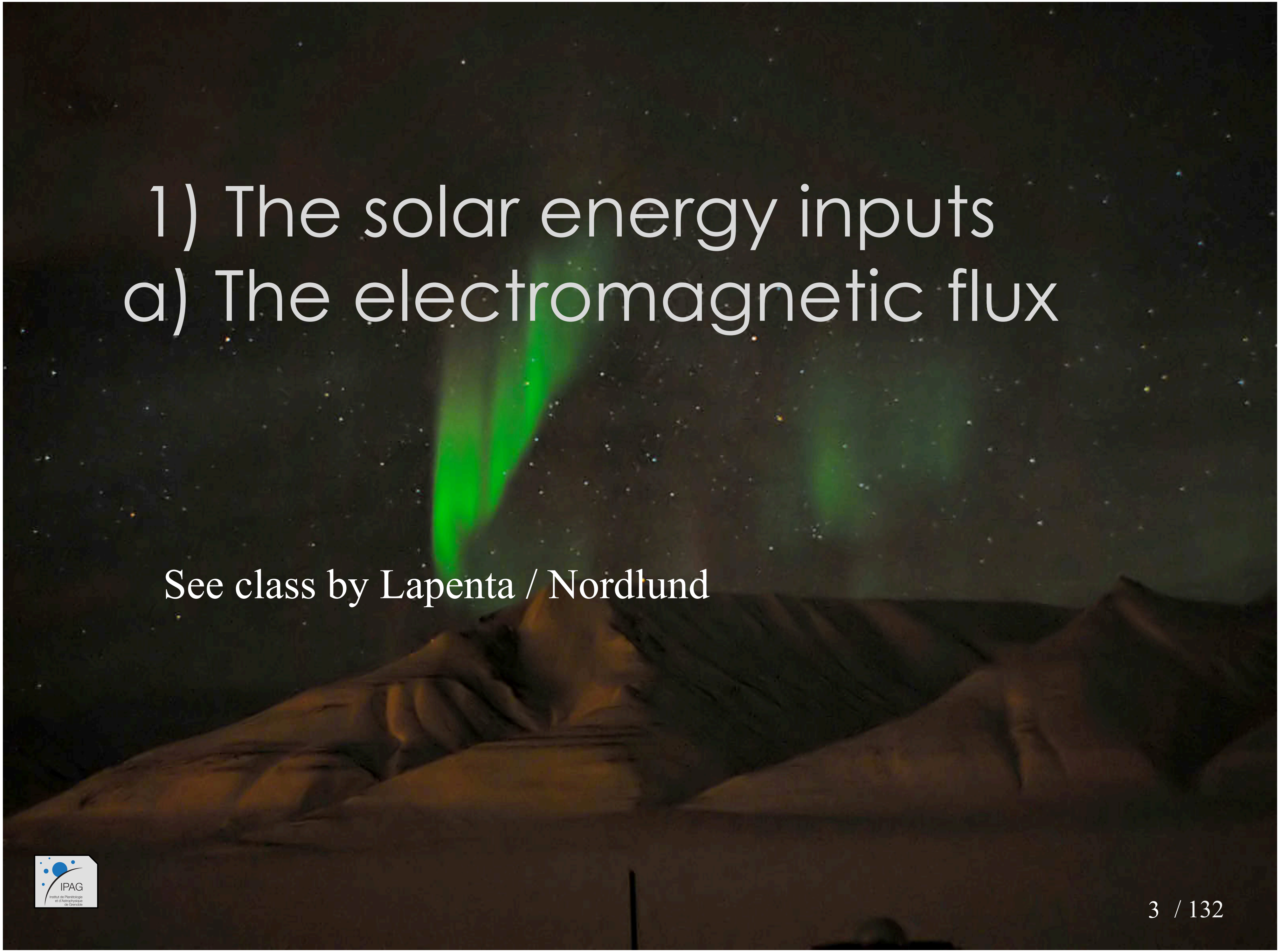
Basic processes for Space Weather

Jean Lilensten

Space weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and nowcasting the possible impacts on biological and technological systems

1) The solar energy inputs
a) The electromagnetic flux

See class by Lapenta / Nordlund

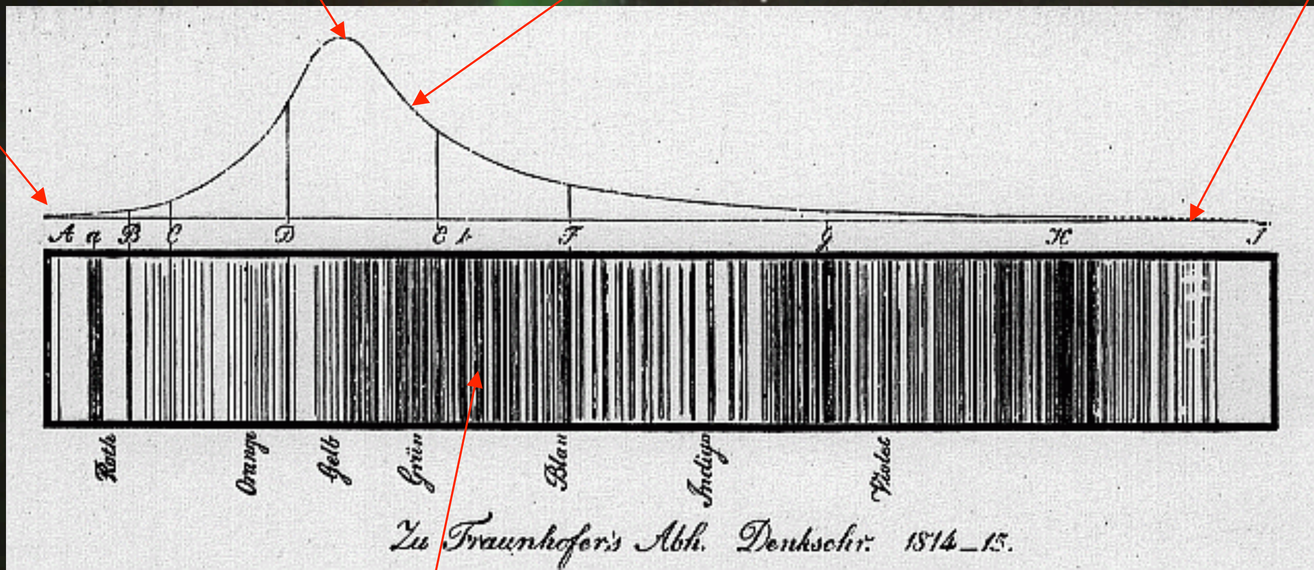


460 nm

Nothing

Plank's law

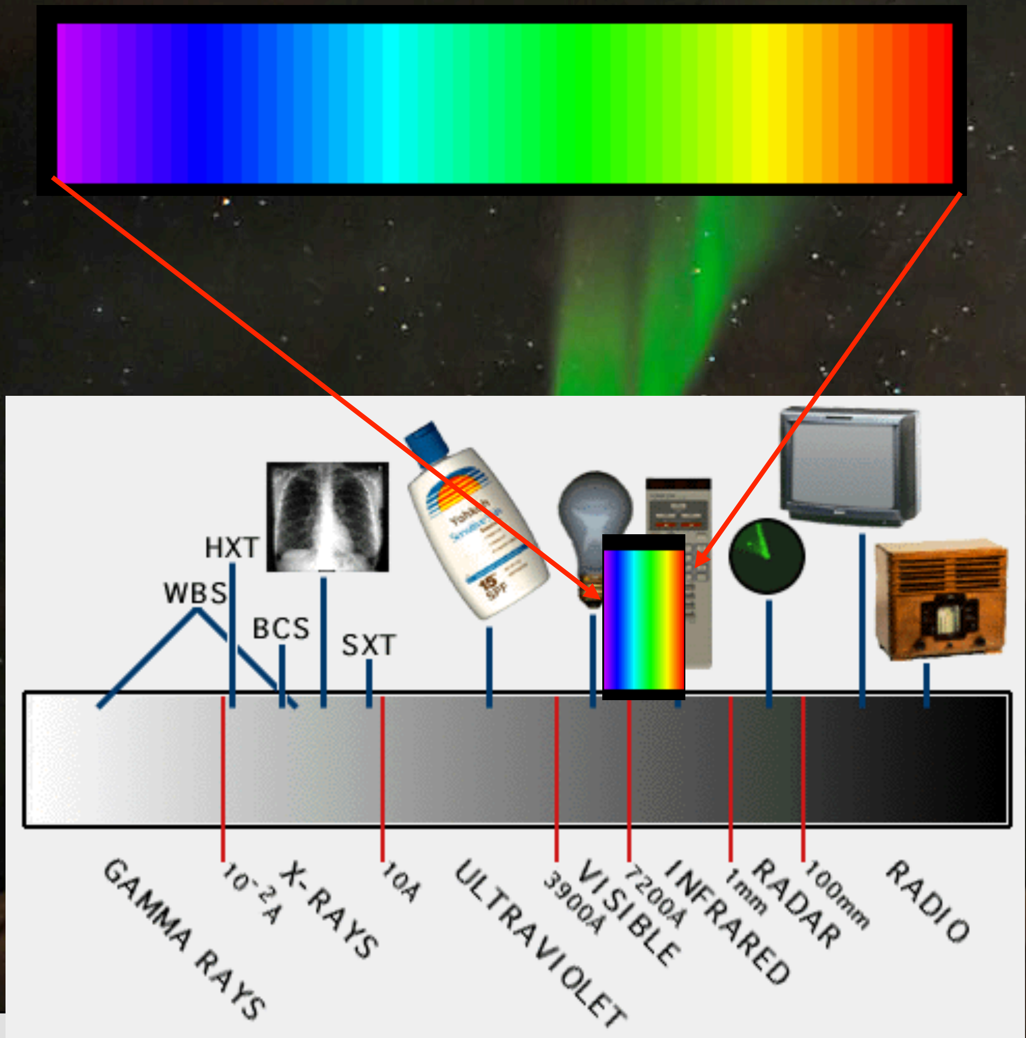
Nothing as well



Fraunhofer absorption lines

Denkschriften der K. Acad. Der Wissenschaften su München, 1814-15, p 193-226

From the Sun, most of what was essentially know until recently its visible light

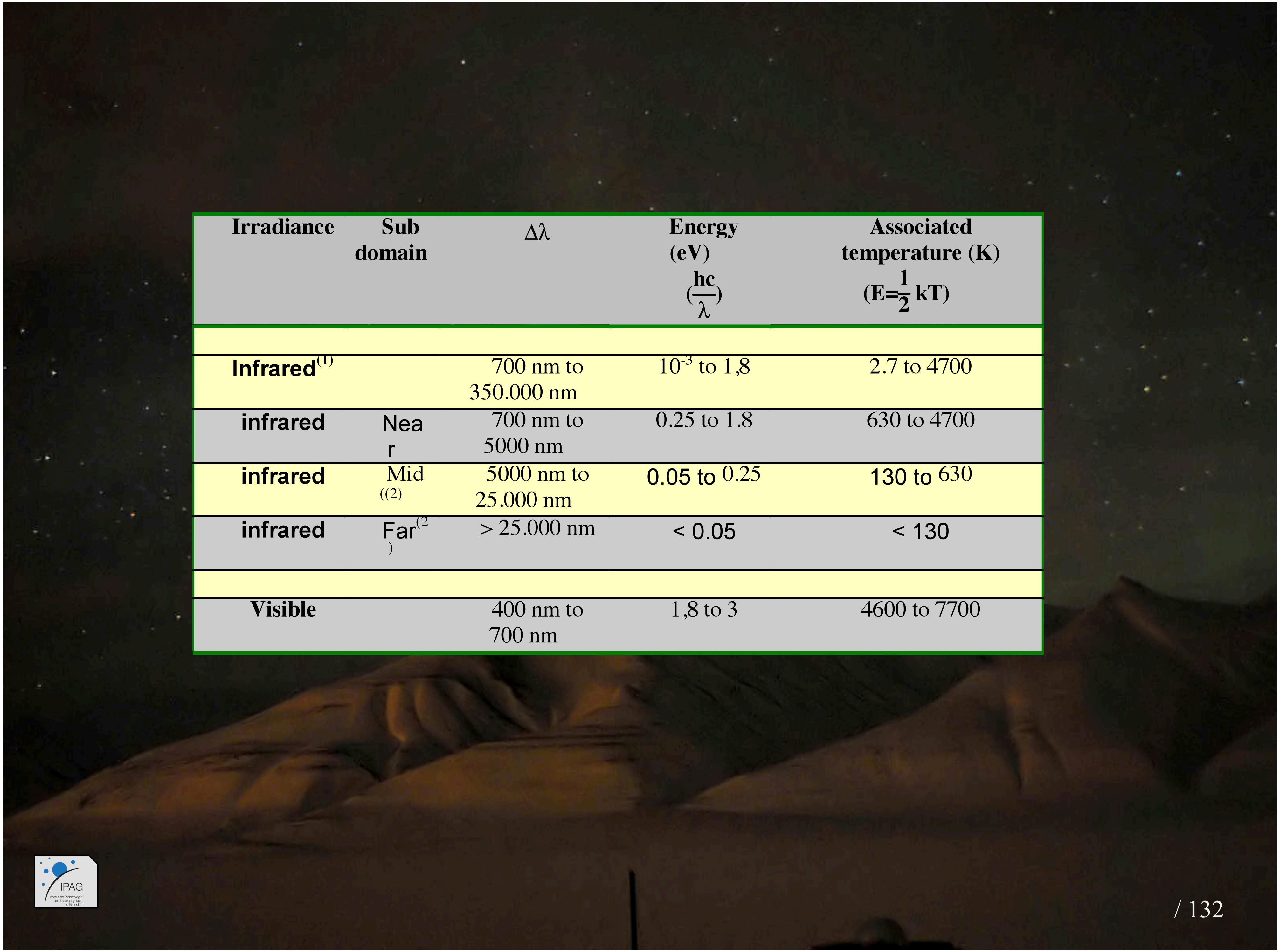


However, the invisible is quite interresting too…


To continue : let’s take some hints of what is a low energy, or a high energy in space weather…

Definition of the UV, EUV and X ranges (ISO)

Irradiance	Sub domain	$\Delta\lambda$	Energy (eV) $(\frac{hc}{\lambda})$	Associated temperature (K) $(E=\frac{1}{2}kT)$
Radio		> 1.5 cm	< 8 x 10^{-5}	< 0.2
Micro-wave		1 mm to 1.5 cm	8 x 10^{-5} to 1.25 x 10^{-3}	0.2 to 3
Micro-wave	W	3.3 mm	3.75 x 10^{-4}	1
Micro-wave	V	5 mm	2.5 x 10^{-4}	0.6
Micro-wave	Q	7.5 mm	1.65 x 10^{-4}	0.5
Micro-wave	Ka	10 mm	1.25 x 10^{-4}	0.4
Micro-wave	K	13.6 mm	9 x 10^{-5}	0.2



Irradiance	Sub domain	$\Delta\lambda$	Energy (eV) $(\frac{hc}{\lambda})$	Associated temperature (K) $(E=\frac{1}{2}kT)$
Infrared[1]		700 nm to 350.000 nm	10^{-3} to 1,8	2.7 to 4700
infrared	Near	700 nm to 5000 nm	0.25 to 1.8	630 to 4700
infrared	Mid ((2)	5000 nm to 25.000 nm	0.05 to 0.25	130 to 630
infrared	Far(2)	> 25.000 nm	< 0.05	< 130
Visible		400 nm to 700 nm	1,8 to 3	4600 to 7700

Irradiance	Sub domain	$\Delta\lambda$	Energy (eV) ($\frac{hc}{\lambda}$)	Associated temperature (K) ($E=\frac{1}{2}kT$)
Ultraviolet		30 nm to 400 nm	3 to 41	7700 to 10^6
Ultraviolet	A(3)	315 nm to 400 nm	3 to 4	7700 to 10^5
Ultraviolet	B(3)	280 nm to 315 nm	4 to 4.5	10^5
Ultraviolet	C(3)	100 nm to 280 nm	4.5 to 12.5	10^5 to 3 10^5
Ultraviolet	Near (4)	200 nm to 400 nm	3 to 6	70.000 to 140.000
Ultraviolet	Far(5)	120 nm to 200 nm	6 to 10	140.000 to 230.000
Ultraviolet	Ex-treme(5)	30 nm to 120 nm	10 to 41	230.000 to 10^6
X-rays(5)		0,005 nm to 30 nm	41 to 2,5 x 10^5	10^6 to 6 10^9
X-rays	XUV or Soft(5)	1 nm to 30 nm	41 to 125	10^6 to 3 10^6
X-rays	Hard	0,005 nm to 1 nm	125 to 2.5 x 10^5	3 10^6 to 6 10^9
γ		< 0,005 nm	> 2.5 x 10^5	> 6 10^9

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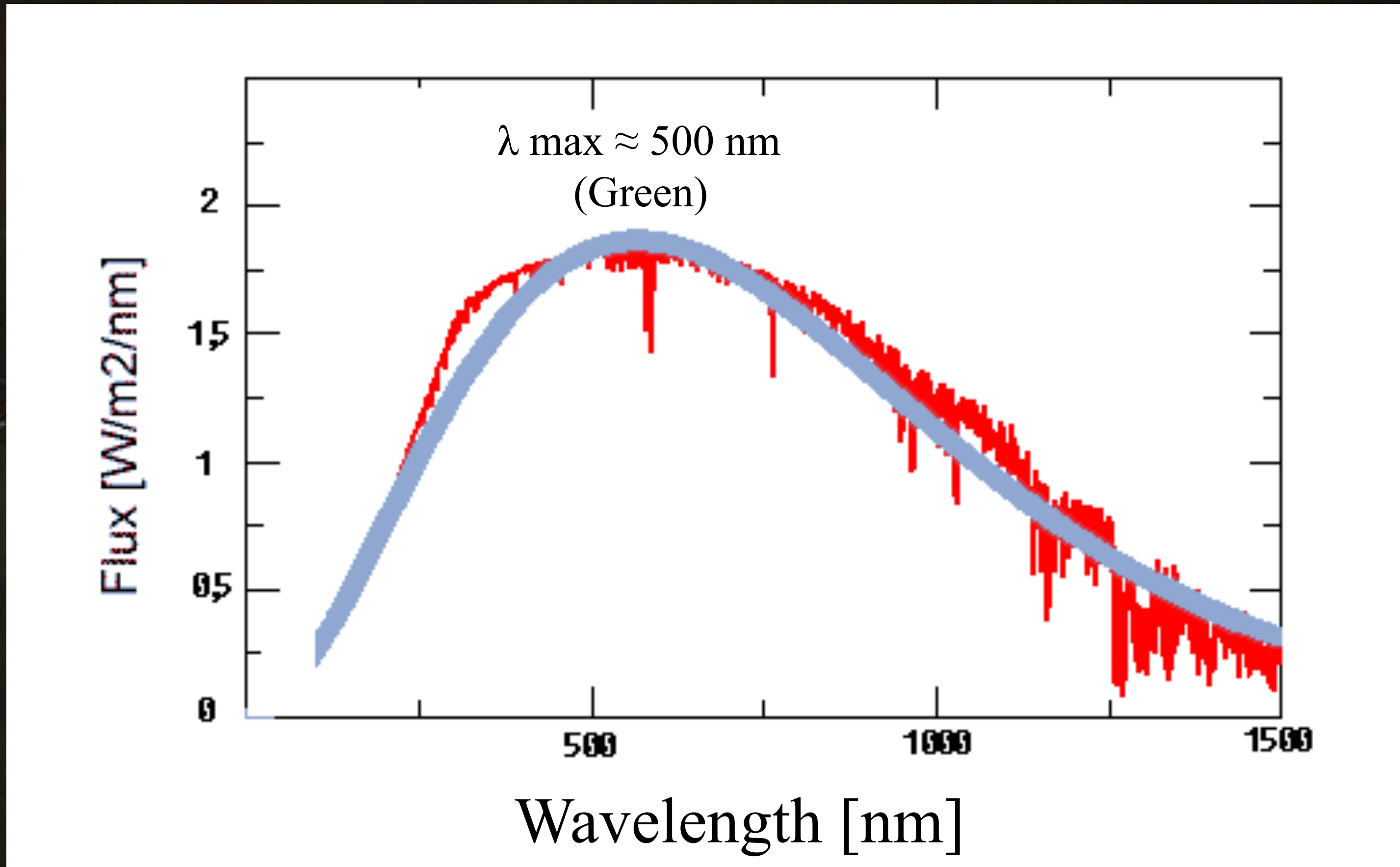
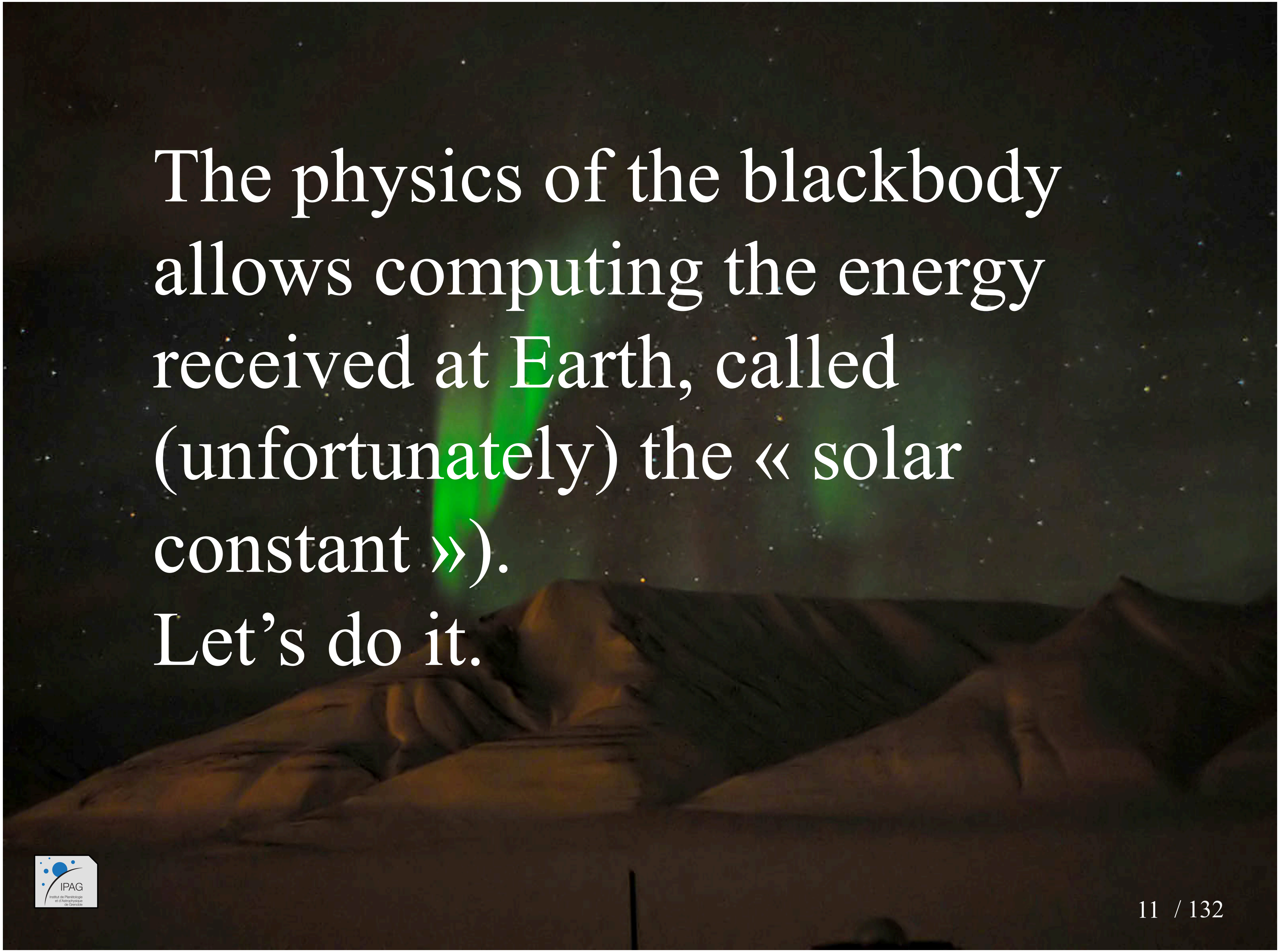
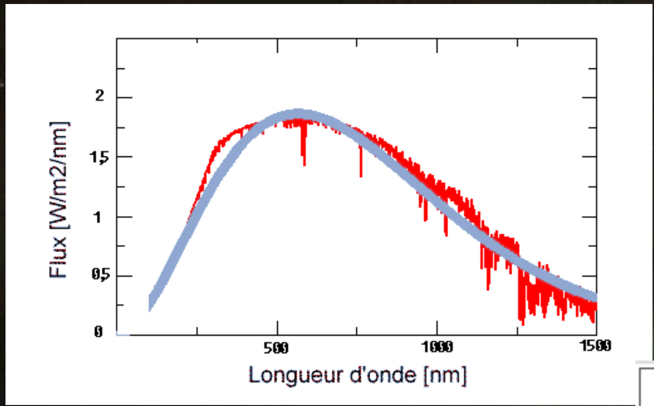


