Ion sputtering and radiolysis of ice at the Galilean moons

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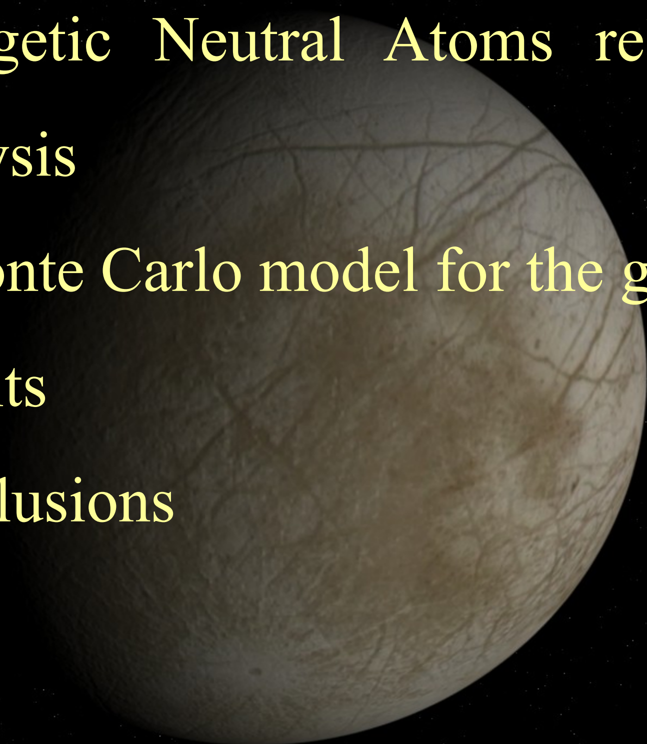
Outline



- Introduction – Exospheres and Energetic Neutral Atoms
- Europa’s characteristics and radiation environment
- Energetic Neutral Atoms release processes : Ion Sputtering and Radiolysis
- A Monte Carlo model for the generation of Europa's exosphere
- Results
- Conclusions

Exospheres of air-less bodies

The exospheres are the boundaries between the bodies and the open space. They are generated by the interaction between environments and body surfaces.

Thus, to investigate the exosphere of different Solar system bodies both the **environment** and the **surface** must be carefully considered.

We study the exospheres of **atmosphereless** bodies through the investigation of **neutral particle release** from their surfaces.

Ion sputtering is the only surface process that leads to emission of energetic neutral atoms' (ENAs).

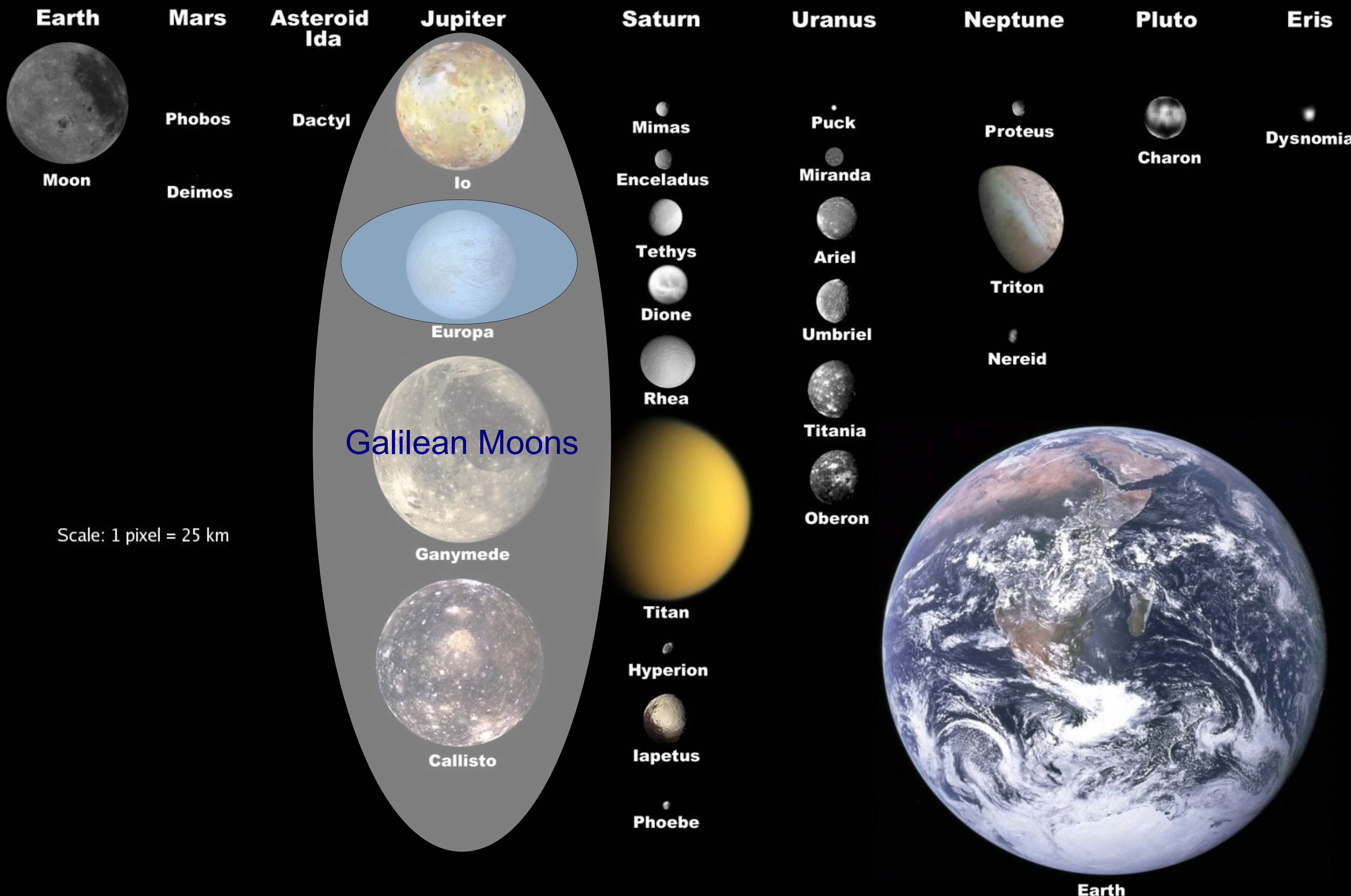
Why the ENAs emitted from the surface of a planetary body are a useful tool for planetary investigations?

The neutral atoms do not interact with electromagnetic fields. Hence, if their energies are high enough to consider the gravitational effects negligible, they have the property to maintain their characteristics (energy distribution and direction) unchanged since the generation time.

As a consequence, the ENA detection provides information about:

- the (remote) generation process
- the properties of the planetary surface
- the characteristics of the generated exosphere

Selected Moons of the Solar System, with Earth for Scale



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Atmosphere/exosphere at the Galilean moons

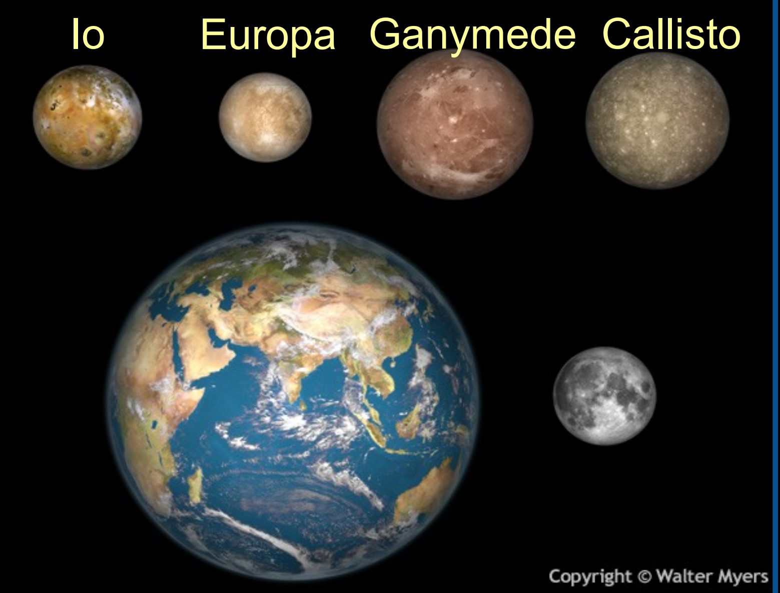
On the basis of the neutral atmospheric densities estimated by Kliore et al. (1997), we estimated a range of the **mean free paths** for O_2 in Europa's atmosphere **from 13 km to 78 km (**Plainaki et al., 2010) .

The estimated **scale height**, on the basis of formula $H=k_BT/(Mg)$ varies **from 17 km to ~26 km** where k_B is the Boltzman's constant, T is Europa's temperature at the surface, M is the molecular weight of O_2 and g is the acceleration due to gravity

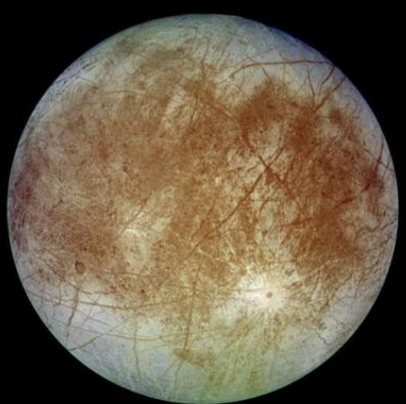
As a first approximation, therefore, a **collision-less atmosphere** can be assumed, where surface ion sputtering is possible.

