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Near-Surface Atmosphere of Europa

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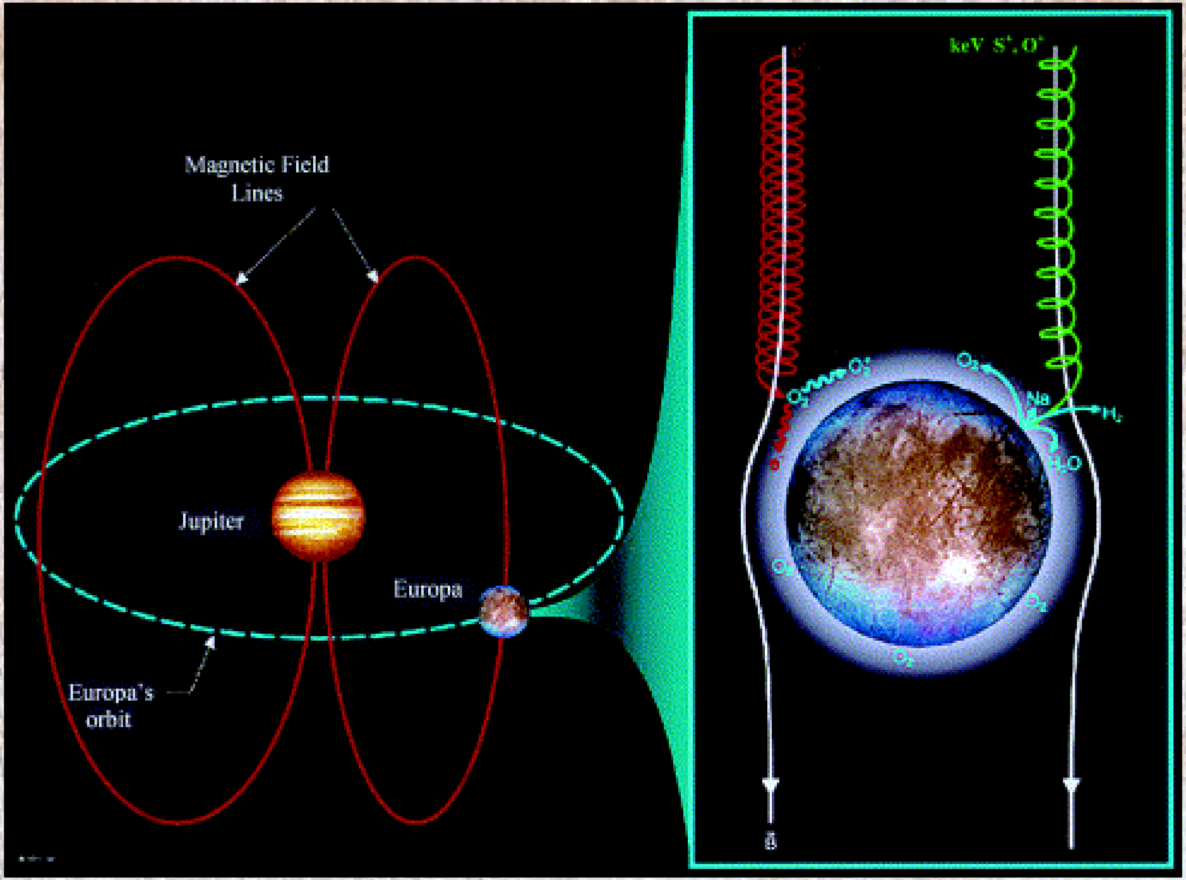
Oxygen atmosphere of Europa:

- **The very tenuous O_2 atmosphere of Europa is a near-surface (or surface-bounded) atmosphere (Johnson 2002);**
- **It is produced by the radiolysis of Europa's surface due to exposure to:**
  - **solar ultraviolet radiation;**
  - **energetic magnetospheric plasma ions and electrons;**

- **This atmosphere was predicted (Johnson et al. 1982) based on laboratory measurements and it was observed recently using HST (Hall et al. 1995, 1998).**

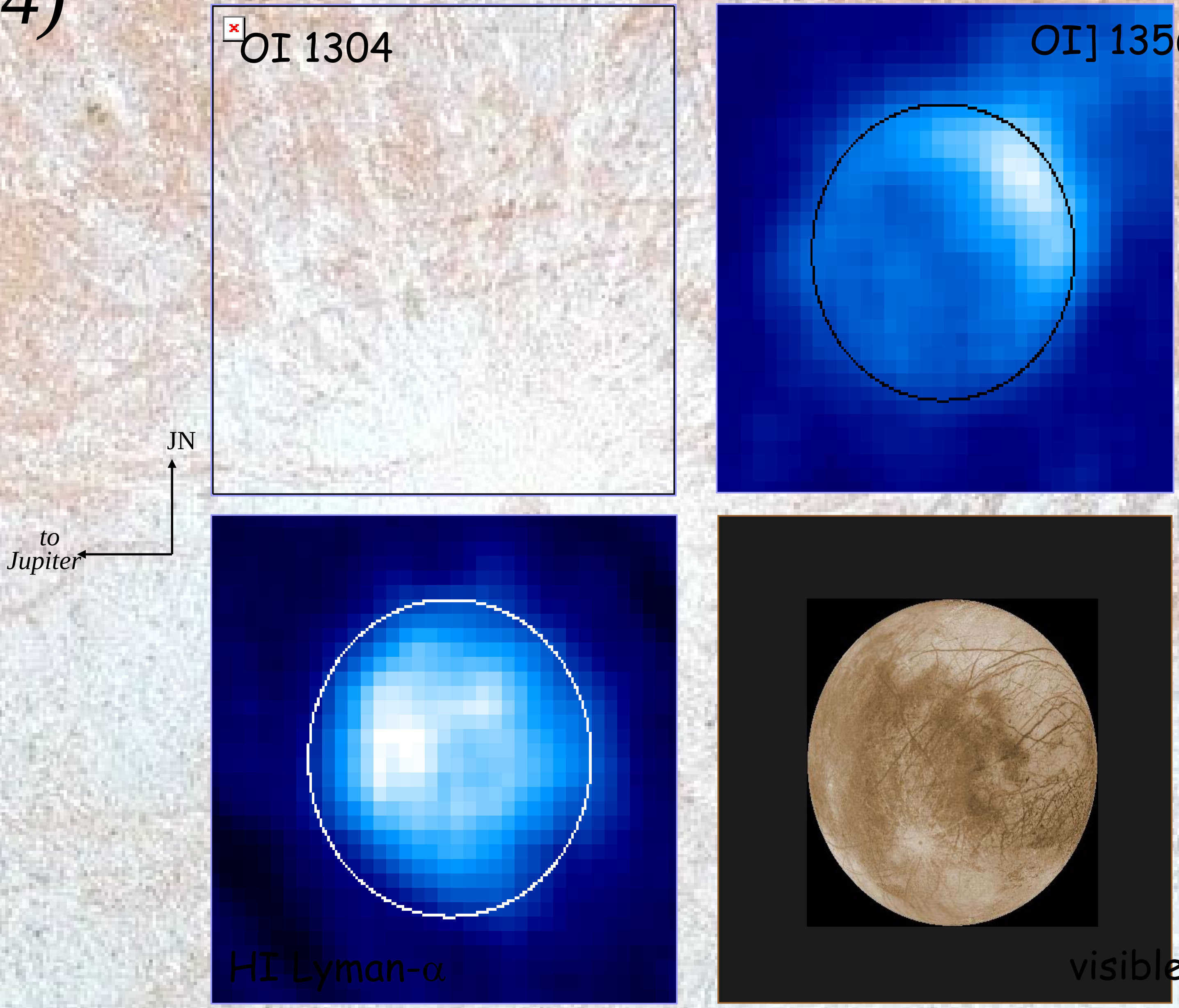
Europa in the Jovian System:



Atmospheric Observations:

- **HST observations - OI 130.4 and 135.6 nm emissions from dissociative excitation of O_2 (Hall et al. 1995,1998);**
- **HST STIS – oxygen emissions were spacially inhomogeneous through the surface (McGrath et al., 2004);**
- **Cassini UVIS detected both hydrogen and oxygen (Hansen et al., 2005). It was determined that atmosphere is dominated by O_2 with small scale height and more tenuous extended O corona;**
- **Galileo observations – ionosphere contains a variety of ions formed from surface material including H^+, H_2^+, H_xO^+,O_2^+, Na^+, K^+, Cl^+, …**