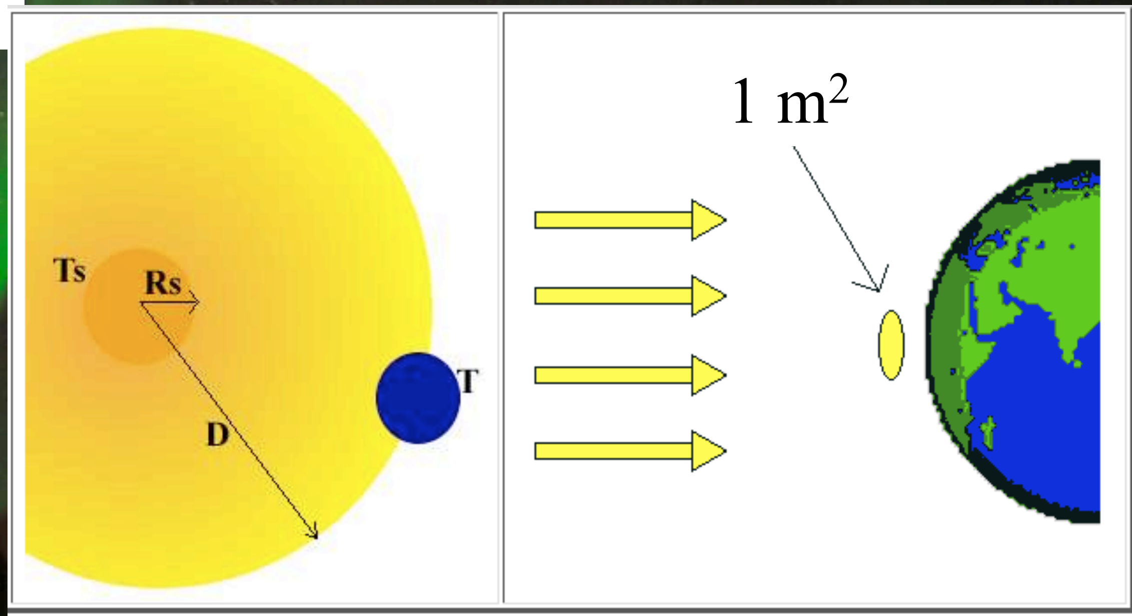
Emittance = Integrated flux over wavelenghts

Total Power / surface ($W.m^{-2}$)



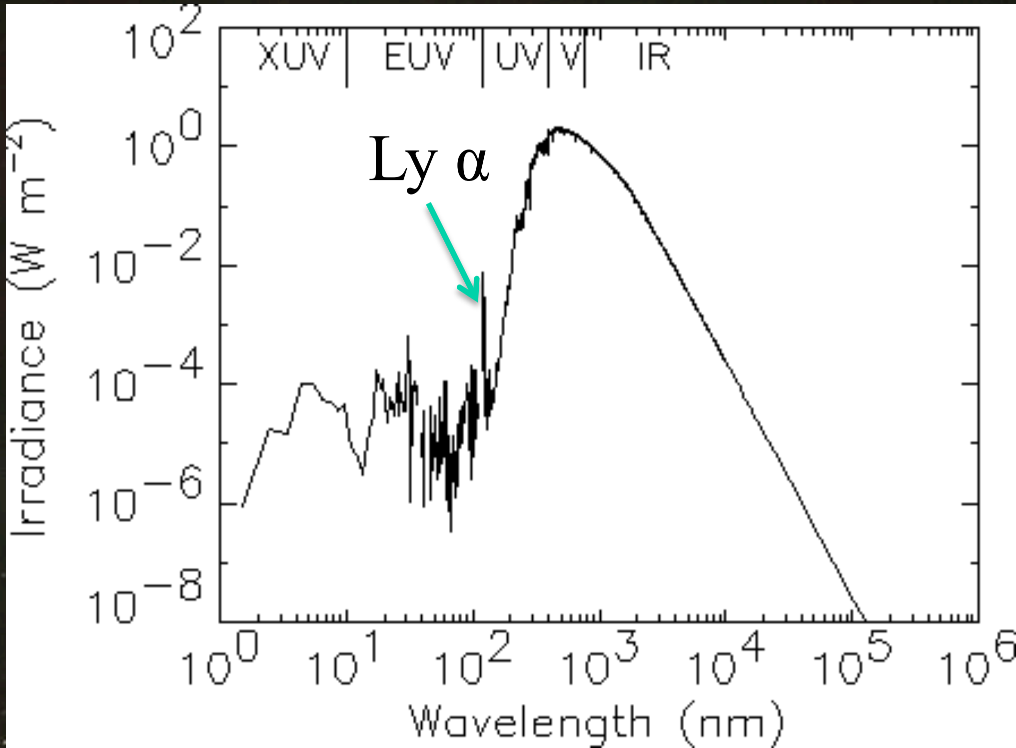
The physics of the blackbody allows computing the energy received at Earth, called (unfortunately) the « solar constant »).
Let’s do it.





The solar « constant »: The aggreed value is

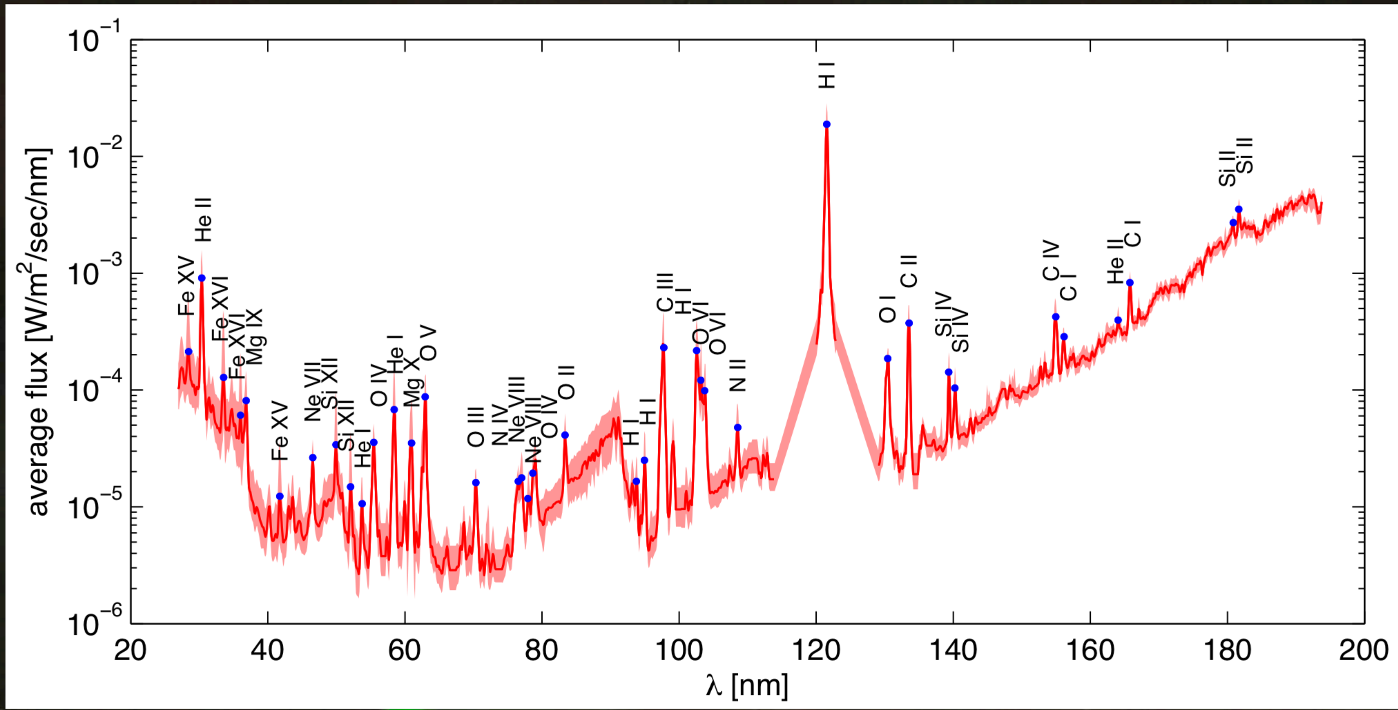
→ $E = 1362\ W.m^{-2}$



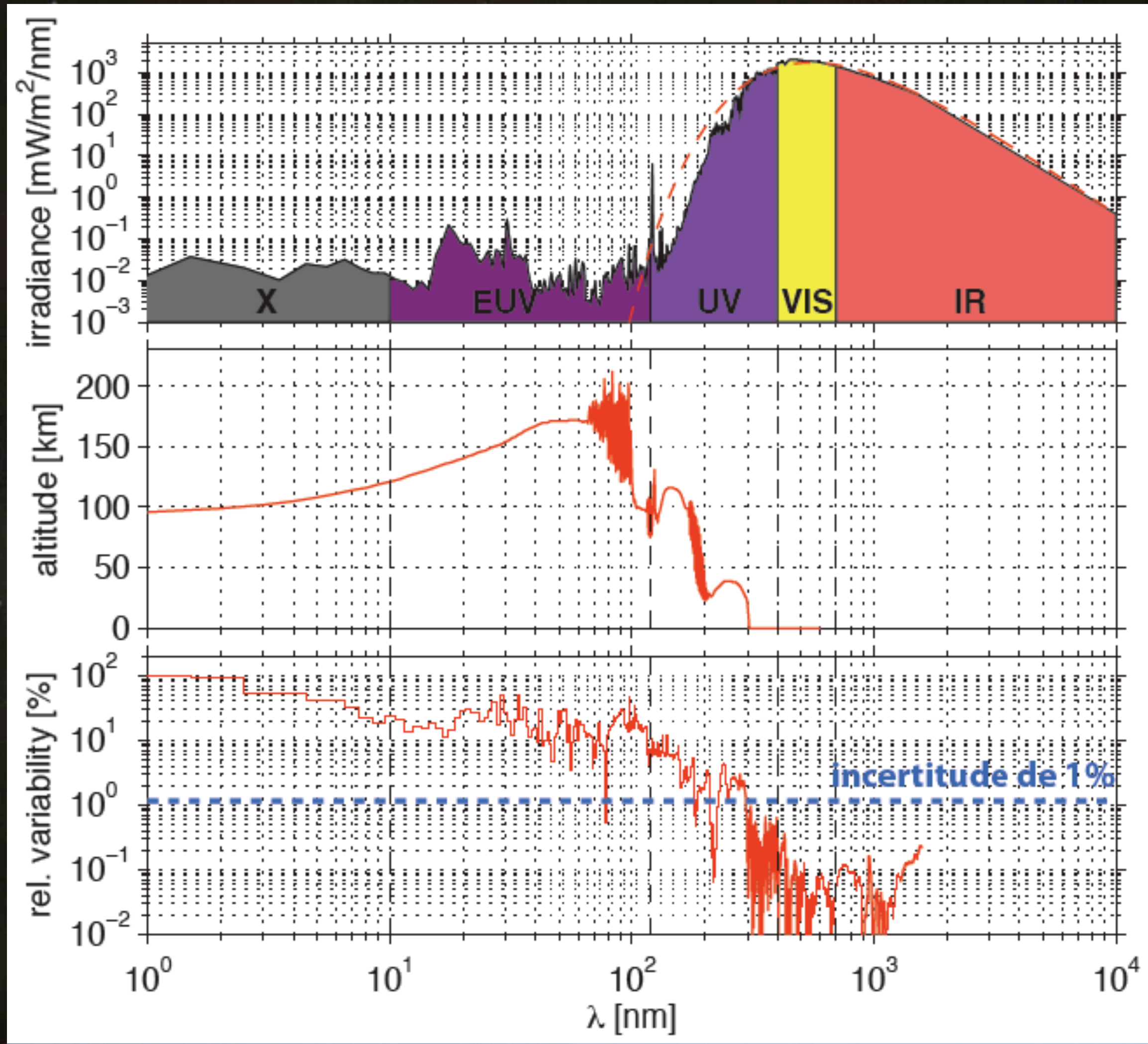
However, even if it only represents a weak part in energy, the energetic spectrum (UV / EUV / XUV) is important

Recall : total Em = 6,4 10^{7} W.m^{-2}

Energetic wavelengths emittance: 10^{5} W.m^{-2} (1/600)

