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NEAR-SURFACE OXYGEN ATMOSPHERE AT EUROPA

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ABSTRACT

The bombardment of the surface of Europa by charged particles trapped in the jovian magnetosphere causes sputtering and decomposition of surface materials leading to the production of a tenuous O_2 atmosphere. In this paper we use a direct Monte Carlo simulation of the atmosphere and we account for adsorption, thermalization and re-emission of condensed O_2, dissociation and ionization by magnetospheric electron and photon impact, and collisional ejection by the low energy plasma in the magnetosphere. Since the ion flux to the surface and the O_2 production are not well constrained, we treat the surface source as a variable parameter. To account for the production of atomic O seen by HST (Hall et al., 1995, 1998), we find that larger surface fluxes are required than those predicted (Cooper et al., 2001). This is due primarily to the inclusion of photo-dissociation which leads to loss. The variation of atmospheric O_2 and O from near equilibrium near the surface to highly non-equilibrium is shown and is poorly approximated by the escape atmosphere assumed by Saur et al. (1998).

INTRODUCTION

The very tenuous atmosphere of Europa is a near-surface (boundary layer) atmosphere produced by the radiolysis of Europa's surface due to exposure to energetic magnetospheric ions. This atmosphere was predicted based on laboratory measurements which showed that ice decomposed efficiently under energetic ion bombardment (Johnson et al., 1982, Johnson, 1990). Quite remarkably, it was observed recently using HST (Hall et al., 1995, 1998), and the ionosphere was observed by Galileo (Kliore et al., 1997). Being able to model the HST observations in principal allows the unique and exciting possibility of being able to determine the rate at which radiolysis occurs on an outer solar system body. This is important as radiolysis is a dominant surface alteration process on outer solar system bodies including those in the Kuiper belt and the Oort cloud. Having an accurate model can also be helpful for predictions, since Europa's atmosphere is expected to contain other interesting, possibly organic, molecules sputtered from the surface (Johnson et al., 1998).

The plasma interaction with the surface is the principal source of O_2, and the plasma interaction with the atmosphere is a principal loss process, and therefore a large atmosphere does not accumulate (Johnson et al., 1982). Ip (1996) modeled the atmosphere using the sputtering rates estimated by Shi et al.(1995) and a simple model for the plasma interaction. More recently, Saur et al. (1998) carried out a detailed description of the plasma interaction with the ionosphere to account for the change in energy and deflection of the flowing plasma. They used this along with a range of surface sputter-sources and a very simple escape atmosphere in order to determine the column density and source rate implied by the HST observations of excited atomic O and the data on the electron densities in the ionosphere. In all of the models the atmosphere was assumed to be global, and that will be the case here also. Therefore, we use a 1-D Direct Simulation Monte Carlo (DSMC) method to model atmospheric thermal structure and the production rate of atomic O when the surface source is purely O_2 due to radiolytic decomposition of ice.

PHYSICAL MODEL

An O_2 surface source rate is chosen based on the sputtering data and the ion flux (Shi et al., 1995; Ip et al., 1998, Cooper et al., 2001), but since the actual ion flux to the surface and the surface composition are not well known, and because there can be a contribution from photolysis (Westley et al., 1995), we vary the surface source rate over a range of reasonable values. The O_2 are ejected from the surface according to a measured energy distribution (Johnson et al., 1983):

$$F_{O2}^{surface}(E) \sim \frac{U}{(E+U)^2}, U = 0.015eV, \tag{1}$$

for which direct escape is small. Therefore, most of the O_2 returns to the surface and is immediately (on the time scale of the simulation) desorbed thermally. Therefore, the source has a non-thermal (Johnson et al., 1983) and, ignoring reactions with the surface, a thermalized component of O_2 (Johnson et al., 1982) A mean surface temperature of 100K is used. In addition, the O_2 may be dissociated or ionized by the UV photons and the plasma electrons:

$$O_2 + h\nu, e_p \to O(^3P) + O(^3P,^1D,^1S) + e_s + \Delta E_{ds} \tag{2}$$

$$O_2 + h\nu, e_p \to O(^3P,^1D,^1S) + O^+(^4S) + e + e_s + \Delta E_{di} \tag{3}$$