HST STIS observations of Europa (*McGrath et al., 2004)*



Radiation environment of Europa:

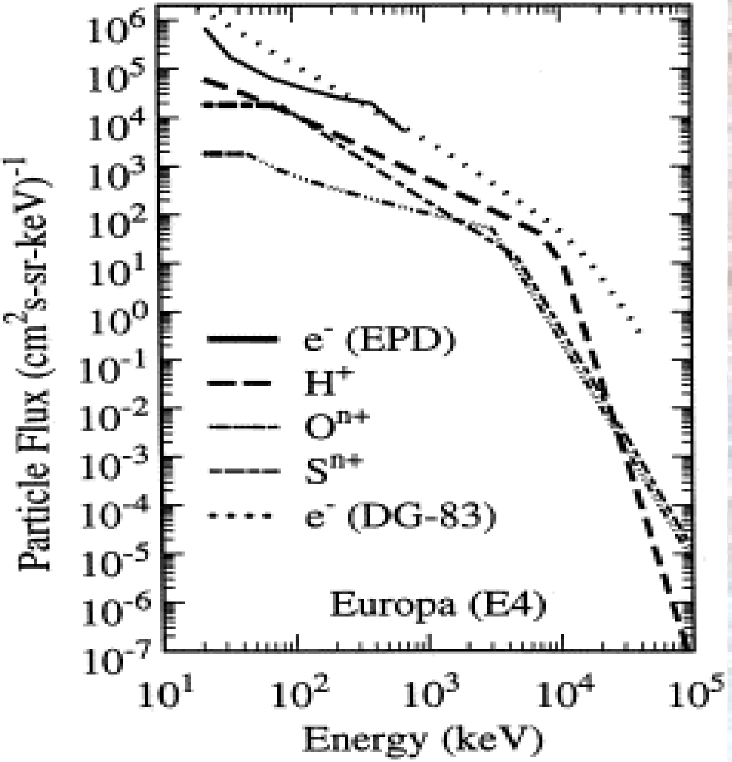
The plasma interaction with the surface is a principal source of O_2 and the plasma interaction with atmosphere is a principal loss process, therefore a large atmosphere does not accumulate (Johnson et al. 1982).

High-energy plasma environment at Europa (Cooper at al. 2001) – H^+, O^+, S^+, O^{++},…

Electrons:

-cold component with $n_{e,c}$=130 cm^{-3} and $T_{e,c}$=18 eV;

-hot component with $n_{e,h}$=3 cm^{-3} and $T_{e,h}$=190 eV.



Surface composition:

- Europa's surface composition determines the composition of its atmosphere. The surface is predominantly water ice with impact craters, ridges, possibly melted regions and trace species determining how its appearance varies;

- Europa's surface is dominated by oxygen rich species – H_2O and its radiolysis product O_2, surface chemistry product H_2O_2, trace species SO_2 and CO_2

- Trace surface species, which are possible atmospheric constituents, can be endogenic, formed by the irradiation, or have been implanted as magnetospheric plasma ions, as neutrals or grains from Io, or meteoroid and comet impacts.

Lower boundary – icy satellite surface:

(i) Sputtering of icy surface by magnetospheric ions with energies of E ~ 10 -1000 keV (Cooper at al. 2001) results in the ejection of parent molecules H_2O and their radiolysis products O_2 and H_2 with energy spectra (Johnson et al. 1983) – *non-thermal source*

$$F_i^{surface}(E) \approx c\,\frac{UE^q}{(E+U)^{2+q}},\quad \frac{q=0, c=1, U=0.015eV, i=O_2}{q=1, c=2, U=0.055eV, i=H_2O}.$$

(ii) UV-photolysis of the icy satellite surface leads to the ejection of H_2O and O_2 with Maxwellian energy distribution with the mean surface temperature T ~ 100 K, – *thermal source*;

(iii) Returning O_2 molecules are desorbed thermally – *thermal source*;

(iv) Returning H_2O, O, and OH stick with unit efficiency.

Upper boundary ~ 400÷1000 km from the surface:

(i) Influx $F \sim 10^8 - 10^9$ см$^{-2}$ s^{-1} of the magnetospheric ions with maxwellian energy spectrum with characteristic energies $E \sim 1 - 10$ keV (Bagenal, 1994);

(ii) Atmospheric sputtering is caused mainly by O$^+$ ions;

(iii) Atmospheric particles which cross 400 km altitude with energies higher than the escape energy enter the inner Jovian magnetosphere.

Atmospheric modeling:

- Surface sputtering is the dominant source of H_2O, O_2, and H_2, also sublimation of H_2O is competitive at the subsolar point;
- Atmospheric loss occurs by gravitational escape, interaction with the ambient plasma and solar UV photons, or removal through interaction with the surface, e.g., the sticking (freezing) of H_2O on Europa’s surface;
- Non-thermal surface source - ~ 2% of the O_2 and ~24% of the H_2O are directly ejected into the Jovian magnetosphere. For thermally accommodated O_2 escape is negligible, but for H_2 about 7% escape at the average temperature ~100K and ~15% at the subsolar point ~130K.

Atmospheric modeling:

•Analytic models (Johnson, 1990): atmosphere is well approximated by an exponential model with a scale height H_{O2}≈20 km for an average temperature of 100K;

•Model of outflowing (coronal) atmosphere (Saur et al., 1998) when the density is exponentially decreasing with the depletion length scale of ~140 km;

•Numerical Monte Carlo models:

- Test Particle models (Ip, 1996; Johnson et al., 2002; Cassidy et al., 2008);

- Direct Simulation Monte Carlo (DSMC) models (Shematovich et al., 2005; Smyth and Marconi, 2006) – analogue MC algorithms for the solution of the Boltzmann equation.

Photolysis by solar UV radiation and photo- and plasma electrons:

- **Dissociation:**

$$O_2 + h\nu, e_\nu \rightarrow O(^3P) + O(^3P, ^1D, ^1S) + (e_\nu) + \Delta E_{dis}$$

- **Direct and dissociative ionization**

$$O_2 + h\nu, e_\nu \rightarrow O_2^+ + e + (e_\nu)$$

$$O_2 + h\nu, e_\nu \rightarrow O(^3P, ^1D) + O^+(^4S) + e + (e_\nu) + \Delta E_{di}$$

Atmospheric sputtering of O_2 by high-energy magnetospheric plasma:

- **Momentum transfer, dissociation, ionization, and charge transfer in collisions with magnetospheric ions:**

$$O_2 + \{O^+,\ldots\} \rightarrow \begin{cases} \{O^+,\ldots\} + O_2^* \rightarrow O + O + \Delta E_{sd} \\ \{O^+,\ldots\} + O_2^+ + e \\ \{O,\ldots\} + O_2^+ \end{cases}$$

Atmospheric sputtering of H_2O by high-energy magnetospheric plasma:

- **Momentum transfer, dissociation, ionization, and charge transfer in collisions with magnetospheric ions:**

$$H_2O + \{O^+, \ldots\} \rightarrow \begin{cases} \{O^+, \ldots\} + H_2O^* \rightarrow OH + H + \Delta E_{sd} \\ \{O^+, \ldots\} + H_2O^+ + e \\ \{O, \ldots\} + H_2O^+ \end{cases}$$

Kinetic description: system of the Boltzmann kinetic equations with source terms

$$\vec{c}\,\frac{\partial}{\partial \vec{r}} F_i + \vec{g}\,\frac{\partial}{\partial \vec{c}} F_i = Q_i^{hot} + L_i^{photo} + \sum_j \sum_\alpha J_\alpha(F_i, F_j),$$

$$(i = O,\ OH,\ H_2O,\ O_2)$$

$$\vec{c}\,\frac{\partial}{\partial \vec{r}} F_{O+} + \vec{g}\,\frac{\partial}{\partial \vec{c}} F_{O+} = \sum_j \sum_\alpha J_\alpha(F_{O+}, F_j),$$

$$(j = O^+, O,\ OH,\ H_2O,\ O_2)$$

Q_i^{hot} – photochemical source terms, *(i=O,OH)*;
L_i^{photo} – photochemical loss terms, *(i=O,OH,H$_2$O,O$_2$)*;
J_α - collisional terms for momentum transfer and dissociation collisions between atmospheric particles and plasma.