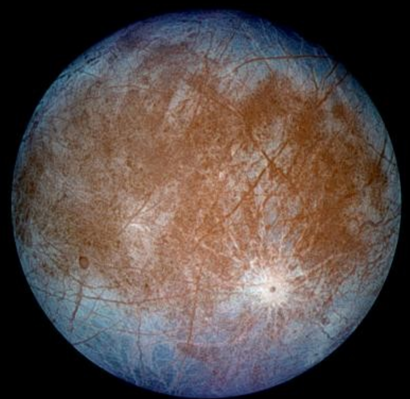
Europa

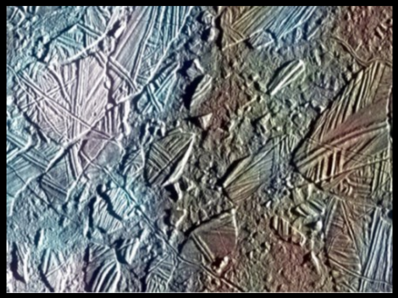
Mean Radius : 1.569d3 km (0.245 RE)
Mean Mass: 4.8d22 kg
Mean distance from Jupiter: 670,900 km
Equarorial surface gravity: 1.314 m/s^2
Surface temperature: 86 – 132 K
Escape velocity: 2.025km/s
Orbital period: 3.551days (average orbital speed: 13.740km/s)
Inclination: 0.470 (to Jupiter's equator)



Galilean Satellites in comparison with Earth and Moon





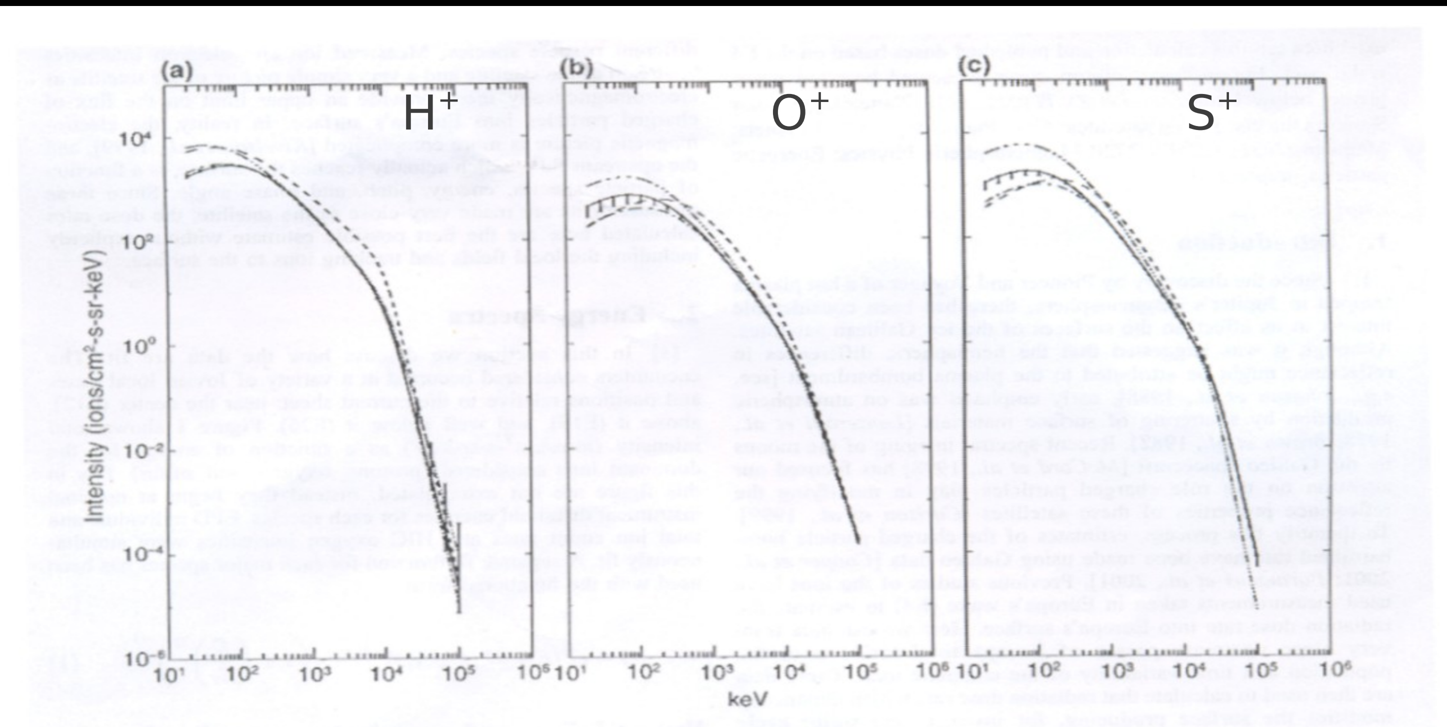


Disrupted ice crust in the Conamara region of Jupiter's moon Europa (NASA courtesy)

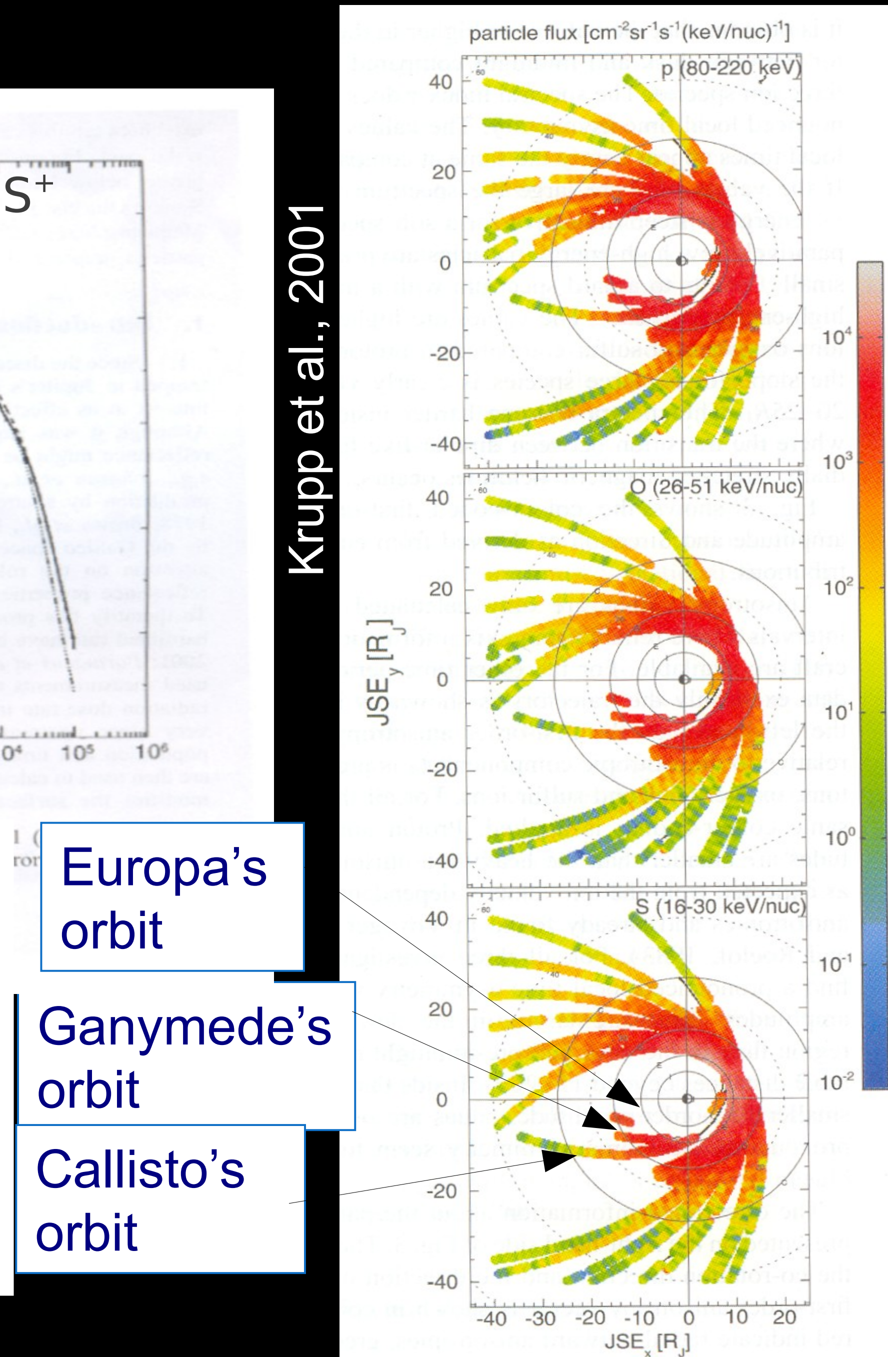
Europa's surface characteristics

- very young surface: between 10^6 – 10^9 years (Moore et al., 1998) covered mainly (>99%) by H_2O ice (Clark, 2004).
- average density ~2.989 g/cm^3 (Anderson et al., 1998)
- traces of non-icy material: H_2O_2 (0.13 % by number of molecules), SO_2 and CO_2, with hemispherical distributions (Tiscareno and Geissler, 2003; McCord et al, 1998).

Plasma in Jupiter’s environment



Energetic ion fluxes observed by Galileo spacecraft impacting on the surface of Europa (*Paranicas et al., 2002*).
Similar fluxes are expected at Ganymede orbit, while ion fluxes at Callisto are two order of magnitude lower.



