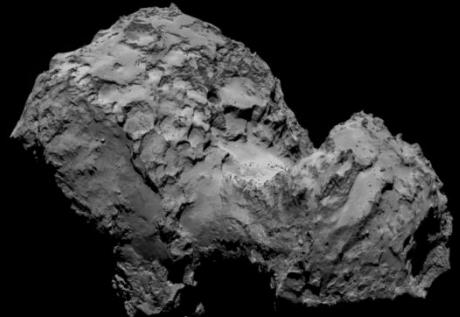


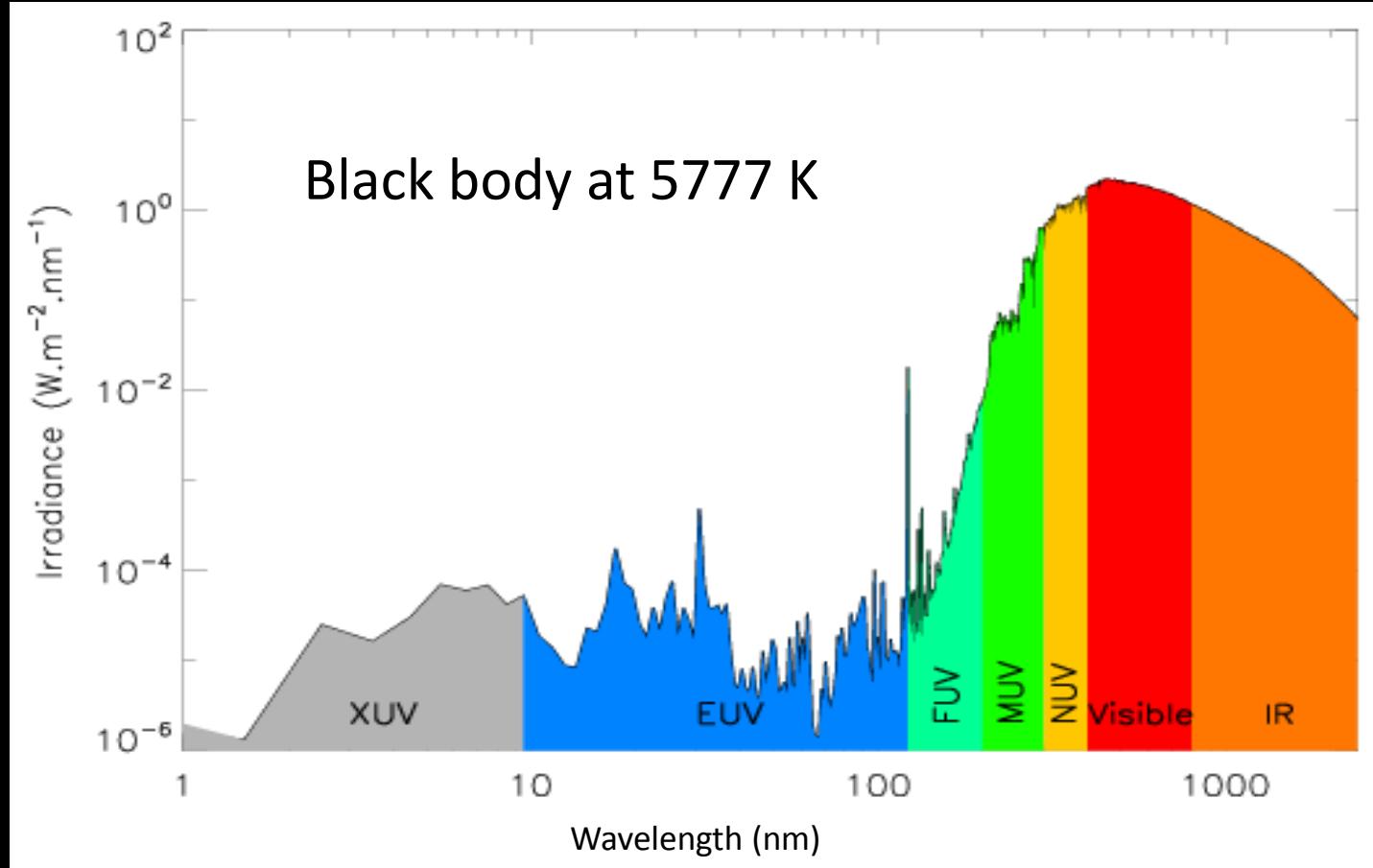
BELGISH INSTITUUT VOOR RUIMTE-AERONOMIE INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE BELGIAN INSTITUTE OF SPACE AERONOMY BELGISH INSTITUUT VOOR RUIMTE-AERONOMIE INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE BELGIAN INSTITUTE OF SPACE AERONOMY BELGISH INSTITUUT VOOR RUIMTE-AERONOMIE INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE BELGIAN INSTITUTE OF SPACE AERONOMY BELGISH INSTITUUT VOOR RUIMTE-AERONOMIE INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE BELGIAN INSTITUTE OF SPACE AERONOMY

Solar Irradiance and Upper Atmospheres

G. Cessateur

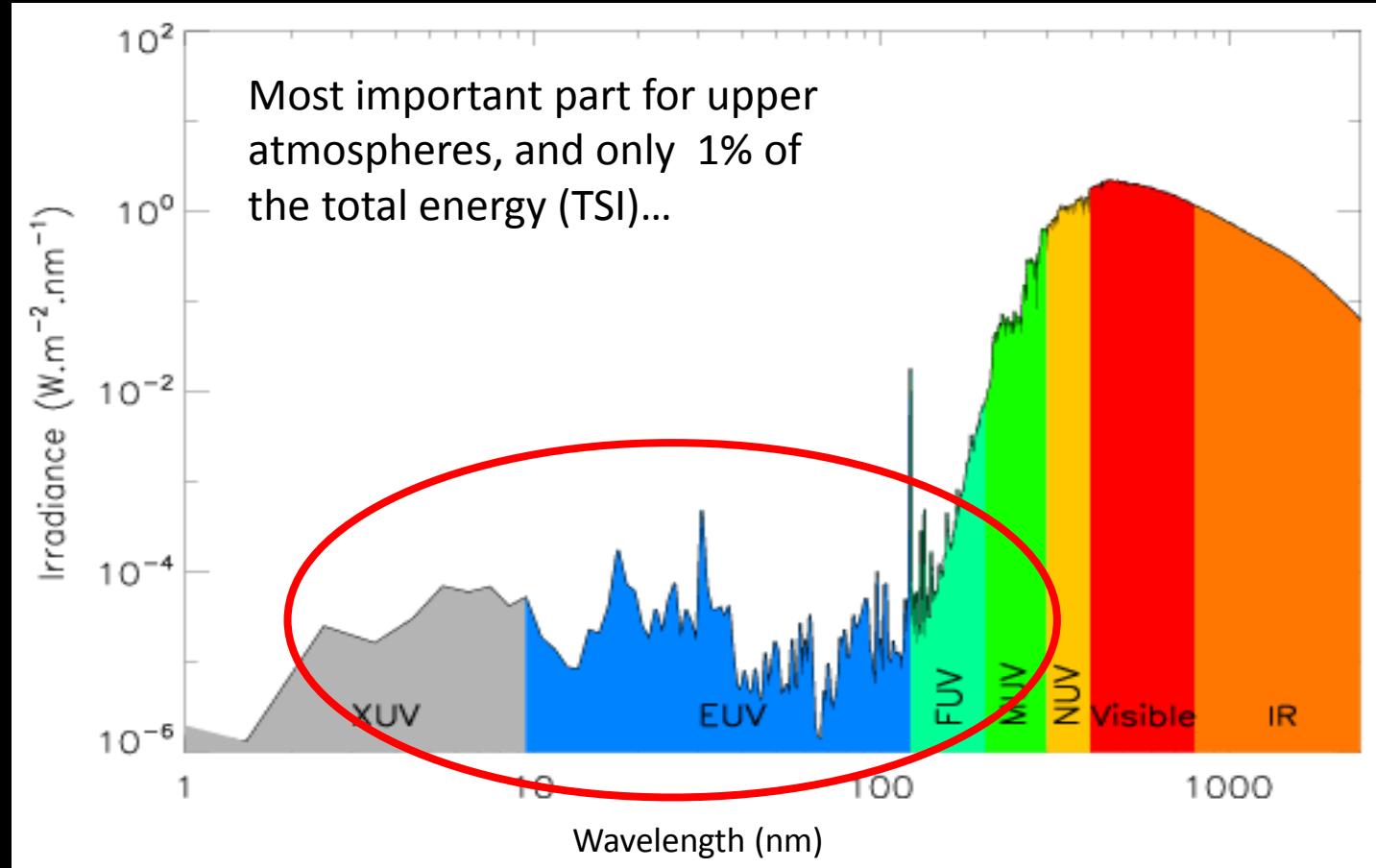


Solar Irradiance = Solar spectrum



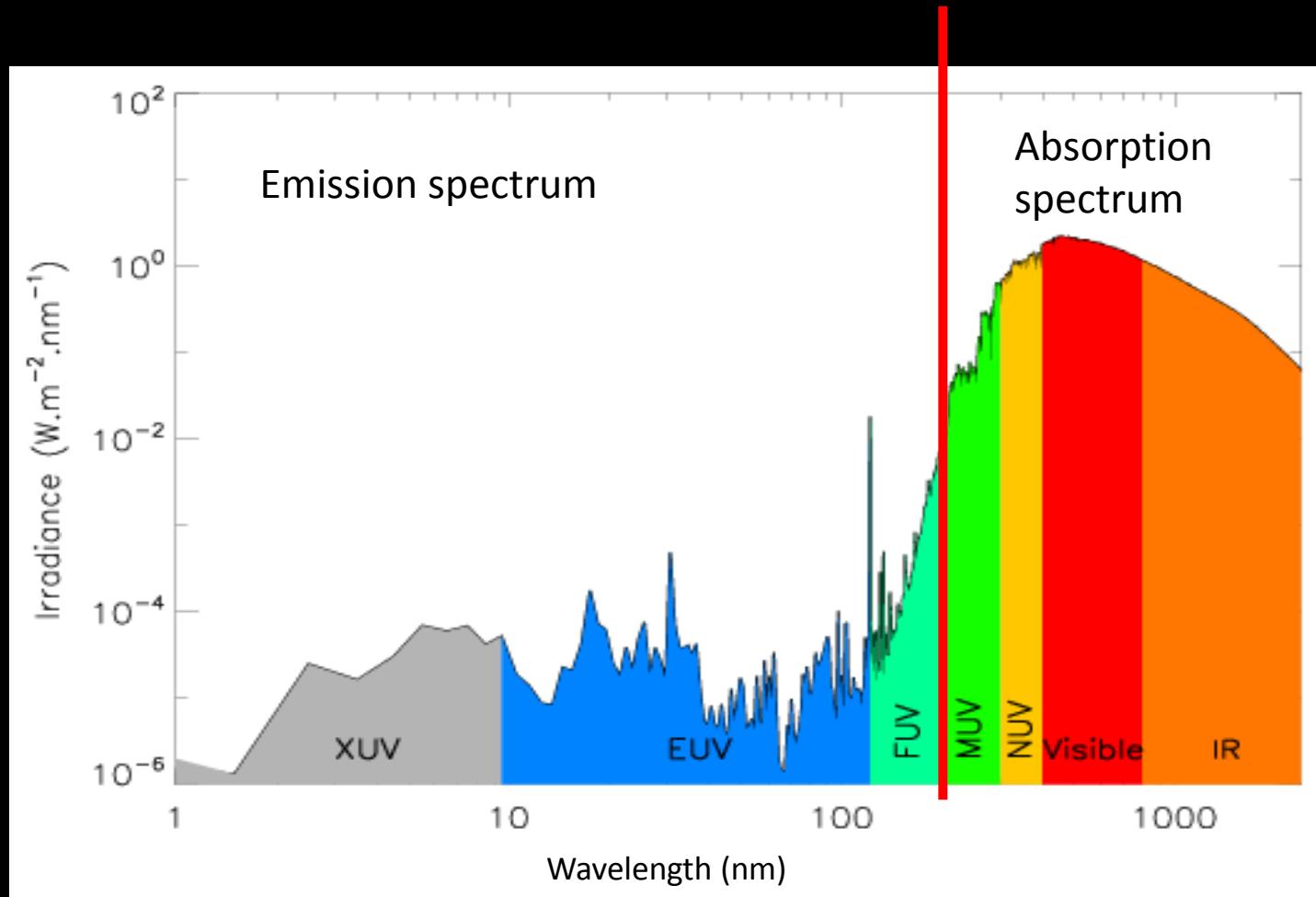
(But the Sun has an atmosphere...)