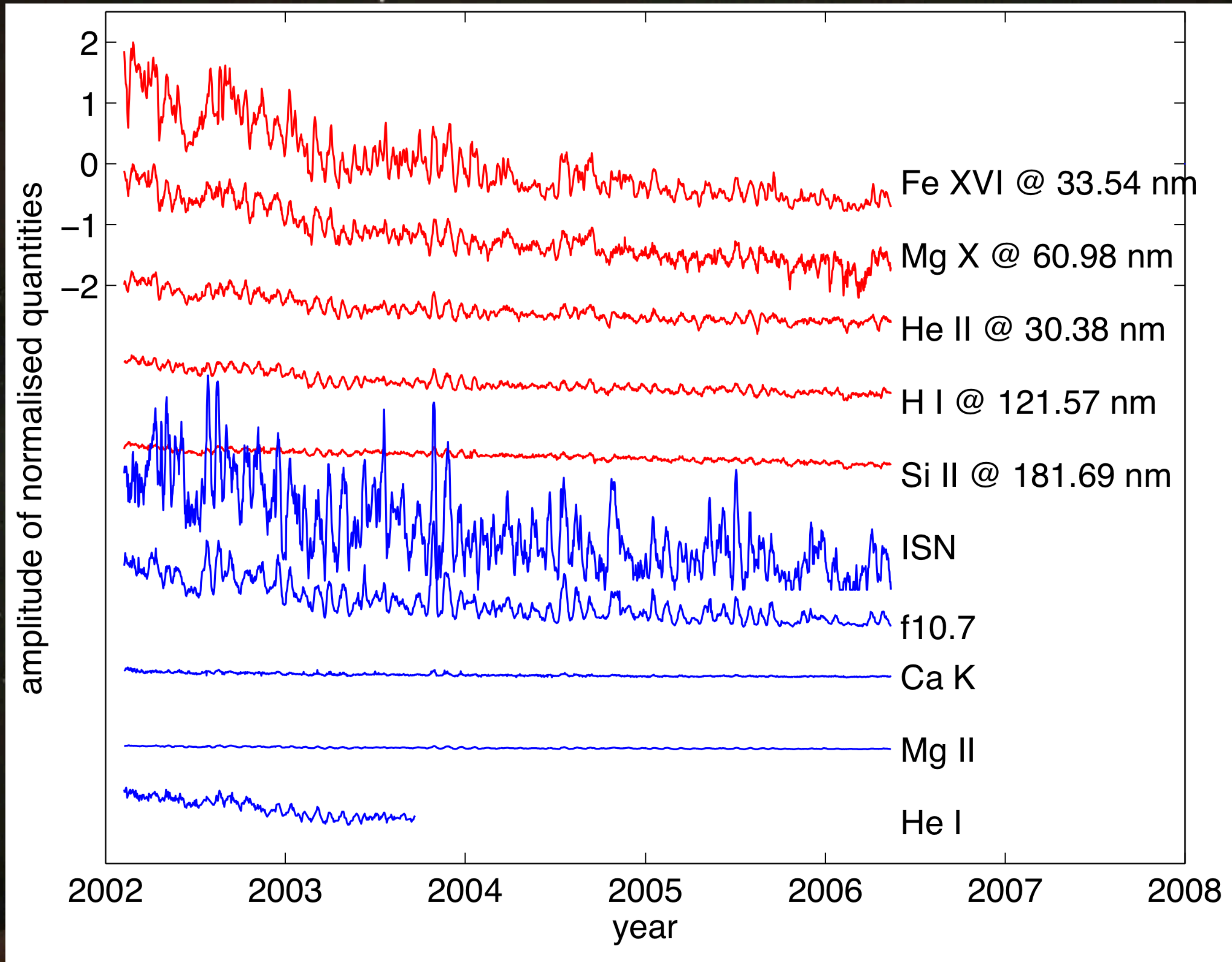


It is made of the superposition of a continuum and emission lines

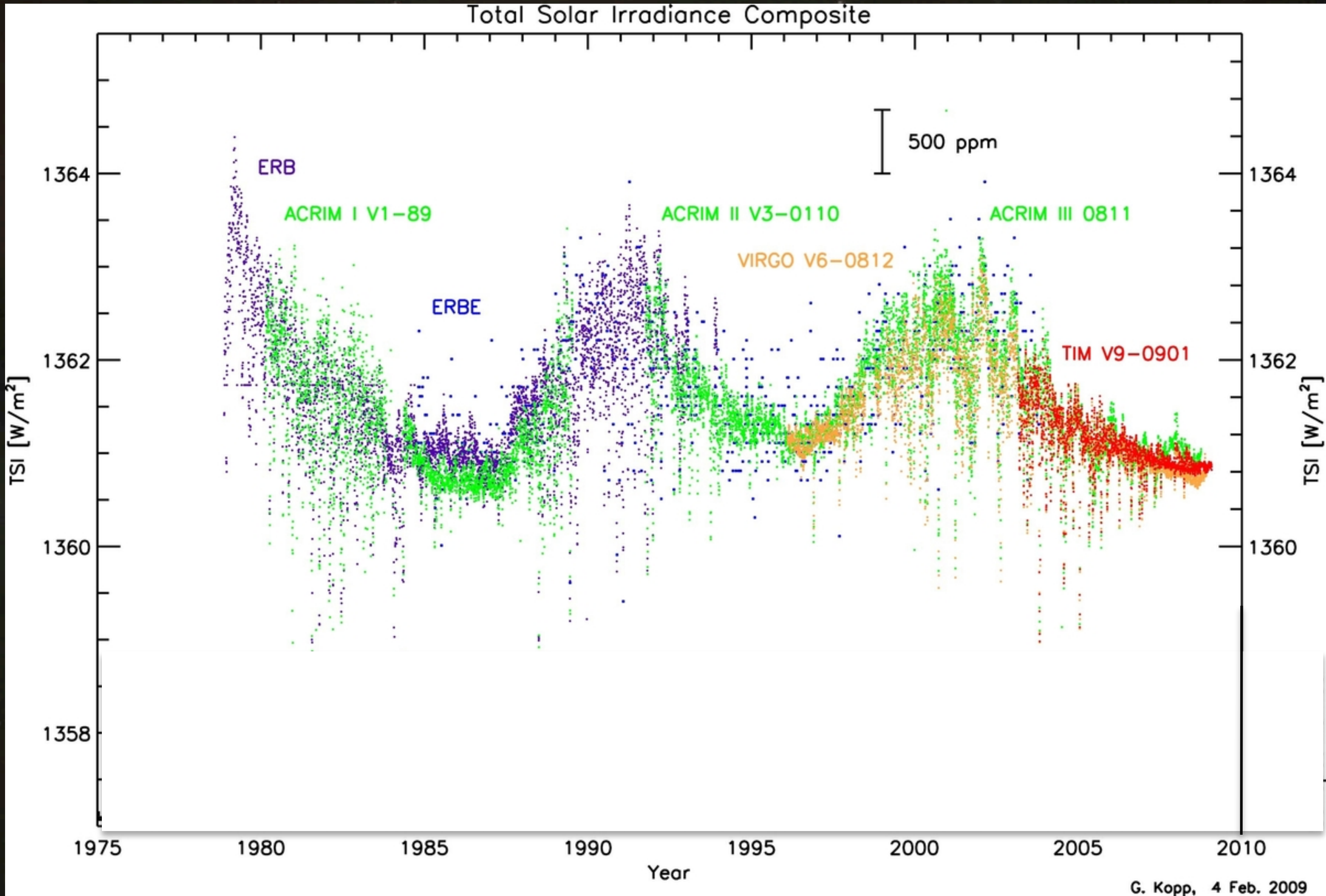


It is very variable

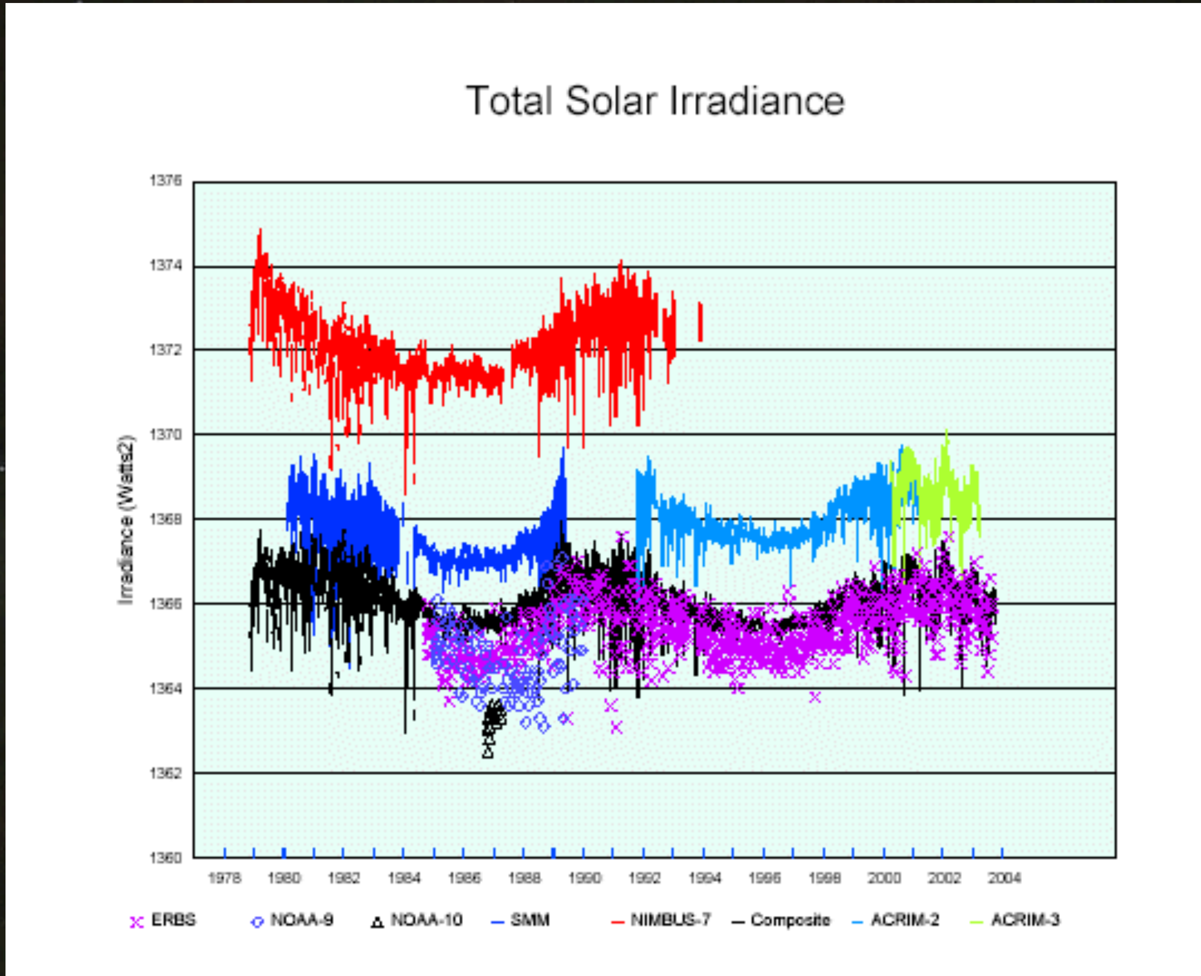
Its variation is one way to define the Schwabe cyle.



The wavelenghts do not vary the same way although they more or less all follow the Schwabe cyle



We know today that the irradiance also varies like the UV flux, although in much smaller extend.



However, a look at the raw data is a call for care

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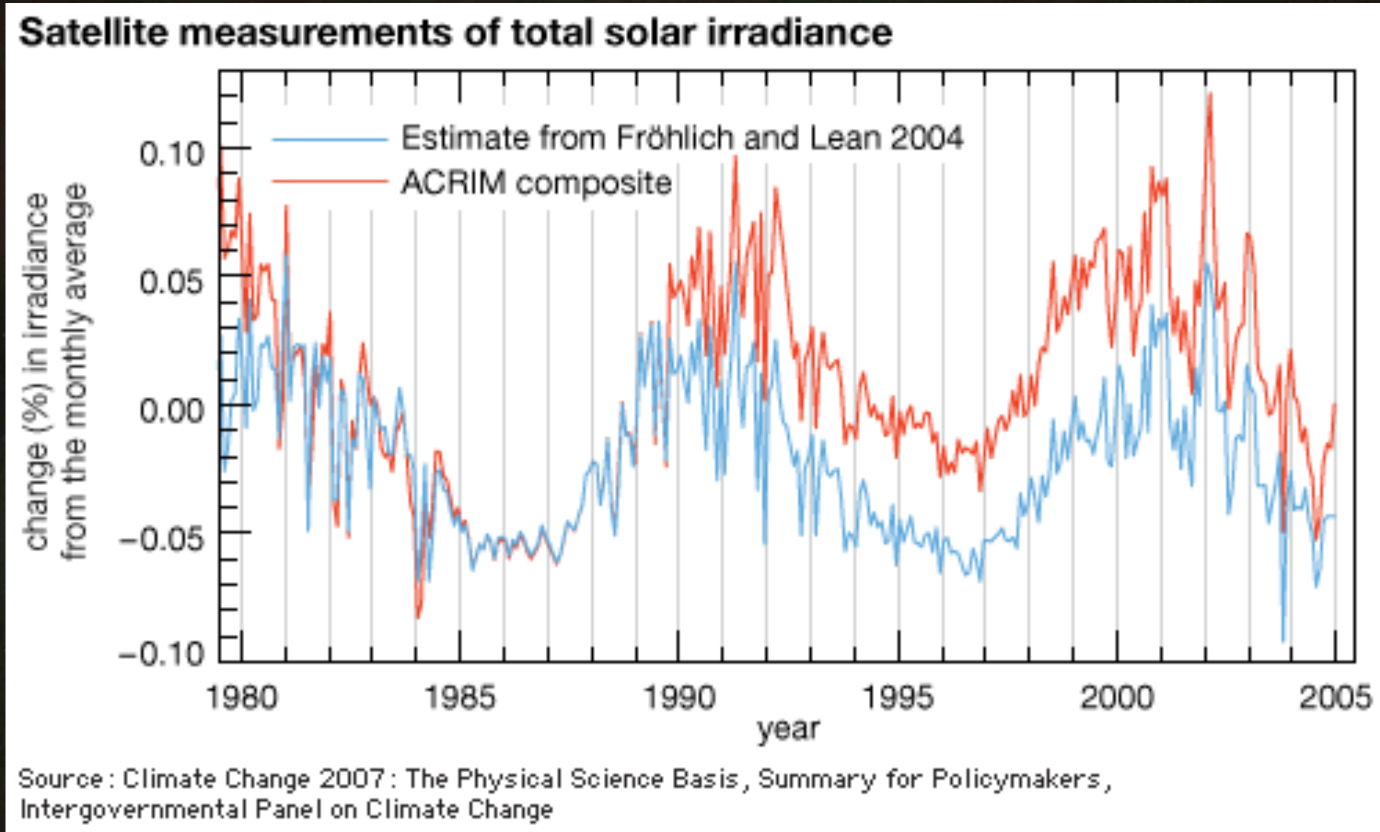


And critical sense is requested when this is invoked to explain the global warming

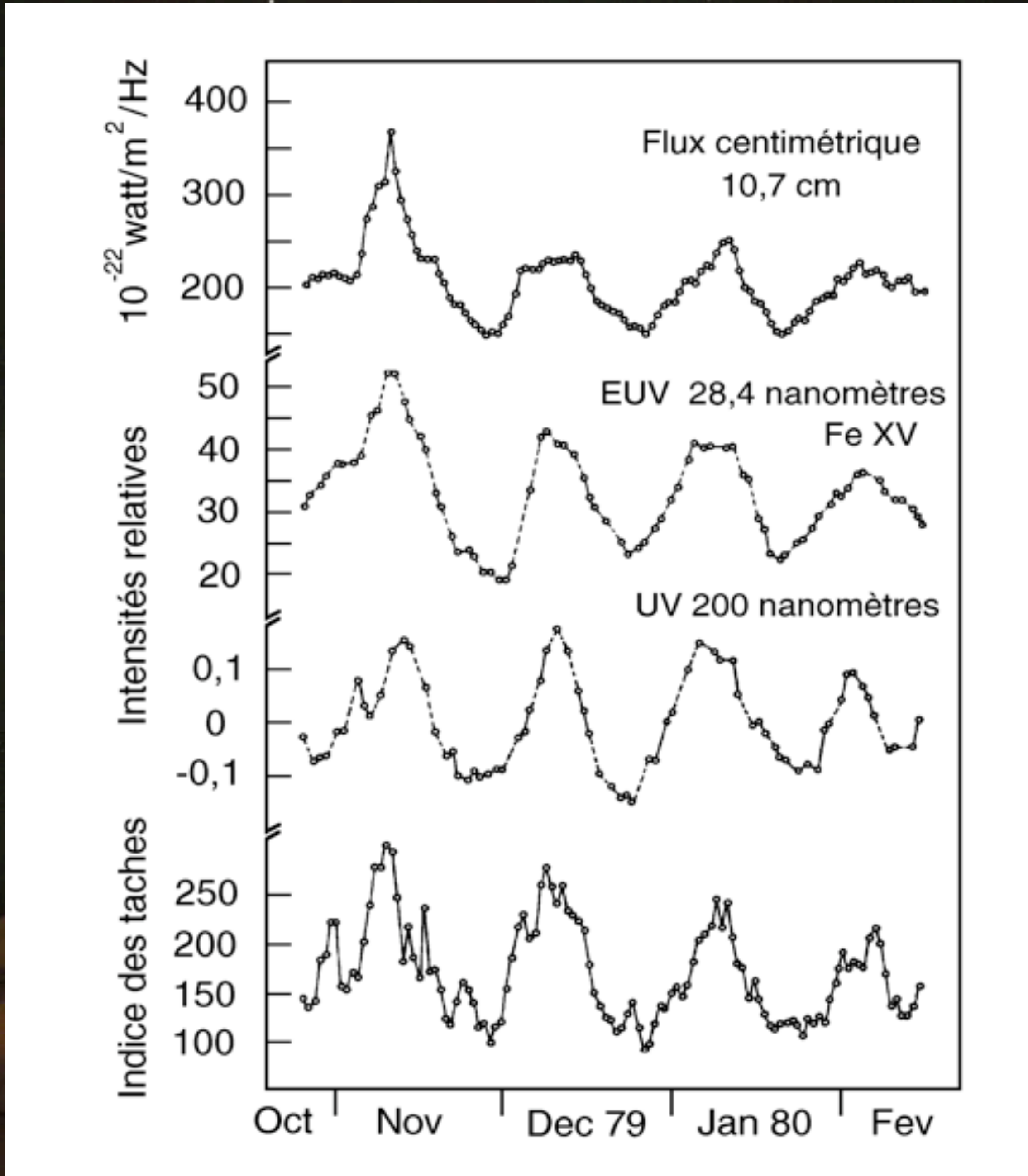
How to monitor the solar EUV flux and its variability ? By using indices (or … proxies).

What is a index?

Indices have been introduced in order to give a simple yet almost exact description of massive data ensembles which vary with time (and eventually in space). Basically, an index is made up from a set of discrete values which provide as pertinent and reliable information as possible about the phenomenon in question by characterising it as a whole. Of course, the validity of the index basically depends on its definition, and on the choice of the described aspect of the phenomenon.

ISN, the international sunspot number (from SIDC, Brussels), which is not really a UV proxy but remains the most widely used gauge of solar activity.

f10.7 is the radio flux at 10.7 cm (from Penticton Observatory, Canada). This proxy is widely used as a solar input to ionosphere/thermosphere models, partly because it can be conveniently measured from ground.



Flux centimétrique
10,7 cm
EUV 28,4 nanomètres
Fe XV
UV 200 nanomètres
10^{-22} watt/m^2/Hz
Intensités relatives
Indice des taches
400
300
200
50
40
30
20
0,1
0
-0,1
250
200
150
100
Oct
Nov
Dec 79
Jan 80
Fev

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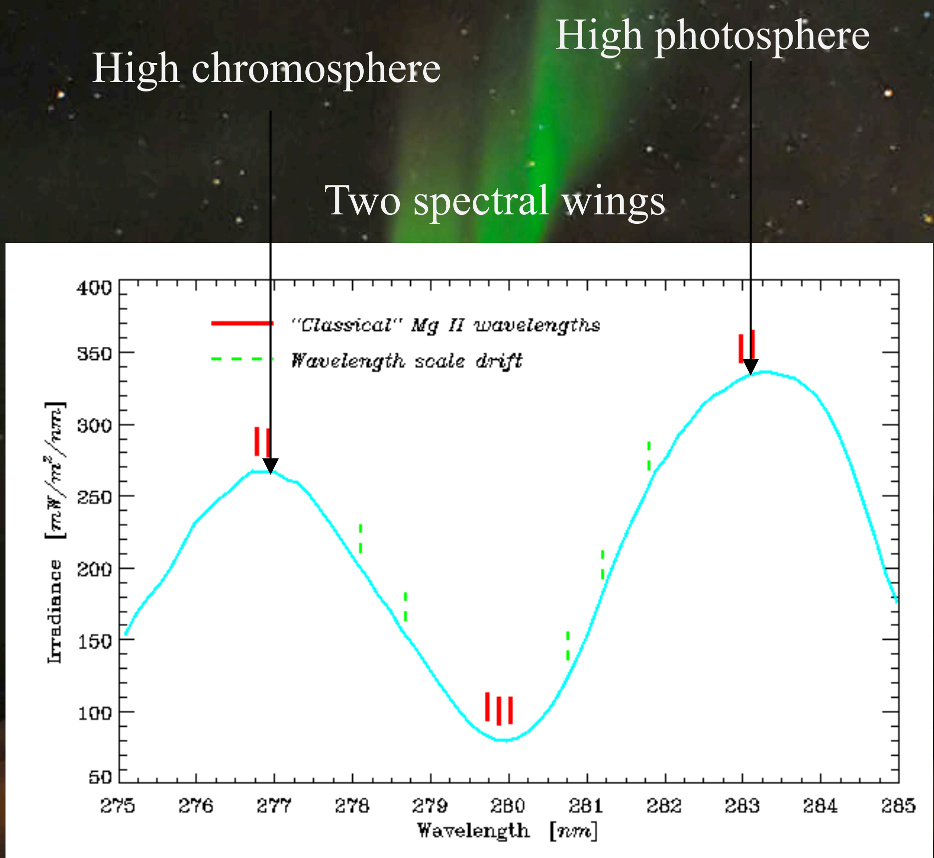
MgII is the core-to-wing ratio of the Mg II line at 280 nm (from SORCE/SOLSTICE, version 9). This index probes the high chromosphere and is often advocated for the FUV [Heath and Schlesinger, 1986].



Indice Mg d'activité solaire (Heath et Schlesinger, 1986) :
= rapport d 'irradiance à 280 nm et moyenne des ailes à 276 nm et 283 nm

Advantage : independant of the instrumental gain

SBUV / 2 discrete MgII k spectrum (Cebula et al., 1992)

CaK is the normalized intensity of the Ca II K-line at 393 nm (from National Solar Observatory at Sacramento Peak). This line originates at nearly the same altitude as the Mg II line and has also been advocated for the FUV [Lean et al., 1982].

MPSI is the magnetic plage strength index (from the Mt. Wilson 150-Foot Solar Tower), which quantifies the relative fraction of the solar surface that is covered by mild magnetic fields (10 < jBj < 100 Gauss). By definition, MPSI index is a proxy for plages and faculae [Parker et al., 1998].

MWSI is the Mount Wilson sunspot index, defined as the MPSI, but for intense magnetic fields (100 Gauss). The MWSI is a proxy for active regions.

s10.7 is computed by Tobiska et al. [2008] out of the integrated 26 – 34 nm emission from the SEM radiometer onboard SoHO, and rescaled to the f10.7 index after a trend correction (version 3.9a). It is dominated by the emission from the chromospheric and transition region He II line at 30.4 nm. Is it a proxy ?

Lyman-a channel (ch-L) is the output of a photodiode from the LYRA radiometer [Hochedez et al., 2006] onboard the PROBA2 satellite, launched in 2010. This channel integrates emissions in the 110 – 210 nm band, with a peak around 125 nm.

Herzberg channel (ch-H) is the output of a photodiode from LYRA in the Herzberg band, here between 195 – 220 nm. Both the Herzberg and the Lyman-a channels are relevant inputs for upper atmospheric models.

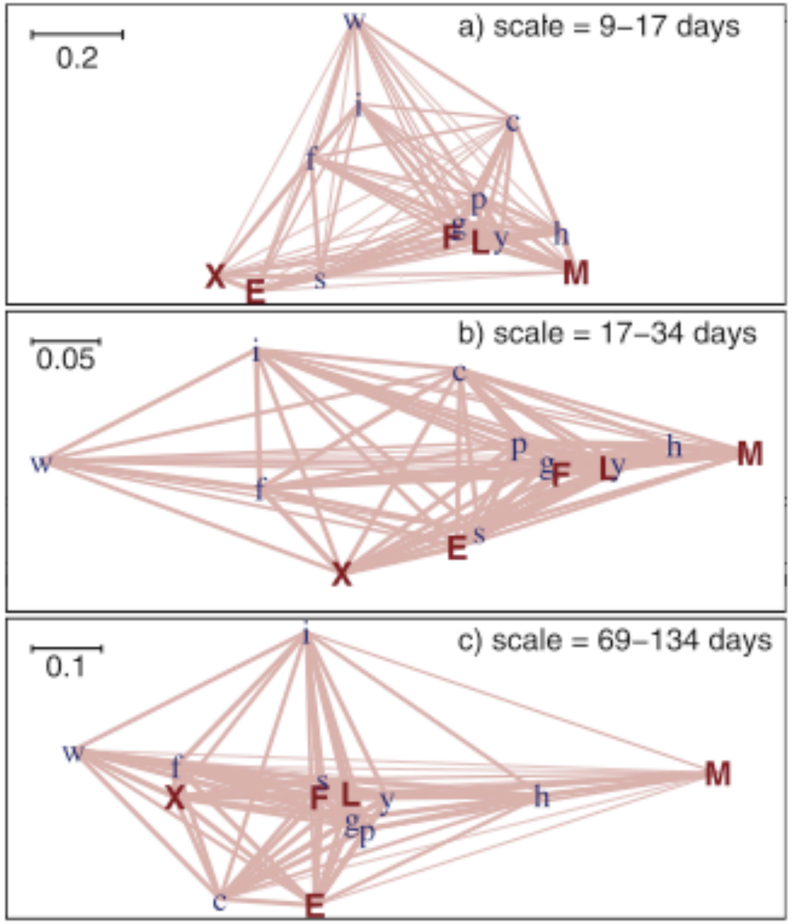


Figure 3. Correspondence maps for three characteristic scales. The distance between each pair of points corresponds to $1 - |r|$ (see text) and the line thickness is proportional to r. Capitals designate our 5 spectral bands: (X)UV, (E)UV, H I (L)yman-α, (F)UV and (M)UV. The other characters correspond to proxies: (i)sn, (f)10.7, (s)10.7, M(g)II, (c)aK, M(p)SI, M(w)SI, L(y)man-α channel, (h)erzberg channel.

Finding the best proxies for the solar UV irradiance, Dudok de Wit et al., Geoph. Res. Let., Vol. 36, L10107, doi: 10.1029/2009GL037825, 2009

What are the best proxies for reconstructing specific spectral bands?