$$O_2 + h\nu, e_p \to O_2^+ + e + e_s. \tag{4}$$

The dissociation and ionization processes lead to the formation of O atoms with excess kinetic energy up to a few eV. Scaled to the jovian orbit, the EUVAC solar flux model (Richards et al., 1994) and the standard set of photoabsorption and electron impact cross sections were used. Because the atmosphere is thin the calculated photo-ionization and dissociation frequencies are found to be practically constant with height. Although Saur et al. (1998) showed that the electron density and temperature changed due to the interaction of the plasma with the ionosphere, the net energy flux through the atmosphere does not change enormously. Therefore, here we treat it as a constant and use the rates associated with the plasma upstream for comparison to the photo-processes. Any O produced by dissociation is tracked and either escapes or at the surface forms O_2 since three body effects in the atmosphere are negligible. The ions formed are assumed to be lost immediately by sweeping.

Finally, we use the data of Bagenal (1994) to estimate the plasma bombardment rate. Whereas the energetic ions (measured by the Galileo EPD; e.g., Cooper et al., 2001) for the most part pass through this thin atmosphere without collisions, the low energy plasma does not. Therefore, it can sputter the atmosphere (Johnson, 1990, 1994) through the momentum transfer, dissociation, ionization, and charge transfer processes:

$$O_2 + p, O^+, S^+, ... \to \begin{cases} p, O^+, S^+, ... + O_2^* \to O + O^* + \Delta E_{dis} \\ p, O^+, S^+, ... + O_2^+ + e \\ H, O, S, ... + O_2^+ \end{cases} \tag{5}$$

Momentum transfer and dissociation collisions with high-energy magnetospheric ions lead to the kinetic energy transfer to O_2 gas and formation of fresh suprathermal O atoms. This energy input to Europa's atmosphere causes additional atmospheric loss. Saur et al. (1998), using a simplified estimate, suggested that this was the dominant loss process. We used two sets of plasma parameters for the convected Maxwellian, the lower of which is close to the Bagenal (1994) data (nominal model of O^+ ion flux - characteristic ion energy E_0=0.75 keV, mean ion energy 1.5 keV, and flux $1.\times10^8$ ions/cm^{2}s) and the higher is a factor ~ 2 hotter as a sensitivity test. However, this is the regime for which the collisional energy loss cross section is relatively flat and the results are comparable with the lower energy plasma producing somewhat larger deflections. In these calculations we use the new collisional momentum transfer and collisional dissociation cross sections from Johnson et al. (2001). A molecular dynamics code was used along with semi-empirical pair potentials to determine the transfer of energy to the motion of the center of mass in O + O_2 and O_2+ O_2 collisions. In determined as well as the probability of dissociation. These were used to calculate the exit speeds of the molecule or its fragments after a collision.

NUMERICAL MODEL

The gas flow in the atmospheric near-surface boundary layer of Europa is strongly non-equilibrium because of the surface-sputtering induced ejection of O_2 molecules and the formation of suprathermal O atoms due to external influences - the solar UV radiation, and the influx of the magnetospheric electrons and high-energy ions. It can be strictly described by a set of kinetic Boltzmann equations for oxygen ions, atoms and molecules:

$$\mathbf{v}\frac{\partial}{\partial \mathbf{r}}f_O + \mathbf{g}\frac{\partial}{\partial \mathbf{v}}f_O = Q_O^{hot} + L_O^{photo} + \sum_{j=O,O_2,O^+}\sum_{\alpha} J_\alpha(f_O, f_j) \tag{6}$$

$$\mathbf{v}\frac{\partial}{\partial \mathbf{r}}f_{O_2} + \mathbf{g}\frac{\partial}{\partial \mathbf{v}}f_{O_2} = L_{O_2}^{photo} + \sum_{j=O,O_2,O^+}\sum_{\alpha} J_\alpha(f_{O_2}, f_j) \tag{7}$$

$$\mathbf{v}\frac{\partial}{\partial \mathbf{r}}f_{O^+} + \mathbf{g}\frac{\partial}{\partial \mathbf{v}}f_{O^+} = \sum_{j=O,O_2,O^+}\sum_{\alpha} J_\alpha(f_{O^+}, f_j) \tag{8}$$

Here the $f_j(\mathbf{r},\mathbf{v})$ is a distribution function for j-species particles by translational and internal degrees of freedom; $\mathbf{g}$ - is a unit-mass gravitational force for Europa; Q^{hot} and L^{photo} are source and loss functions for O and O_2 in the photolytic and electron impact processes; and J_α are the collision terms for elastic, inelastic, dissociation, ionization, and charge transfer collisions (Marov et al., 1997). The O_2 source term due to the surface sputtering is taken into account through the surface boundary condition.