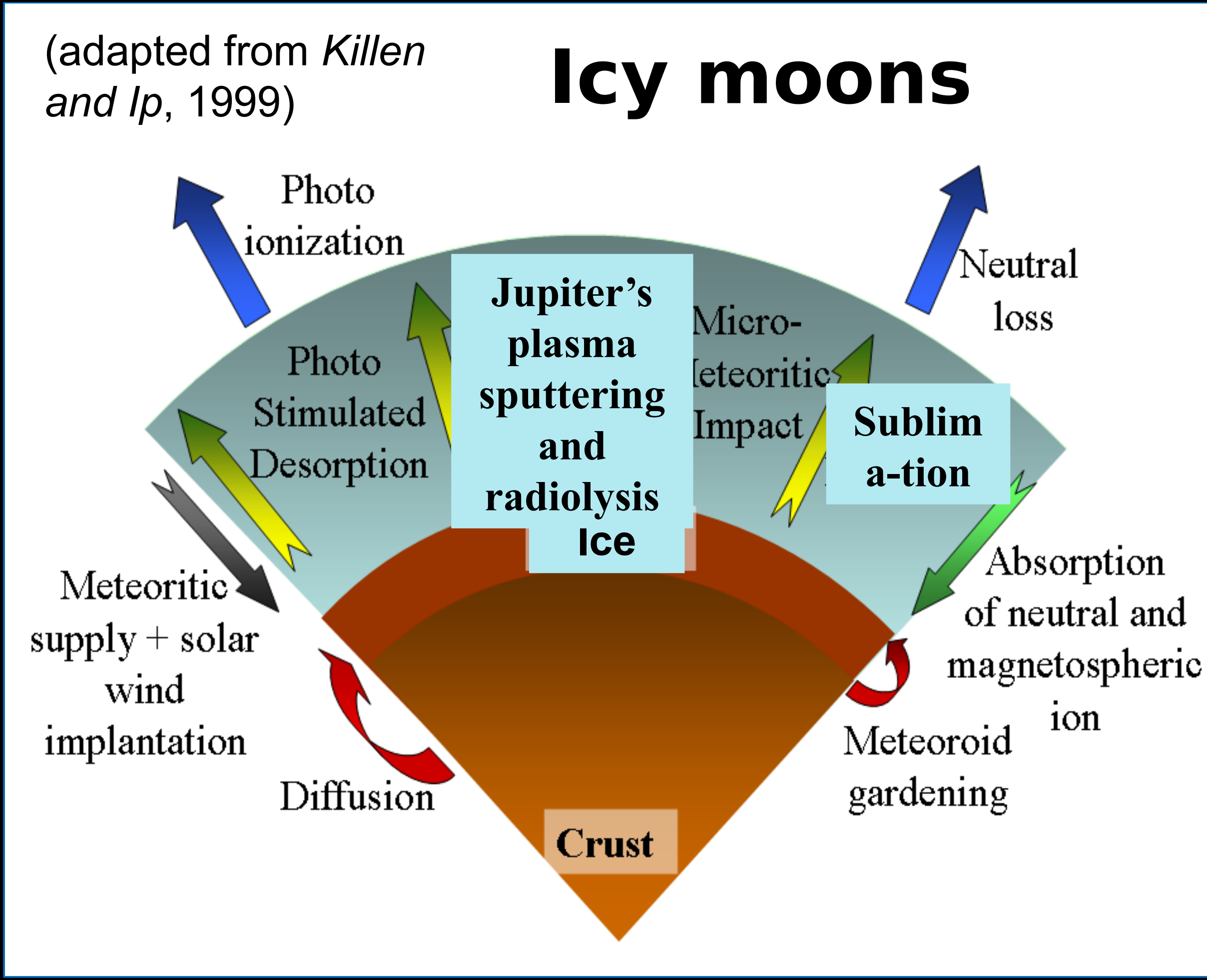
What processes happen on the moon's surface

Ion Sputtering (IS)
removal of a part of atoms or molecules from a solid surface, due to the interaction of a projectile ion with target surface atoms and secondary cascades of collisions between target atoms (Sigmund, 1981).

Radiolysis of ice
Decomposition of water molecules after being irradiated by energetic ions. The new molecules are then released.

Ion Back-scattering
Light impacting ions can interact with the surface and be scattered back as neutrals. The IBS efficiency depends on the surface type.

Photon Stimulated Desorption
desorption of neutrals or ions as a result of direct excitation of surface atoms by photons (Hurych, 1988). It is most effective for volatiles (like H, He, Na, K, H_2O).

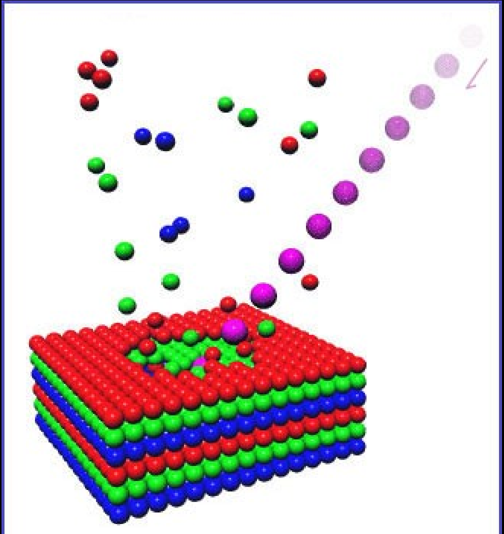


Sublimation
Since the surface molecules have a thermal distribution, the vapor pressure can produce sublimation.

Micrometeoroid Impact Vaporization
impact vaporization caused by micrometeorites hitting the surface.

Ion Sputtering

The emitted neutral flux is proportional to the yield, *Y*, (the number of sputtered atoms produced by one single impinging ion) much higher for higher energies and for heavier ions (*Baragiola et al., 2003*).


(Greg Gillen, www.simsworkshop.org)

Warning: the yields obtained by laboratory simulations could be different (lower or higher) in the planetary environments since the aggregation status of the surface material could be different from the sample.

New observations are really important in this frame!

Sputtering and radiolysis yield from icy surface bombarded by energetic ions

When an ion impacts a surface, different species are released

H_2O directly sputtered

O_2 and H_2 molecules ejected in a two-phase process (i.e. water dissociation via radiolysis (OH + H) and recombination, followed by ion sputtering).

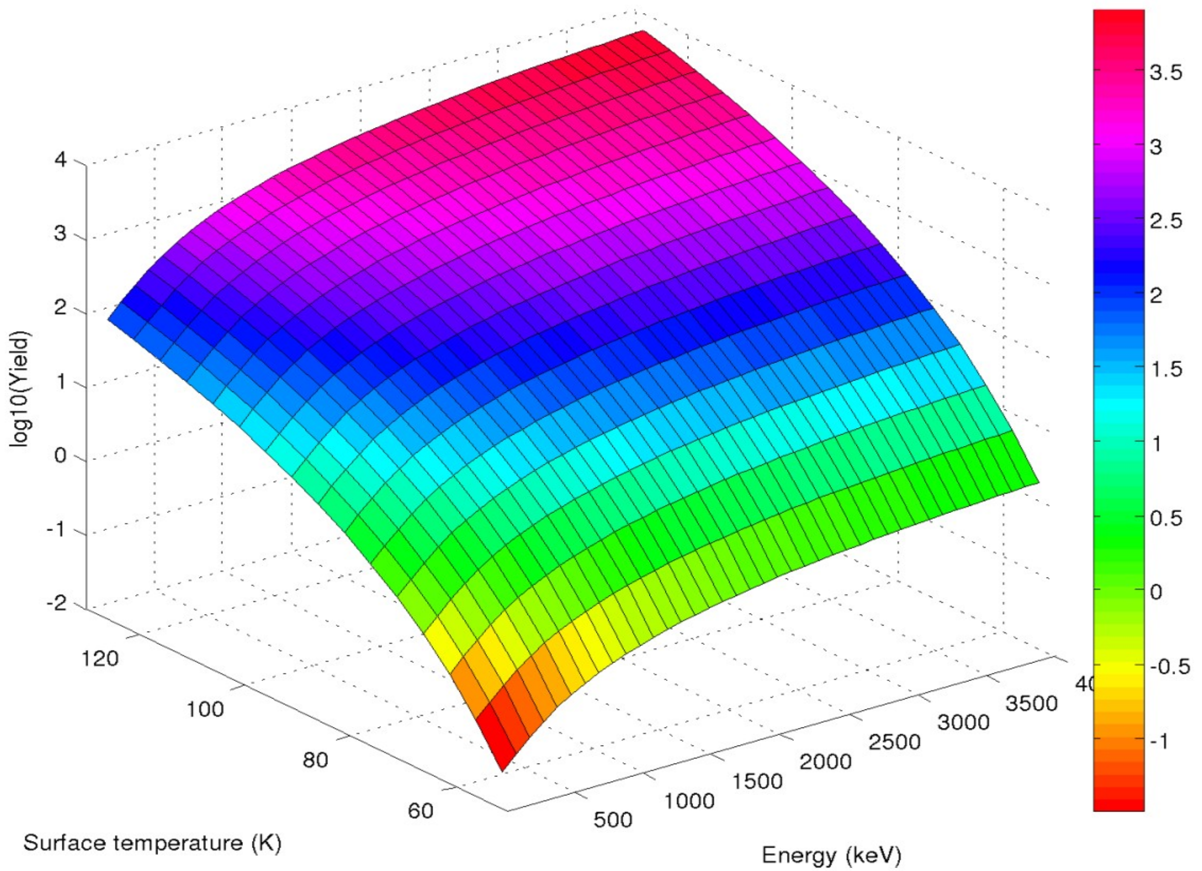
The **total yield** of the 'sputtered' products can be expressed as follows:

$$Y_{total} = Y_{water}(E)+Y_{diss}(E,T)$$

where $Y_{H2O}(E)$ is the portion of the sputtering yield that is **independent of temperature**, that we assign to the ejection of **sputtered H_2O molecules**, and $Y_{diss}(E,T(long,lat))$ is the yield associated to the **loss of O_2 and H_2**, produced on ice after irradiation of energetic ions **(radiolysis)** and **subsequent release**.