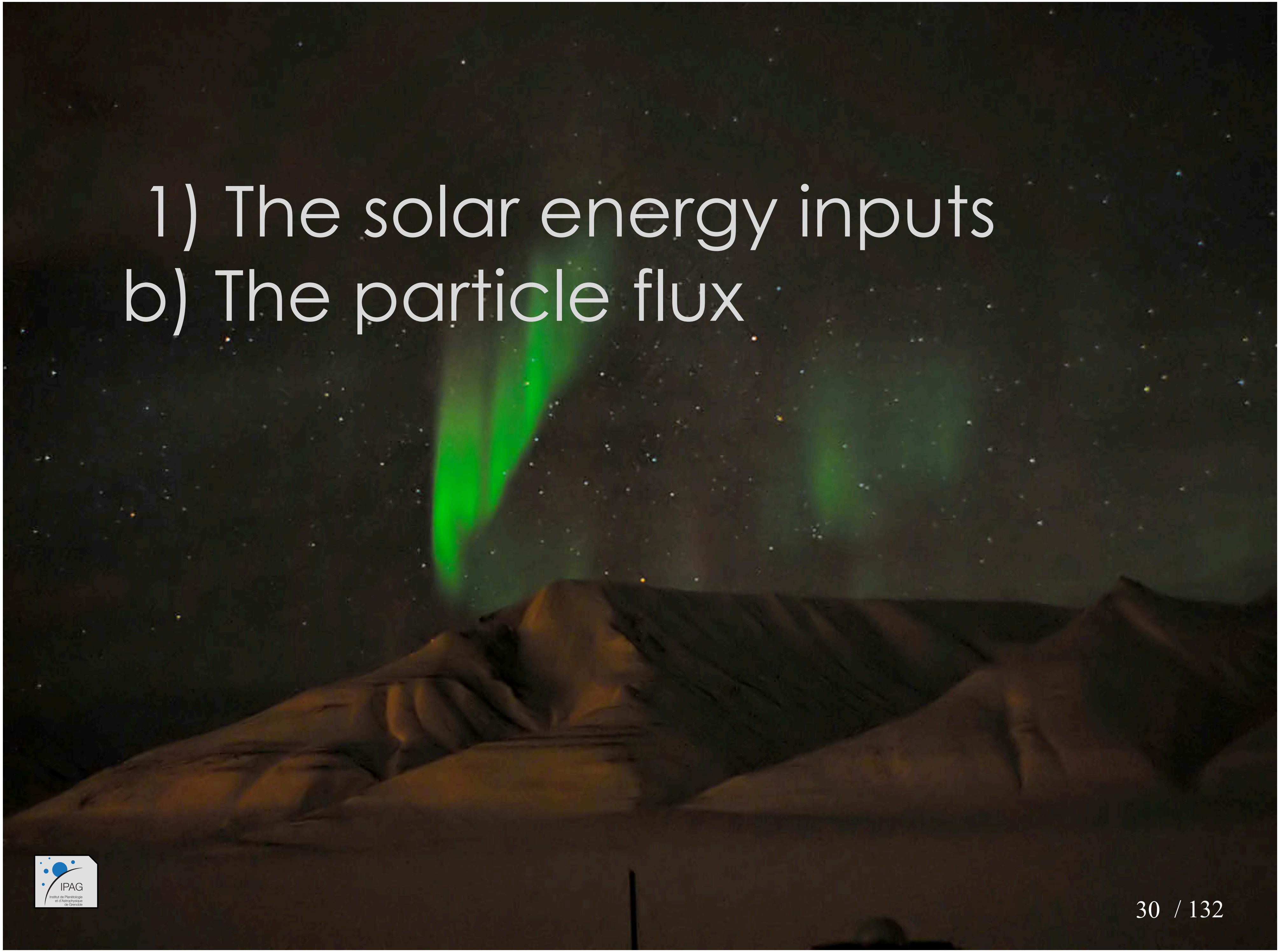
- The answer very much depends on the time-scale of interest.
- Proxies that are derived from real irradiance data do match their corresponding spectral band quite well. The correlation between the LYRA Lyman-a channel and the Lyman-a band, for example, always exceeds 0.95.
- The MgII index shows the best global performance since it is always located close to the center of the cloud of points. It is particularly well suited for the FUV band. The MPSI index is a backup solution, but is not measured continuously.
- Apart from these, no single spectral band can be properly reconstructed at all scales from one single proxy.
- There is no good (non irradiance-derived) proxy for the XUV and EUV bands. The f10.7 index would be the least bad solution.
- None of our proxies properly fits the MUV band, for which a better gauge of photospheric emissions is needed

http://www.swpc.noaa.gov/ftpmenu/indices.html

http://www.stce.be/

http://swc.nict.go.jp/sunspot/index_e.php

http://lpc2e.cnrs-orleans.fr/~soteria/



1) The solar energy inputs
b) The particle flux


Where does it come from ?
See class by A. Aylward
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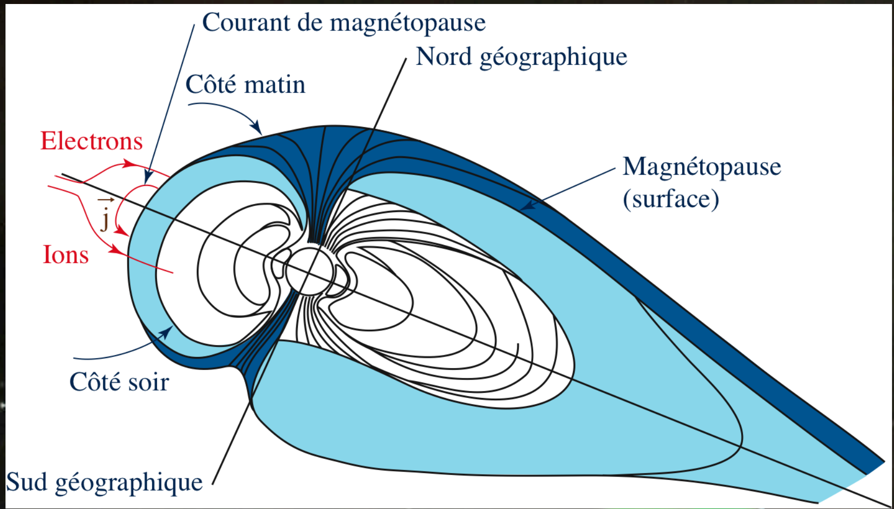
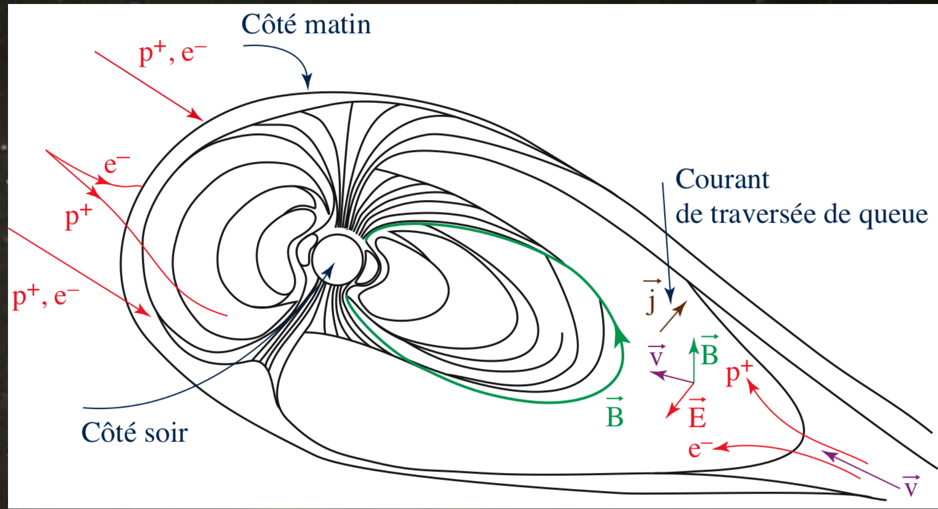
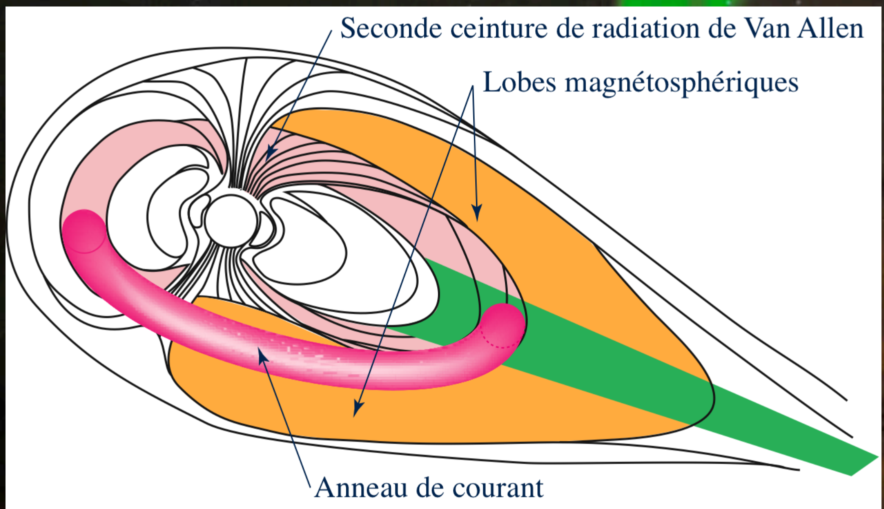


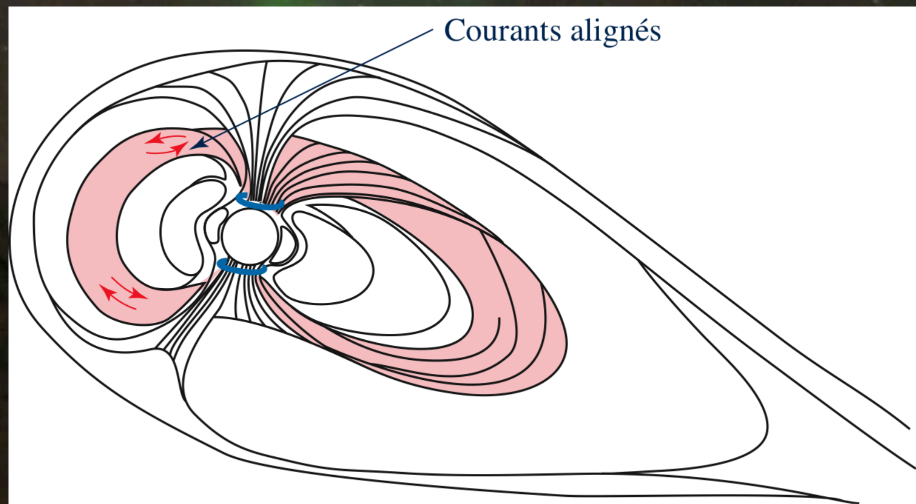
Courant de magnétopause
Nord géographique
Côté matin
Electrons
Magnétopause
(surface)
$\vec{j}$
Ions
Côté soir
Sud géographique



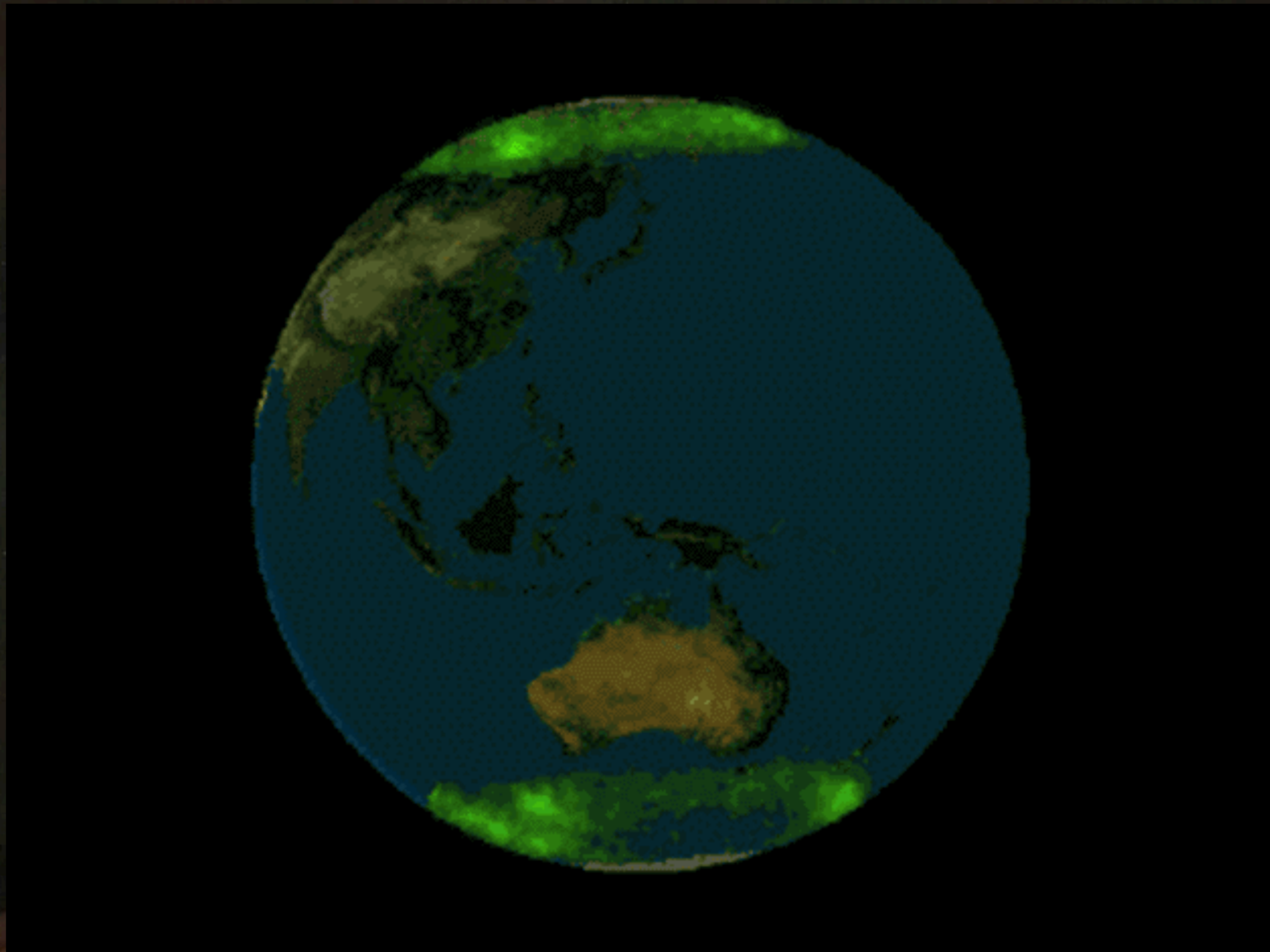
Côté matin
p^+, e^-
e^-
p^+
p^+, e^-
Courant
de traversée de queue
$\vec{j}$
$\vec{v}$
$\vec{B}$
p^+
$\vec{B}$
$\vec{E}$
e^-
Côté soir
$\vec{v}$



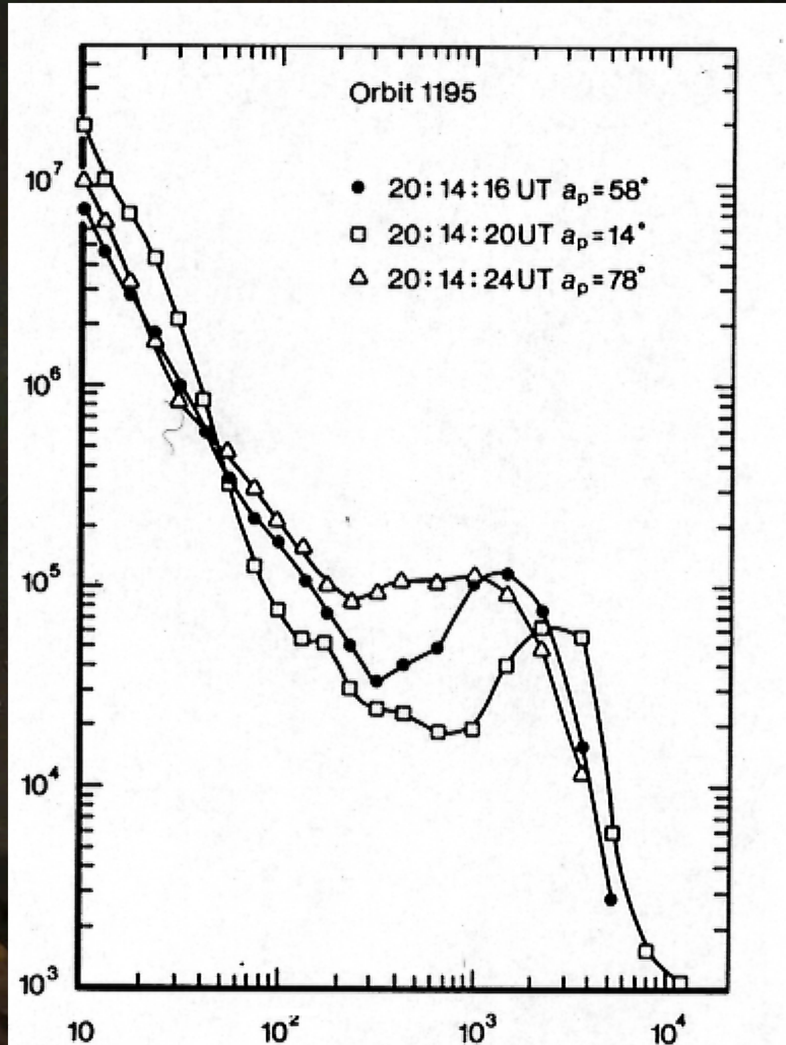
Seconde ceinture de radiation de Van Allen
Lobes magnétosphériques
Anneau de courant



Courants alignés

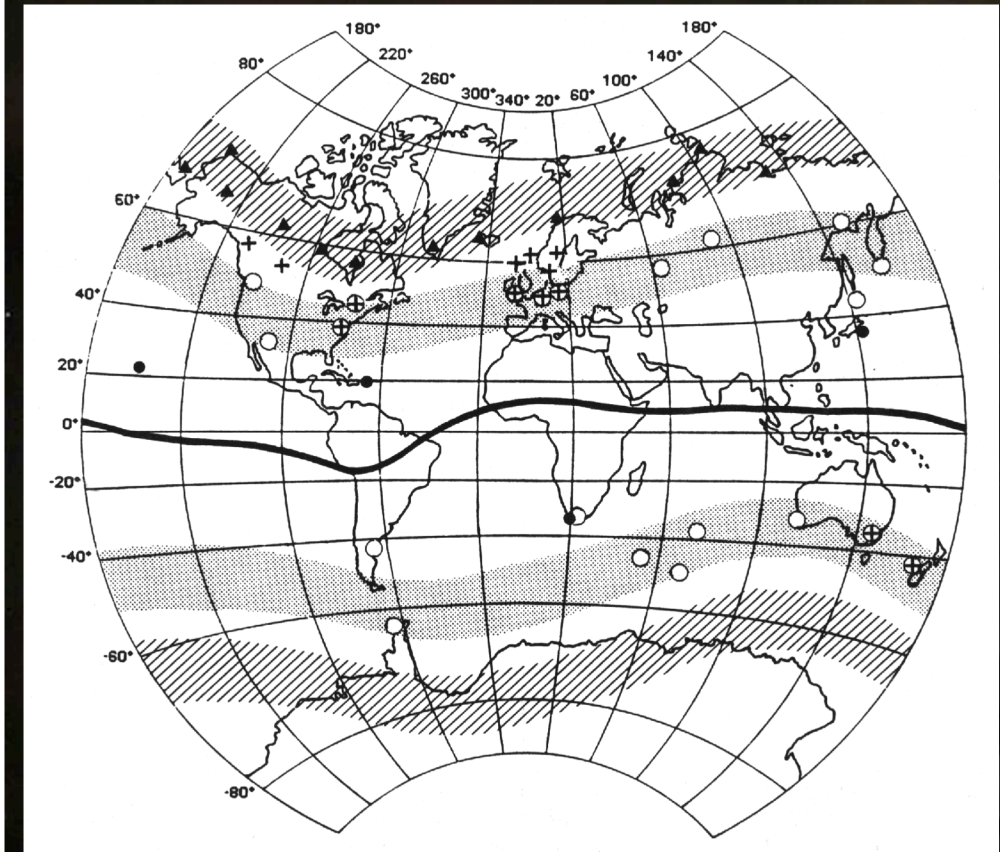


In the cusps, energies of typically 500 eV (polar rain), relatively constant (slightly depending on the solar activity)



In the auroral ovals, energies ranging from 100s' eV to 100s' keV, strongly depending on the solar activity

How to monitor the geomagnetic activity and its variability ? By using proxies again !



Geographical world map on which are indicated the positions of stations belonging to the different networks used in deriving geomagnetic indices: ▲ for AE, ● for Dst, + for Kp, ap, O for am, Km, and ⊕ for stations belonging to both Kp, ap, and am, Km networks. A solid line indicates the position of the dip equator. The average extension of the auroral zone is sketched by the hatched area, that of the subauroral region by the shaded area (after Berthelier, 1993).