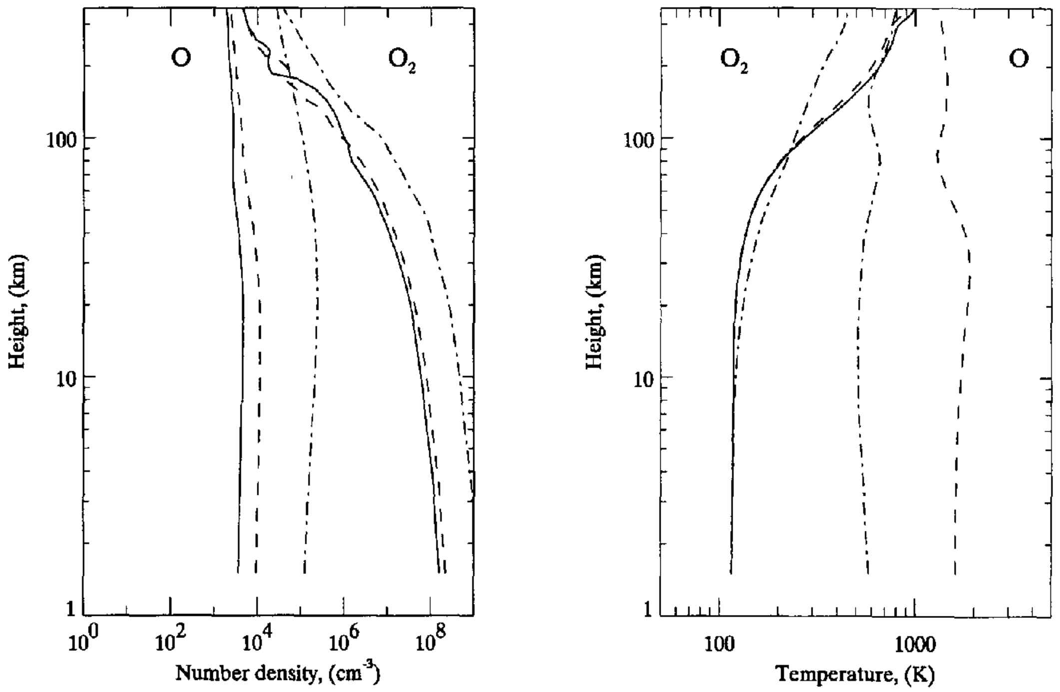

Fig. 1. Density (left panel) and temperature (right panel) profiles for atomic and molecular oxygen in the near-surface atmosphere at Europa. Solid lines are for nominal model with O_2 surface flux $F_{O_2}=2.\times10^9$ $cm^{-2}s^{-1}$ and characteristic energy of soft magnetospheric O^+ ions $E_0=0.75$ keV; dashed - same but $E_0=1.5$ keV; dash-dotted - same but $F_{O_2}=2.\times10^{10}$ $cm^{-2}s^{-1}$.

This system of kinetic Boltzmann equations is non-linear and is solved using the DSMC model (Bird, 1994). This approach has been used by us before to describe the hot oxygen geocorona and hot hydrogen corona at Jupiter (Marov et al., 1997). Representative modeling atoms and molecules ejected from the surface or formed in the atmosphere are tracked between collisions, and a stochastic scheme is used to choose the position, type and outcome of the next collision. At the top of the atmosphere, well above the exobase, those atoms or molecules with suffficent energy to escape are removed and the others are reflected. With this numerical model we obtain the velocity distribution functions of the atomic and molecular oxygen, and consequently, the atmospheric density, temperature, and escape flux versus altitude.