H_2 is eventually lost from ice stoichimetrically in a 2 to 1 ratio with O_2 .

Yield for O_2 released from icy surface bombarded by sulphur ions



$$Y_{H_2O}(E, m_1, Z_1, \theta, T) = \frac{1}{U_0}\left(\frac{3}{4\pi^2 C_0}\alpha S_n + \eta S_e^2\right) \times \left(1 + \frac{Y_1}{Y_0} e^{-E_a/kT}\right) \cos^{-f}(\theta)$$

Fama et al., 2008

where E, m_1, Z_1, θ are the energy, mass, atomic number, and angle of incidence, respectively, of the emitted particle. T is the surface temperature, U_o is the surface-binding energy, α is an energy-independent function of the ratio between the mass of the target m_2 and of the projectile m_1 .S_n is the nuclear-stopping cross section, S_e is the electronic stopping cross section, η is an oscillatory function of the atomic number of the projectile, and f is the exponent in the angular dependence term.

A MC Model for the Europa's exosphere

MODEL ASSUMPTIONS

Impacting ions trailing/leading asymmetry: A+B cos(θ) H (Ip et al., 1998, Cassidy et al., 2007)

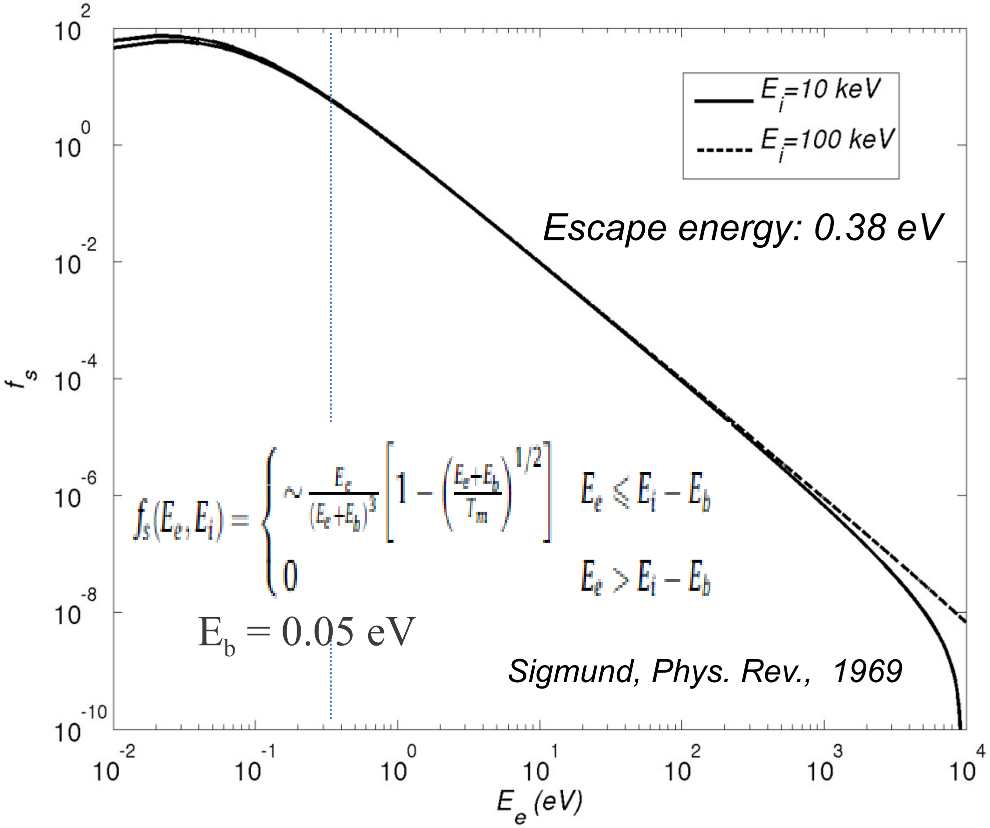
Surface composition : Water ice.

Release Processes : IS and radiolysis, IBS and PSD.
Energy and temperature dependent yield (Fama et al., 2008)
Surface temperature map of Spencer et al. (1999)
The released O_2 molecules re-impact to the surface, get thermalized and re-impact until electron impact ionization (τ=6 days) (Saur et al., 1998).

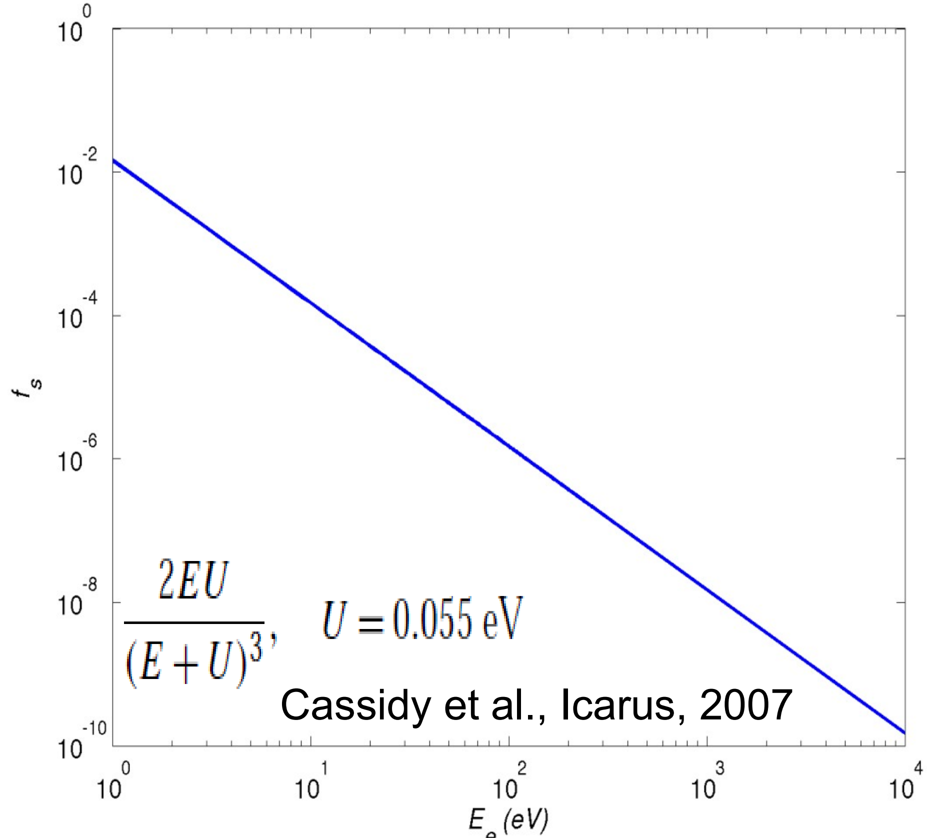
Sublimation is estimated on average.
MIV is considered negligible. In fact, although meteoroid energy influx may be locally and temporarily important, it is not significant for the global energy influx onto any of the Galilean satellites (Cooper et al. 2001).