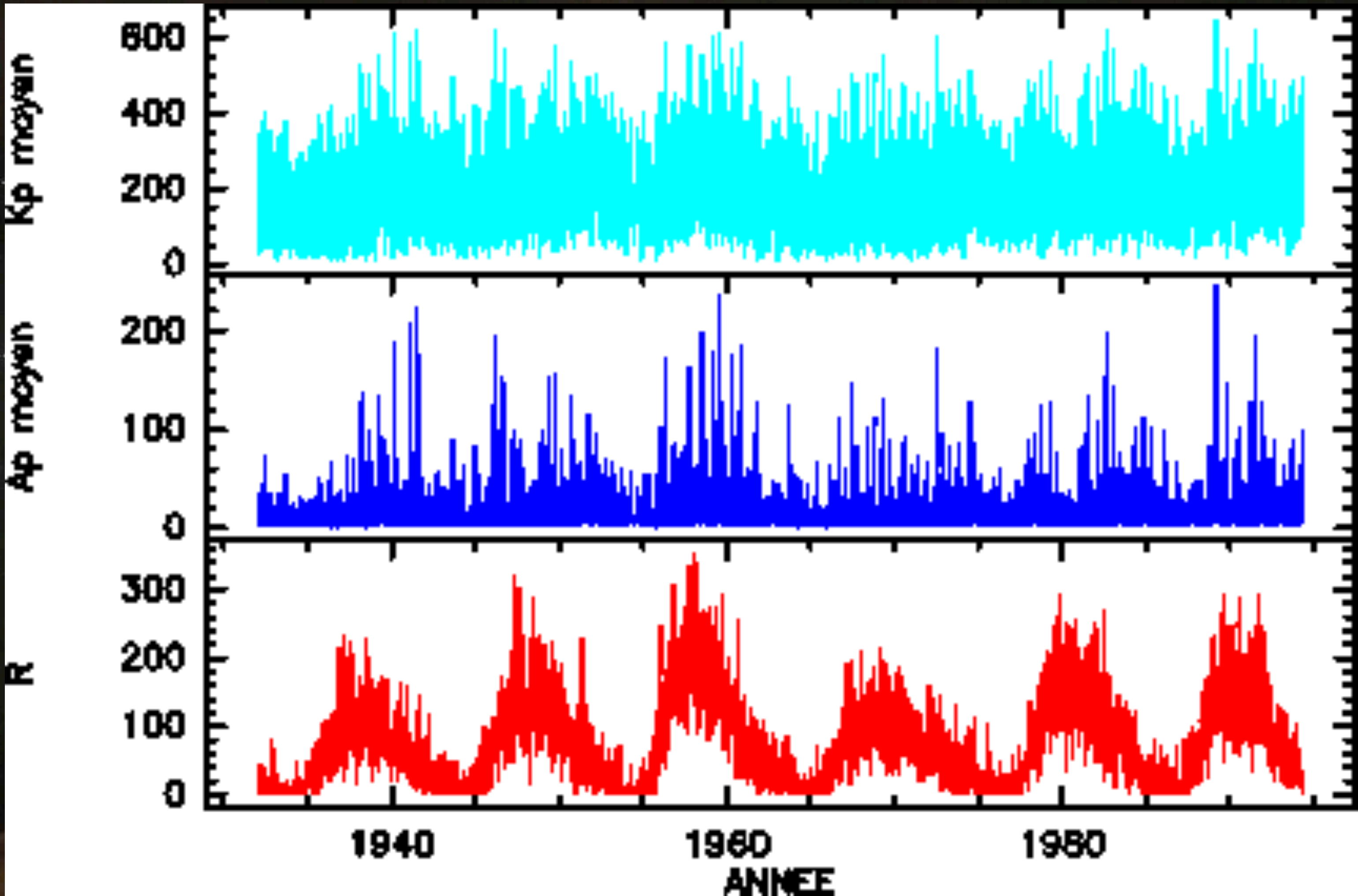
Indices *(beginning of the data series)*	**(1) Measured quantity Baseline**	**(2) Time interval**	**(3) Network**	**(4) Derivation process**
Auroral indices AE, AU, AL, A0 *(Since July 1957 ; missing data in 1976-1977)*	Deviation ΔH (nT) of the horizontal component Baseline: Sq* variation (see text)	1 minute (since 1978)	Network of stations in the boreal auroral zone Modification of the network in 1966 (see Figure 8 the network since 1966)	AU : largest observed value of ΔH(*t*) at the network stations and at time *t* (upper envelope) AL : smallest observed value of ΔH(*t*) (lower envelope) AE = AU + |AL| A0 = (AU + AL) / 2 *Unit: nT*
Equatorial index Dst *(since 1957)*	ΔH (nT) variation of the horizontal component; Baseline: secular variation	1 hour	Network of 4 low latitude stations (see Figure 8)	Hourly values of the perturbation D are computed at each station : D = ΔH - Sq** (see text) Dst = *Moy*(D) / *Moy*(cosϕ) ϕ : dipolar latitude of the stations *Unit: nT*

Indices *(beginning of the data series)*	(1) **Measured quantity** **Baseline**	(2) **Time interval**	(3) **Network**	(4) **Derivation process**
Local indices K	Amplitude of the irregular variations: ranges Baseline: S_R variation (see text)	3 hours (UT) : 00-03, 03-06, … …, 18-21, 21-24	K indices are defined everywhere, but their meaning is the best at subauroral latitudes	K is a code (a number: 0 to 9) corresponding to the class in which falls the measured range. The limits of the classes are defined according to a quasi logarithmic scale (see text and Figure 8) a_K(nT) is the mid-class amplitude associated to the K value.

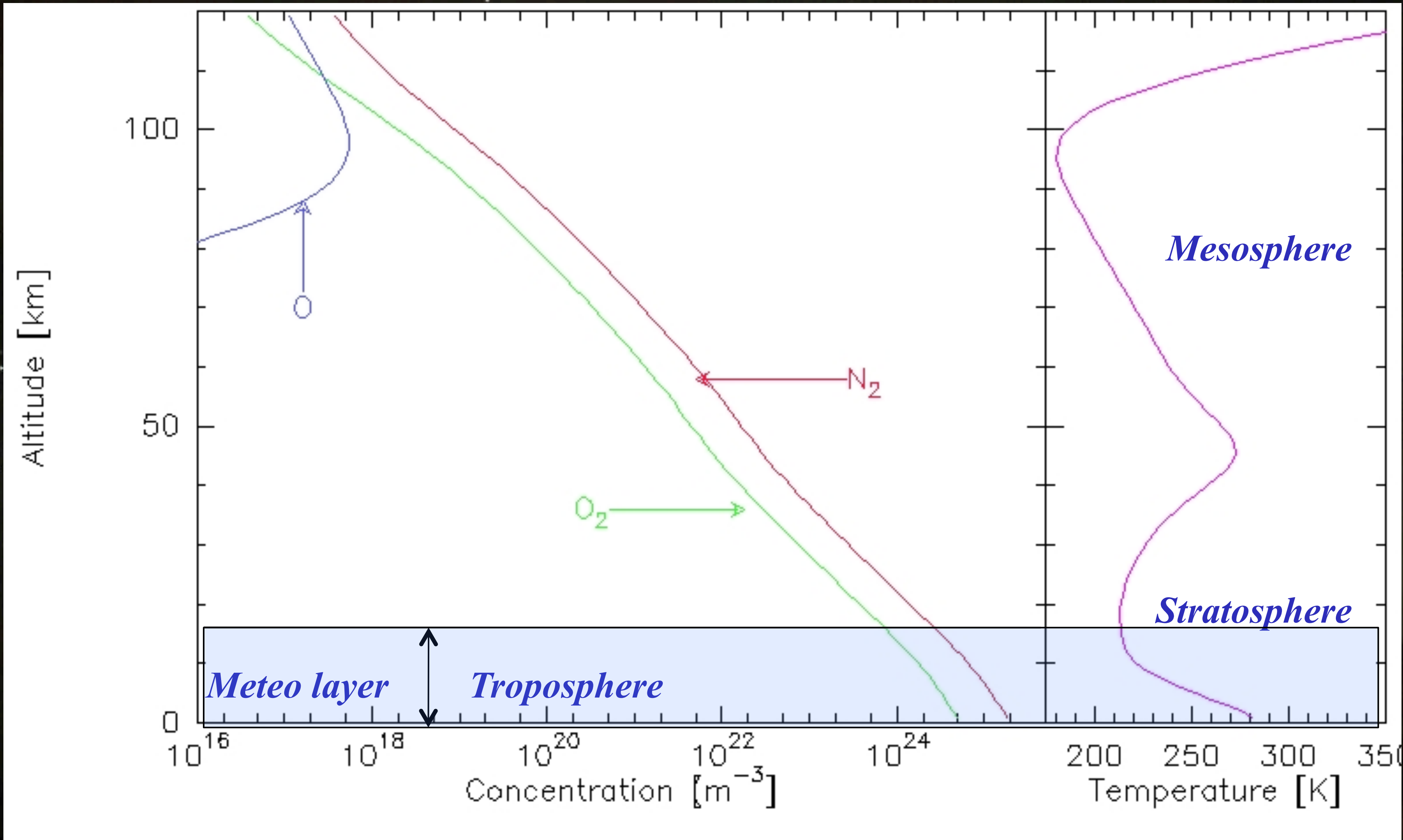
Indices *(beginning of the data series)*	(1) Measured quantity Baseline	(2) Time interval	(3) Network	(4) Derivation process
Planetary indices	K indices	3 hours (UT)	Network of	K codes from each station are
Kp			13 stations :	converted to standardised codes "3Ks"
ap, Ap		(*cf.* K indices)	11 boreal ones and	3Kp=Σ3Ks/12
			2 austral ones.	3Ks et 3Kp : integers, 0 to 27
(since 1932)				Kp: 0o, 0+, 1-, to 9o
			(see Figure 8)	ap: deduced from Kp through
				conversion tables *(unit: 2nT)*
				Ap: daily mean value of ap

Indices *(beginning of the data series)*	(1) **Measured quantity Baseline**	(2) **Time interval**	(3) **Network**	(4) **Derivation process**
Planetary indices	Amplitudes deduced	3 hours (UT)	Network of	For each longitude sector Gi, the
an, as and am	from K indices		subauroral latitude	average of Ks in converted to
An, As and Am		(*cf.* K indices)	stations:	equivalent amplitudes: a_{Gi}(nT)
Kpn, Kps and Kpm			13 boreal ones and	an: $\Sigma\lambda_{Gi}a_{Gi}$ (boreal hemisphere)
			10 austral ones	as: $\Sigma\lambda_{Gi}a_{Gi}$ (austral hemisphere)
			arranged in groups	λ_{Gi} : weighting factor accounting
(since 1959)			each group	for the longitude width of Gi
			representing	am = (an + as) / 2
			a longitude sector	An, As, Am: daily mean values of
				an, as, am
			(see Figure 8)	Kpn, Kps, Kpm: deduced from am, an, as
				through conversion tables
				Unit for am, an, as: nT
				Unit for Kpn, Kps, Kpm: Kp unit

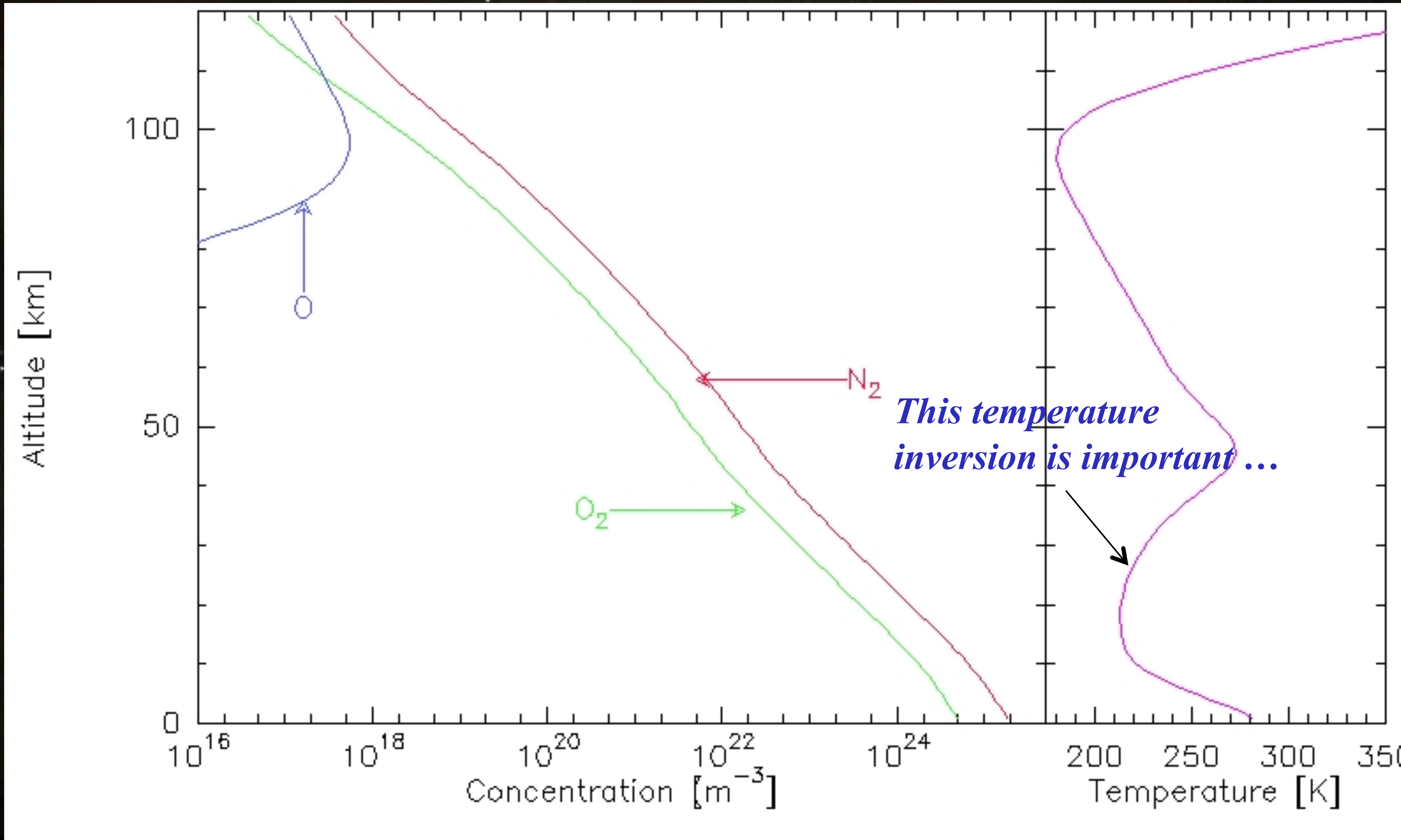
Indices *(beginning of the data series)*	(1) **Measured quantity** **Baseline**	(2) **Time interval**	(3) **Network**	(4) **Derivation process**
Planetary index aa *(since 1868)*	Amplitudes deduced from K indices	derivation: 3 hours (UT) meaningful when averaged over at least 4 intervals	Network of 2 antipodal subauroral latitude stations: HAD and CAN (see Figure 8)	For each station, the a_K values are corrected to take into account the small differences between the latitudes of the 2 stations aa: average of the 2 corrected amplitudes *Unit: nT*

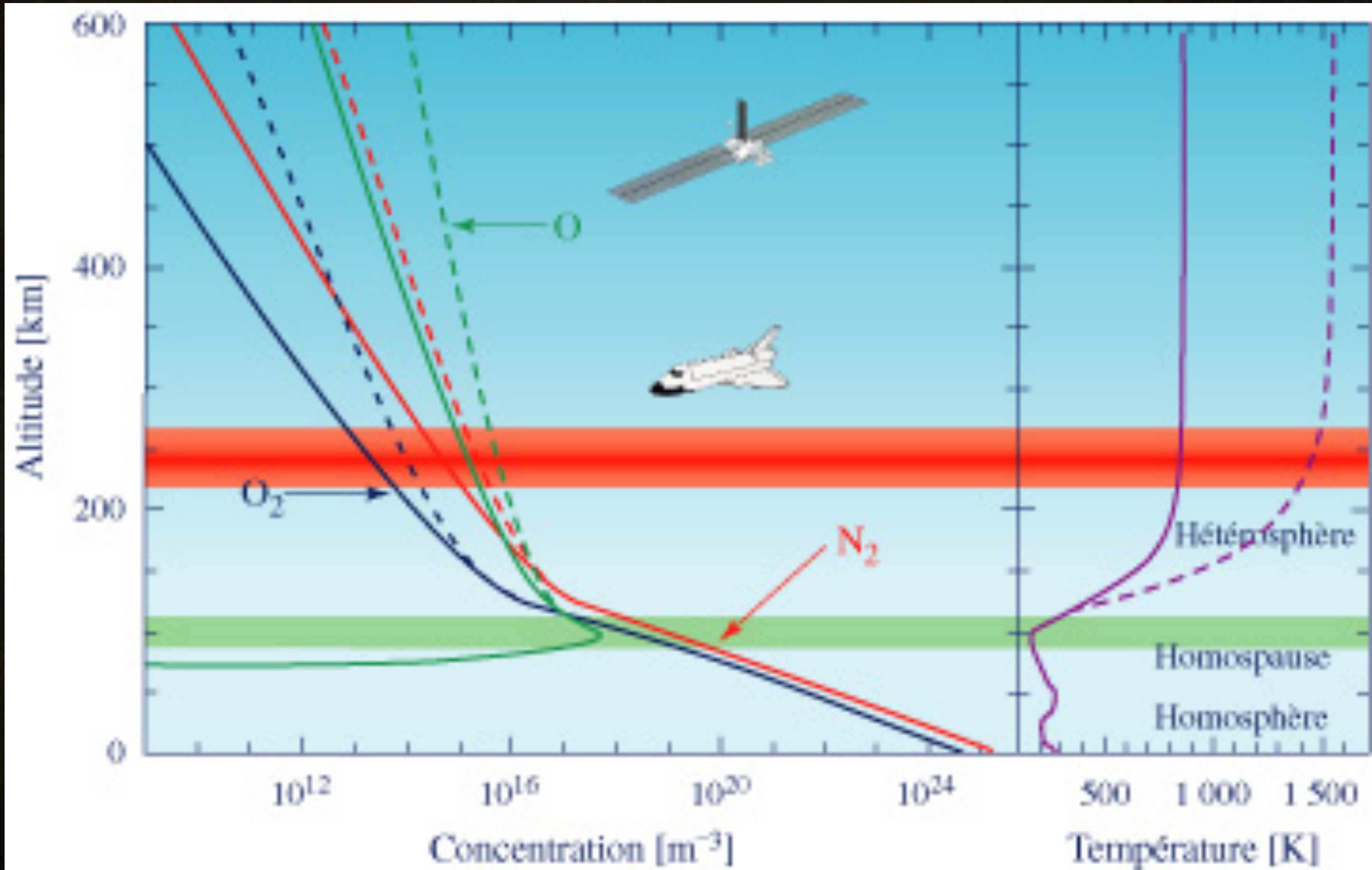

Kp moyen
600
400
200
0
Ap moyen
200
100
0
R
300
200
100
0
1940
1960
1980
ANNEE

2) The Earth Atmosphere

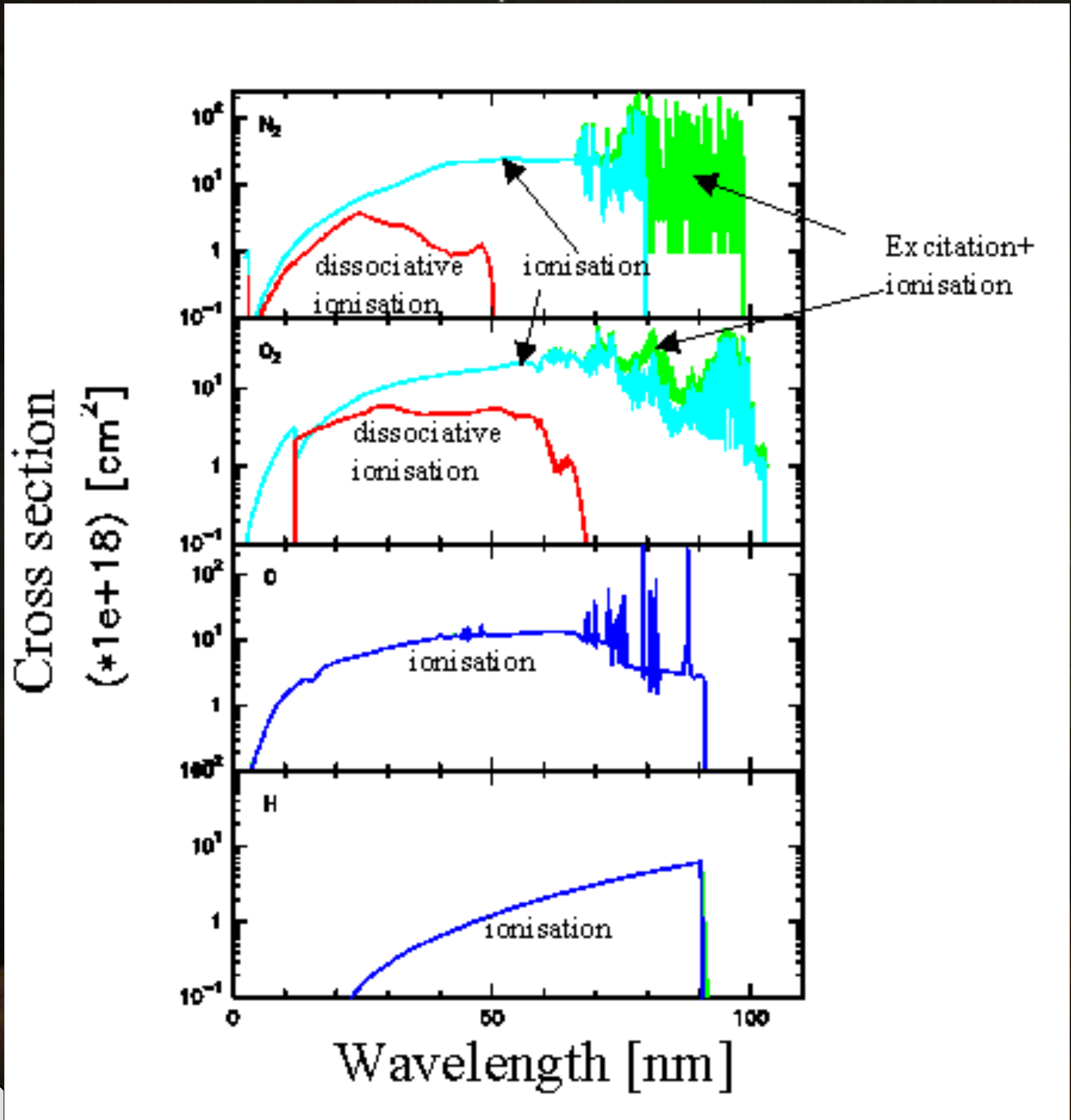


Altitude [km]
100
50
0
O
N_2
O_2
Mesosphere
Stratosphere
Meteo layer
Troposphere
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
Concentration [m^{-3}]
200
250
300
350
Temperature [K]