RESULTS

In Figure 1 we plot the O_2 and O density and T versus altitude for surface source rates $F_{O_2}=2.\times10^9 - 2.\times10^{10}$ $cm^{-2}s^{-1}$ and for two plasma temperatures, 0.75 keV and 1.5 keV. It is seen that O_2 gas flow in the near-surface layer strongly depends on the O_2 surface flux induced by the surface sputtering by the high-energy magnetospheric ions.

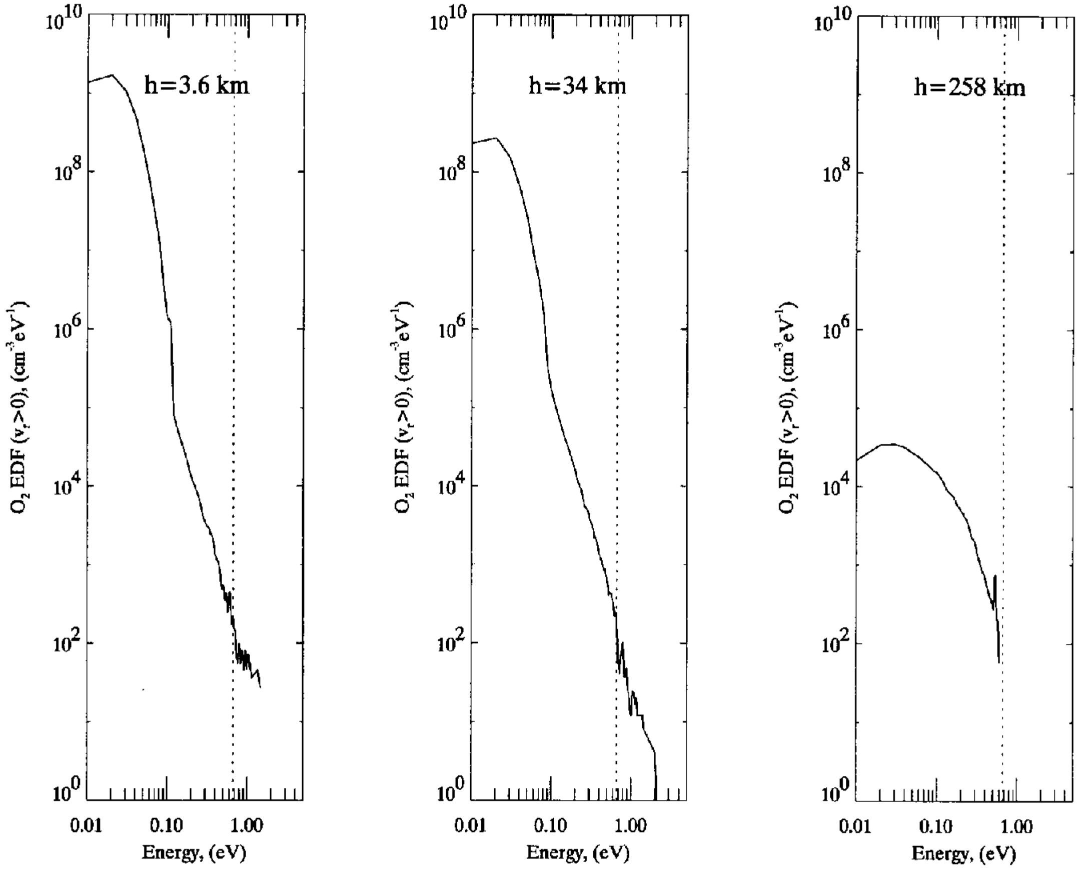

Fig. 2. Distribution functions of upward moving oxygen molecules by kinetic energy at different heights (indicated in panels) for nominal model. Vertical dotted line indicates the escape energy (0.67 eV) for O_2 in Europa's atmosphere.

The atmospheric gas state is characterized by a distribution function of O_2 molecules by kinetic energy. The calculated energy distribution functions of upward moving O_2 molecules are shown in Figure 2 for the three different heights. It is seen that at lower altitudes gas state is determined by the thermal part of O_2 molecules' surface source (e.g., by molecules accommodated to the surface temperature 100 K) and energy distribution function has a Maxwellian core. Higher altitudes are populated by the suprathermal oxygen molecules formed due to the non-thermal part of the surface source, and by collisions with suprathermal atomic oxygen. It is worthwhile to note that at all heights there is a significant population of O_2 molecules with suprathermal energies, e.g., the suprathermal tails in the energy distribution functions are formed.