This physical system was simulated using the modification of the Direct Simulation Monte Carlo method (Shematovich et al., 2005).

Calculated models:

- Model A - H_2O and O_2 are ejected from the surface due to sputtering by high-energy magnetospheric ions;
- Model B - H_2O and O_2 are ejected due to radiolysis by solar UV radiation and magnetospheric plasma;
- Model C - H_2O are ejected from the surface due to evaporation and O_2 due to sputtering;
- In all cases the O_2 flux was taken equal to 2×10^9 $cm^{-2}s^{-1}$ (Johnson et al., 2003). For this study we used a total H_2O flux (sublimation and sputtering) about 10 times that;
- In all models the photo- and electron impact dissociation and ionization were taken into account.

Near-surface atmosphere of Europa:

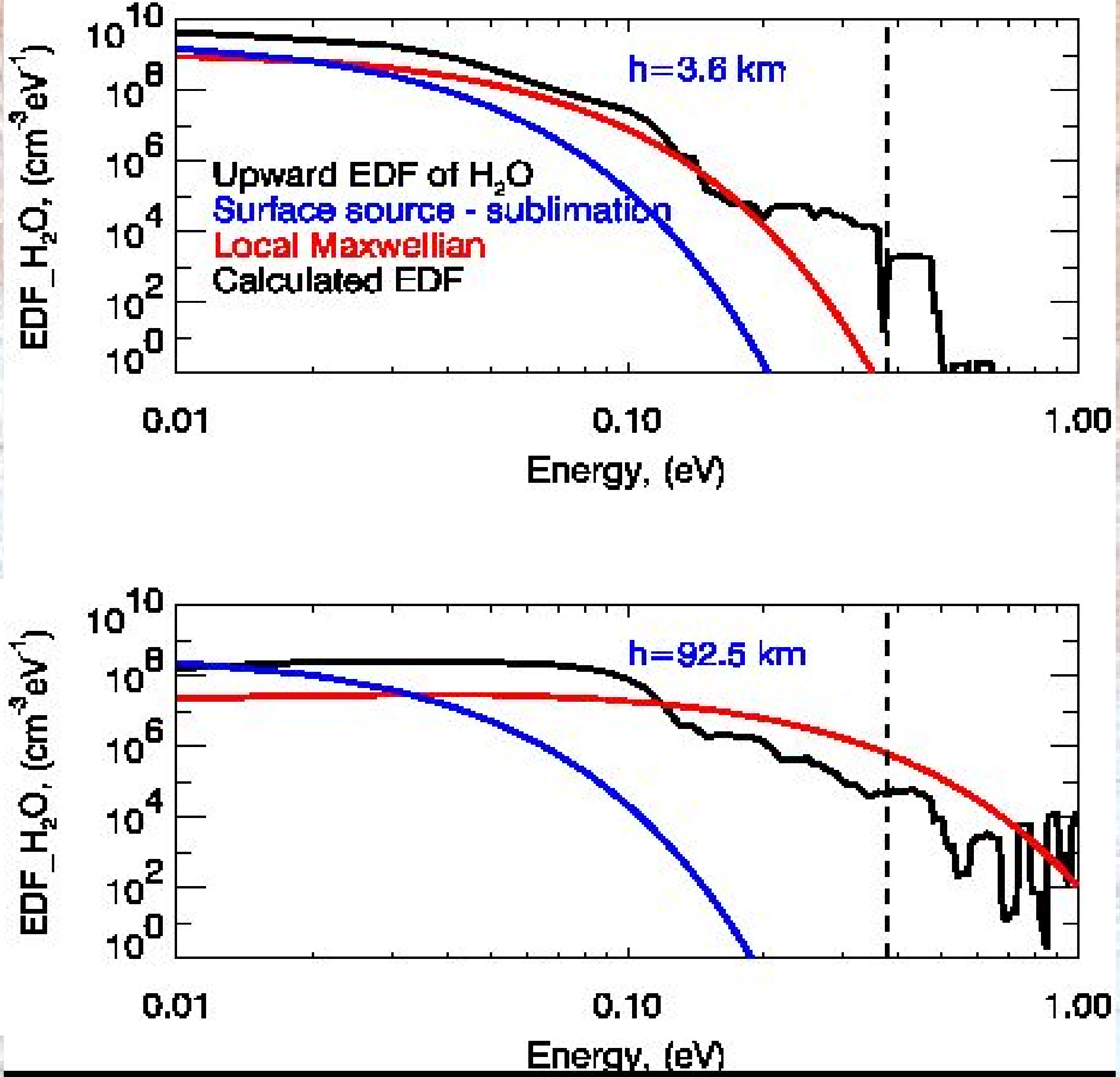
In the runs for Models A, B, and C the statistics on the particle velocities were stored allowing to estimate the energy distributions of all species. In the two following graphs the calculated energy distributions (EDF, black lines) of upward moving H_2O and O_2 molecules are shown for Model C in which the surface sources (energy spectra of sources are given in blue lines) of H_2O and O_2 are the evaporation at mean surface temperature of 100 K and the surface sputtering by high-energy magnetospheric ions, correpondingly. The local Maxwellian distributions are also shown (red lines).

It is seen that the suprathermal tails in the H_2O and O_2 EDFs are formed due to the atmospheric sputtering and the energies allowing the H_2O ($E > 0.38$ eV) and O_2 ($E > 0.67$ eV) escape are significantly populated.

Near-surface atmosphere of Europa:

H_2O kinetic energy distributions – Model C

**Surface source of H_2O :
evaporation at mean surface temperature of 100 K (blue line).**



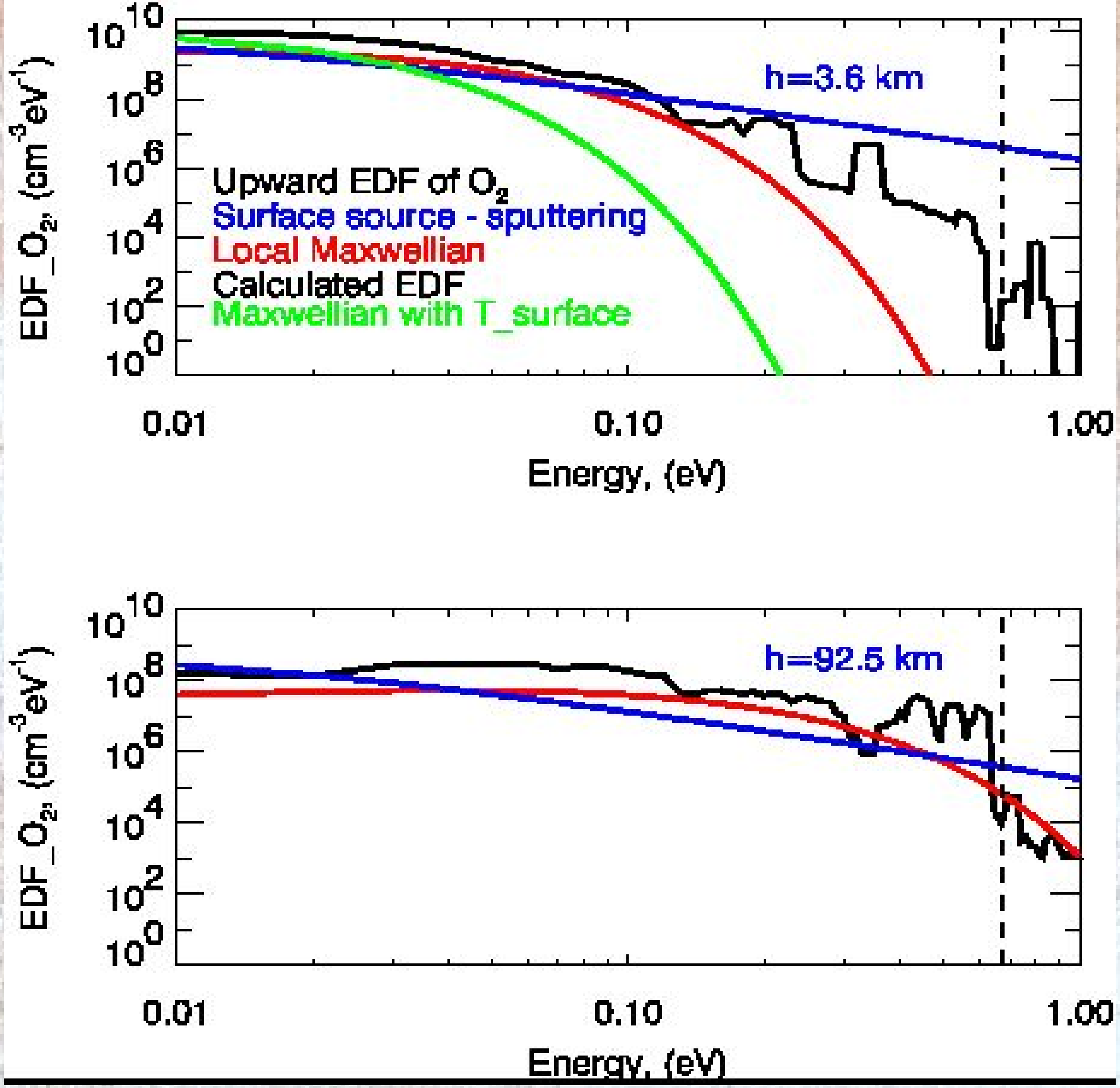
Suprathermal tails at energies higher than escape energy ($E > 0.38$ eV) are formed due to the atmospheric sputtering.