Energy distribution of the sputtered H_2O and O_2 particles for S^+ fluxes

H_2O



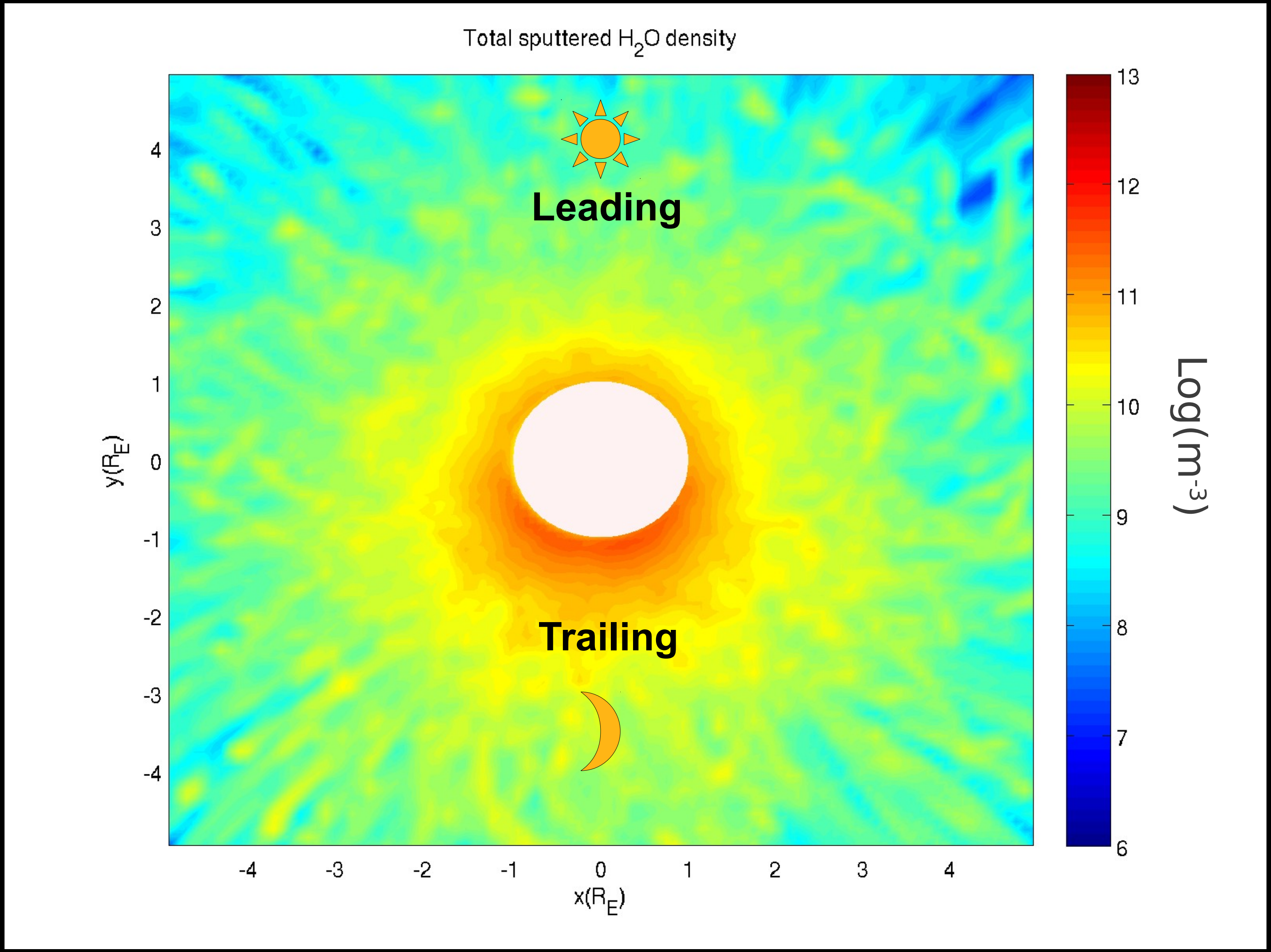
O_2



Plainaki presentation in HEWG Workshop, 12-16 June 2011, Italy

Results

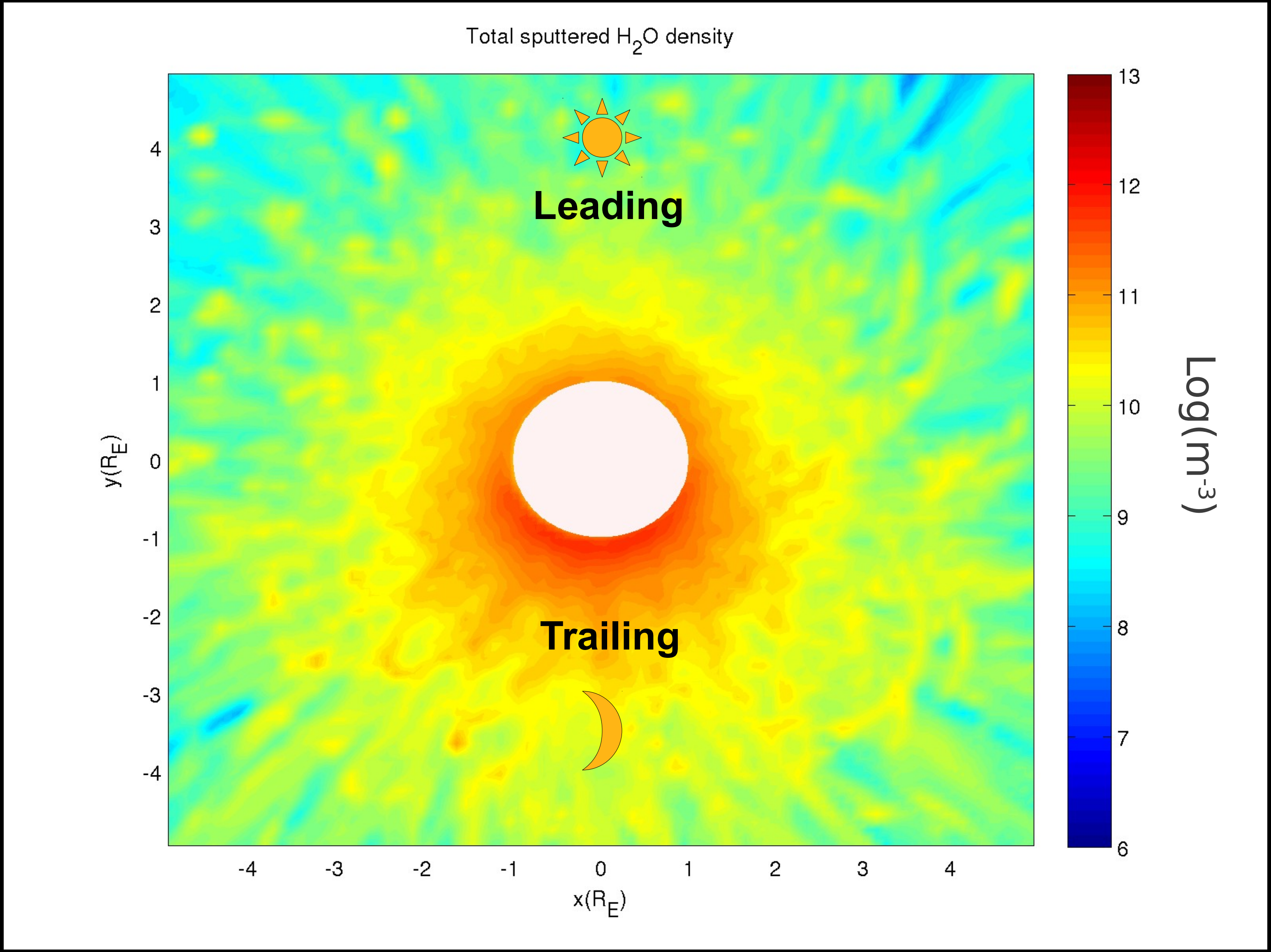
Sputtered H_2O molecules from S^+ bombardment



Plainaki et al., EGU, 2011

Density at the surface 5.6 10^{11} m^{-3}
Flux at the surface 7.4 10^{14} m^{-2} s^{-1}

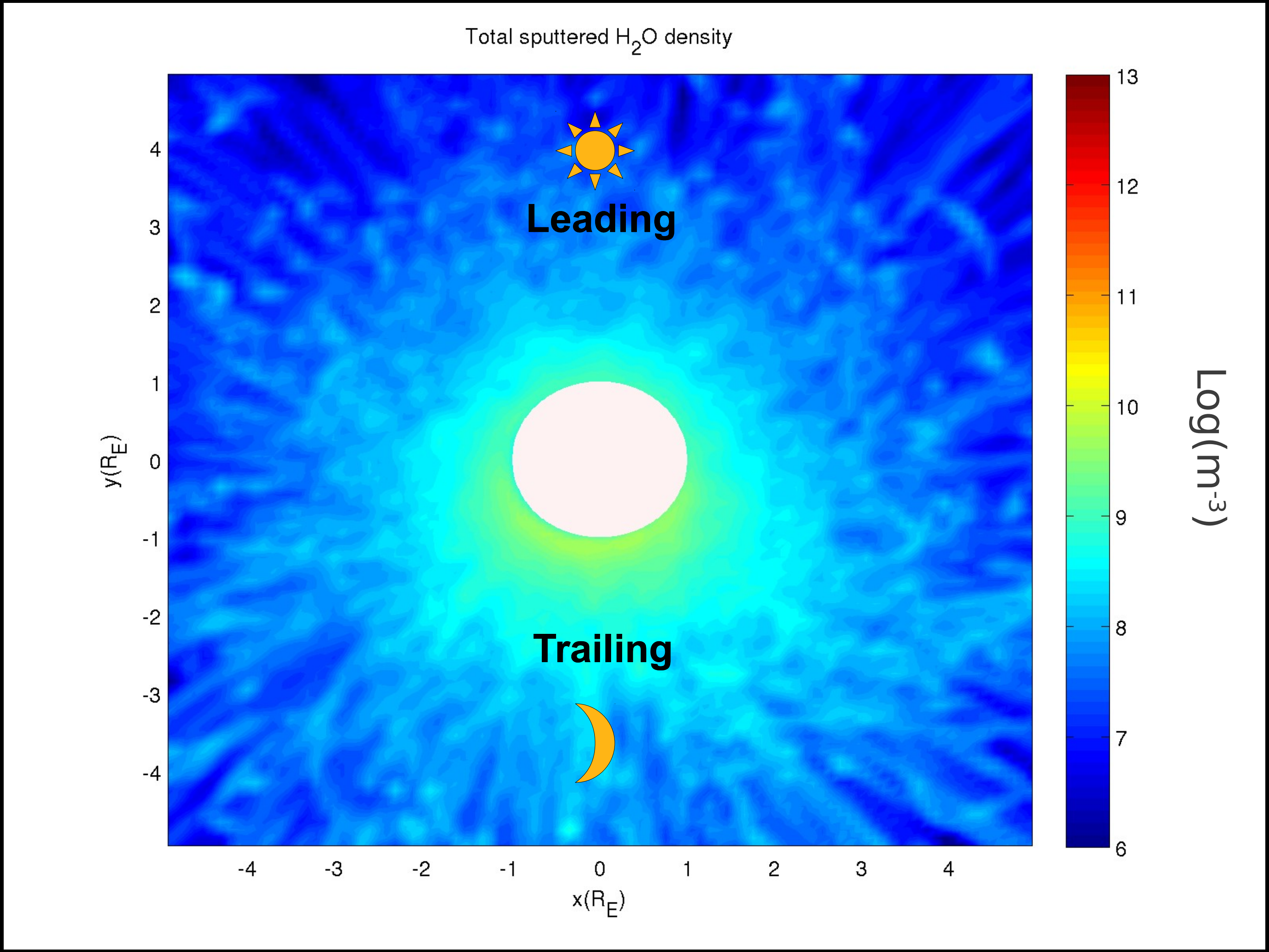
Sputtered H_2O molecules from O^+ bombardment