Solar Irradiance = Solar spectrum



Direct link with planetary space weather as we shall see at the end....

Solar Irradiance = Solar spectrum



How to model the Solar Spectral Irradiance ?

And why ?

Solar Irradiance

Rayleigh-Jeans law (XIXè)

But “Ultraviolet problem”...

$$I(\lambda) = \frac{2k_B c T}{\lambda^4}$$

Planck law (Black Body) (1900)

Correct at the 1st order....

$$U(\lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

....but can not explain the observed ionized nitrogen in the Earth's upper atmosphere (Saha, 1937)....

At least 10^6 EUV photons are missing...

Solar Irradiance

Talk from M. West : upper solar atmosphere (corona) is much more hotter (i.e. energetic) than the photosphere

The solar corona is extremely hot (10^6 K), but most importantly not very dense... composed by ionized and excited elements.

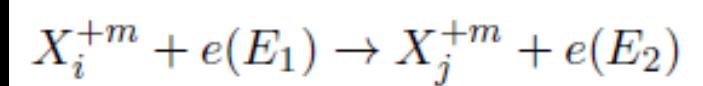


Emission Processes ?

Solar Irradiance

Excited elements ?

Inelastic collisions (no conservation of the kinetic energy)



i<j: excitation

i>j: desexcitation

Electron with an energy E_1 will give to the ion some energy through collision, so that the ion energy will go from level i to level j so,

$$E_1 \geq E_j - E_i.$$

Rate coefficient of this reaction ?

Solar Irradiance

Electron population , with a velocity interval $[v, v+dv]$

$$N_e(v, v + dv) = N_e f(v) 4\pi v^2 dv$$

with N_e the electron density and $f(v)$ the electrons velocity distribution

$$f(v) = \left(\frac{m}{2\pi k_b T} \right)^{\frac{3}{2}} \exp \left(-\frac{mv^2}{2k_B T} \right)$$

Maxwell-Boltzmann distribution

Total number of collisions for the $j \rightarrow i$ transition

$$N_{coll}^{ji} = N_e \int_0^\infty f(v) \sigma_{ij}(v) v 4\pi v^2 dv$$

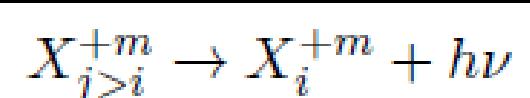
Solar Irradiance

By dividing by N_e , we get the reaction coefficient for the deexcitation by collisions. Same idea for obtaining the reaction rate for the excitation by collisions.

$$C_{ji}^d = \int_0^\infty f(v) \sigma_{ij}(v) v 4\pi v^2 dv , \text{ en cm}^3 \text{s}^{-1}$$

σ , the cross section for the collision process, which depends on the considered ions.

We also have to consider another loss reaction, i.e. the radiative decay, with the Einstein coefficient A_{ij}



Solar Irradiance

Equilibrium state (Conservation law)

1. Excitation process: collisions by electrons
 2. De-excitation processes: collisions and radiation

Oversimplified model with only two levels (g and i)

$$N_e N_g C_{gi}^e = N_i (N_e C_{ig}^d + A_{ig})$$

Coronal assumption, very low density

$$\rightarrow N_e N_g C_{gi}^e = N_i A_{ig}$$

In fine, everything is proportional to the Electron density !!!

Solar Irradiance

Demonstration correct only for the corona !!!!

For the photosphere and chromosphere, the density is more important, so that the radiative transfert has to be taken into account

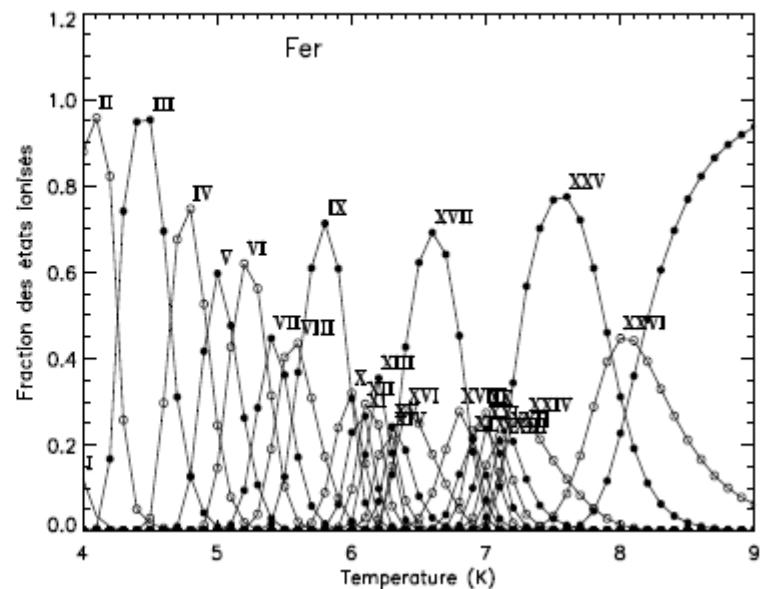
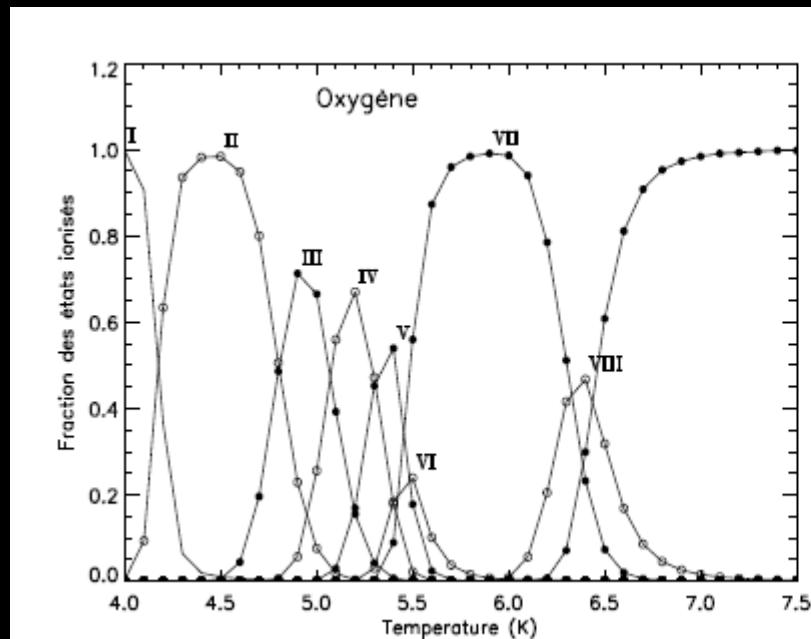


But in that case, we will be within the absorption part of the solar solar spectrum ($\sim > 200 \text{ nm} =$)!

Solar Irradiance

What about the ionized elements ?

Very similar approach compared to the excited elements...



Mazotta et al, 1998

Solar Irradiance

General rule: more the temperature and density are high enough



More the higher levels states will be occupied

Ex: $\log(T) = 5.8 \longrightarrow$ Fe IX, and the most probable excitation state leads to emission at 17.1 nm

As a reminder, observations at one particular wavelength give structural information for a one particular altitude.

Solar Irradiance

General rule enough

ire high

More the

Ex: $\log(T)$
excitation

able

As a remir 2003/08/12 13:00 elength
give structural information for a one particular altitude.

Solar Irradiance

How to estimate the solar irradiance from this ?

Emitted power through radiative decay

Optically thin medium

$$P_{ij} = N_j(X^{+m}) A_{ji} \Delta E_{ij} \quad \text{erg} \cdot \text{cm}^{-3} \cdot \text{s}^{-1}$$



Irradiance calculation on top the solar atmosphere

$$I = \frac{1}{4\pi} \int P_{ij} ds$$

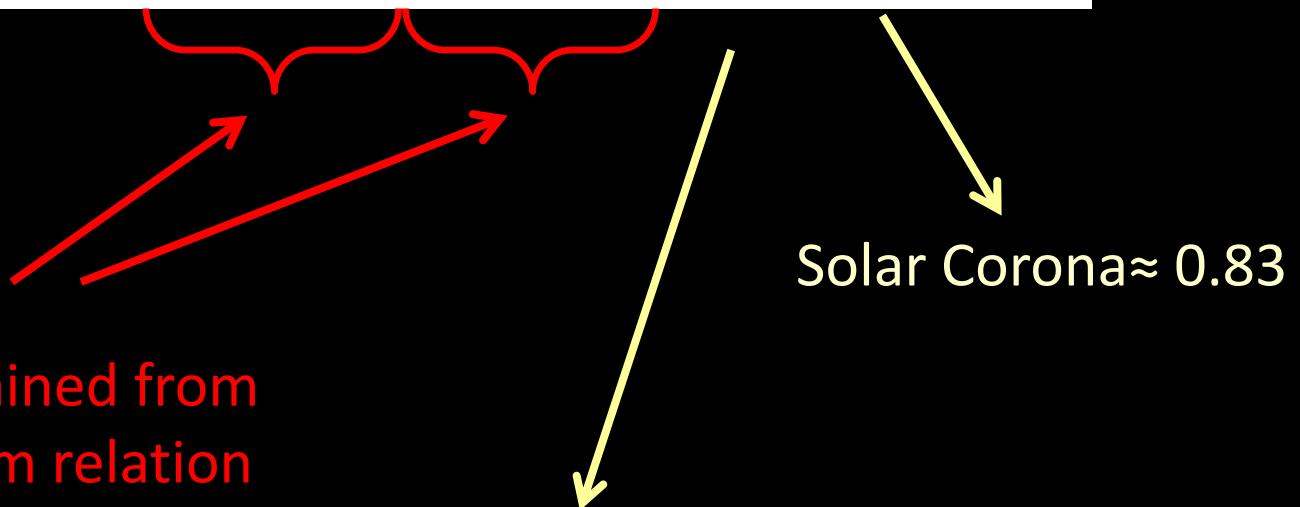


Line of sight

Solar Irradiance

Let us try to find some known parameters

$$N_j(X^{+m}) = \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} N_e$$



Solar Corona ≈ 0.83

Ratio obtained from equilibrium relation

Abundance model depending on the star; Key parameter for the absorption spectrum

Solar Irradiance

$$P_{ij} = N_j(X^{+m}) \ A_{ji} \ \Delta E_{ij} \quad erg \cdot cm^{-3} \cdot s^{-1}$$

+

$$G(T, N_e) = \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} \frac{A_{ji}}{N_e} \Delta E_{ij}$$

$$I = \frac{1}{4\pi} \int G(T, N_e) N_e^2 ds$$

Physics of the transition

Physical parameter of the medium

Solar Irradiance

Almost done....