Near-surface atmosphere of Europa:

O_2 kinetic energy distributions – Model C

Surface source of O_2: surface sputtering by high-energy magnetospheric ions (blue line).

Suprathermal tails at energies higher than escape energy (E > 0.67 eV) are formed due to the atmospheric sputtering



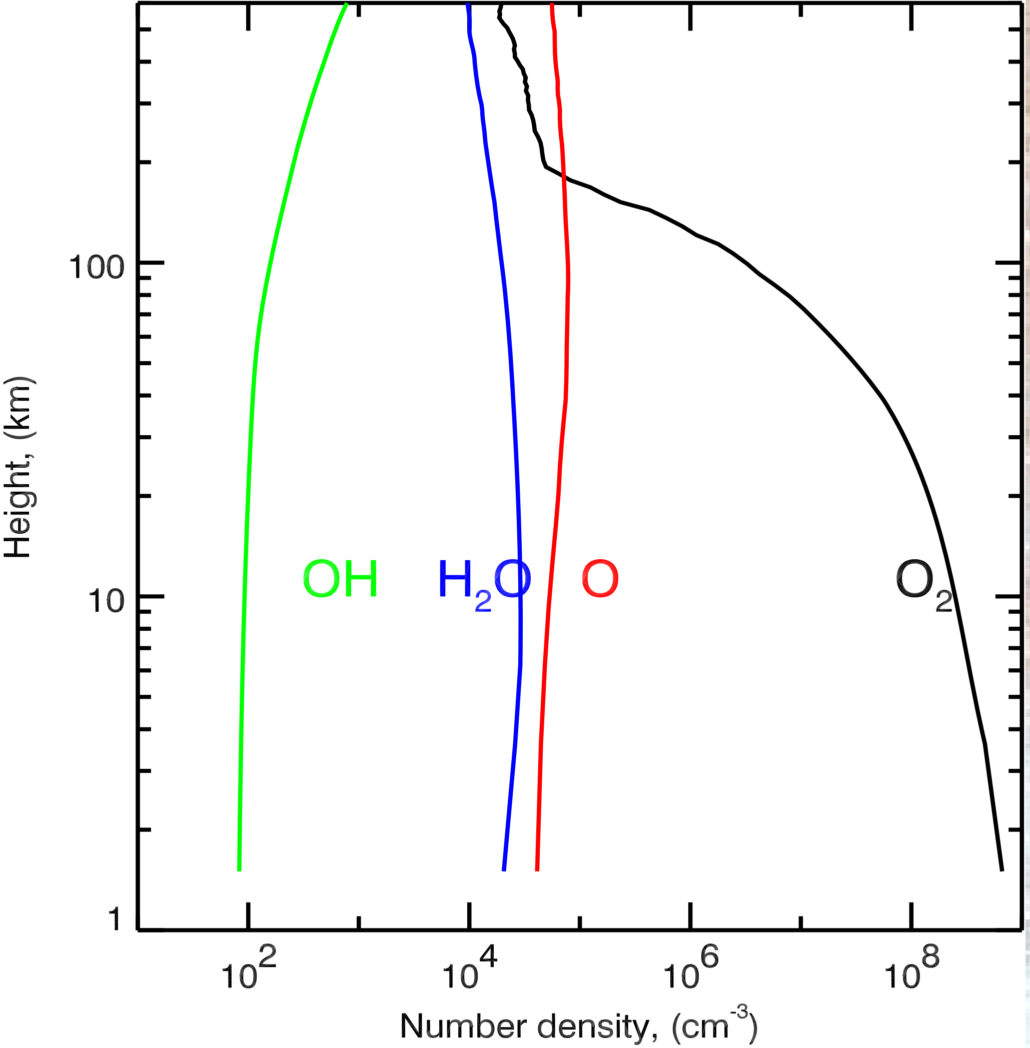
Near-surface atmosphere of Europa: *density distributions*

Near-surface atmosphere is composed mainly of O_2, and is formed and maintained owing to both thermal and non-thermal sources of parent O_2:

- Below 10 -20 km atmosphere is populated by O_2 accommodated to the surface temperature.

- The transition region between 10 and 100 km is mostly populated by molecules with kinetic energies increasing up to 0.1 eV due to the atmospheric sputtering.

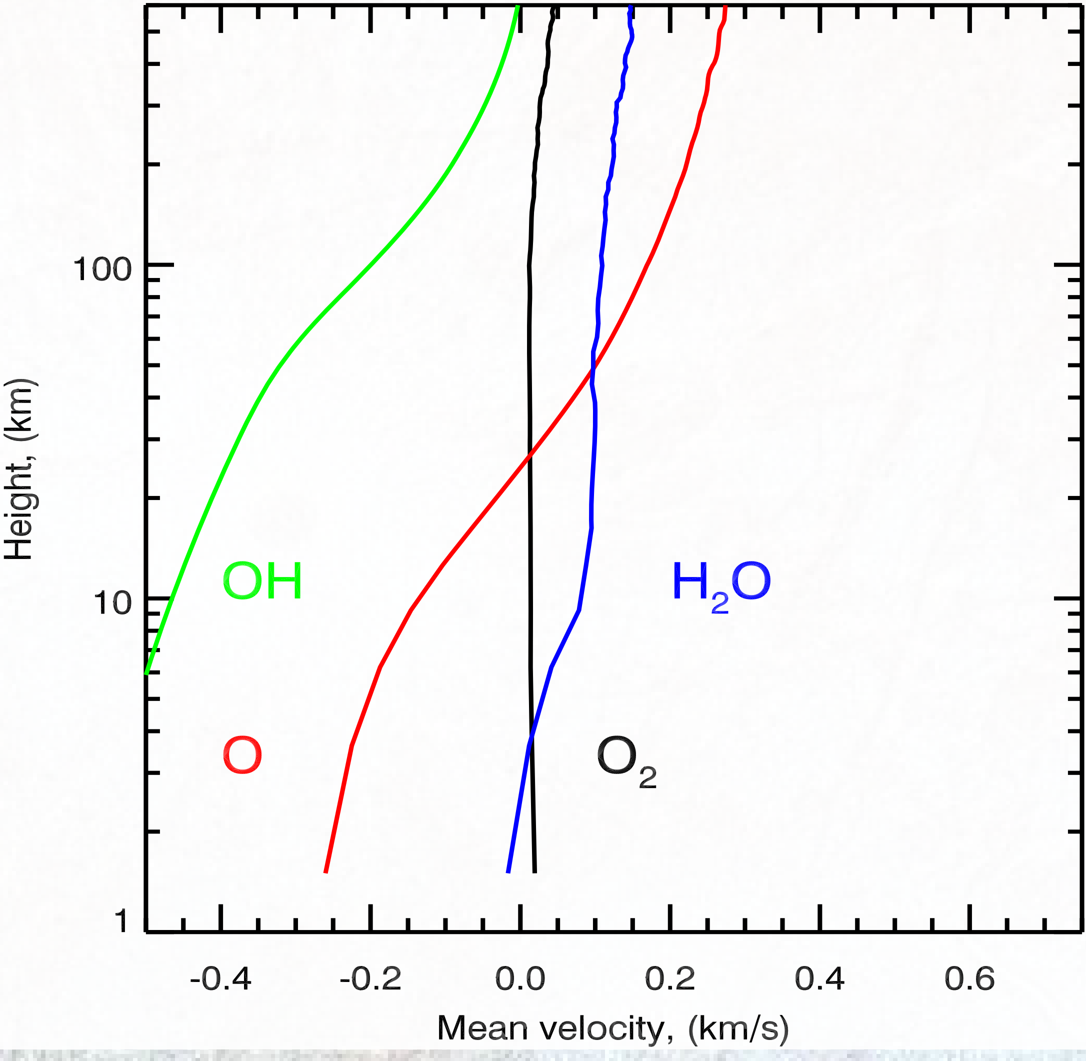
- Layers above 100 km are populated by O2 from the high-energy tail of the surface source distribution $F^{surface}(E)$.