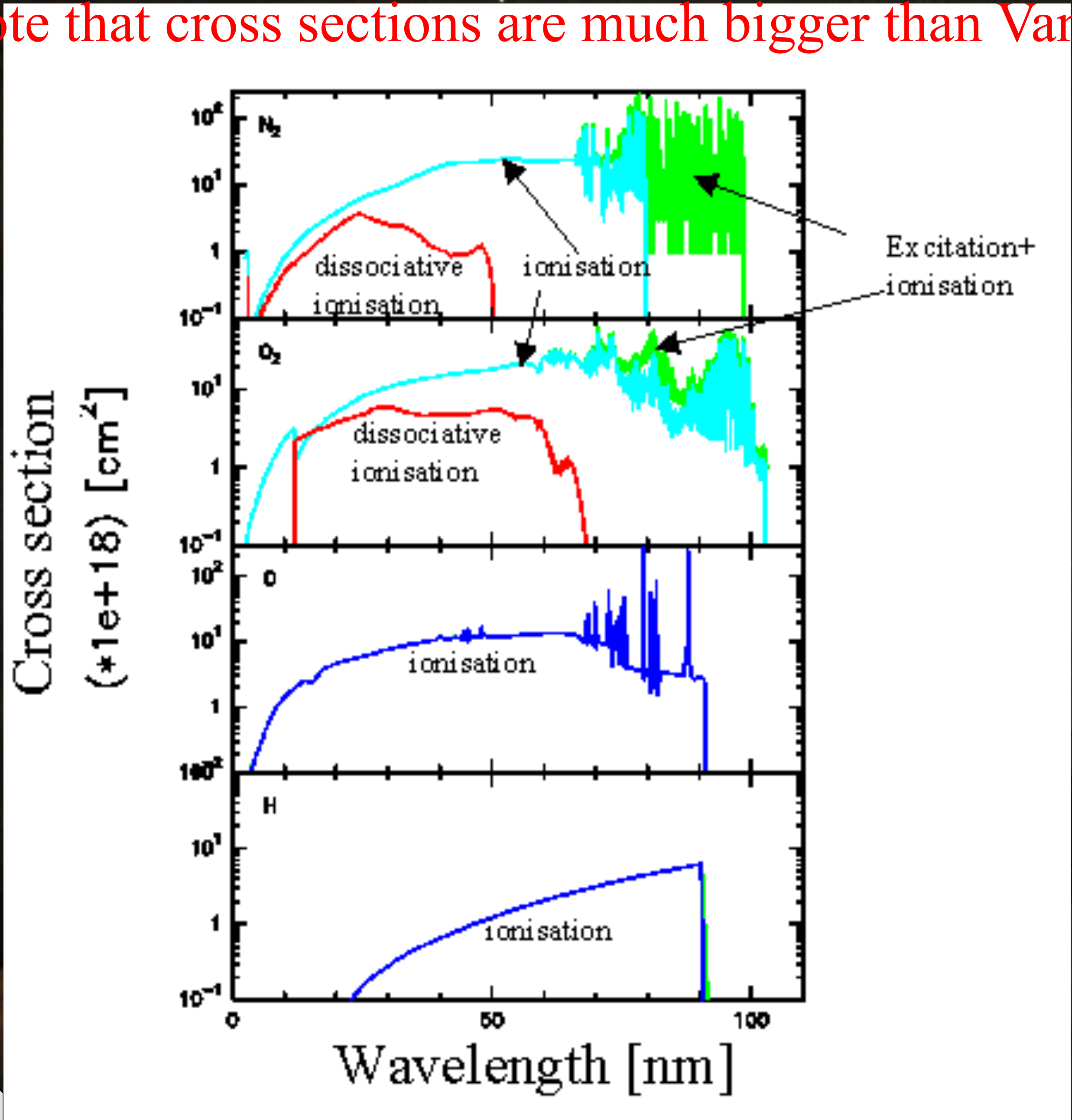

100
50
0
Altitude [km]
O
N_2
O_2
10^{16} 10^{18} 10^{20} 10^{22} 10^{24}
Concentration [m^{-3}]
200 250 300 350
Temperature [K]
This temperature inversion is important …



600
400
200
0
Altitude [km]
O
O_2
N_2
Hétérosphère
Homospause
Homosphère
10^{12}
10^{16}
10^{20}
10^{24}
Concentration [m^{-3}]
500
1 000
1 500
Température [K]


N2
O2
O
H
dissociative ionisation
ionisation
Excitation+ ionisation
dissociative ionisation
ionisation
ionisation
Cross section (*1e+18) [cm2]
Wavelength [nm]
0
50
100

Note that cross sections are much bigger than Van der Walls sections



L (N2) = 0.1098 nm

S ≈ 0.15 10^{-22} cm^2

L (O2) = 0,292 nm

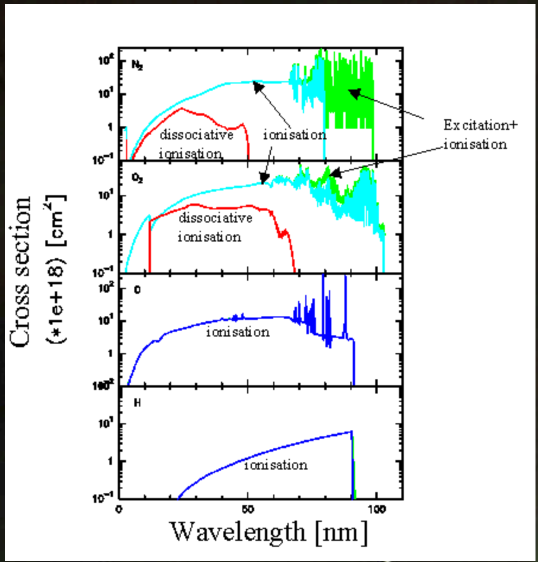
S ≈ 1.07 10^{-22} cm^2

L (O) = 0,066 nm

S ≈ 0.55 10^{-23} cm^2

L (H) = 0,025 nm

S ≈ 0.79 10^{-24} cm^2



For atmospheric gazes, keep in mind values of :

$S \approx 1$ to $20\ 10^{-24}\ cm^2 \quad = 1$ to $20\ 10^{-28}\ m^2$

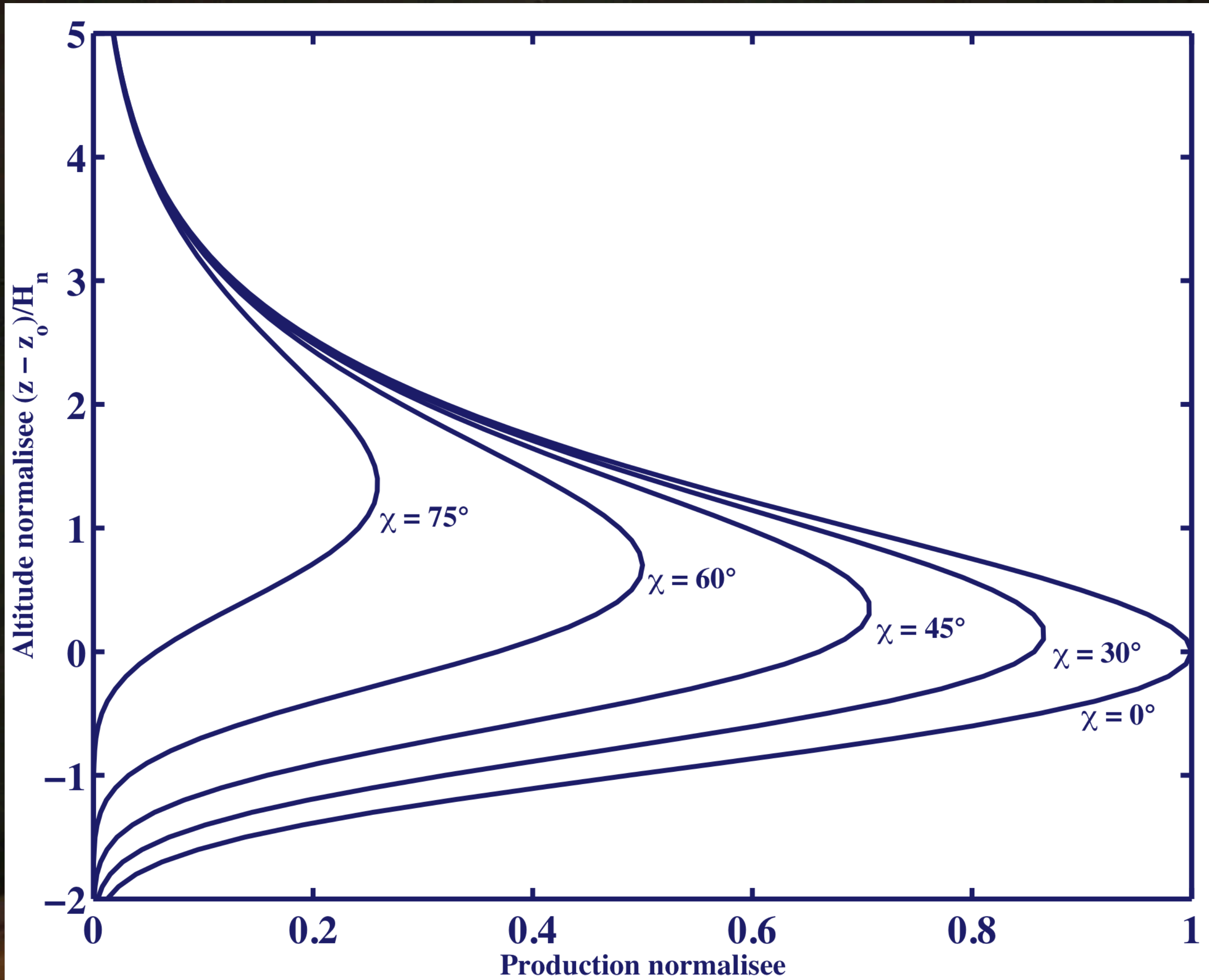
$= 1$ to 20 barn

$\sigma_{ion} \approx 10^{-17}\ cm^2 \quad = 10^{-21}\ m^2$

$\sigma_{dissoc} \approx 10^{-18}\ cm^2 \quad = 10^{-22}\ m^2$

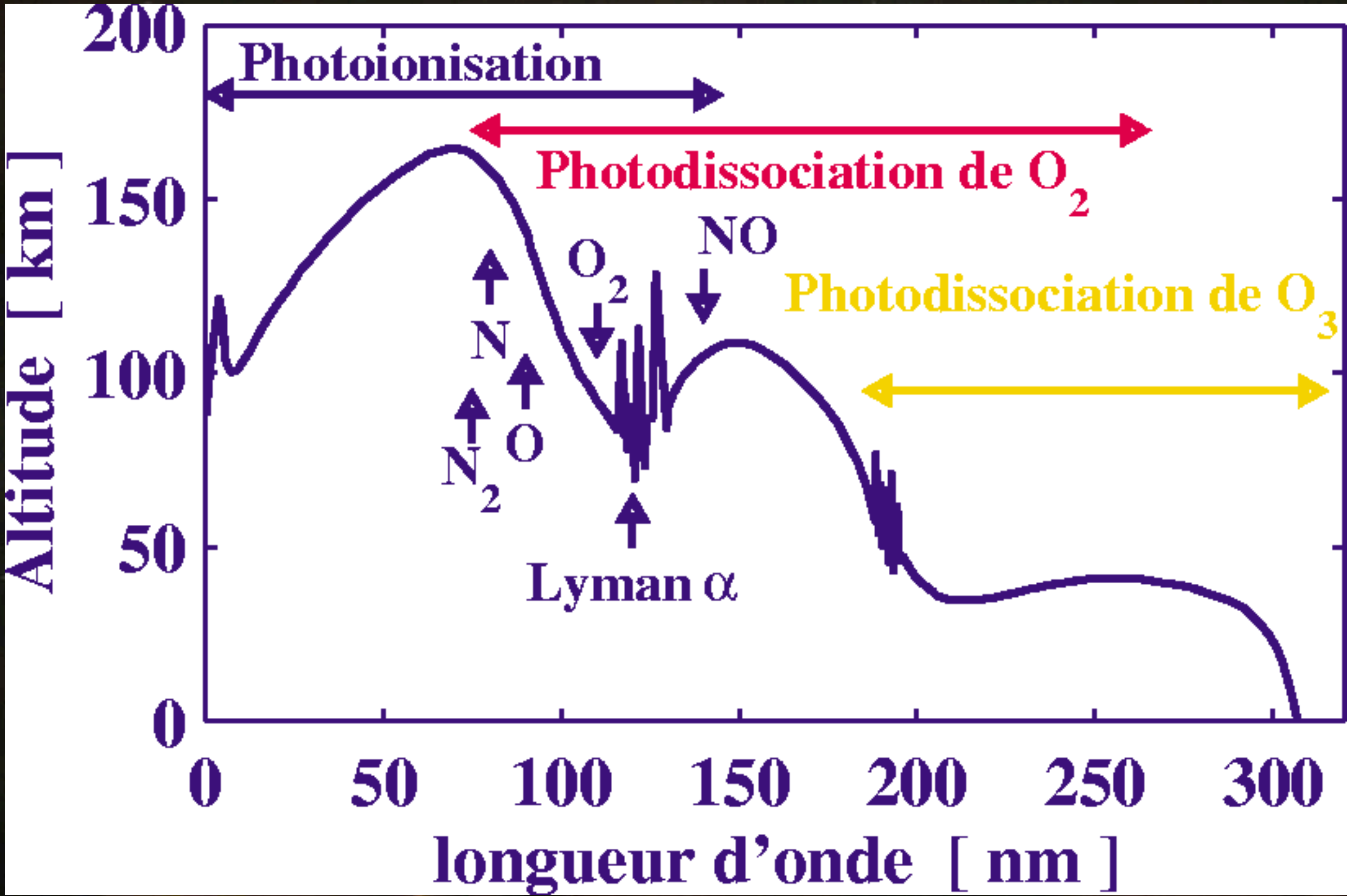
We can now start making some computations (on the board).

The hydrostatic equilibrium, the scale height and the Chapman theory



5
4
3
2
1
0
−1
−2
0
0.2
0.4
0.6
0.8
1
Altitude normalisee (z − z0)/Hn
Production normalisee
χ = 75°
χ = 60°
χ = 45°
χ = 30°
χ = 0°

IPAG



Photoionisation
Photodissociation de O2
Photodissociation de O3
NO
O2
N
O
N2
Lyman α
Altitude [km]
longueur d'onde [nm]
0
50
100
150
200
250
300

However, it is not that simple …
Let’s have a look to the kinetic theory
(on the board first)

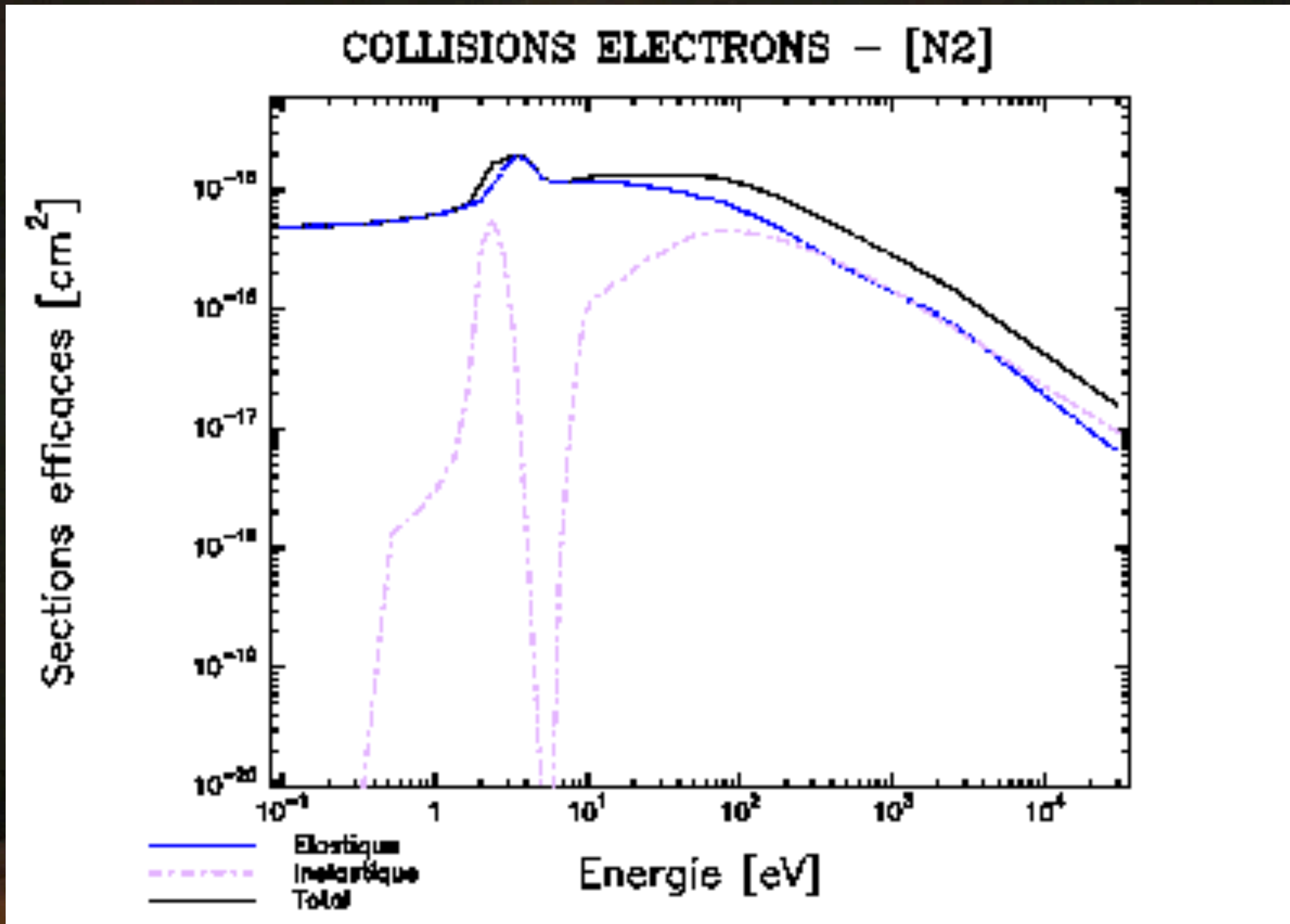
… and see also class by Valentini and Mignone
For instabilities: see class by Califano
For modeling: see class by Lapenta

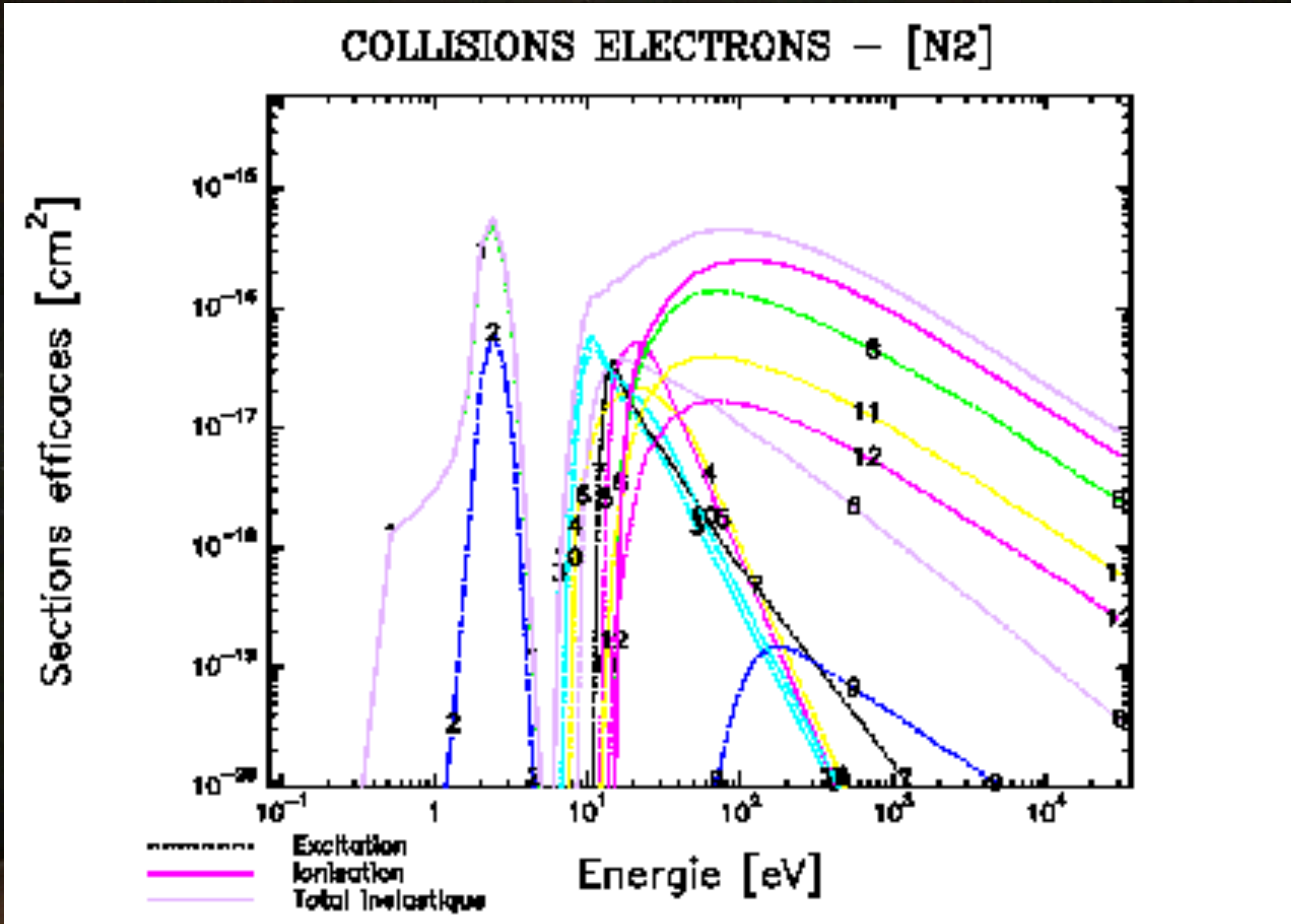
Kinetic Boltzmann equation for dissipative forces

