of the corotating flow speed relative to the satellite, and R_c is assumed to be the radius of Europa (R_E). The above approximation shows that the flow velocity of the corotating plasma will be reduced to $V = \alpha V_o$ inside the Europa flux tube while the flow velocity is increased to $(1+\alpha)V_o$ near the two flanks where the streamlines of the plasma flow are nearly tangential to the flux tube.

The electric field components can be derived by using the relation that $\mathbf{E} = -\mathbf{V}\times\mathbf{B}_o/c$ where $\mathbf{B}_o$($\approx$400 nT) is the ambient magnetic field near Europa. The motion of a newly created exospheric ion under the effect of the Lorentz force is determined by the equation of motion,

$$m\frac{d\mathbf{u}}{\mathrm{dt}} = e\left(\mathbf{E} + \frac{\mathbf{u}\times\mathbf{B}_o}{\mathbf{c}}\right). \tag{10}$$

In the reference frame of Europa, the new ion will basically perform a cycloidal motion starting with $u = 0$ at the beginning and then, at half of the gyroperiod, reaching a maximum relative value of about 2 times the local corotational speed. The ion speed will subsequently decrease to zero in the next half-gyration. The effective impact velocity of the O_2^+ ion at surface collision thus depends on the phase of its orbital motion and the local electric field.

In the next step we make use of a spherically symmetric model of the oxygen exosphere characterized by a scale height of $h = 20$ km. New O_2^+ ions are injected randomly on the hemisphere in the ram direction of the corotating plasma flow according to the exponential distribution law given by $n(O_2) = n_o\exp(-z/H)$. The relative velocities (u_i) of the ions at surface impact are registered. The cumulative velocity distribution for the impact velocity larger than a certain value ($<u_i$) can be obtained from the statistical

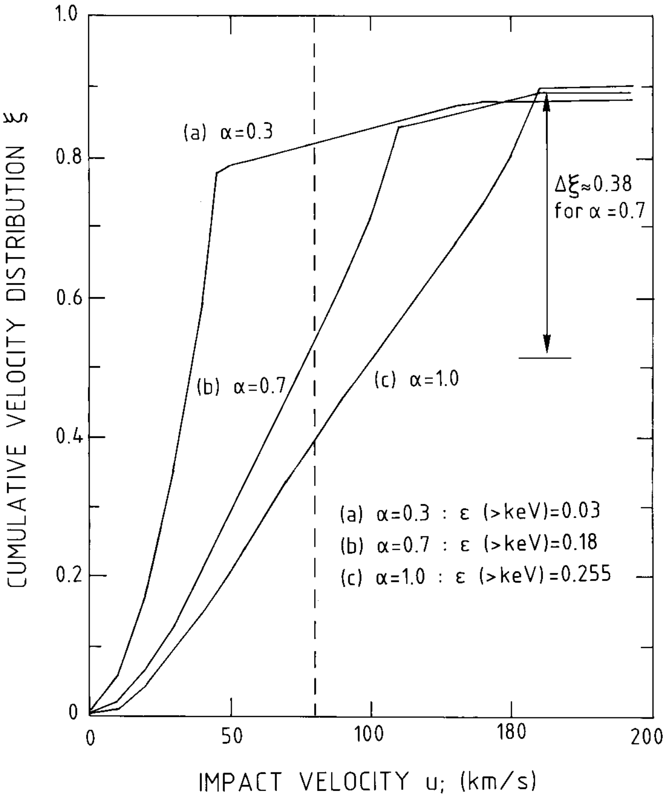

FIG. 5. The cumulative velocity distribution functions (ξ) for different values of α: (a) $\alpha = 0.3$; (b) $\alpha = 0.7$, and (c) $\alpha = 1$ (no flow diversion). The discontinuities in cases (a) and (b) are due to the slowdown of the corotating plasma flow inside the Europa flux tube region. The proportion of recycled ions with $u_i > 80$ km/sec for $\alpha = 0.7$ is indicated by the vertical bar ($\Delta\xi$). The fraction of returned O_2^+ ions at keV energy can be given to be $\varepsilon = 0.5\ \Delta\xi$ to account for the total ion population created in both hemispheres.

results (see Fig. 5). We find that about 90% of the new ions injected in the ram hemisphere will be recycled back to the satellite surface because the scale height (H) is considerably smaller than the ion gyroradius ($\approx$100 km). Of the injected ions, 40% of them will have $u_i < V_o$ (or impact energy < 1 keV) for $\alpha = 1$, 50% for $\alpha = 0.7$, and 75% for $\alpha = 0.3$, according to our trajectory calculations.