Atmospheric sputtering by the magnetospheric ions with energies less than 10 keV, and photolytic and electron impact dissociation, lead to the loss of O_2 molecules and to the formation of atomic oxygen with the suprathermal kinetic energies. It is seen that for the higher surface source ($2.\times10^{10}$ $cm^{-2}s^{-1}$) there is a stronger collisional relaxation of hot O, but the thermalization rate is limited by the escape of hot O and

O_2 into the jovian system. Results are not very different for the two plasma temperatures used.

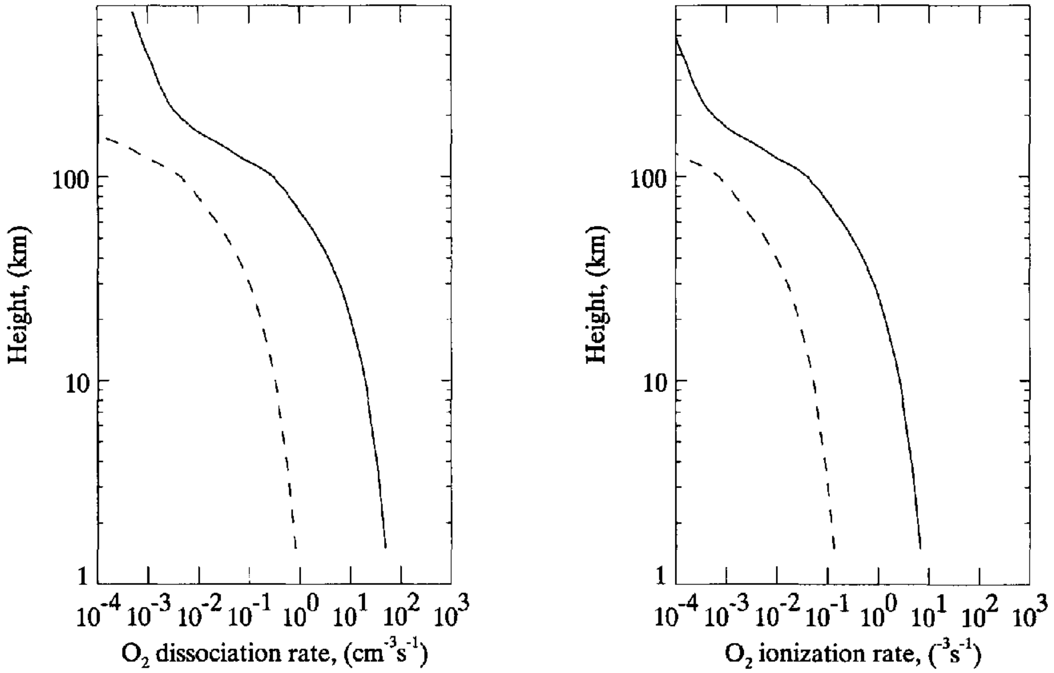

Fig. 3. Kinetic rates of the O_2 dissociation (left panel) and ionization (right panel) by solar UV-radiation (solid lines) and by photo- and magnetospheric electrons (dash lines) for the nominal model.