Near-surface atmosphere of Europa: *velocity distributions*

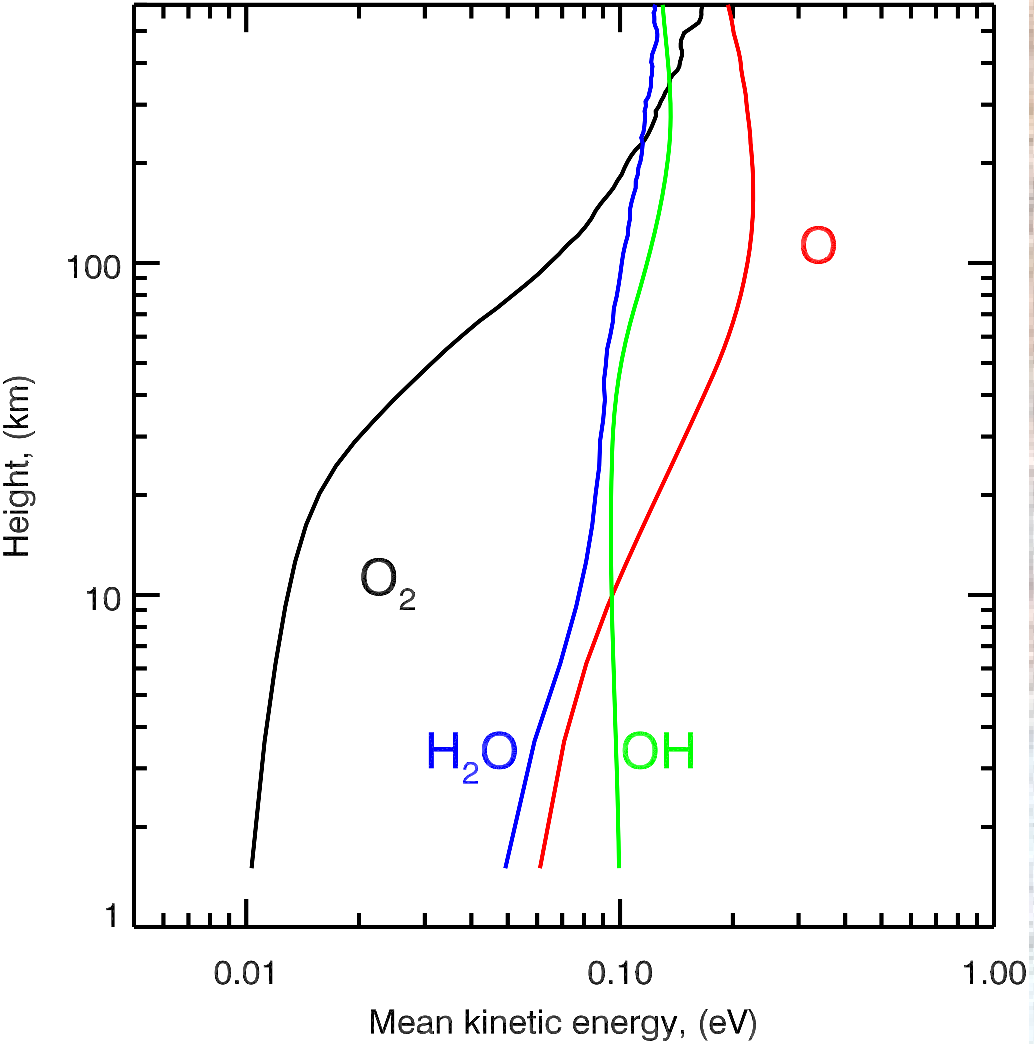
Near-surface atmosphere is dynamically stable because the bulk velocity of O_2 is practically close to zero.

Dissociation products O and OH are outflowing from the atmosphere or removed to the surface.



Near-surface atmosphere of Europa: *temperature distributions*

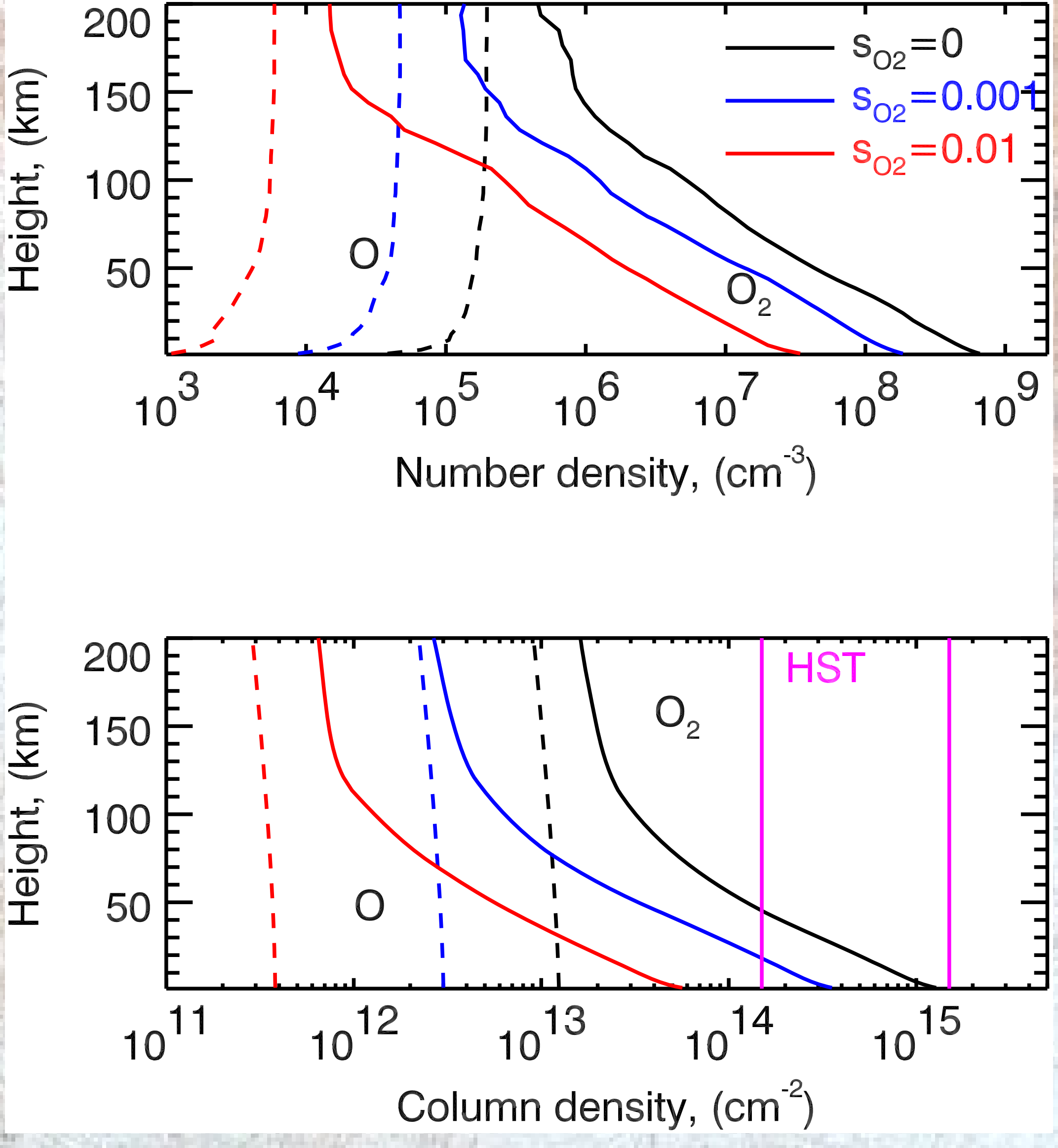
The upper layers (>100 km) of the atmosphere demonstrate a progressive heating of molecular oxygen as a result of collisions with magnetospheric ions and suprathermal oxygen atoms, which leads to the formation of the extended oxygen exosphere of Europa.