Density at the surface 1.1 10^{12} m^{-3}

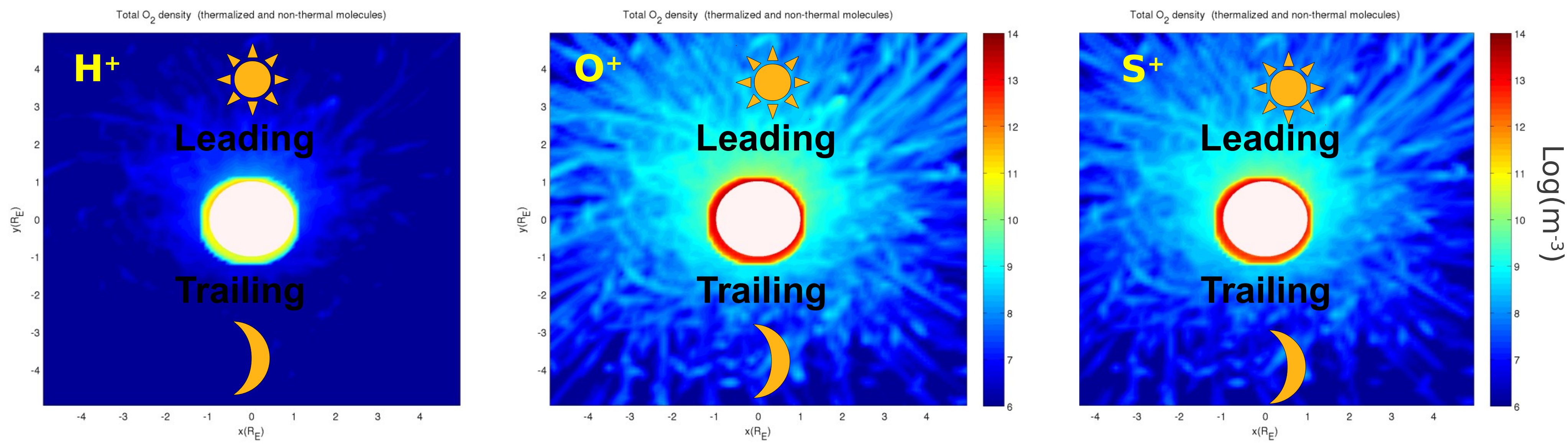
Flux at the surface 1.5 10^{15} m^{-2} s^{-1}

Sputtered H_2O molecules from H^+ bombardment



Density at the surface 9.6 10^{9} m^{-3}
Flux at the surface 1.1 10^{13} m^{-2} s^{-1}

Released O_2 molecules generated via radiolysis due to H^+, O^+, S^+ bombardment

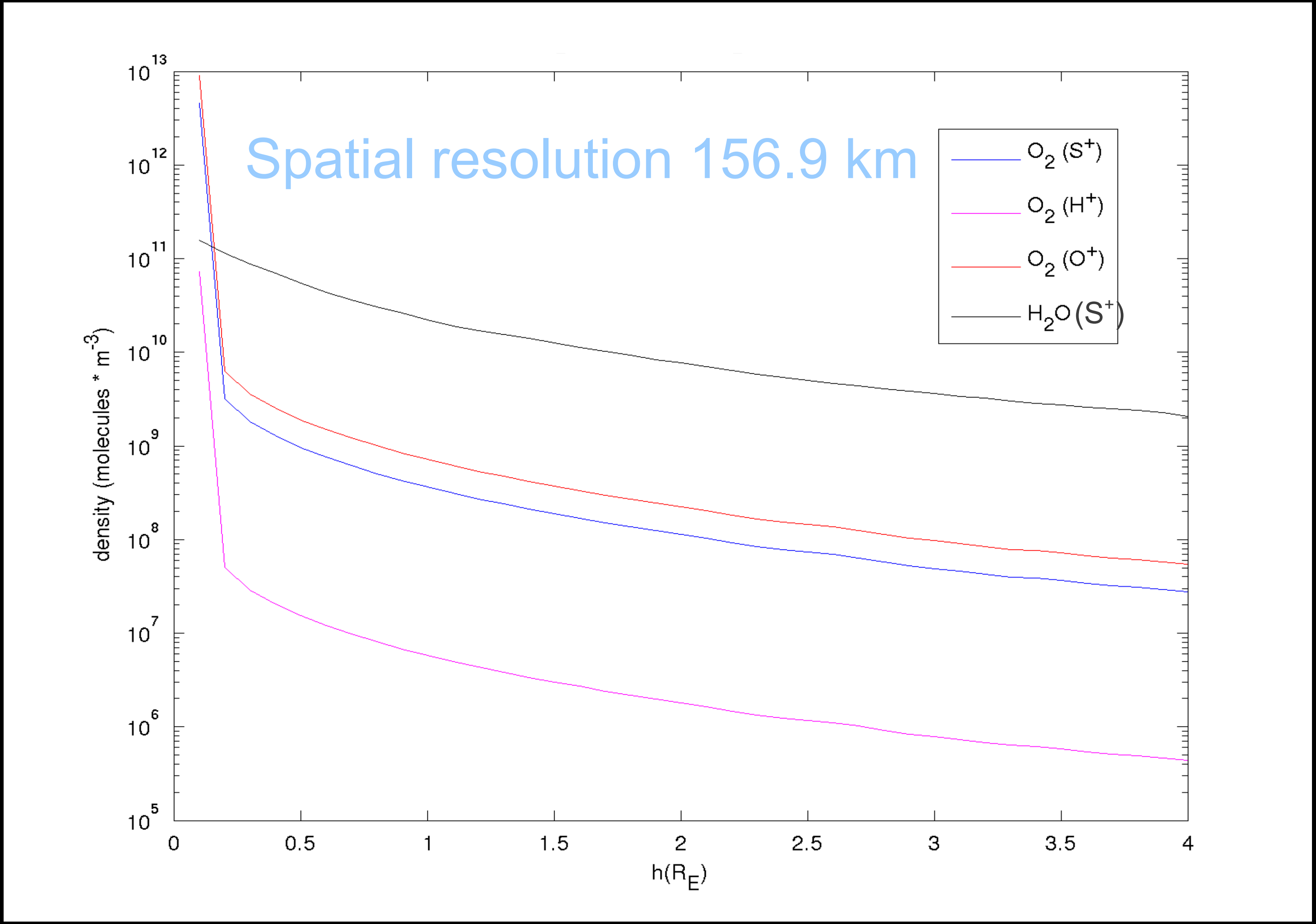


Total density at the surface $9.8\ 10^{13}\ m^{-3}$

The O_2 densities at high altitudes are much more significant at the sunlit hemisphere. At low altitudes the thermalization process dominates.

O_2 column density calculated on the basis of our simulation ($1.4\ 10^{19}\ m^{-2}$ dayside, $2\ 10^{18}\ m^{-2}$ nightside) are **similar to those obtained from the HST and those simulated by Cassidy et al. (2007).**

Globally averaged O_2 and sputtered water densities as a function of altitude from the surface



SHEA

The Sputtered High Energy Atoms (SHEA), that is, the high energy tail of the sputtered distribution (Ee>10 eV) (Mililllo et al., JGR, 2011) are about 22% of the total release.

SHEA detection provides a map of plasma precipitation regions and an imaging of particle emission from surface.
The problem here is the number of unknown parameters: *Y* (surface mineralogy, *Eb*, …), *c*, *Fion* (species, energy, impact angle,…).

Why is SHEA imaging important as well as of surrounding gas analysis?

The detection of particles above 10 eVs is a method to identify that the ion-sputtering is active and to define the region of its action.

A joint observation of surrounding gas and SHEA will permit to know **where, when and how** the ion sputtering release takes place and will permit a more clear **estimation of the escaping material**.

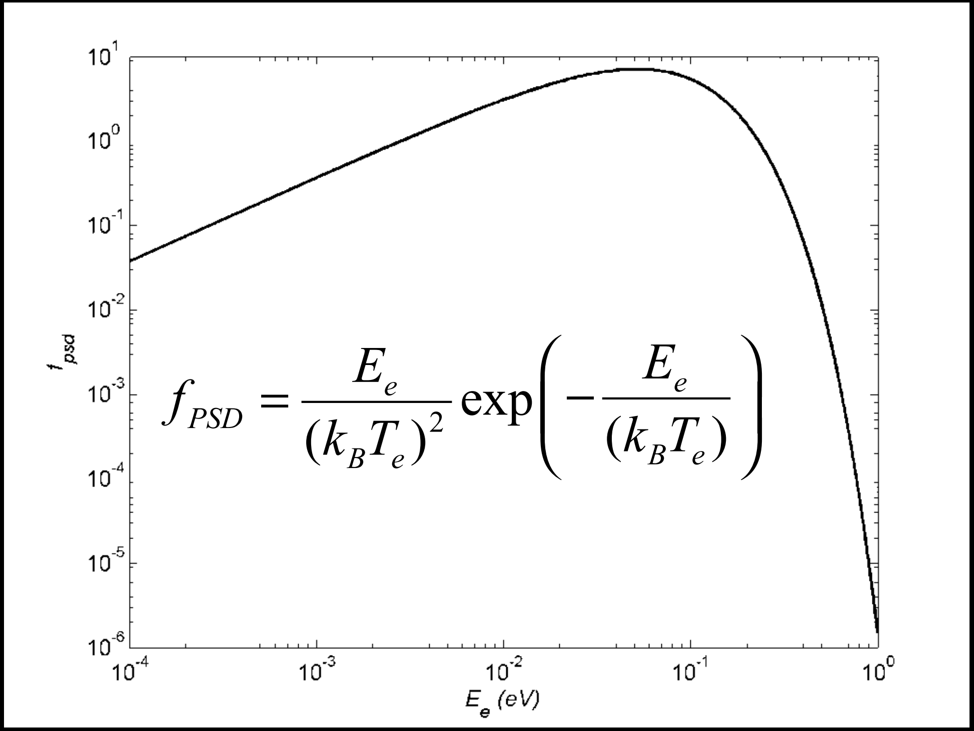
Photon stimulated desorption

The neutral flux released via PSD from the icy surface of Europa can be calculated on the basis of the following equation (Wurz and Lammer, 2003):

$$f_{\mathrm{PSD}} \approx \frac{1}{4} f_{\mathrm{photon}} \sigma_{\mathrm{PSD}} F d \cos(\phi)$$