The electronic density evolves accordingly to the altitude, and then to the temperature. We introduce the Differential Emission Measure (DEM)

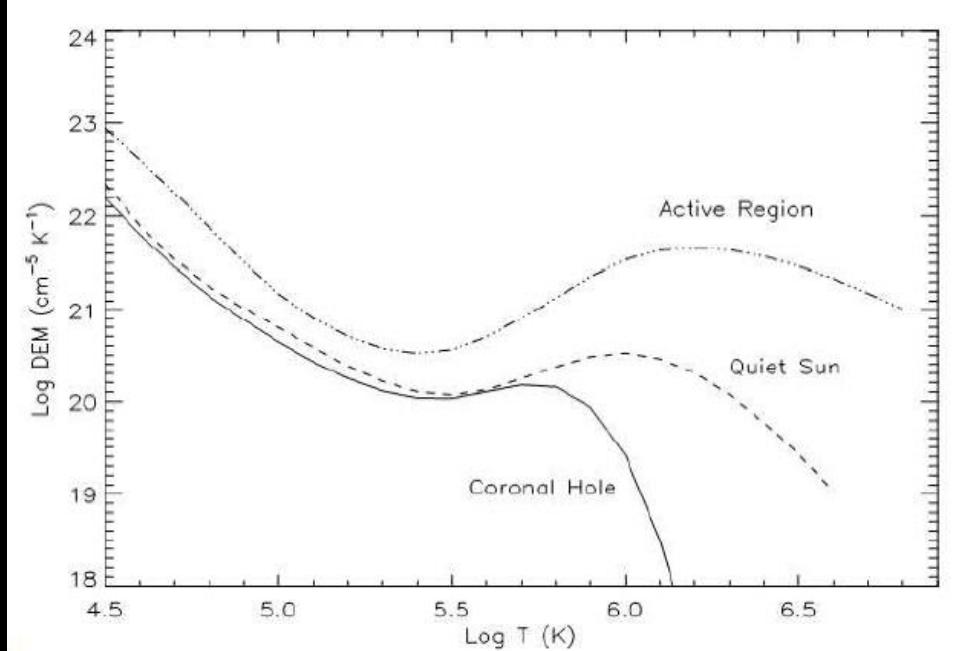
$$\xi(T) = N_e^2 \frac{ds}{dT}$$



$$I = \frac{1}{4\pi} \int G(T, N_e) \xi(T) dT$$

Each structure has his own DEM, with an associated radiance.

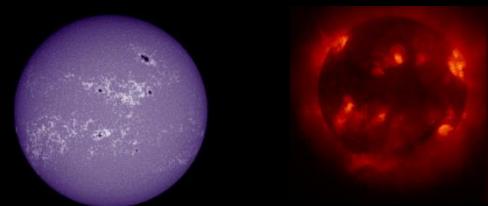
Solar Irradiance



Philips et al, 2008

We should in theory retrieve the irradiance from the typical DEM, but not very precise method...

Empirical or Semi-Empirical methods do work better...



“Filling Factors” obtained from EUV images

Warren et al, 1998, 2001;
Kretzschmar et al, 2006

Solar Irradiance

And the continuum...



(i) Free-Free emission: Bremsstrahlung

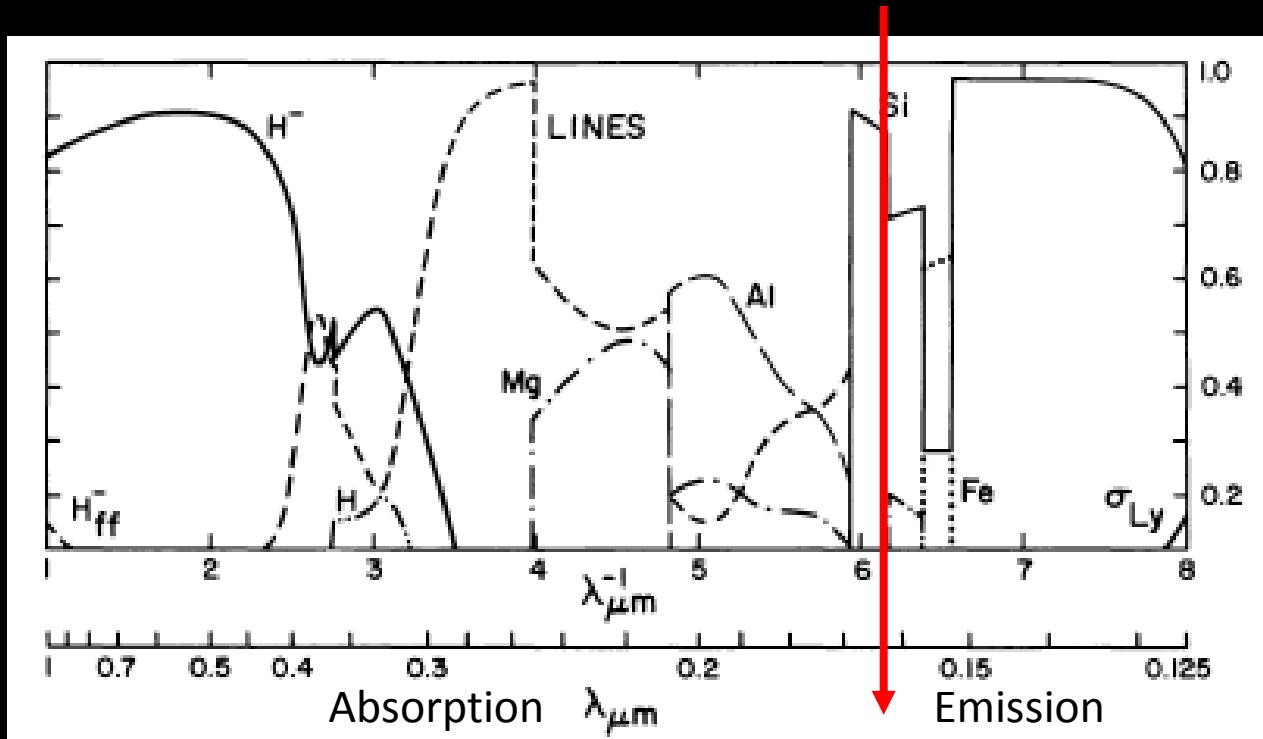
(ii) Free-bound emission

Photons energy can not down below the ionization energy for a considered element, E_i

$$h\nu_c = E_I - E_{i+}$$

Solar Irradiance

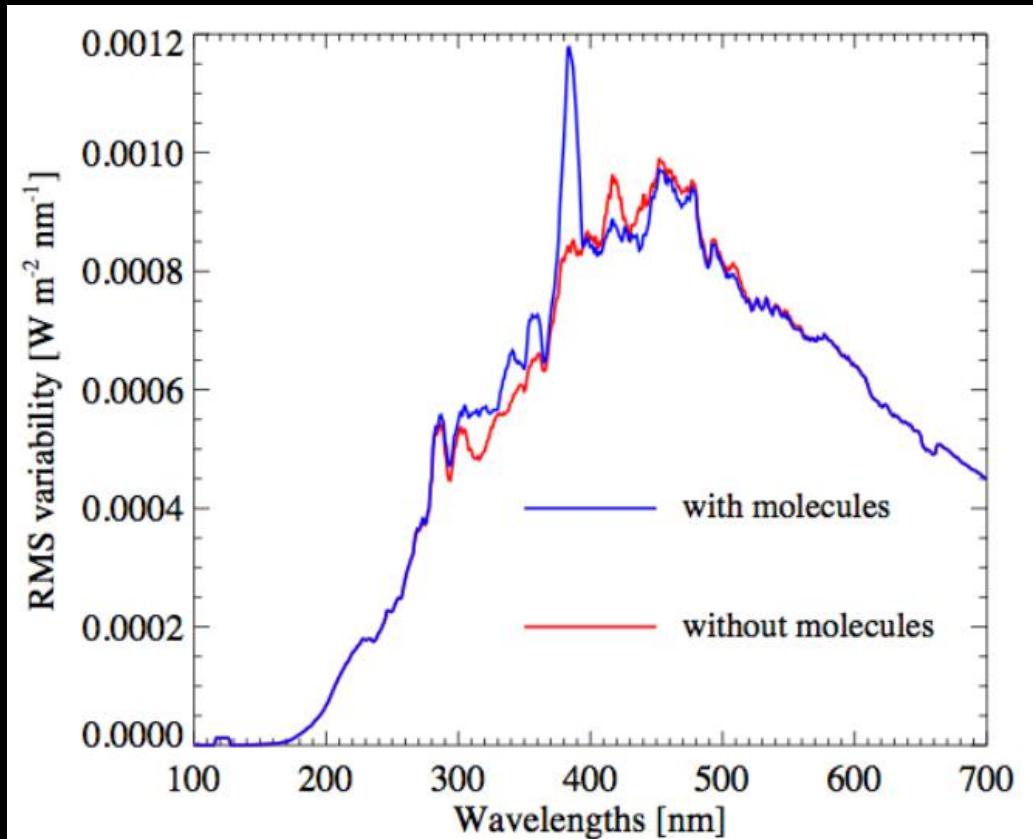
Typical threshold for each element



Vernazza et al, 1976

Solar Irradiance

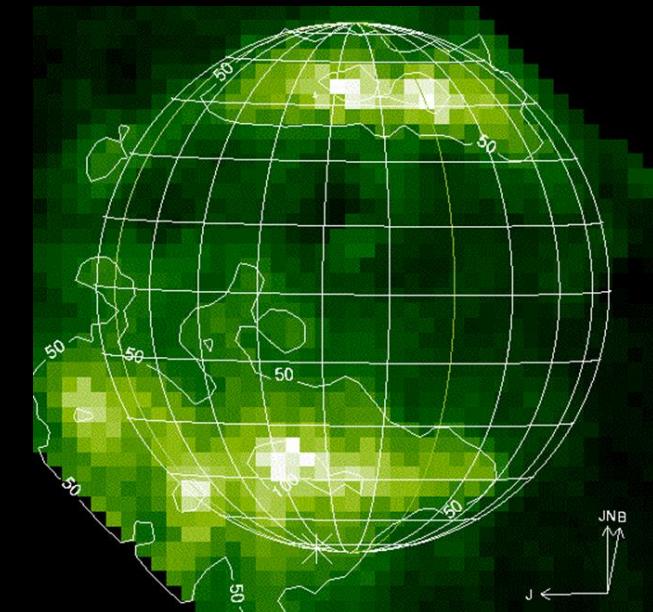
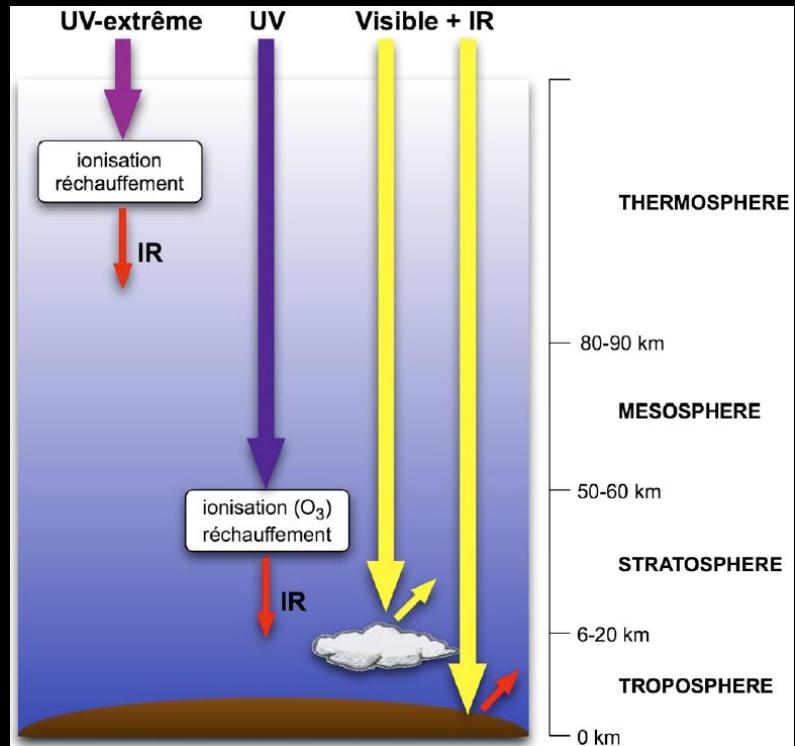
What about molecules ?