Near-surface atmosphere of Europa: *O_2 density for models with different sticking coefficients* S

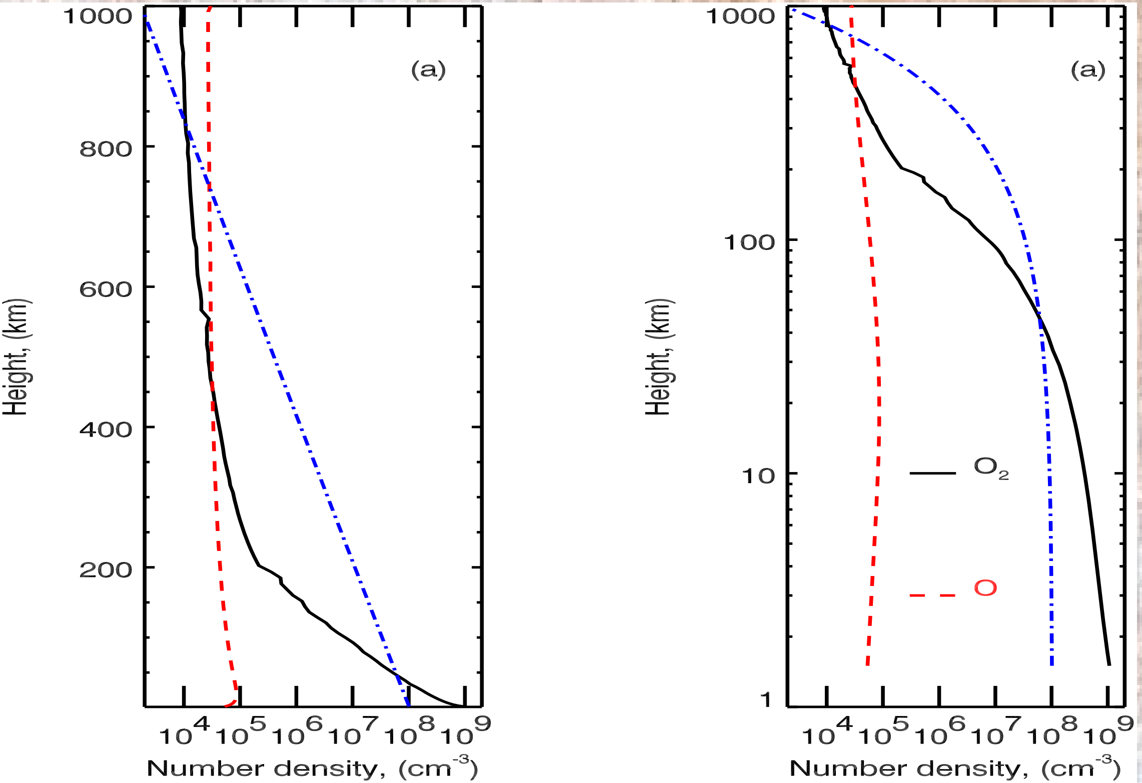
Small S for O_2 correspond to the chemical interaction with the surface regions where water ice is covered by the refractory material. This can cause the spatial inhomogeneity of near-surface atmosphere.

Another possible reason – local gas venting at young icy regions (Enceladus-like geyzers!). It can result in a relatively dense local atmosphere – important to survey the landing sites!!!



Hot corona of Europa: *O_2 and O densities*

Distributions of atomic and molecular oxygen in the extended exosphere of Europa are shown in logarithmic and linear scales of altitude. Comparison with the ouflowing atmosphere model (Saur et al., 1998) is also given.



Atomic oxygen is only a small admixture to the main atmospheric component O_2 in the near-surface part of the atmosphere. However, outer exospheric layers of Europa's atmosphere are populated mostly by suprathermal oxygen atoms. The near-surface molecular envelope of Europa is surrounded by a tenuous extended corona made up of atomic oxygen in accordance with UVIS observations (Hansen et al., 2005).

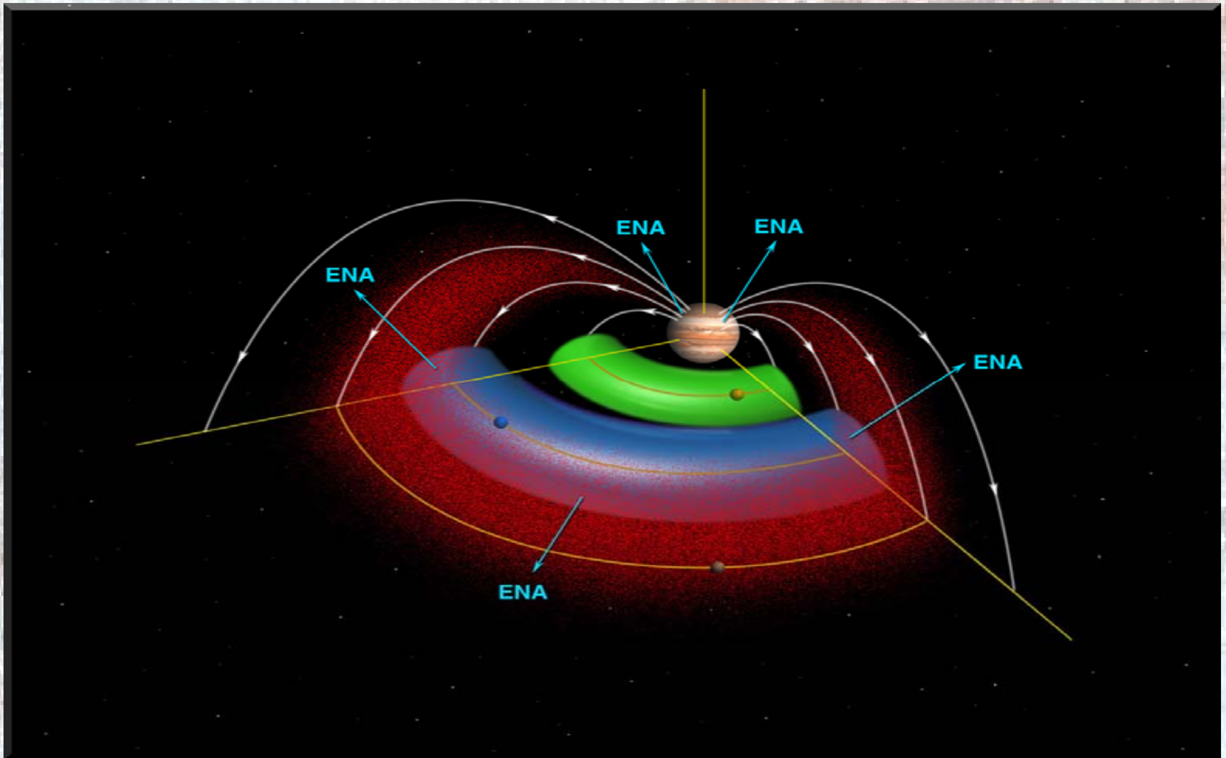
Hot corona of Europa: *Total loss of neutrals*