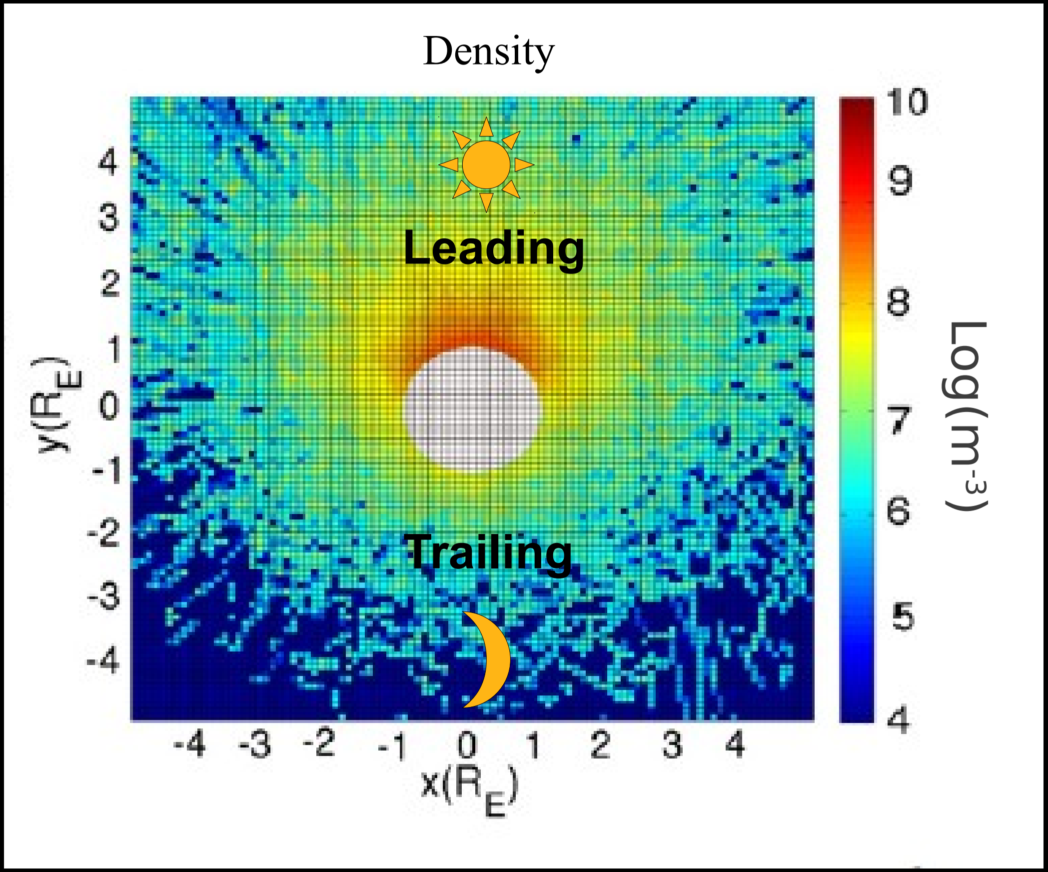
where f_{PSD} is the photon flux per unit area per time, integrated over the photon energy range > 7eV and equal to $5.8 \cdot 10^{10}$ $cm^{-2}s^{-1}$, F is the fraction of H_2O ice on the surface, equal to 0.99, d is the surface density, equal to $1.1 \cdot 10^{15}$ molecules/cm^2 (Dulieu et al., 2005) and σ_{PSD} is the PSD cross-section, calculated equal to 10^{-18} cm^2 .

Energy distribution function



Photon Stimulated Desorption

H_2O particles released via PSD from the iced surface of Europa



- The **H_2O density released via PSD** ($6\ 10^8$ H_2O/m^3 on the surface of the illuminated side) is **lower than that due to sputtering by 2 orders of magnitude**.
- The fraction of escaping particles via PSD is 30% thus meaning a total rate $3{,}3\ 10^{24}\ s^{-1}$.

Ion back scattering

When an ion is scattered from a target atom at an angle θ, the ratio of the scattered-ion energy *E* to the incident energy, *E*i, can be calculated using the laws of conservation of energy and momentum.

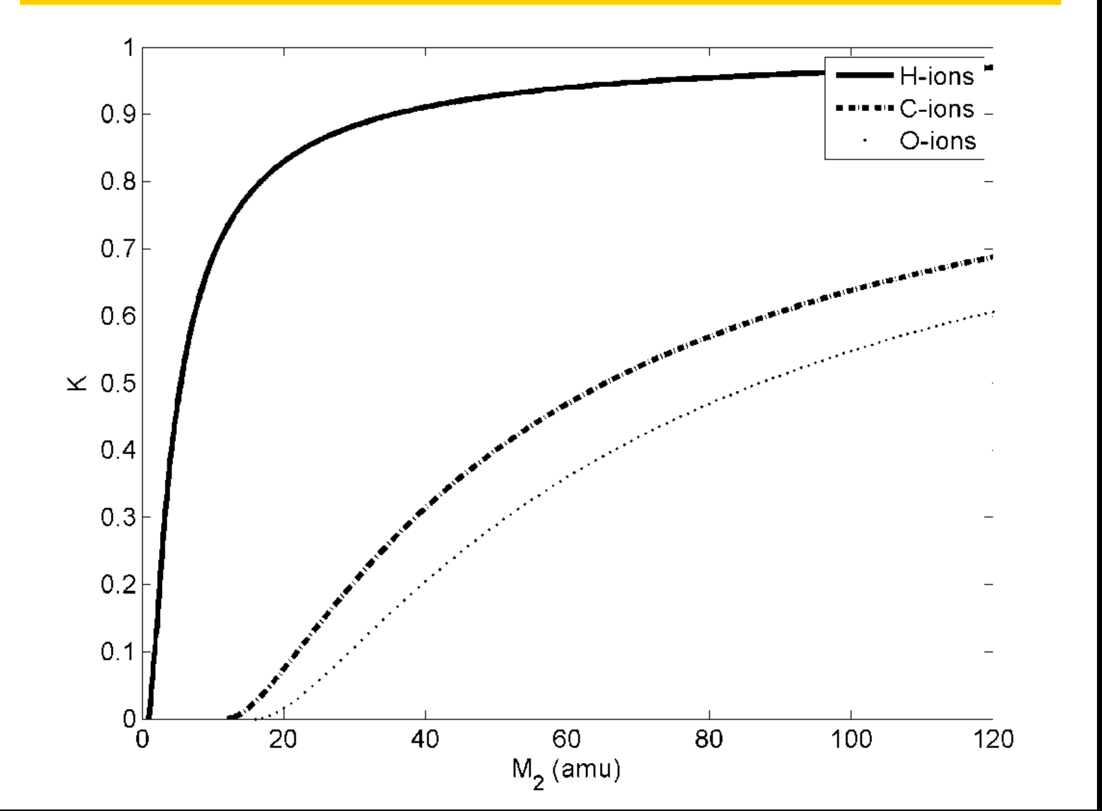
Kinematic factor

$$K = \frac{E}{E_i} = \left[\frac{\sqrt{M_2^2 - M_1^2 \sin^2\theta} + M_1 \cos\theta}{M_1 + M_2} \right]^2$$

where M1, M2 are the masses of the incident ion and target atom, respectively, θ is the scattering angle, Ei is the incident energy of the ion and E is the energy of the back-scattered ion.