CN: only important for the solar spectrum > 300 nm

External forcing and upper planetary atmospheres

Solar UV flux impact leading to dayglow emissions

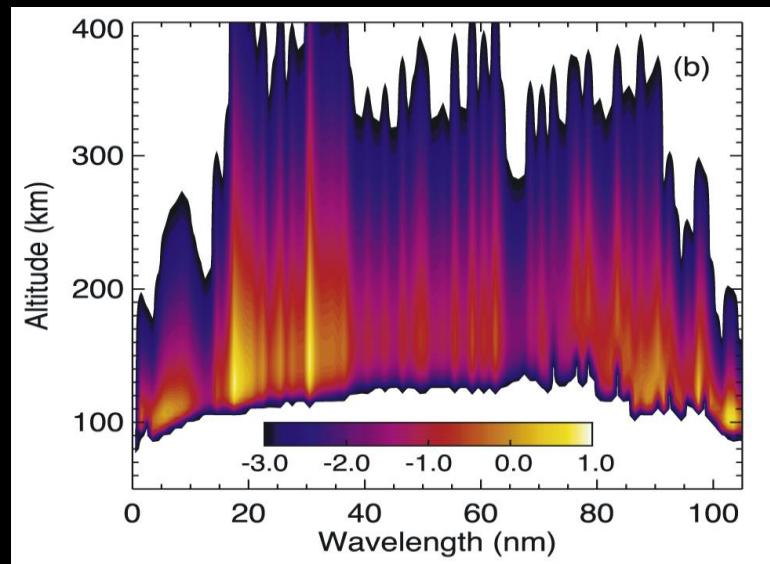


Electronic precipitations leading to auroral emissions

Solar Irradiance and upper planetary atmospheres

The UV part is critical for the upper planetary atmosphere

- EUV does control the ionosphere
 - 1-300 nm: chemistry and dynamic of the atmospheres (i.e. ozone et O₂)
 - 200-350 nm: main heat source for the mesosphere and stratosphere.



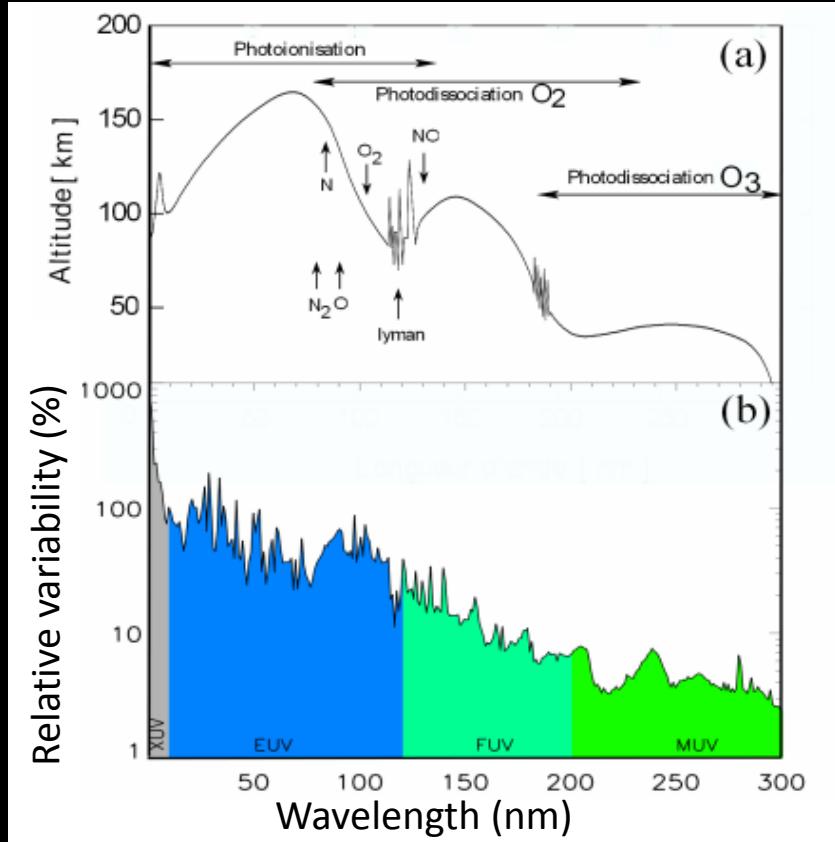
From Solomon and Qian 2005

UV flux heats the thermosphere

Thermal expansion of the atmosphere,
neutral density can doubled at 400 km.

$$R = \frac{1}{2} \rho v^2 A C_d$$

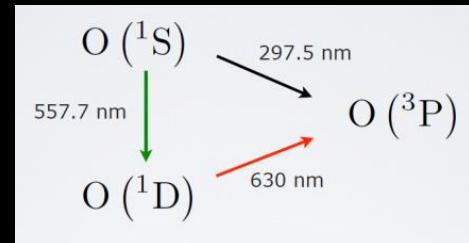
Solar Irradiance and upper planetary atmospheres



O₂ Photodissociation due to the Solar UV flux



Production of different excited oxygen states

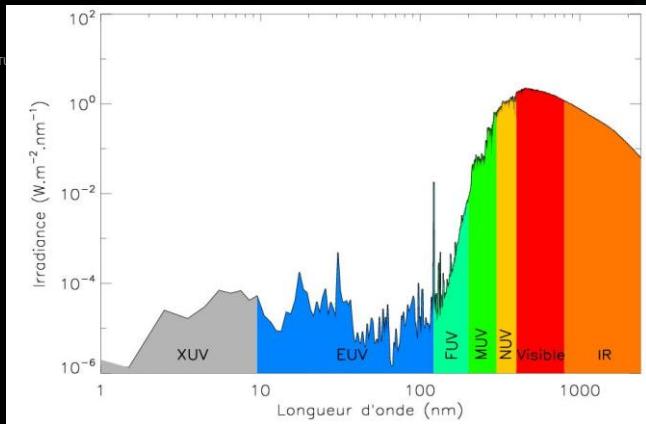


Planetary atmospheric emissions from oxygen

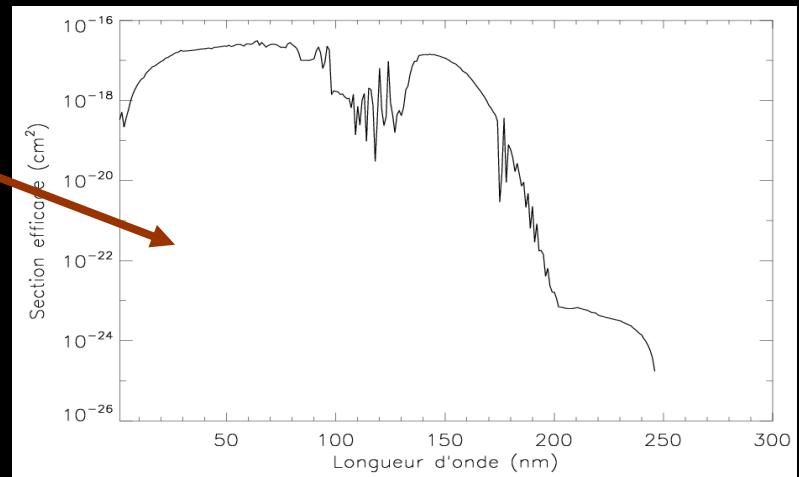
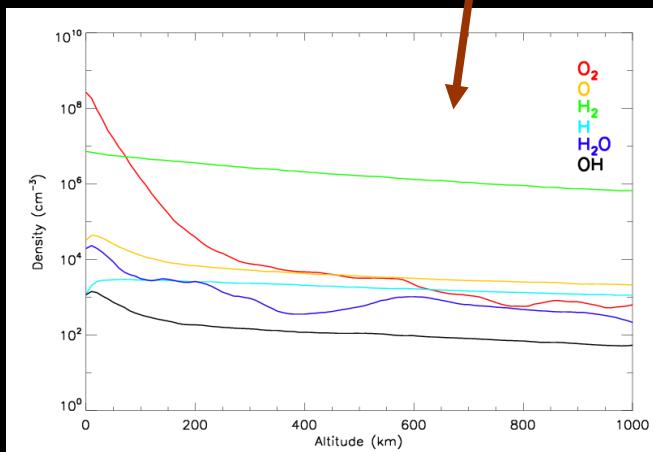
Solar Irradiance and upper planetary atmospheres



Beer-Lambert law



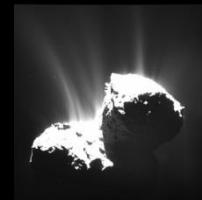
$$F(z, \lambda) = F_\infty \exp\left[\int_z^\infty n_k(s) \sigma_k ds\right]$$



Solar UV for each altitude within the atmosphere



Cometary neutral atmosphere for 67P



Haser model: spherical model



Water abundance

$$n_i(r) = \frac{Q_p}{4\pi v_i r^2} (e^{-\beta_i/r})$$

$$Q_p = 4 \times 10^{27} \text{ s}^{-1}$$

$$V_i = 0.8 \text{ km.s}^{-1}$$

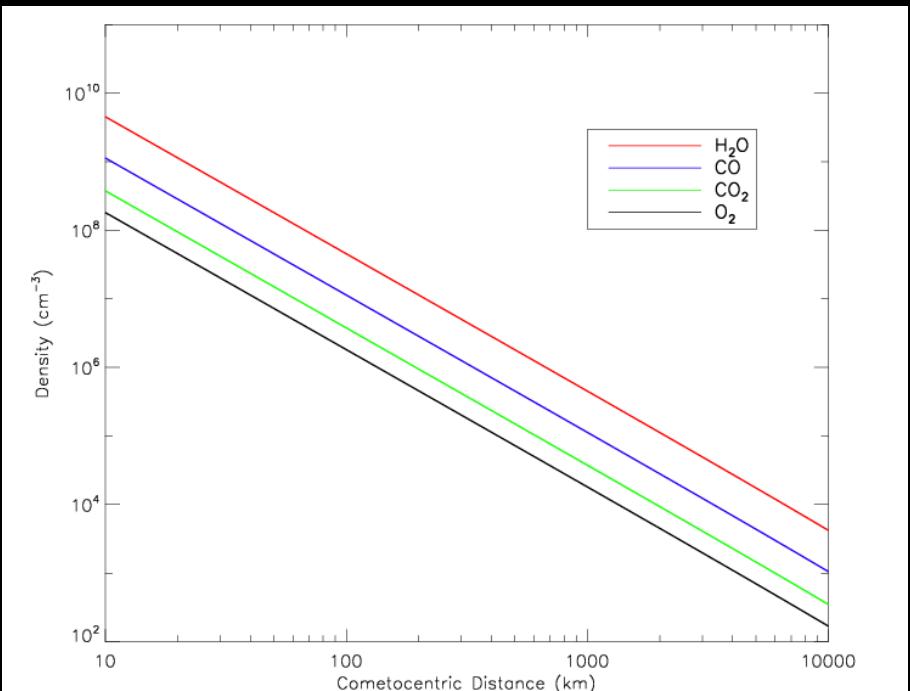
$$\beta_i = 8.2 \times 10^4 \text{ km.s}^{-1}$$