Total loss of oxygen and hydrogen from the surface-bounded atmosphere of Europa (Shematovich et al., 2005):

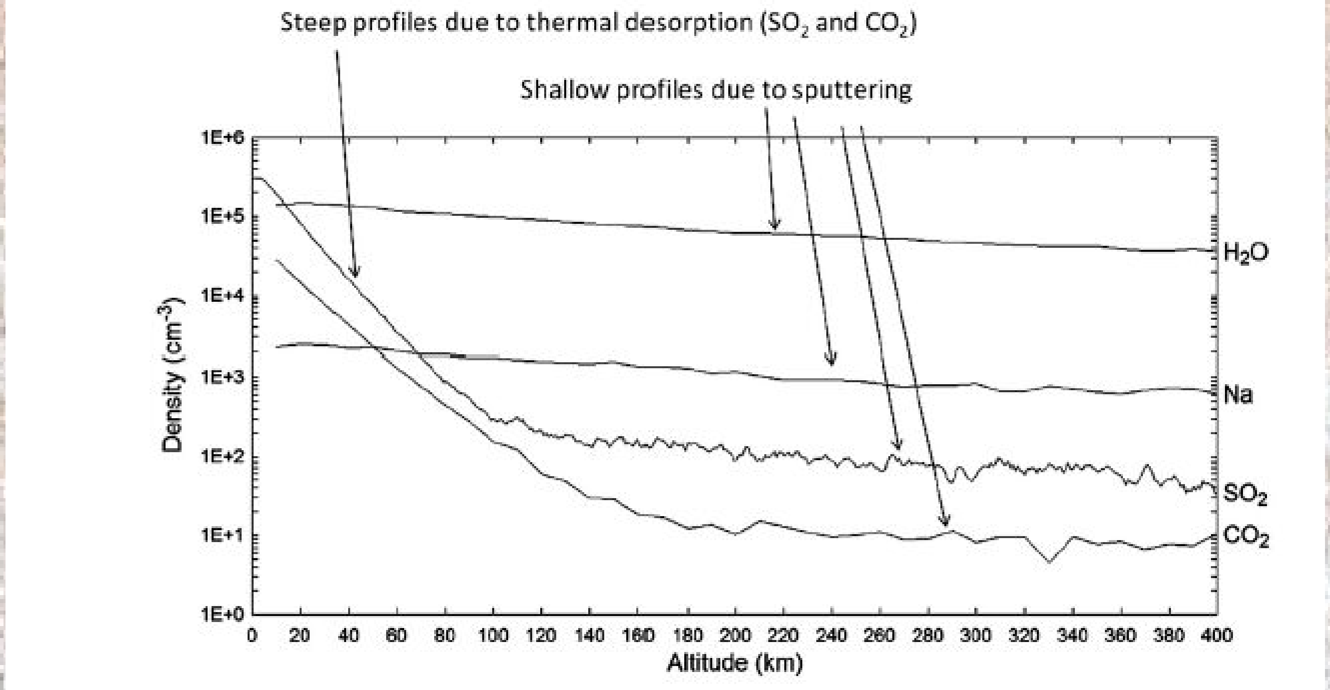
$Q_{loss,O}$ =(1.2 ÷ 2.6)×10^{26} O atoms/s and $Q_{loss,H}$ ≈3.0×10^{27} H atoms/s

Total supply of H and O to the neutral cloud is about 8×10^{33} neutral atoms which is close to the observational estimate (6.0 ± 2.5) ×10^{33} (H and O) atoms (Mauk et al., 2004).

Torus of neutral gas along the orbit of Europa observed by NASA CASSINI spacecraft (Mauk et al. 2003)



Near-surface atmosphere of Europa: *trace species*



Distribution of the trace species SO_2 and CO_2 (Cassidy et al., 2009)

Near-surface atmosphere of Europa:

ionospheric species

Estimates of ion distribution in the of the Europa's ionosphere (Johnson et al., 1998)

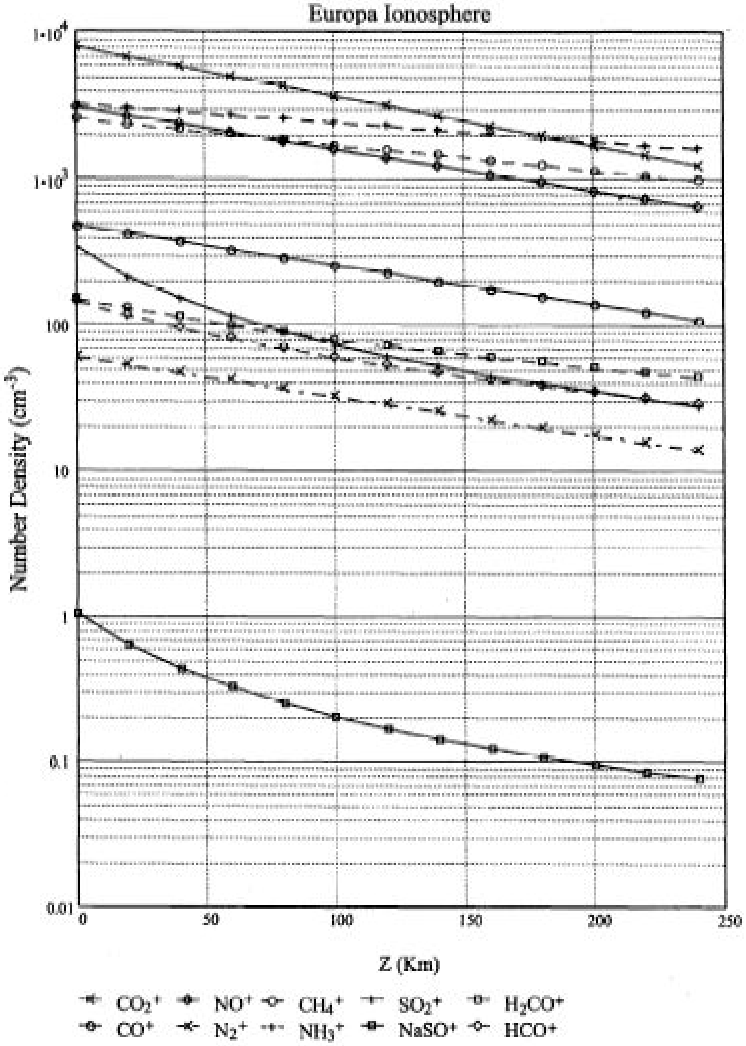
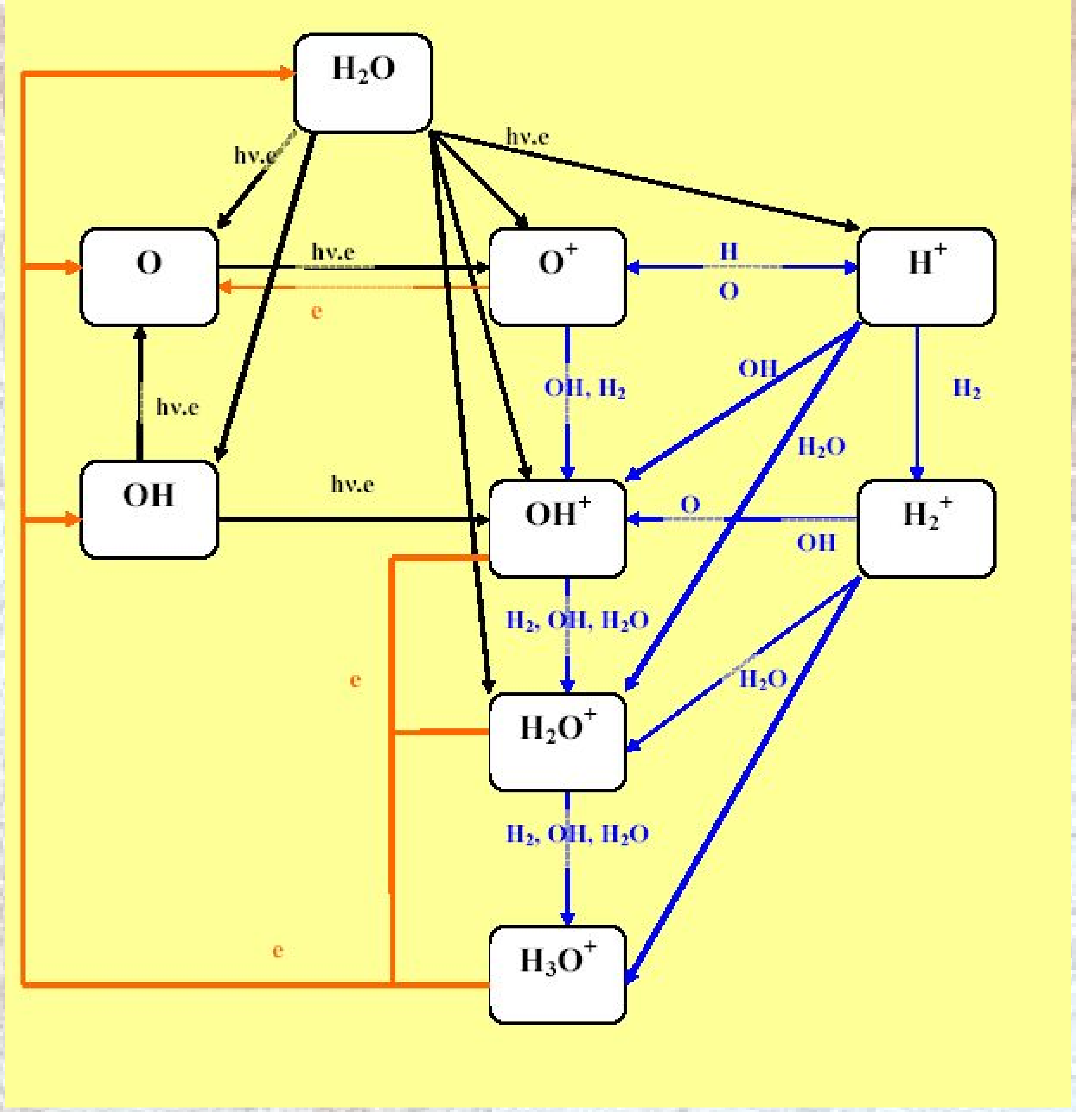