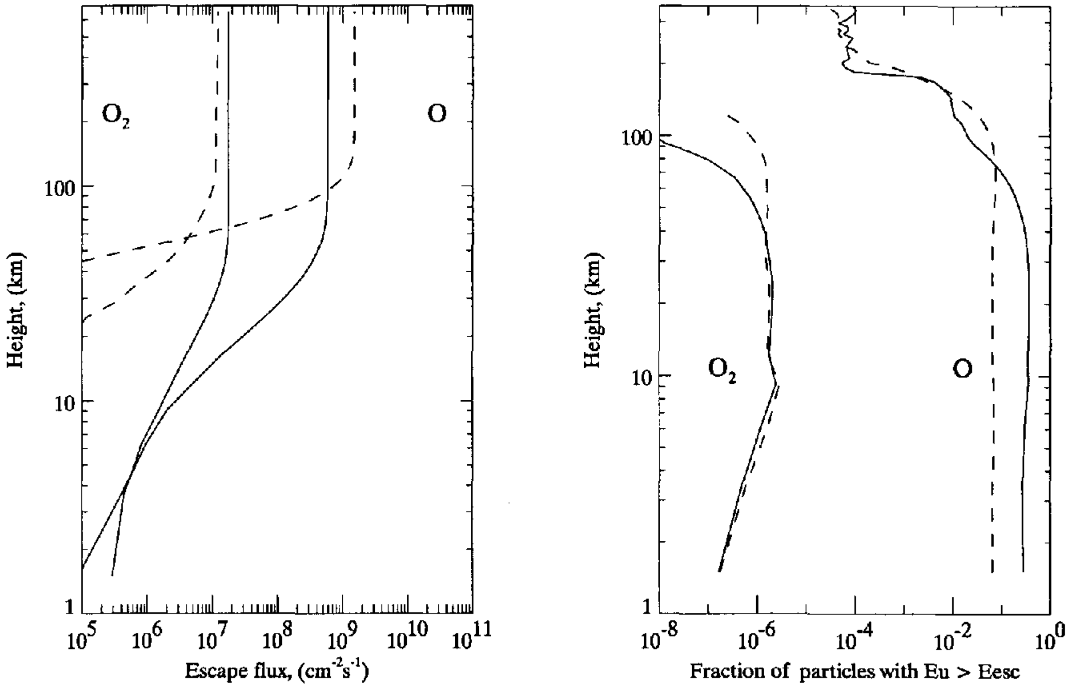

Fig. 4. Escape flux (left panel) and escape fraction (right panel) profiles for atomic and molecular oxygen in the near-surface atmosphere at Europa. Solid lines are for nominal model; dashed - same but O_2 surface flux is 10 times higher.

Finally, we found that photo-dissociation, ignored by Saur et al. (1998), provides an important source of hot atomic oxygen (dissociation rates are shown in the left panel of Figure 3). Because O atoms produced in photo-dissociation can escape, the source and loss rates differ from those estimated by Saur et al. (1998). Moreover, O_2 ionization by both solar UV-photons and high-energy electrons (ionization rates are given in the right panel of Figure 3) lead to the oxygen loss through the sweeping of these ions by the jovian magnetic field or their dissociative recombination.

In Figure 4 the escape characteristics are shown. The escape fraction (ratio of upward moving particles with kinetic energy higher than escape energy to total number of upward moving particles) shows that collisions between O_2 and suprathermal O are mostly important at altitudes below 100 km (this altitude can be considered as an exobase height for Europa's O_2 atmosphere). Moreover, the momentum transfer collisions of magnetospheric oxygen ions with O_2 also are an additional source of formation of escaping molecules. Behavior of the total O_2 and O escape fluxes versus altitude (left panel of Figure 3) show that atmosphere is lost via both suprathermal fractions of molecular and atomic oxygen.

Interpreting the O_2 surface source as a free parameter and changing it in the range (2. - 200.)$\times 10^9$ cm^{-2}s^{-1}, it is possible to estimate the column densities of atomic and molecular oxygen and the total escape losses in Europa's atmosphere. These values are presented in Figure 5. It is seen that the O_2 column densities inferred from the HST observations (Hall et al., 1995, 1998) correspond to surface fluxes 1. - 2.$\times 10^{10}$ cm^{-2}s^{-1} (see left panel of Figure 5).