*Others volatile elements
(ROSINA/DFMS, July 2015)*

$$CO/H_2O = 25 \%$$

$$CO_2/H_2O = 8.3 \%$$

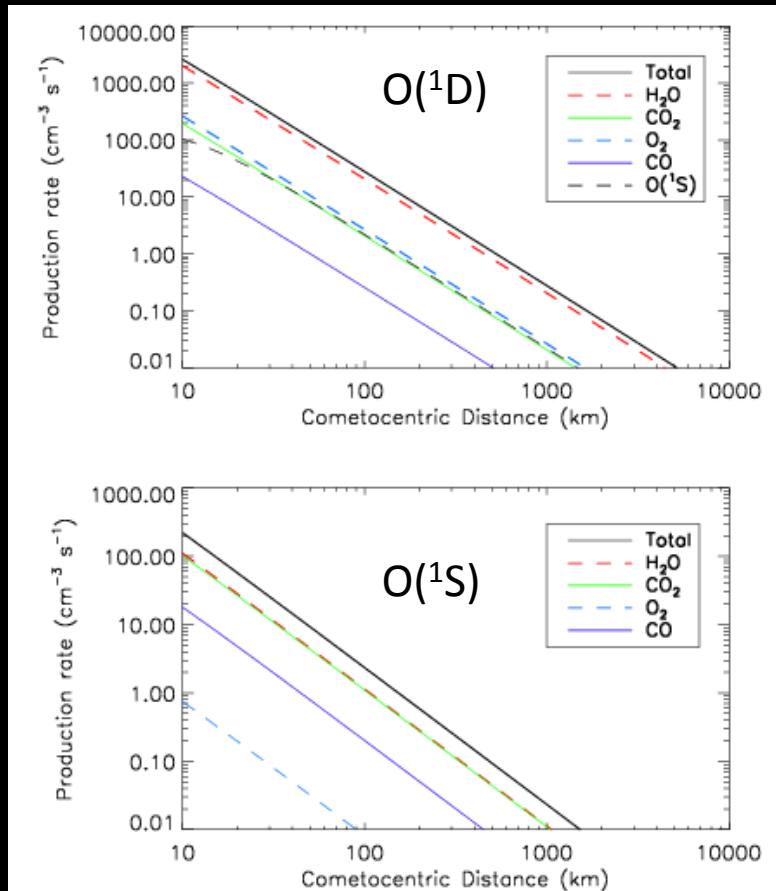
$$O_2/H_2O = 3.8 \% \quad (Bieler \text{ et al. } 2015)$$



Production of O(¹D) and O(¹S) oxygen states

- ✓ 99% comes from photodissociation processes
- ✓ Rate constant depends on the altitude, accordingly to the degraded solar UV flux : $k = k(z)$

Reaction	Rate Coefficients
$\text{H}_2\text{O} + h\nu \rightarrow \text{O}(\text{¹D}) + \text{H}_2$	4.91×10^{-7} (-3%)
$\text{CO}_2 + h\nu \rightarrow \text{O}(\text{¹D}) + \text{CO}$	5.52×10^{-7} (-7.3%)
$\text{CO} + h\nu \rightarrow \text{O}(\text{¹D}) + \text{C}$	2.28×10^{-8} (-11.8%)
$\text{O}_2 + h\nu \rightarrow \text{O}(\text{¹D}) + \text{O}$	1.46×10^{-6} (-1.21%)
$\text{H}_2\text{O} + h\nu \rightarrow \text{O}(\text{¹S}) + \text{H}_2$	2.55×10^{-8} (-2.7%)
$\text{CO}_2 + h\nu \rightarrow \text{O}(\text{¹S}) + \text{CO}$	2.93×10^{-7} (-8.24%)
$\text{CO} + h\nu \rightarrow \text{O}(\text{¹S}) + \text{C}$	1.78×10^{-8} (-11.8%)
$\text{O}_2 + h\nu \rightarrow \text{O}(\text{¹S}) + \text{O}$	4.5×10^{-9} (-8.92%)



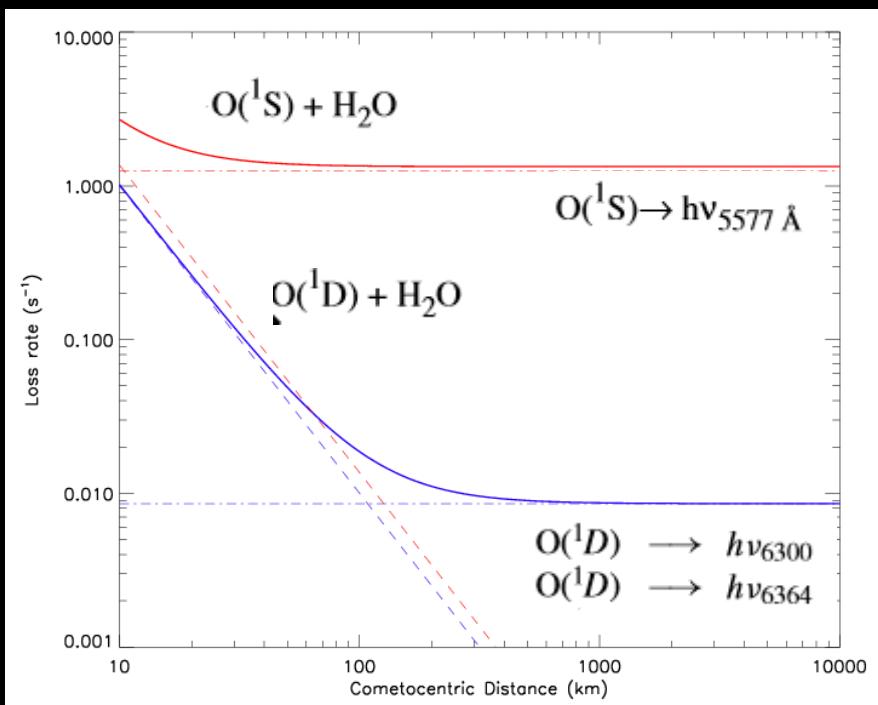
Loss of O(¹D) and O(¹S) oxygen states

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Loss reaction

- ✓ Radiative decay
 - ✓ Collisional reaction with neutral species

Reaction	Rate Coefficients ^a
(1) O(¹ D) + H ₂ O → OH + OH	$k_1 = 2.2 \times 10^{-10}$
(2) O(¹ D) + CO ₂ → O + CO ₂	$k_2 = 6.8 \times 10^{-11} e^{-117/T}$
(3) O(¹ D) + CO → O + CO	$k_3 = 5.5 \times 10^{-10} e^{-625/T}$
(4) O(¹ D) → O(³ P) + $h\nu$ (630 nm)	$A_1 = 6.478 \times 10^{-3}$
(5) O(¹ D) → O(³ P) + $h\nu$ (634.4 nm)	$A_2 = 2.097 \times 10^{-3}$
(6) O(¹ D) + O ₂ → O(³ P) + O ₂	$k_{11} = 3.2 \times 10^{-11}$
(7) O(¹ S) + H ₂ O → OH + OH	$k_6 = 3 \times 10^{-10}$
(8) O(¹ S) + CO ₂ → O + CO ₂	$k_7 = 3.1 \times 10^{-11} e^{-1330/T}$
(9) O(¹ S) + CO → O + CO	$k_8 = 3.21 \times 10^{-12} e^{-1327/T}$
(10) O(¹ S) → O(¹ D) + $h\nu$ (557.7 nm)	$A_3 = 1.26$
(11) O(¹ S) → O(³ P) + $h\nu$ (297.7 nm)	$A_4 = 0.134$
(12) O(¹ S) + O ₂ → O(³ P) + O ₂	$k_{12} = 3.2 \times 10^{-13}$

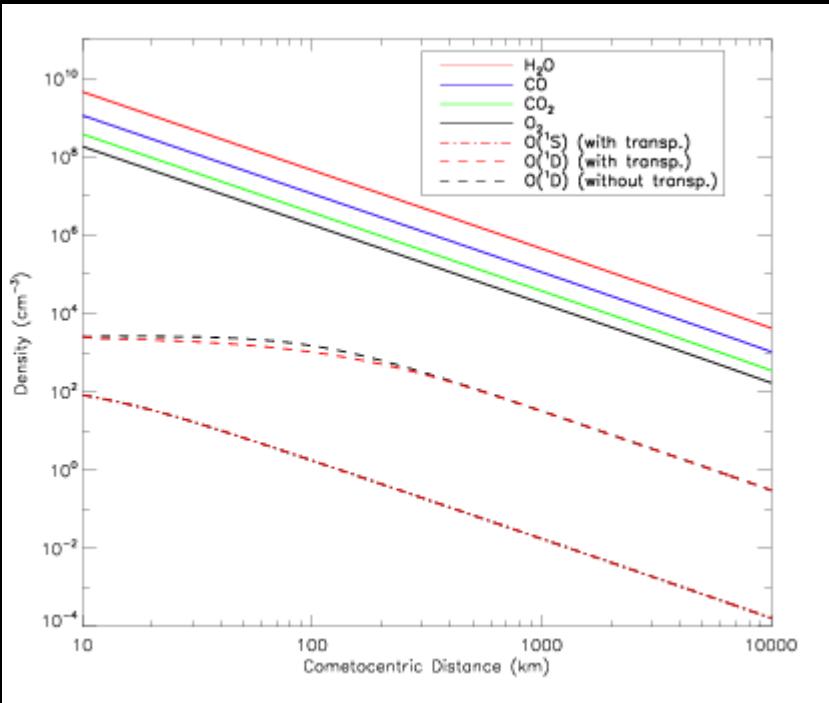


Red and Green line emissions

O(¹D) and O(¹S) number densities

$$\frac{1}{r^2} \frac{d}{dr} (r^2 N_i v) = P_i - L_i$$

- ✓ High velocity of neutral oxygen atoms.
- ✓ O(¹D) lifetime about 130 s: transport should be taken into account