Figure 2. Ionospheric densities vs altitude, determined as discussed in the text, for molecules sputtered from the surface due to the presence of suggested surface materials. All densities exceed the detection limit (10^{-3} cm^{-3}) of a modern time of flight mass spectrometer such as the Cassini Plasma Spectrometer.

Ionization chemistry in the H_2O-dominant atmosphere

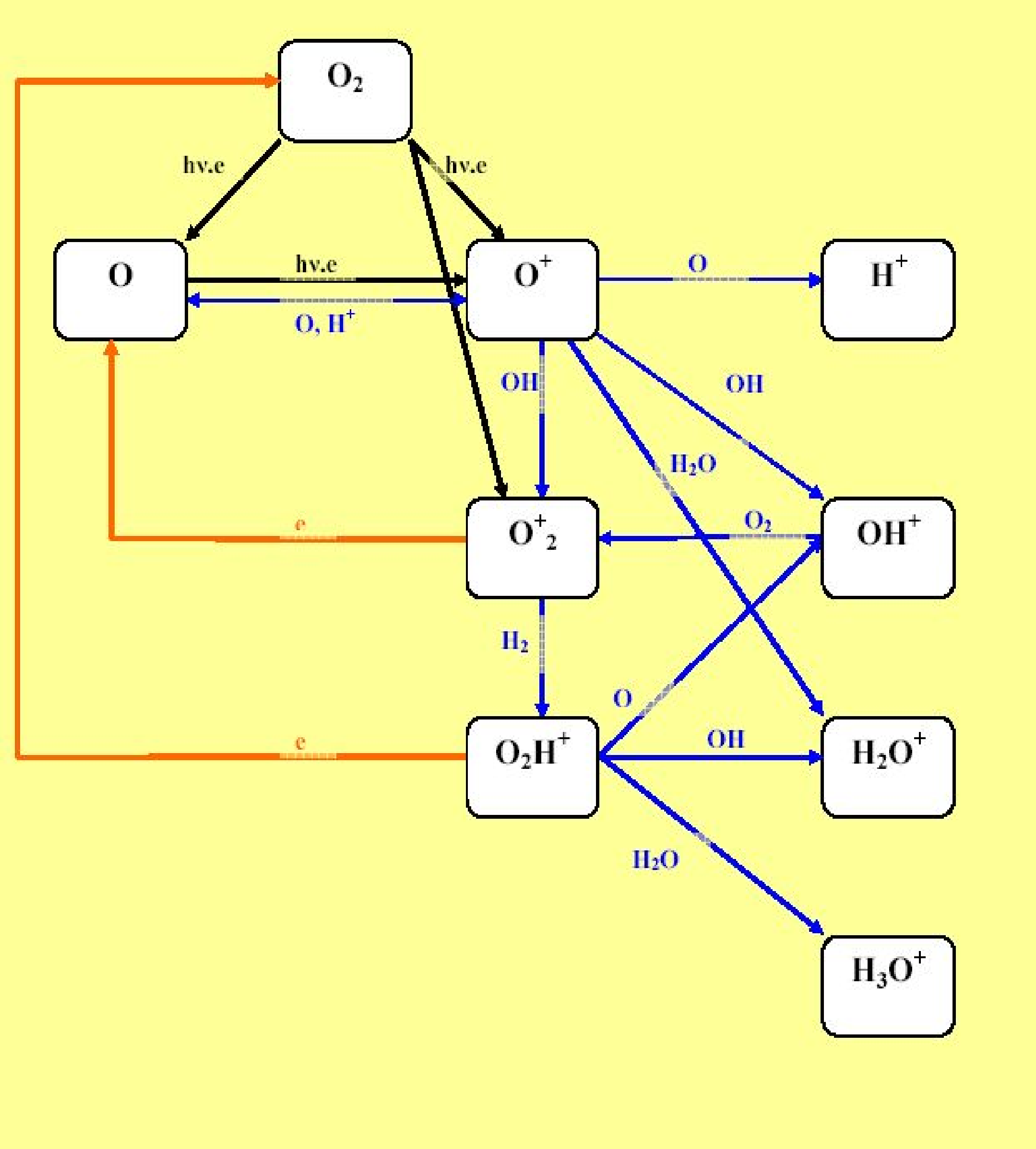
The parent H_2O molecules are easily dissociated and ionized by the solar UV-radiation and the energetic magnetospheric electrons forming secondaries: chemically active radicals, O and OH, and ions, H+, H_2+, O+, OH+, and H_2O+ . Secondary ions in H_2O-dominant atmospheres are efficiently transformed to H_3O+ hydroxonium ions in the fast ion-molecular reactions; The H_3O+ hydroxonium ion does not chemically interact with other neutrals, and is destroyed by dissociative recombination with thermal electrons producing H, H_2, O, and OH (Shematovich, 2008)



Near-surface atmosphere of Europa: *ionization chemistry in the H_2O+O_2-dominant atmosphere*

In a mixed $H_2O + O_2$ atmosphere ionization chemistry results in the formation of a second major ion O_2^+ - since O_2 has a lower ionization potential than other species –H_2, H_2O, OH, CO_2. When there is a significant admixture of H_2 then O_2^+ can be converted to the O_2H^+ through the fast reaction with H_2 and then to the H_3O^+ through low speed ion-molecular reaction with H_2O.

Therefore, the minor O_2H^+ ion is an important indicator at what partition between O_2 and H_2O does ionization chemistry result in the major O_2^+ or H_3O^+ ion (Johnson et al., 2006).



Near-surface atmosphere of Europa is:

- of interest as an extension of its surface and indicator of surface composition and chemistry;

- a hot corona due to the atmospheric sputtering;

- an important source of neutral gas causing the formation of the neutral gas torus along the Europa orbit;

- There is a critical need for detailed modeling of the desorption of important trace surface constituents related to exo- and endogenic sources of the Europa’s surface composition.

Thank you for your attention!

Near-surface atmosphere of Europa: *ionization chemistry in the $H_2O+H_2+O_2$-dominant atmosphere*