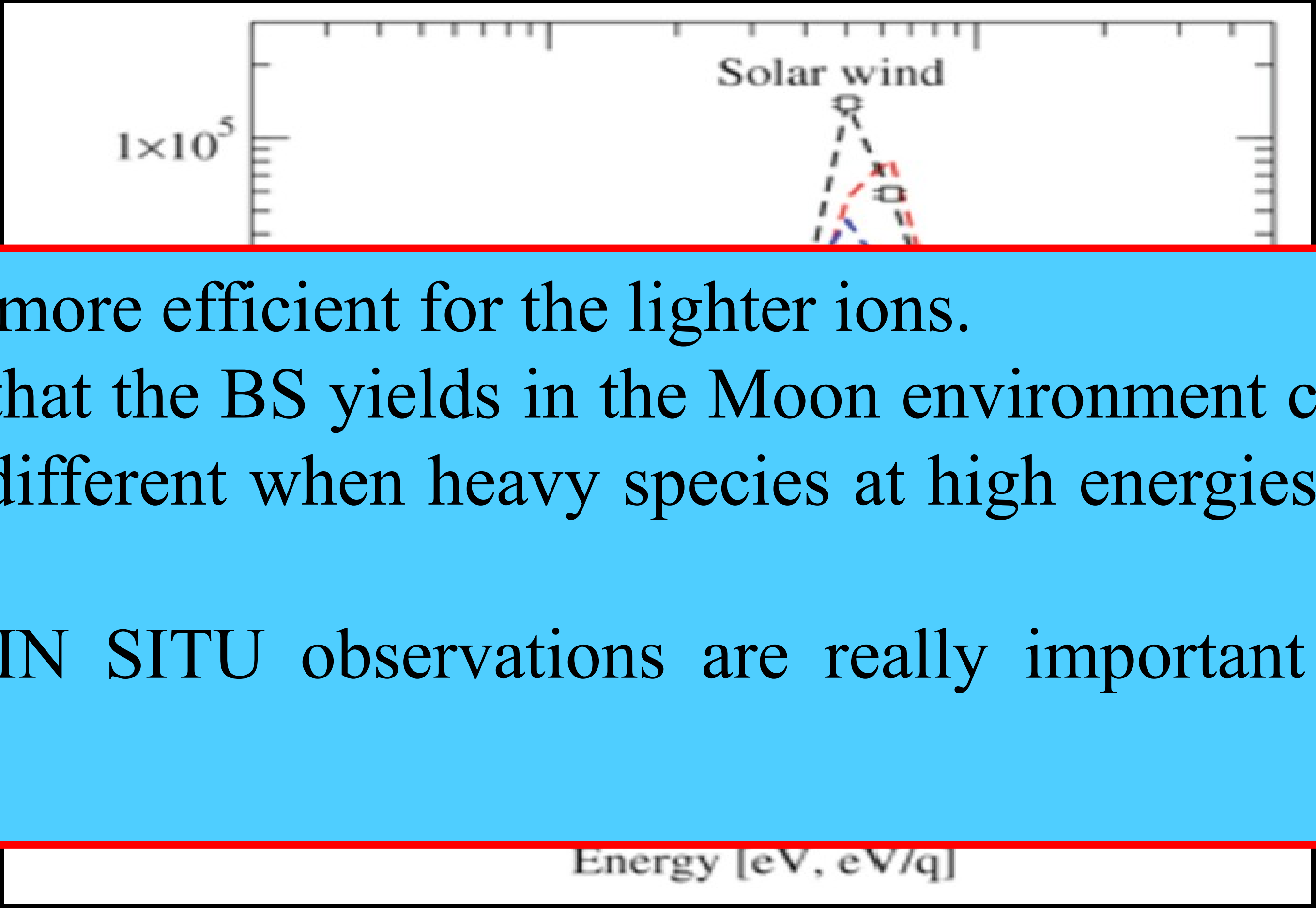
Back-scattering exists for cases where $\theta > 90^0$.

Kinematic factor as a function of various projectile ion masses masses scattered by different molecules (for example at 150 degrees).



Back-scattering from regolith (Moon)

Recenty, ENA measurements from the Moon, resulting from solar wind backscattering (McComas et al., 2009; Wieser et al., 2009), demonstrated that the **10-20%** of the impinging ion-flux is backscattered .



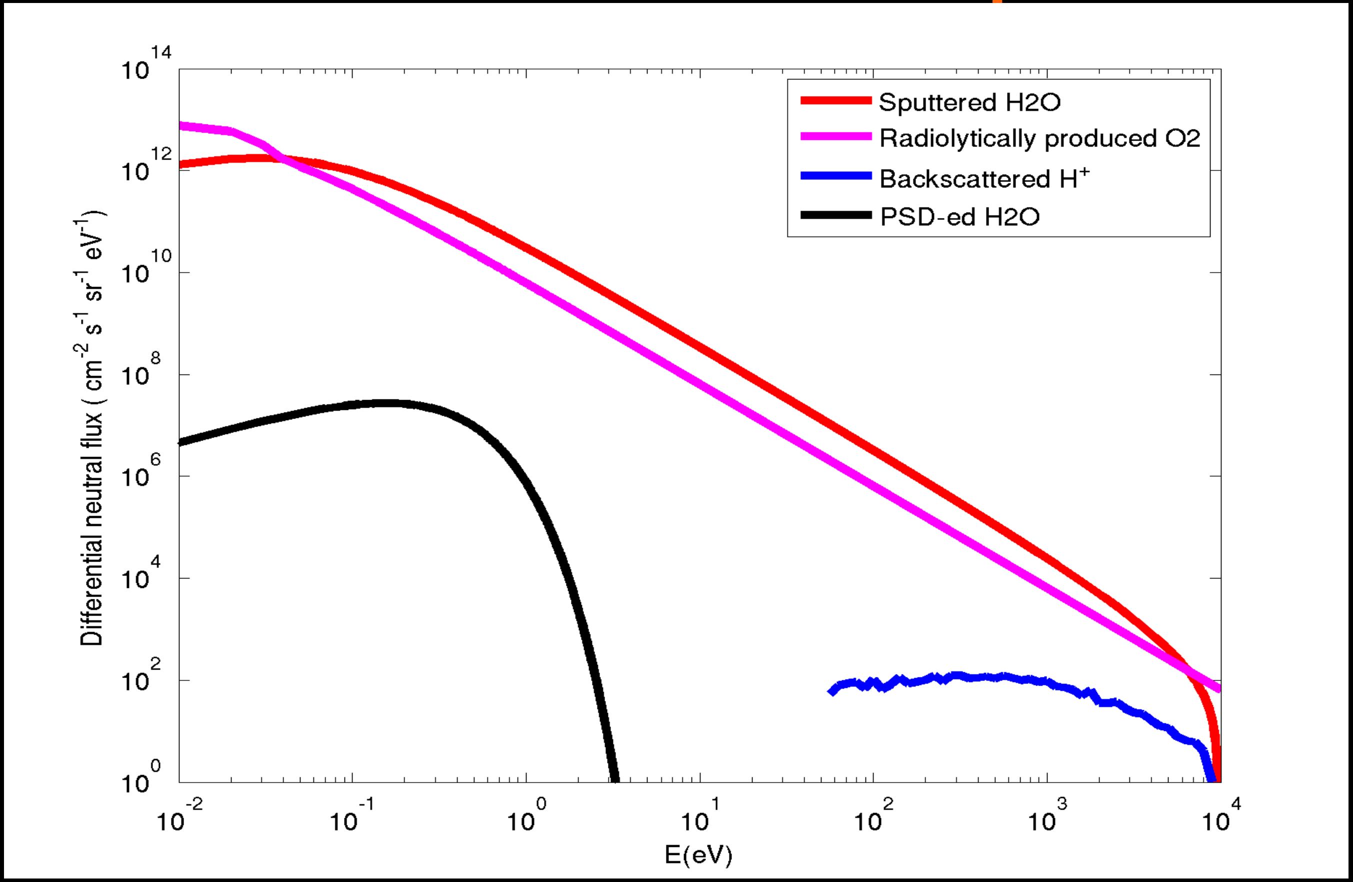
BS is more efficient for the lighter ions.

Note that the BS yields in the Moon environment could be much different when heavy species at high energies impact on ice.

New IN SITU observations are really important in this frame!

- The BS energy spectrum goes up to almost 1 keV (*Wieser et al.,* 2009)

Released flux spectra @ Europa



Exospheric spectra @ Europa due to IS,, Radiolysis+O_2 Thermalization, IBS and PSD

Different release mechanisms at the iced moons.

Sputtered H_2O are the most intense component in the energy range 10-1000 eV,

The **thermalized O_2 population** has a significant contribution in the lower energy range.

PSD for H_2O works but it is negligible.

Other release mechanisms **sublimation** and **MIV** should be better investigated .

Thermal desorption and Sublimation

Europa's temperature: 86 K - 132 K (Spencer et al., 1999).

The thermal energy of an ice H_2O molecule ranges between 0.011 eV and 0.017eV.

The binding energy holding the ice molecules on the surface of Europa, is 0.05 eV (Boring et al., 1984).

Consequently the particle release via the TD mechanism can be considered in general negligible.

However, locally, at sites where the temperature is relatively high, the H_2O vapour pressure and the sublimation rate increase (for 132K they become of the order of 10-11 dyn/cm^2 and 10^{11} H2O cm^{-2} s^{-1} respectively).

A more detailed calculation based on the surface temperature map of Spencer et al. (2005) is intended.

Conclusions

- Due to **asymetric ion precipitation, higher (lower) in the trailing (leading) hemisphere**, the **densities of sputtered H_2O molecules in the trailing hemisphere** are **bigger** than those at the leading hemisphere by a factor up to ~**4.**

- The **O_2 released molecules** due to radiolysis create a tenuous atmosphere **denser in the illuminated side (density at the surface of the illuminated hemisphere 9.8 $\cdot 10^{12}$ H_2O /m^3) .**

- The major agent for **Europa's surface erosion is ion sputtering** on both the non-illuminated and illuminated side.

- The **H_2O density due to PSD** (6 $\cdot 10^{8}$ H_2O /m^3, on the surface of the illuminated side) is much **lower than that due to sputtering (total sputtered water density 1.8** $\cdot 10^{12}$ H_2O /m^3**)**

Conclusions

- **The most significant sputtered-particle flux and density** come from the **O** impinging ions ($1.5 \cdot 10^{15}$ H_2O /m^2 /s and $1.1 \cdot 10^{12}$ H_2O /m^3, respectively).

- **At the surface of the trailing hemisphere** the total sputtered-water **flux** and **density** are $2.2 \cdot 10^{15}$ H_2O /m^2 /s and $1.8 \cdot 10^{12}$ respectively H_2O /m^3 .