If we omit the contribution of the recycled particles created on the opposite hemisphere, the corresponding value of ε for O_2^+ ions impacting the satellite surface with $u_i > 80$ km sec^{-1}, or kinetic energy >1 keV, can be estimated to be $\varepsilon \approx 0.25$ for $\alpha = 1$, $\varepsilon \approx 0.19$ for $\alpha = 0.7$, and $\varepsilon \approx 0.03$ for $\alpha = 0.3$, respectively. As will be discussed in the next section, the electrodynamic interaction of Europa with the jovian magnetosphere might be characterized by $\alpha \approx 0.8$; the assumption of $\varepsilon \approx 0.2$ in Eq.(7) is therefore valid.

5. MAGNETOSPHERIC INTERACTION

Even though the surface number density of Europa's exosphere and the "outgassing" rate are both approximately two orders of magnitude lower than the corresponding values at Io, Europe may still have a very interesting plasma interaction with the jovian magnetosphere. As in the case of Io, a unipolar dynamo mechanism could take place if Europa's atmosphere is partially conducting (see Fig. 6). This conductivity could be achieved by invoking the pickup current in the ionization region of the atmosphere. At creation the new ions will perform cycloidal motion in the local plasma flow with gyration velocity (v_g) similar to the flow velocity. On the other hand, because of the small values of the gyroradii the new electrons will be tied to the magnetic field lines where they are created. Such differential motion thus constitutes a pickup current flow given as

$$j_p \approx \dot{n}_i e R_g, \tag{11}$$

where $\dot{n}_i$ is the production rate of the pickup ions near Europa and e is the electronic charge (Ip and Axford 1980, Goertz 1980). The total current can be estimated by integrating j_p over the volume where electron impact ionization is significant; hence

$$I_p \approx Q_i e R_g / 2R_{\mathrm{E}}. \tag{12}$$

With $R_g \approx 100$ km, $R_{\mathrm{E}} \approx 1560$ km, and $Q_i \approx (1\text{–}3) \times 10^{26}$ O_2^+ sec^{-1}, we have $I_p \approx 0.5 - 1.5 \times 10^6$ A. This current flow will be channeled to the jovian ionosphere by a pair of field-aligned currents as observed at Io by Voyager 1 (Ness *et al.* 1979). The total pickup current at Europa is not much smaller than the Io current of 3×10^6 A; it will likely produce certain modifications to the electric field distribution and the flow pattern around Europa. In a sim-

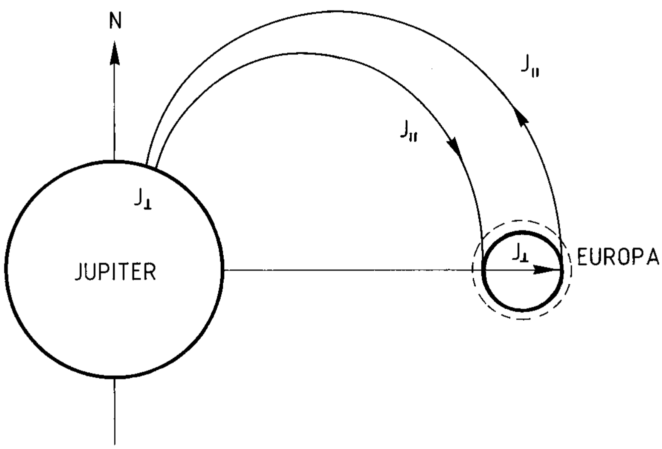

FIG. 6. A sketch of the possible existence of a field-aligned current system driven by the mass-loading of new pickup ions in the vicinity of Europa. The fraction of returned O_2^+ ions at keV energy can be given to be $\varepsilon = 0.5\ \Delta\xi$ to account for the total ion population created in both hemispheres.