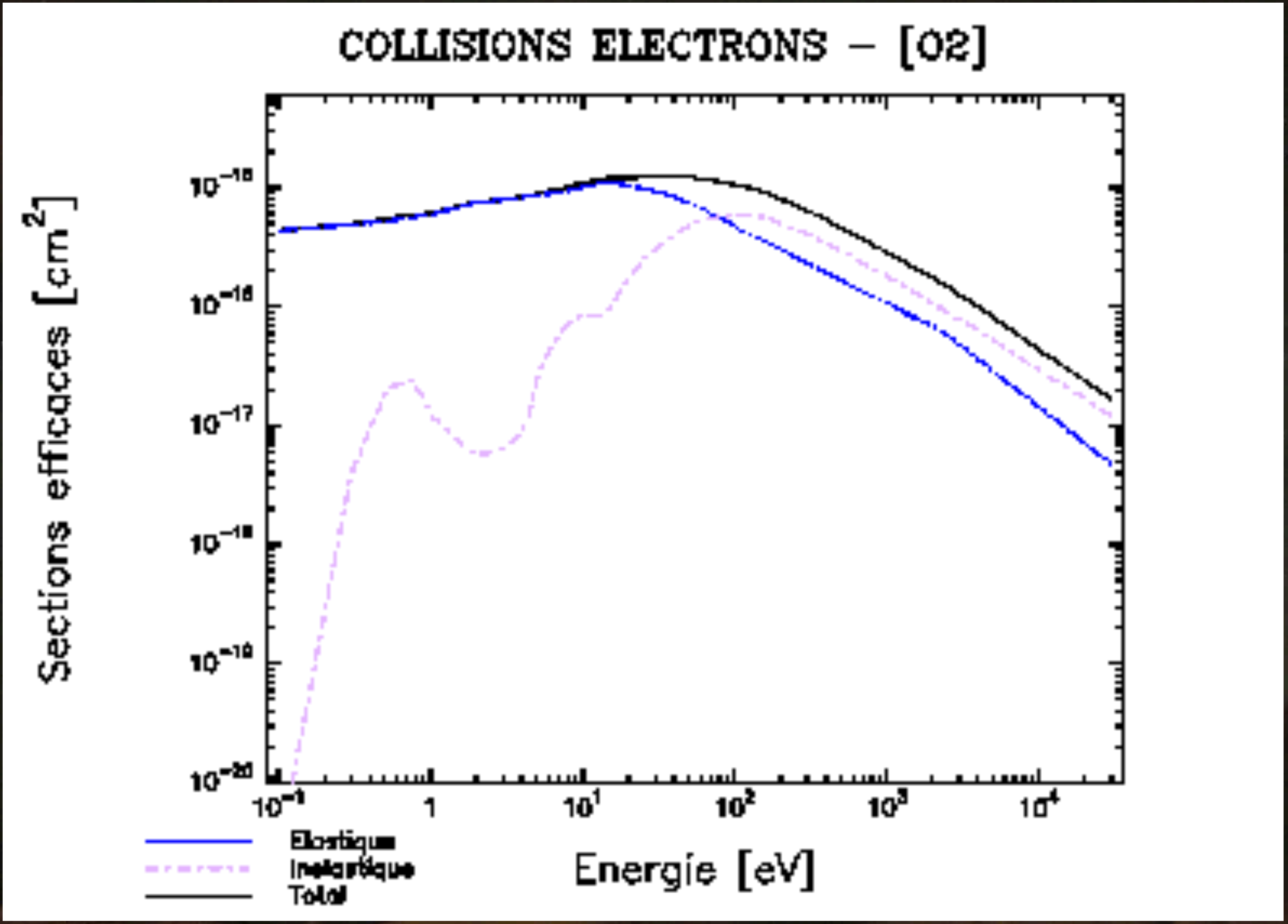
$$\frac{\partial f}{\partial t}+\frac{\partial \vec{v} f}{\partial \vec{r}}+\frac{\partial \frac{\vec{F}}{m} f}{\partial \vec{v}}=\left(\frac{\delta f}{\delta t}\right)_{collisions}$$

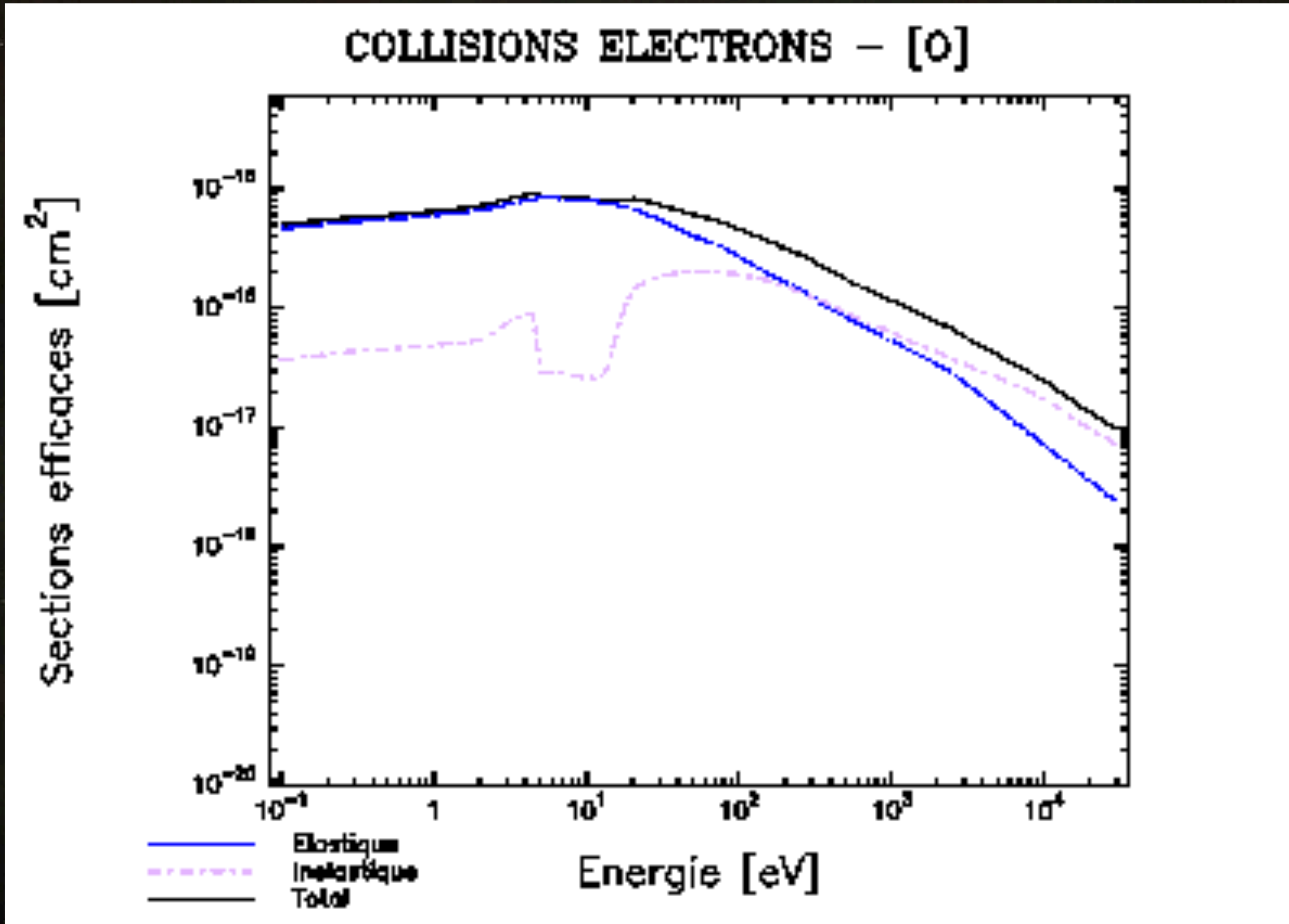
For the study of the ionosphere, use of the : stationnary particle flux

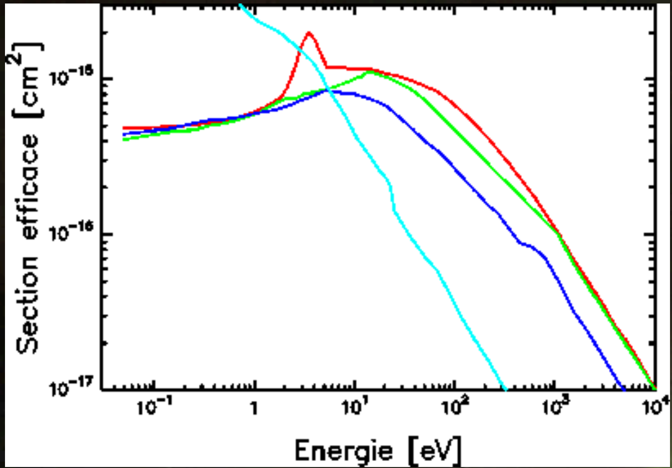
$$\Phi(z,E,\mu)=\frac{|\vec{v}|^2}{m} f(t,\vec{v},\vec{r})$$


COLLISIONS ELECTRONS – [N2]
Sections efficaces [cm^2]
Energie [eV]
Elastique
Inelastique
Total


COLLISIONS ELECTRONS – [N2]
Sections efficaces [cm^2]
Energie [eV]
Excitation
Ionisation
Total Inelastique


COLLISIONS ELECTRONS – [O2]
Sections efficaces [cm2]
Energie [eV]
Elastique
Inelastique
Total

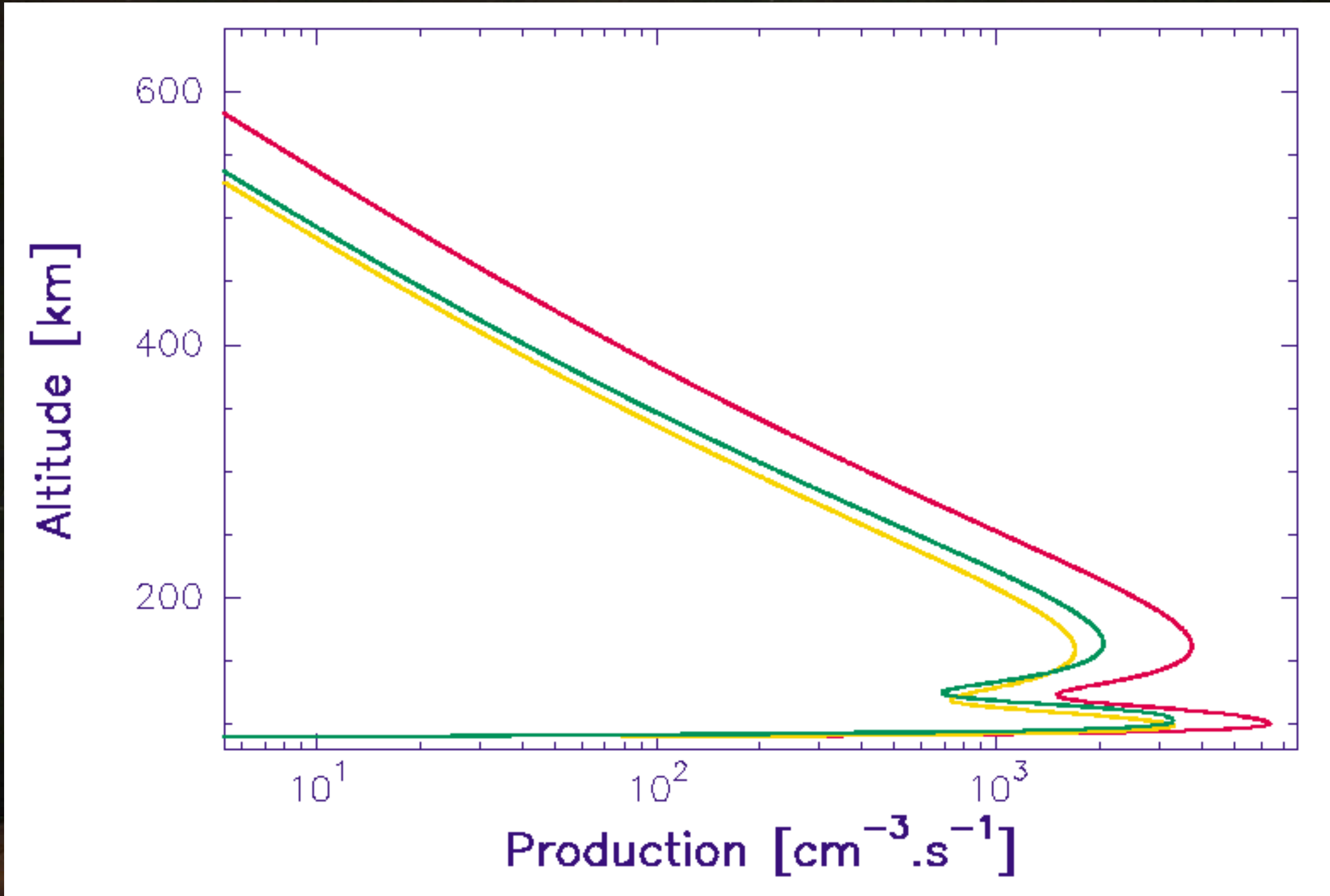

COLLISIONS ELECTRONS – [O]
Sections efficaces [cm²]
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻¹
1
10¹
10²
10³
10⁴
Energie [eV]
Elastique
Inelastique
Total

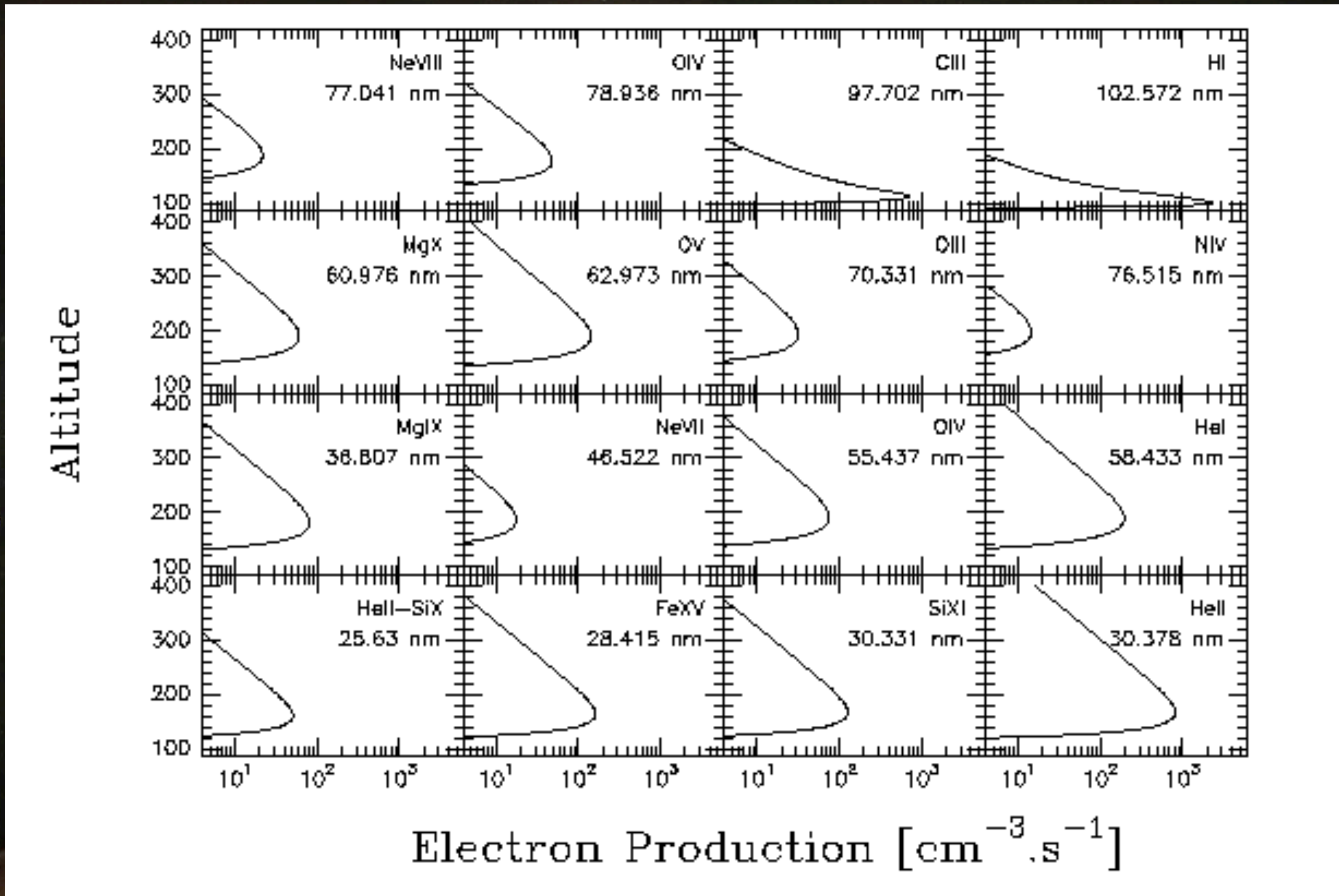


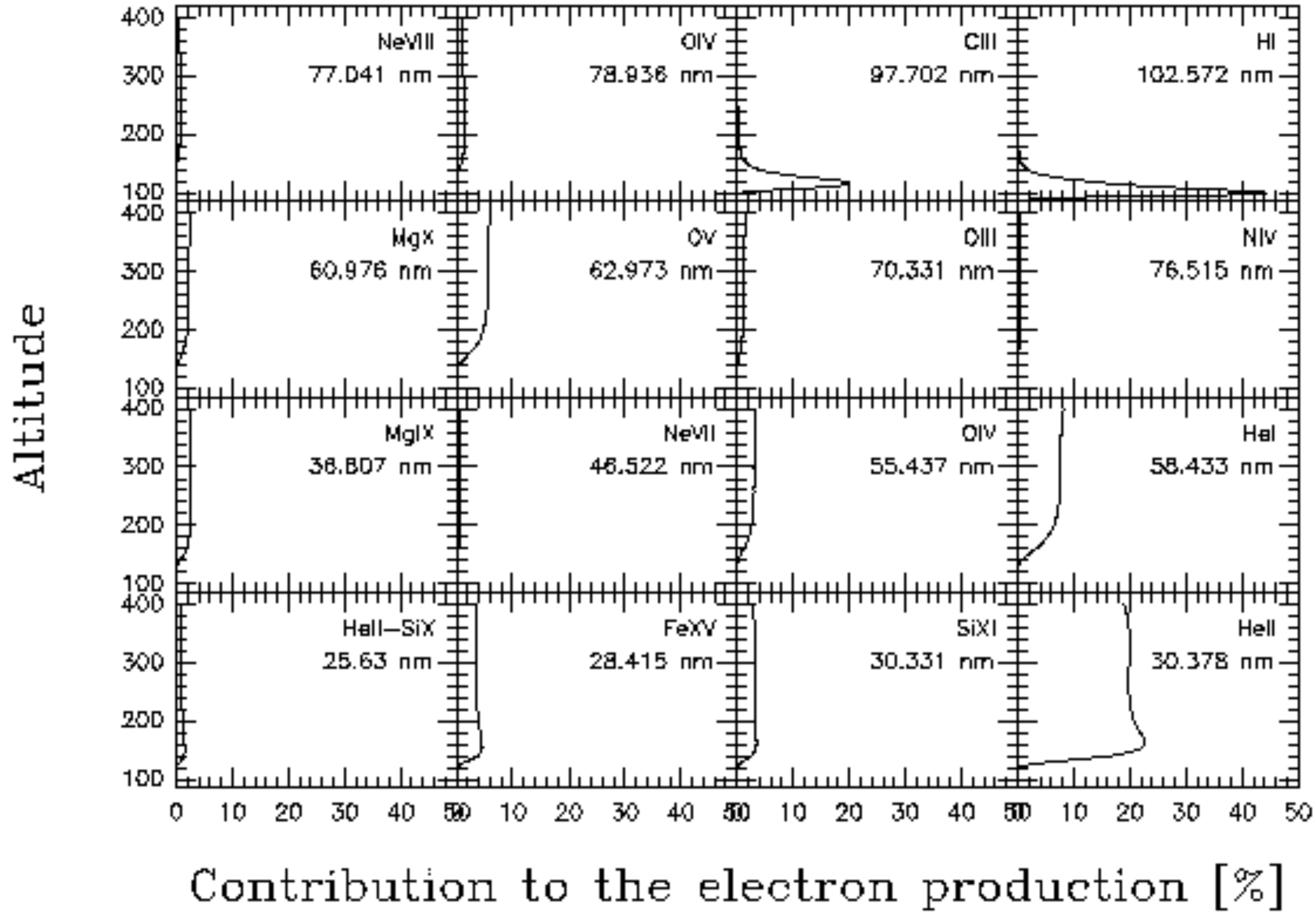
For atmospheric gazes, keep in mind values of :
Collision cross sections about 10 times biger than absorption cross sections
$\sigma \approx 10^{-16}$ to 10^{-15} cm^2 = 10^{-20} to 10^{-19} m^2

Note also that the collision frequency concept is linked to the cross sections:

$$\nu_{coll} = \sigma_{tot} \; N \, v$$


600
400
200
Altitude [km]
10^1
10^2
10^3
Production [$cm^{-3}.s^{-1}$]


Altitude
NeVIII 77.041 nm
OIV 78.936 nm
CIII 97.702 nm
HI 102.572 nm
MgX 60.976 nm
OV 62.973 nm
OIII 70.331 nm
NIV 76.515 nm
MgIX 36.807 nm
NeVII 46.522 nm
OIV 55.437 nm
HeI 58.433 nm
HeII–SiX 25.63 nm
FeXV 28.415 nm
SiXI 30.331 nm
HeII 30.378 nm
Electron Production [cm^{-3}.s^{-1}]