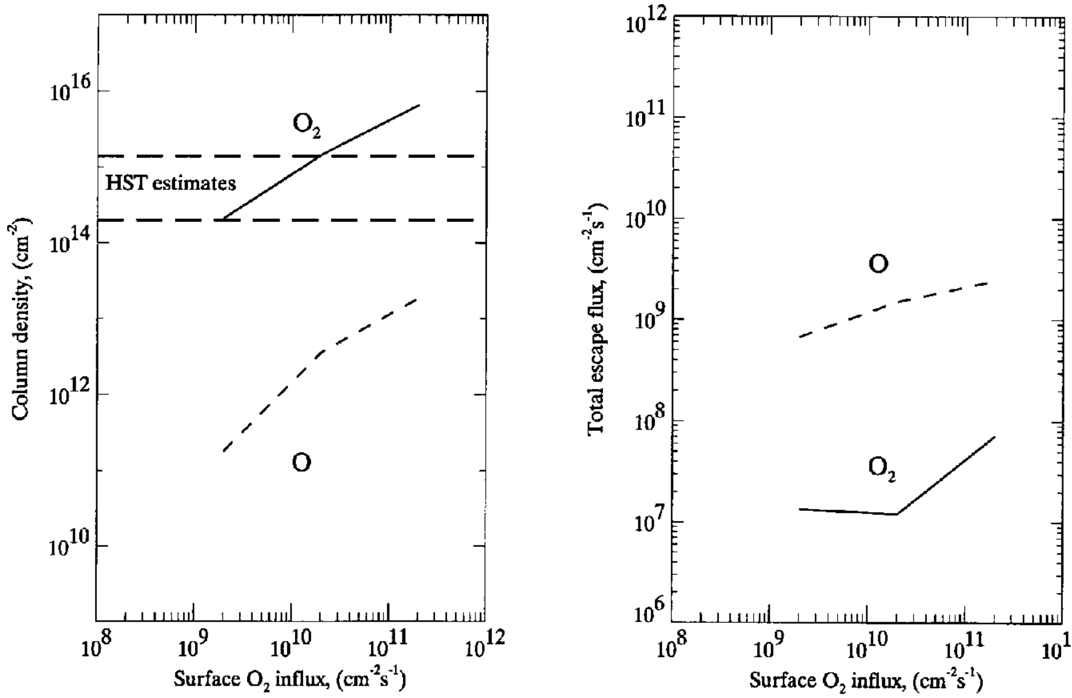

Fig. 5. Column densities (left panel) and escape fluxes (right panel) for atomic and molecular oxygen in the near-surface atmosphere at Europa depending on the surface influx of O_2 molecules.

SUMMARY AND CONCLUSIONS

In this paper we have carried out the first detailed, collisional model of Europa's tenuous atmosphere. If the O_2 produced does not react when it returns to the surface, then as shown here the near-surface atmosphere is dominated by the thermal component. This atmosphere then gives way to a highly non-equilibrium atmosphere at higher altitudes. If we use the HST estimates of the atmospheric density, then the surface source rate required is 1. - 2 .$\times 10^{10}$ cm^{-2}s^{-1}. This flux is more than a factor of two larger than that found by Saur et al. (1998) to be their best fit. This flux is also much larger than the total ion sputtering rate estimates for those ions measured by the Galileo energetic particle detector (> 10 keV)

$2.\times10^9$ $cm^{-2}s^{-1}$ (Cooper et al., 2001). Since the O_2 fraction of the sputter flux for these ions is less then 20%, this suggests there is a large undetermined source of O_2. This could be the 'thermal' plasma, for which Bar-Nun et al. (1985) show that oxygen is produced very efficiently, or the energetic electrons, a large source of energy flux to Europa's surface (Cooper et al., 2001). Using a globally averaged energy flux to the surface for the electrons of $6.\times 10^{10}$ keV/cm^2s (Cooper et al., 2001), this source rate suggests a G-value (O_2 produced per 100 eV deposited) > 0.03. This is larger than results based on recent experiments for pure ice (0.01 - 0.003) but smaller than that found in early experiments (~ 0.15) (see, e.g., Johnson, 2000). The high G-values have been suggested to be due to contaminant gases, which of course are likely to be present on Europa. Finally, Ip (1996) has suggested that pick-up ion impact is important. Although a source rate estimated by Ip (1996) is close to that found here, Saur et al. (1998) dispute Ip's result.

We have shown here that dissociation by photons, electrons and the incident plasma all need to be included in describing Europa's atmosphere. Based on our model a source rate of $> 1.\times10^{10}$ $cm^{-2}s^{-1}$ is required to account for the HST observations. This is much larger than the estimates of the sputtering rate by the energetic plasma measured by Galileo suggesting other surface sources.

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