plified treatment of the electric field distribution around Io, Goertz (1980) showed that the reduction factor for the plasma flow absorption cross section can be approximated as

$$\alpha = \frac{2}{2 + (3h/V_A \tau_p)}, \tag{13}$$

where h is the atmospheric scale height, V_A is the Alfven speed, and $\tau_p = n_i/\dot{n}_i$. With $h \approx 20$ km, $V_A \approx 4 \times 10^2$ km sec^{-1}, $\dot{n}_i \approx 500$ cm^{-3} sec^{-1}, and the ionospheric electron number density $n_i \approx 100$–200 cm^{-3}, we find $\alpha \approx 0.8$. In other words, the influx of the corotating thermal ions will be reduced by about 20% as Europa sweeps past the magnetospheric plasma. In comparison, the corresponding α value for Io was estimated to be ≈ 0.5. The magnetospheric interaction of Europa is characterized by an Alfvenic Mach number $M_A \approx 0.2$ and a sonic Mach number $M_s \approx 2.7$. We therefore expect that the magnetometer experiment onboard Galileo spacecraft will detect the signatures of the formation of a pair of Alfven wings in the wake of Europa. An ion tail composed of new exospheric molecular ions (H_2O^+, O_2^+, OH^+, . . .) with a number density of 20–40 cm^{-3} (or more) should be observed as well.

6. DISCUSSION

Taking advantage of the experimental data on the heavy ion sputtering of water ice, we are able to develop a simple exospheric model of Europa involving two main components: (a) an extended corona of direct sputtering neutrals, and (b) a thermal population from the recycled oxygen molecules with a scale height of about 20 km. Our calculations show that the thermal portion of the oxygen exosphere could account for the HST observations by Hall *et al.* (1995). While the detailed structure of the tenuous corona with a size of a few R_E depends on the energy spectrum of the sputtered O_2 molecules extrapolated from Reimann *et al.* (1984), the formation of the near-surface layer of oxygen gas with an average number density of 10^8–10^9 cm^{-3} should be less dependent on this assumption. One crucial step, however, is in the surface recycling process. It would be very useful if more laboratory measurements could be performed to study not just the energetic ion sputtering effects but also the ensuing gas–surface grain interactions because of their important implications on planetary magnetospheres and interstellar chemistry.

Another key element concerns the resputtering process of the new exospheric ions. Our simplified model calculations show that the resputtering rate is indeed what is required (e.g., $\xi \approx 0.2$ with $\alpha \approx 0.8$). It is noteworthy that such a resputtering mechanism should probably be self-limiting in nature. After an exosphere reaches a column number density of a few times 10^{15} cm^{-2} it will shield the new exospheric ions—via collisional thermalization from reaching the satellite surface directly. The possible inference will be examined in the case of the magnetospheric process of other planetary satellites such as Io. The relative importance of the resputtering effect will be tested by the Galileo measurements of the fluxes of the keV heavy ions in the vicinity of Europa's orbit.

In the present "minimal" approach we have established that the oxygen exosphere detected by HST could be maintained by the sputtering effect of the corotating thermal ions alone. The possibility that the suprathermal and energetic ion populations do contribute significantly cannot be ruled out. The *in situ* plasma measurements by the Galileo Orbiter will undoubtedly shed new light on this interesting issue.

Finally, a somewhat surprising result of the present study is the prediction that Europa could have a relatively strong magnetospheric interaction and the associated pickup current flow can be estimated to be on the order of 5×10^5 A. It is indeed fortunate that the Galileo spacecraft will be able to investigate, almost immediately, these interesting new phenomena in detail—after a pause of more than twenty years since the Pioneer 10 Jupiter encounter.

ACKNOWLEDGMENT

I thank A. Eviatar for useful discussions, and the reviewers, R. E. Johnson and J. D. Richardson, for constructive comments and useful suggestions.

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