From the number densities to the atmospheric emissions

$$V_{6300+6364} = A_{6300+6364} \ N[O(^1D)]$$

$$\text{with } A_{6300+6364} = 8.58 \cdot 10^{-3} \text{ s}^{-1}$$

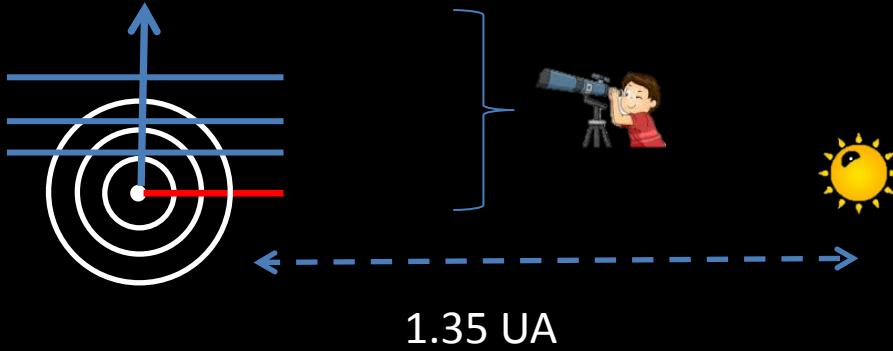
$$V_{5777} = A_{5777} \ N[O(^1S)]$$

$$\text{with } A_{5777} = 1.26 \text{ s}^{-1}$$

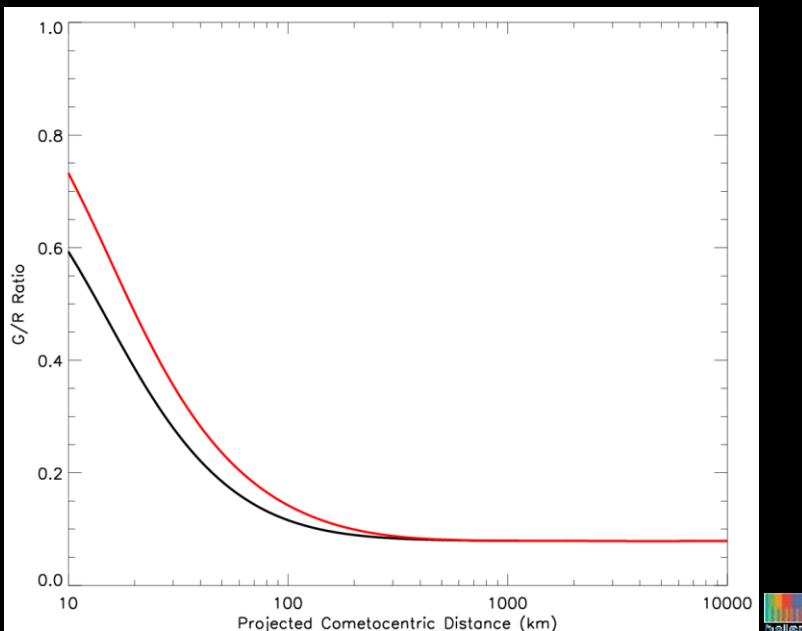
Red and Green line emissions

1D photochemical model

- the computed line of sight (red) is projected over different line of sight along the y-axis
 - The 1D model assumes then a symmetry

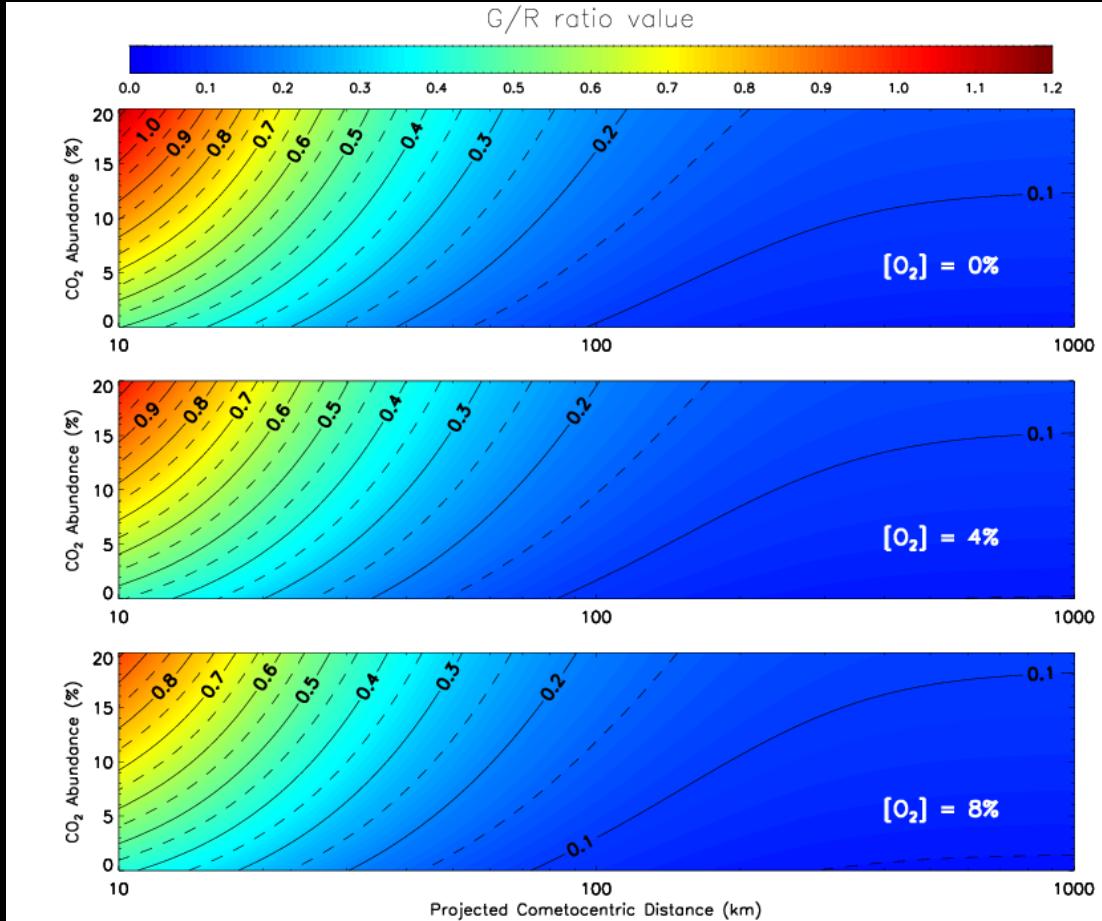


- ✓ In the case of 67P, red and green line emissions at 10 km are estimated of about 673 R and 493 R, respectively
 - ✓ The Green to Red emissions ratio (G/R) deduced from ground observations

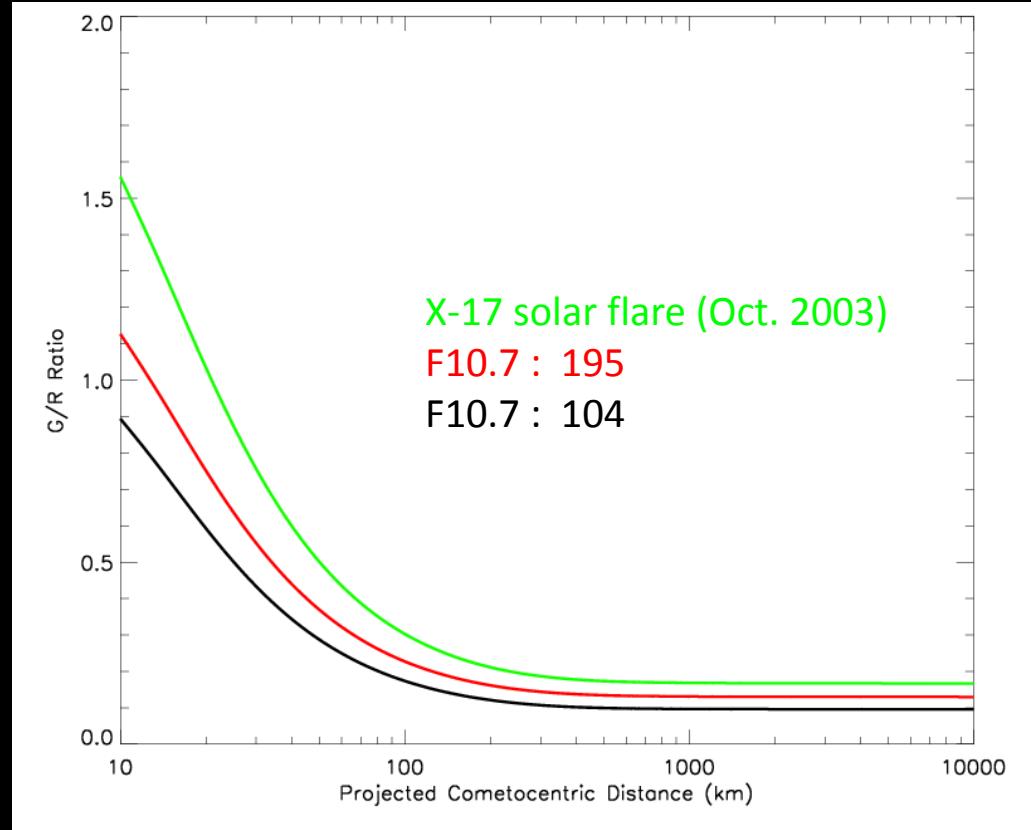


Influence of the O₂ presence ?

- ✓ The G/R ratio is used to constrain the CO₂ abundance
- ✓ BUT O₂ leads also to the production of O(¹D) and O(¹S)...
- ✓ CO₂ → G/R ratio
O₂ → G/R ratio
- ✓ Previous conclusions regarding the CO₂ abundances have to be revised !



Space weather: solar irradiance variability



- Production of O(¹S) oxygen state comes from spectral regions lower than 115 nm, with a high variability
- G/R ratio > 1 for a X-class solar flare
- 11-year cycle has a marked impact
- No sign of the 27-day solar modulation

Cometary neutral atmosphere for 1P/Halley



DSMC model, spherical model (*Rubin et al. 2011*)



$$1P: Q_p = 7 \times 10^{29} \text{ s}^{-1}$$

$$67P : Q_p = 4 \times 10^{27} \text{ s}^{-1}$$

Others volatile elements

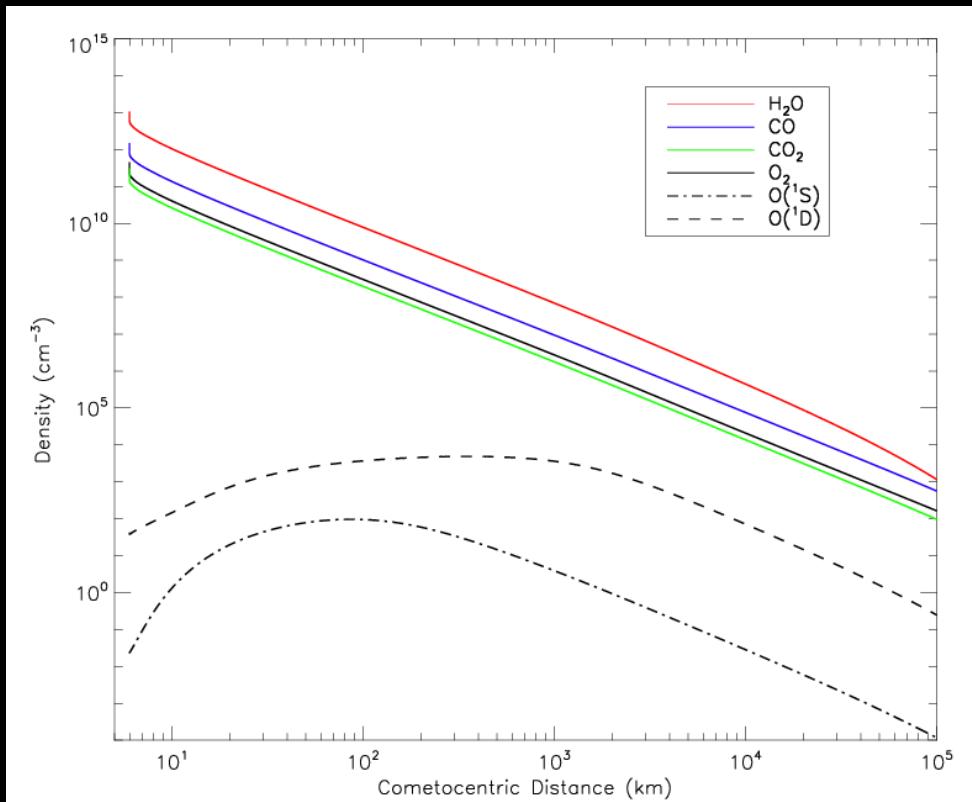
$$CO/H_2O = 22 \%$$

$$CO_2/H_2O = 2.5 \%$$

$O_2/H_2O = 3.7\% \text{ (Rubin et al. 2015)}$

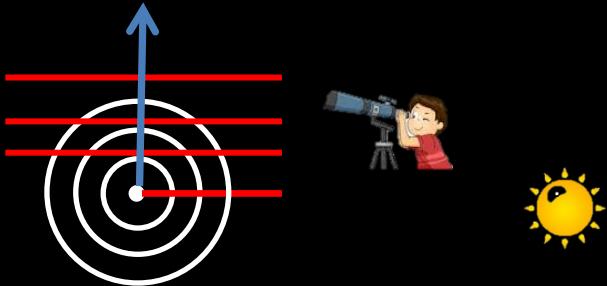
Strong absorption of the solar UV flux !

1D model is not enough, because no symmetry anymore !

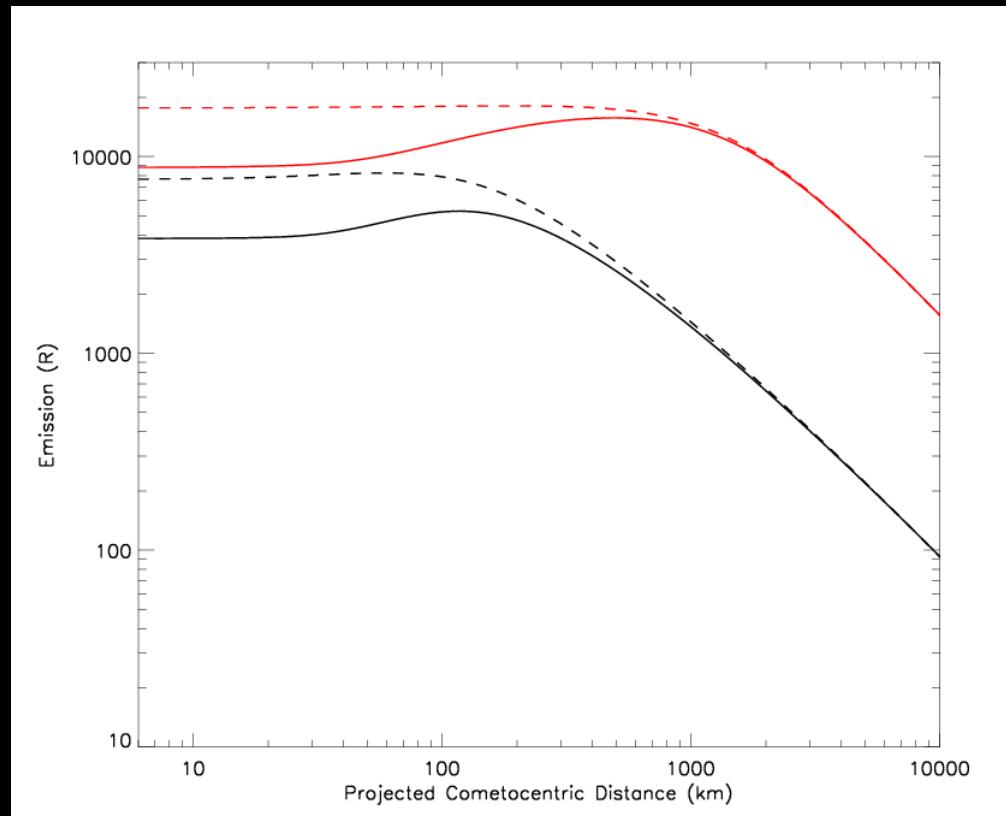


Red and Green line emissions for 1P/Halley

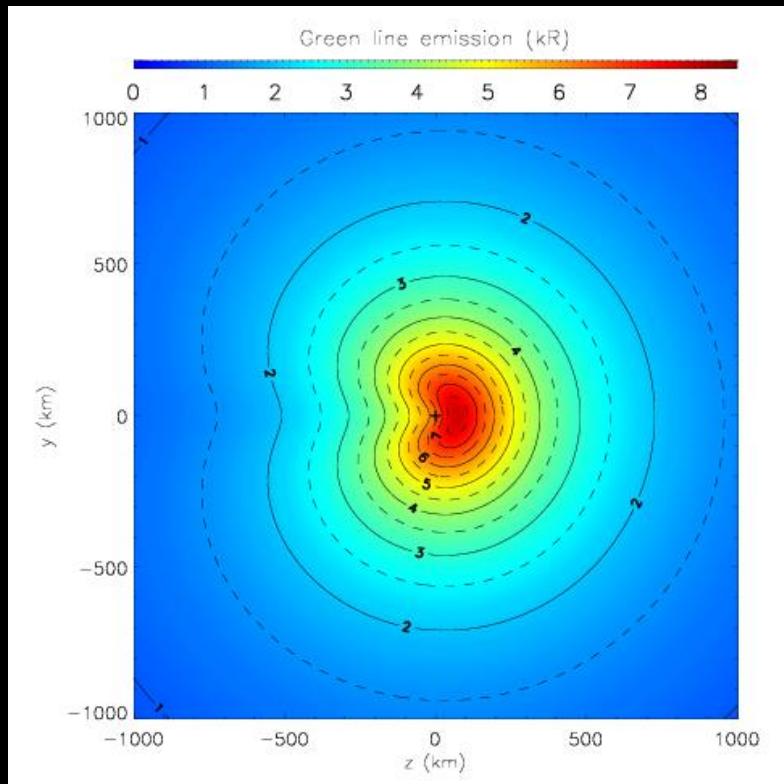
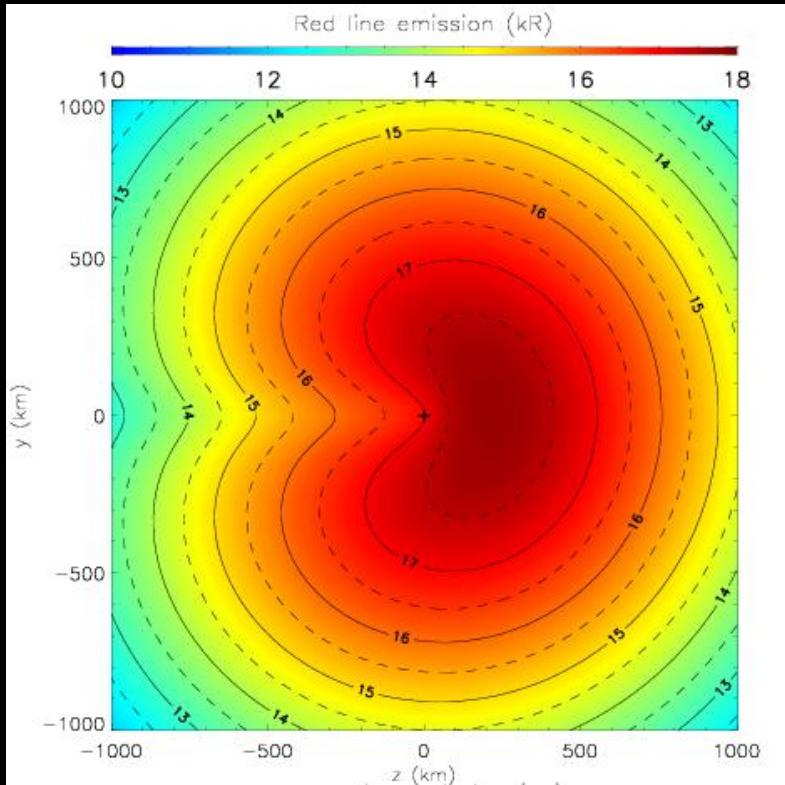
*2D approach: considering
1135x1136 parallel lines of sight
through the coma*



At 10 km above the nucleus
1D model: 17689 R and 7689 R
2D model: 8836 R and 3842 R



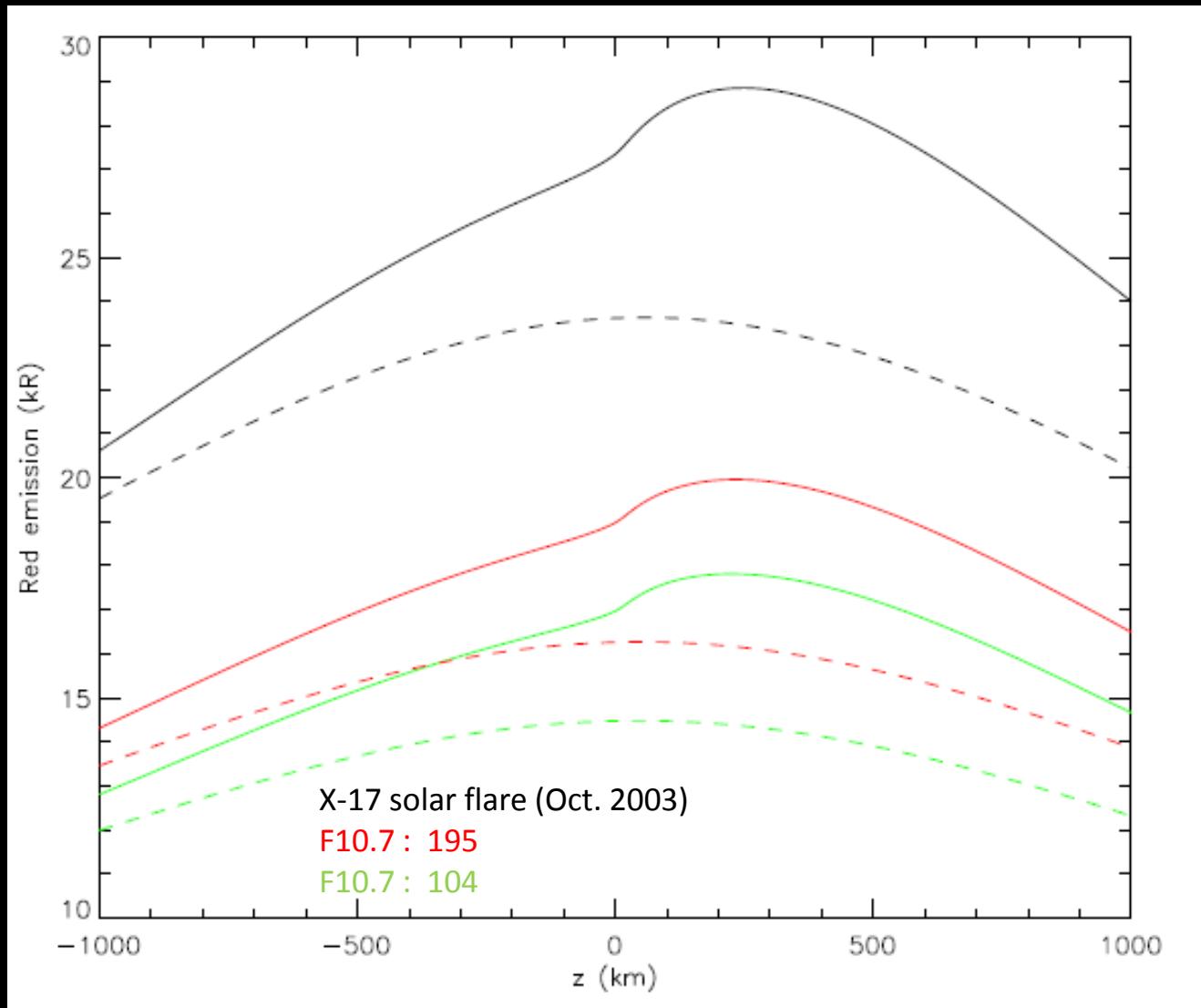
Emission maps: quadrature view



Asymmetries for the red and green line emissions: important information for constraining the neutral atmospheric models !

Space weather

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Space weather

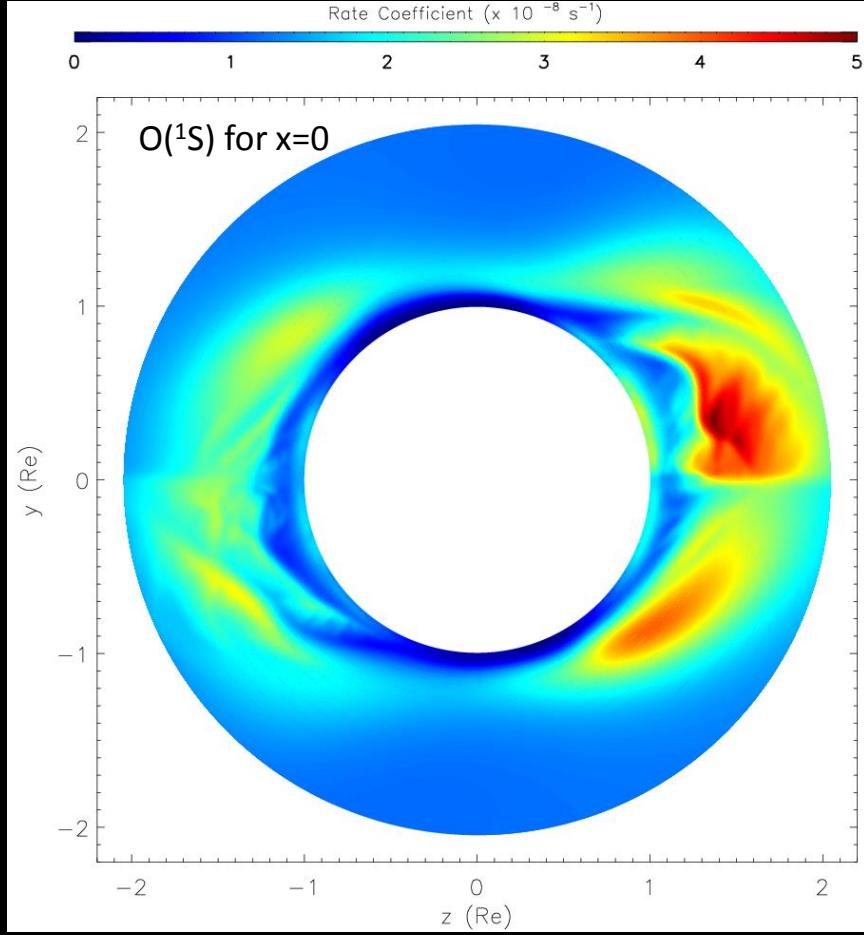
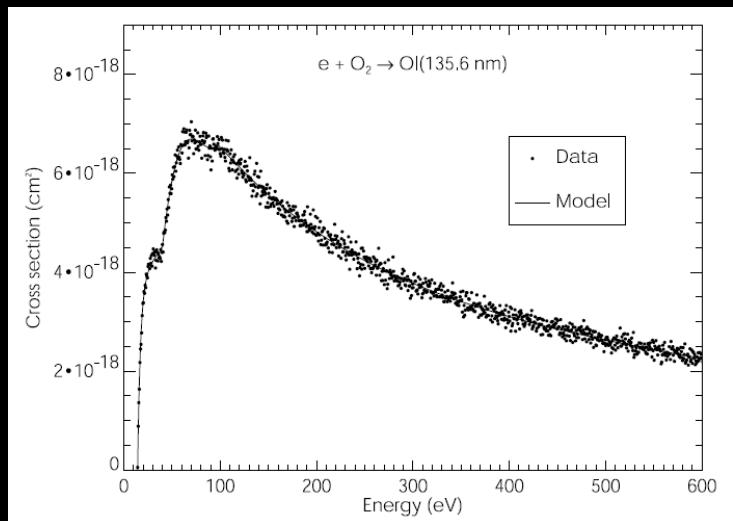
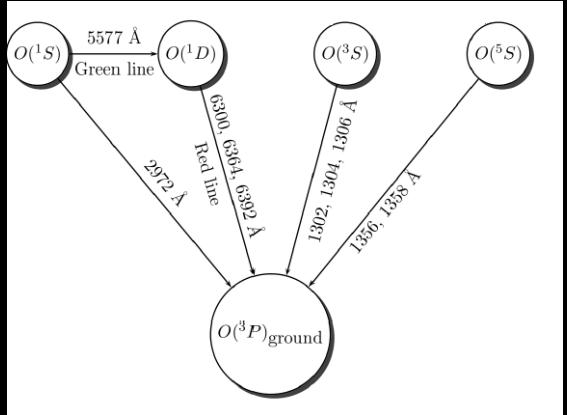
- ## ✓ Planetary space weather: impact of solar flares

Events dates	Class	Location on solar surface	Red line emission (in Rayleigh)
January, 15 th 2005	X-1.2	Center	409.8
January, 20 th 2005	X-7	Limb	411.3
October, 28 th 2003	X-17	Center	644.6
November, 4 th 2003	X-17.4	Limb	519
F10.7=195	-	-	408.5

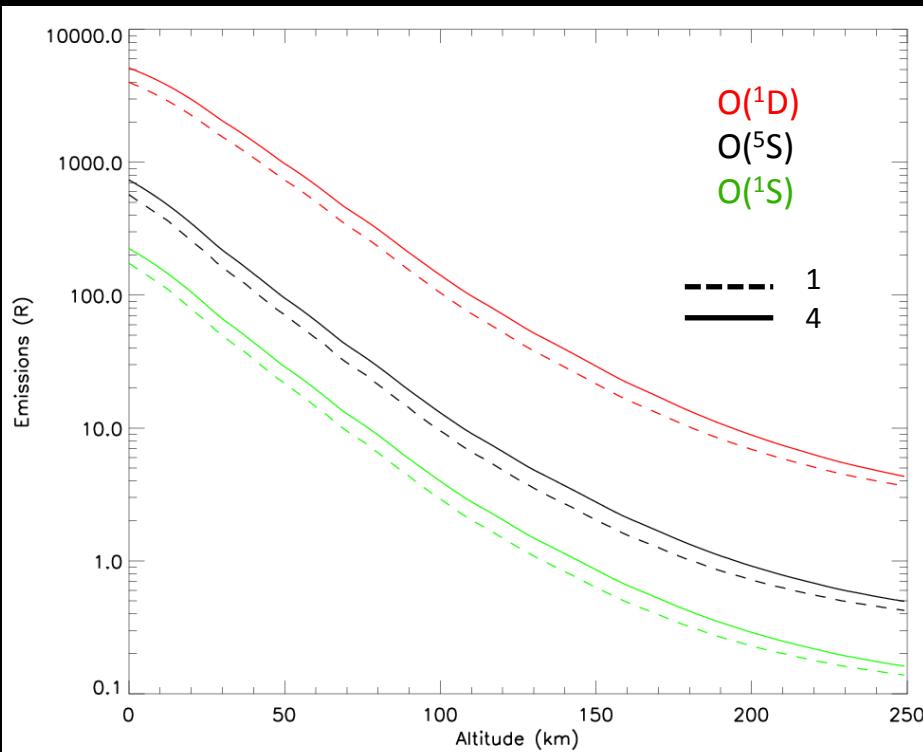
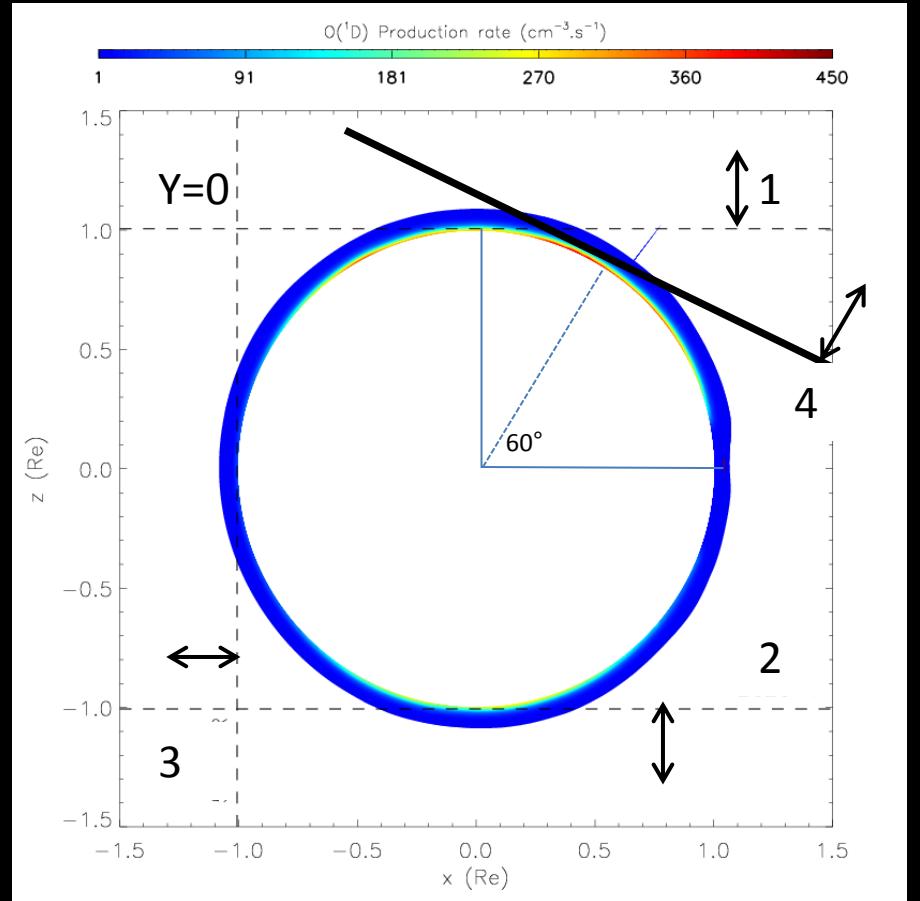
- ✓ Red line emissions increase by 58% compared to high quiet solar conditions for a X-17 class flare
 - ✓ Impact of the flare location on the Sun as viewed from the moon

Auroral emissions for Europa

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Auroral emissions for Europa



Line of sight "2" similar to "1"

Line of sight "3" less emissions compared to the others ones

Similar emissions profiles for $z=0$ and $x=0$

Emissions profiles available for any angles

To go further

- ✓ *Physics and Chemistry of the upper atmosphere, Rees, 1989*
- ✓ *The Aeroplanets model: see Gronoff et al.*
- ✓ *"Du Soleil à la Terre: Aéronomie et Météorologie de l'Espace", Jean Liliensten and Pierre-Louis Blelly*
- ✓ *"Planetary space weather: scientific aspects and future perspectives", Plainaki et al. 2016, JSWSC*
- ✓ *Physics of the Solar Corona: An Introduction with Problems and Solutions, M. Aschwanden*