NeVIII
77.041 nm
OIV
78.936 nm
CIII
97.702 nm
HI
102.572 nm
MgX
60.976 nm
OV
62.973 nm
OIII
70.331 nm
NIV
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MgIX
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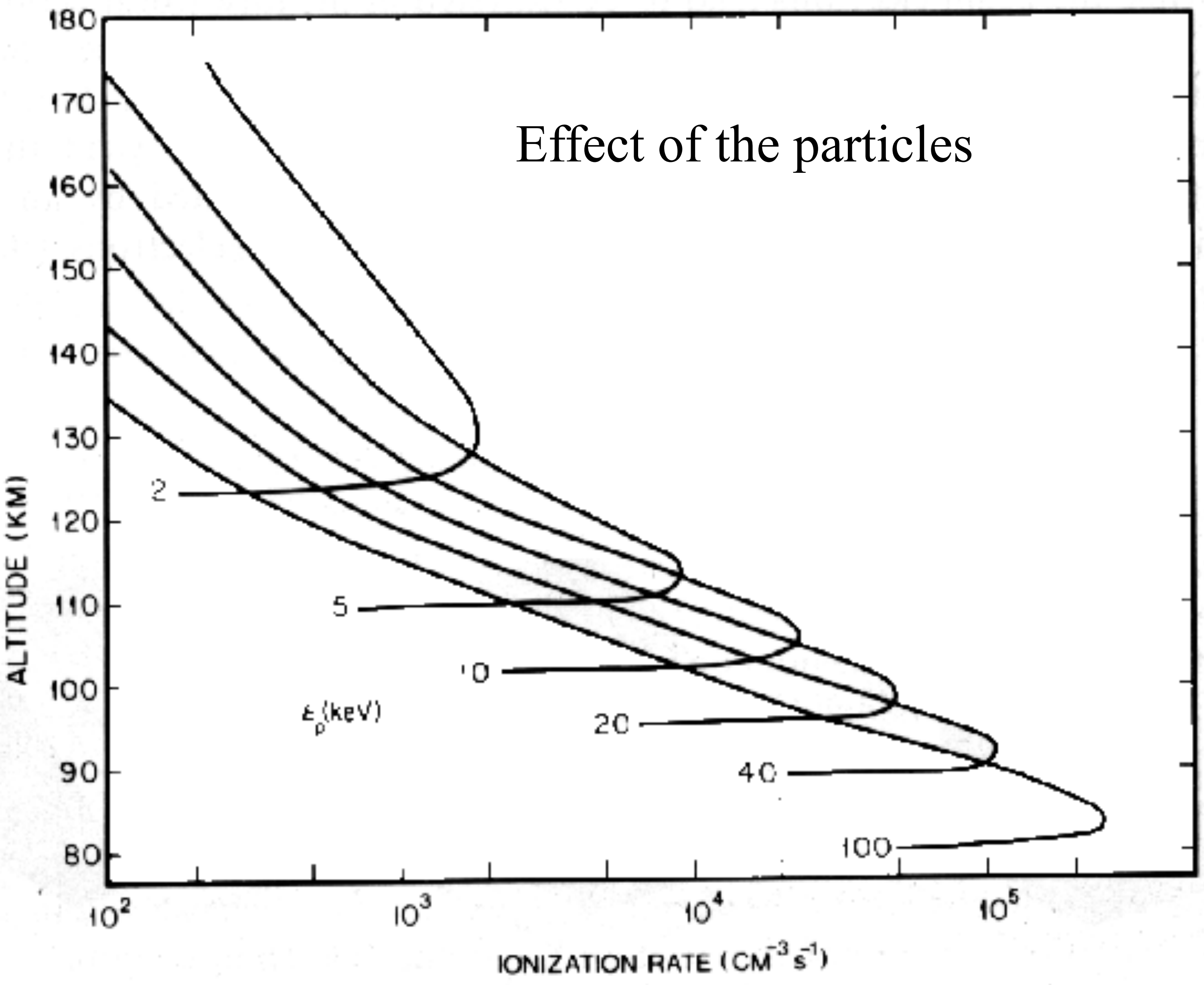
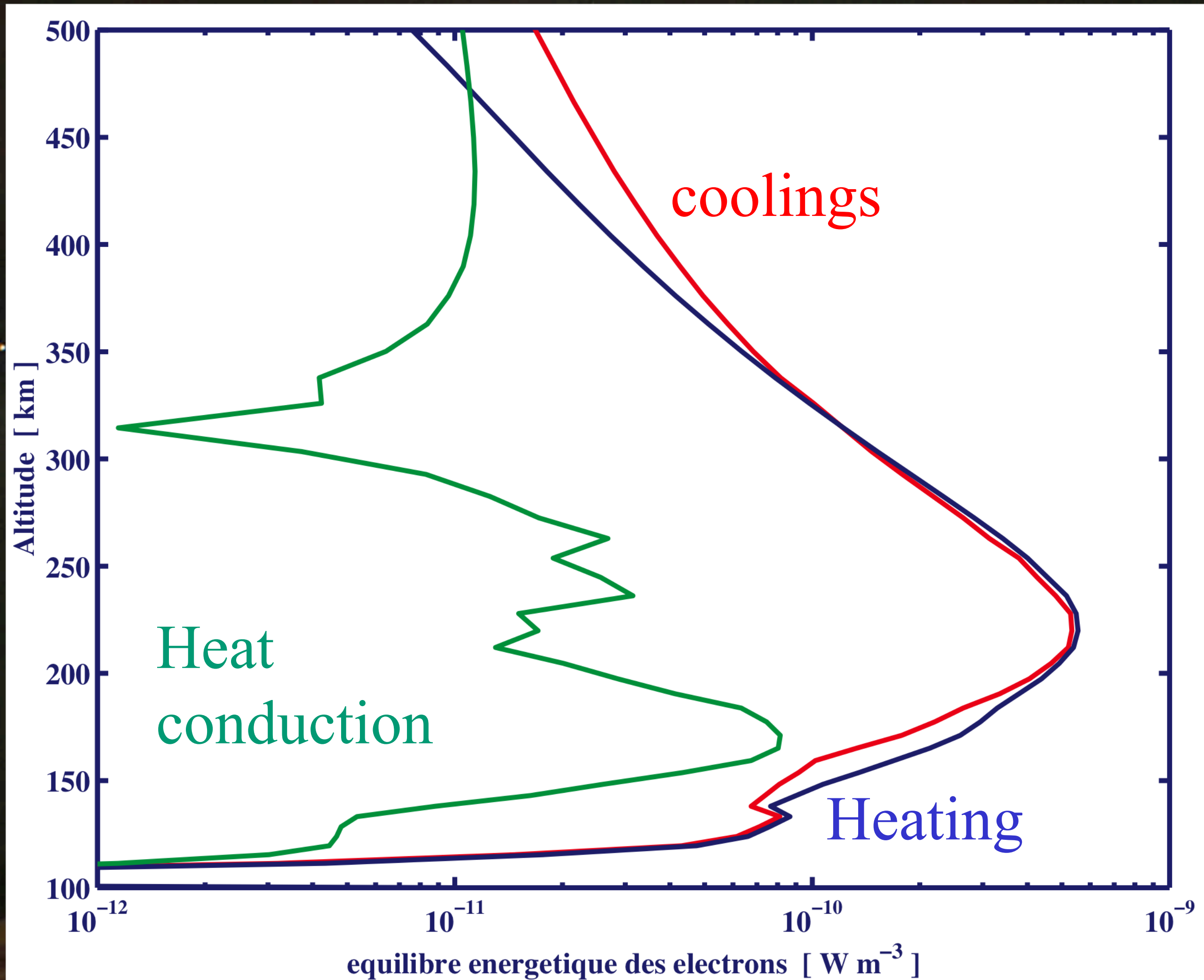
NeVII
46.522 nm
OIV
55.437 nm
HeI
58.433 nm
HeII–SiX
25.63 nm
FeXV
28.415 nm
SiXI
30.331 nm
HeII
30.378 nm
Altitude
Contribution to the electron production [%]

Effect of the particles

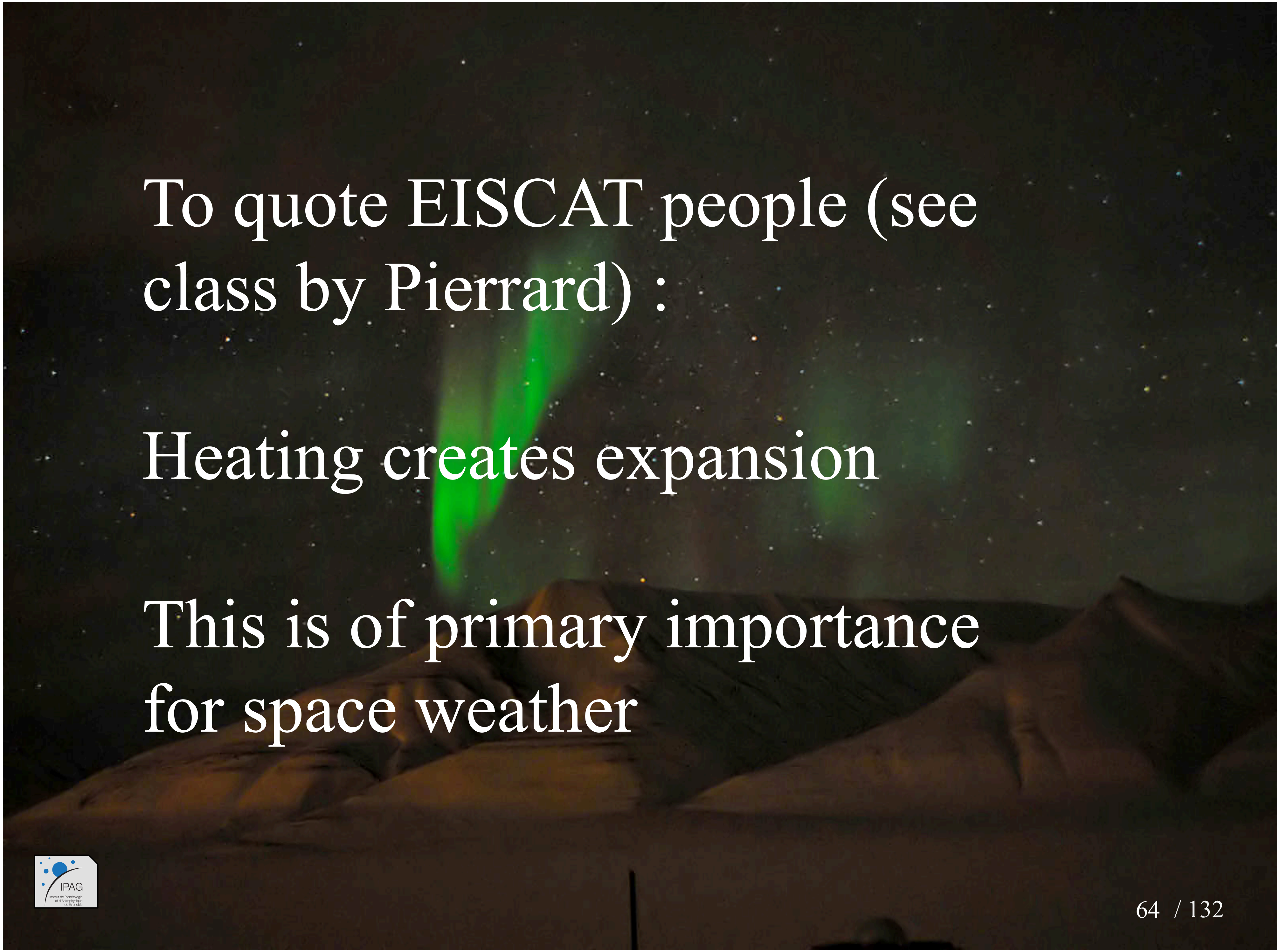


The heating rate



Here for high solar activity

Note that this is efficient above about 100 km

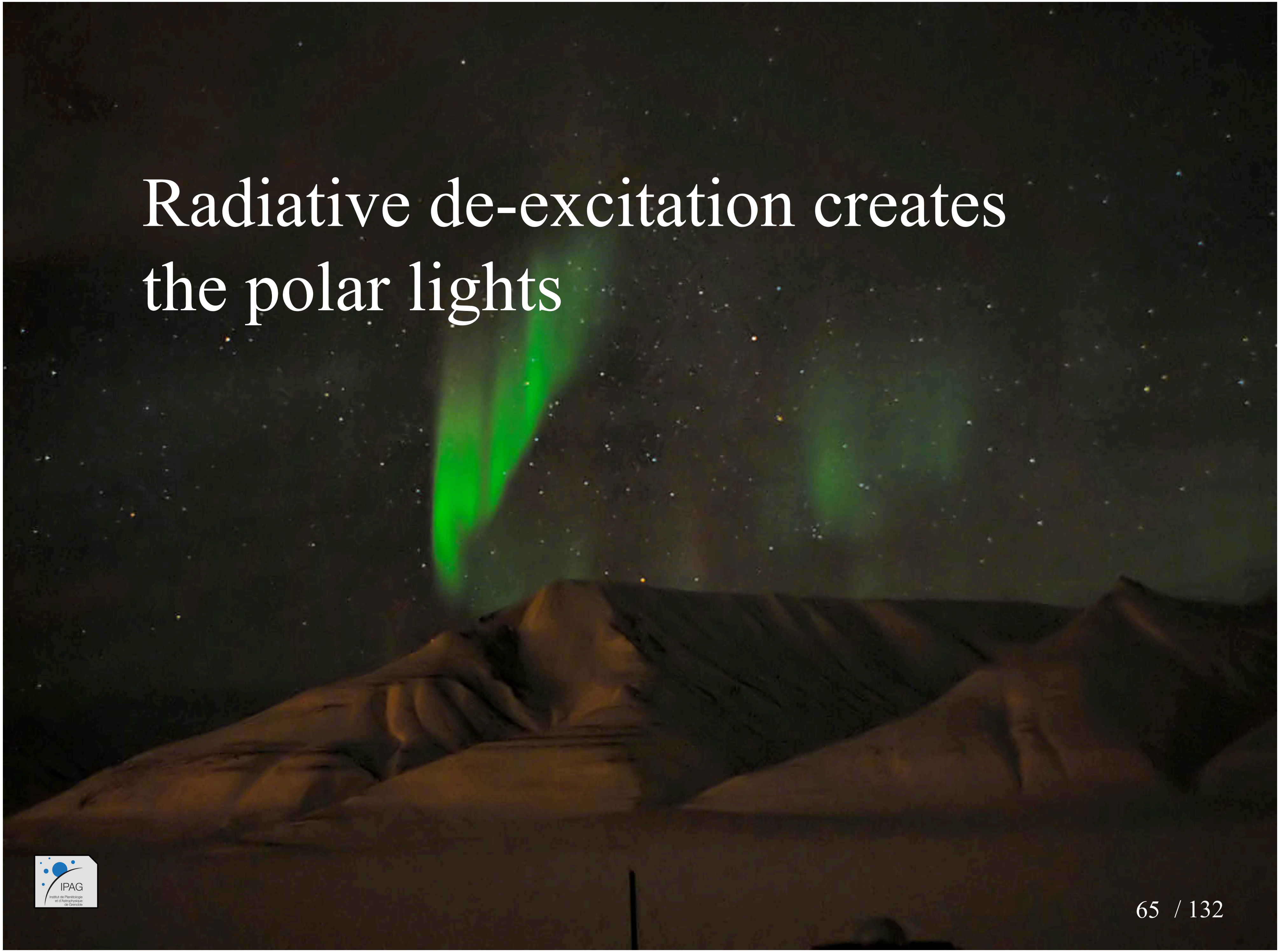


To quote EISCAT people (see class by Pierrard) :

Heating creates expansion

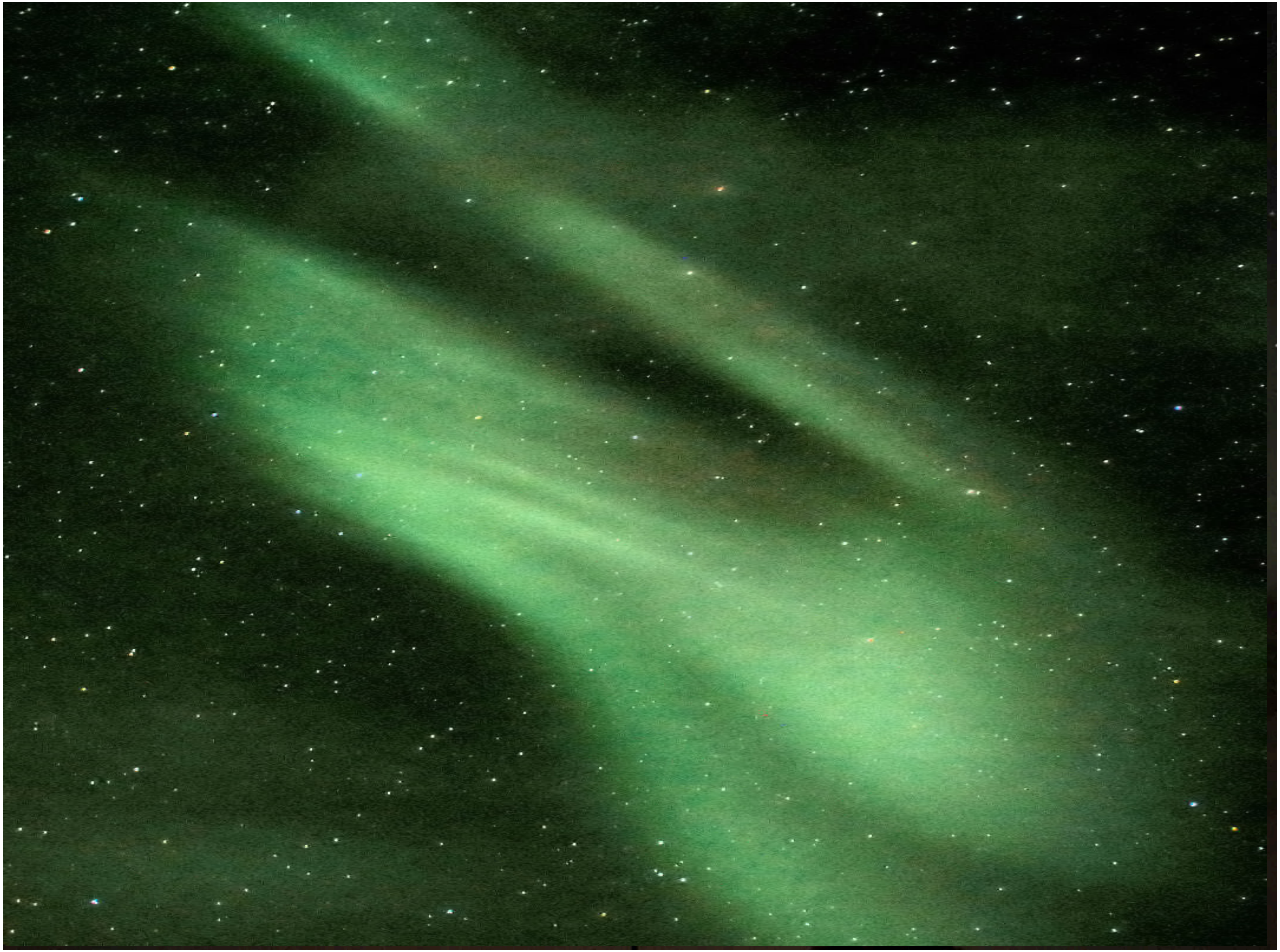
This is of primary importance for space weather

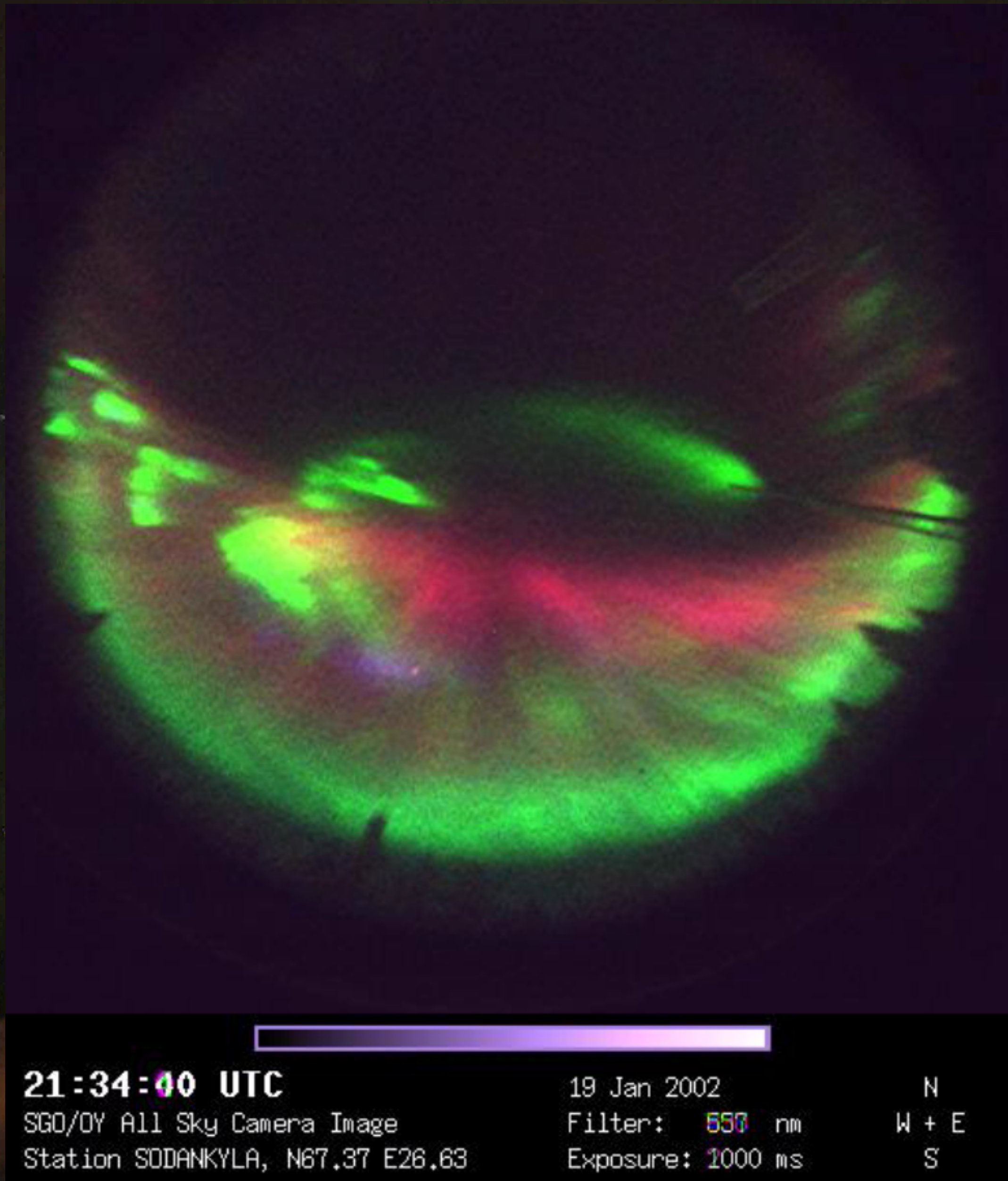
Radiative de-excitation creates the polar lights



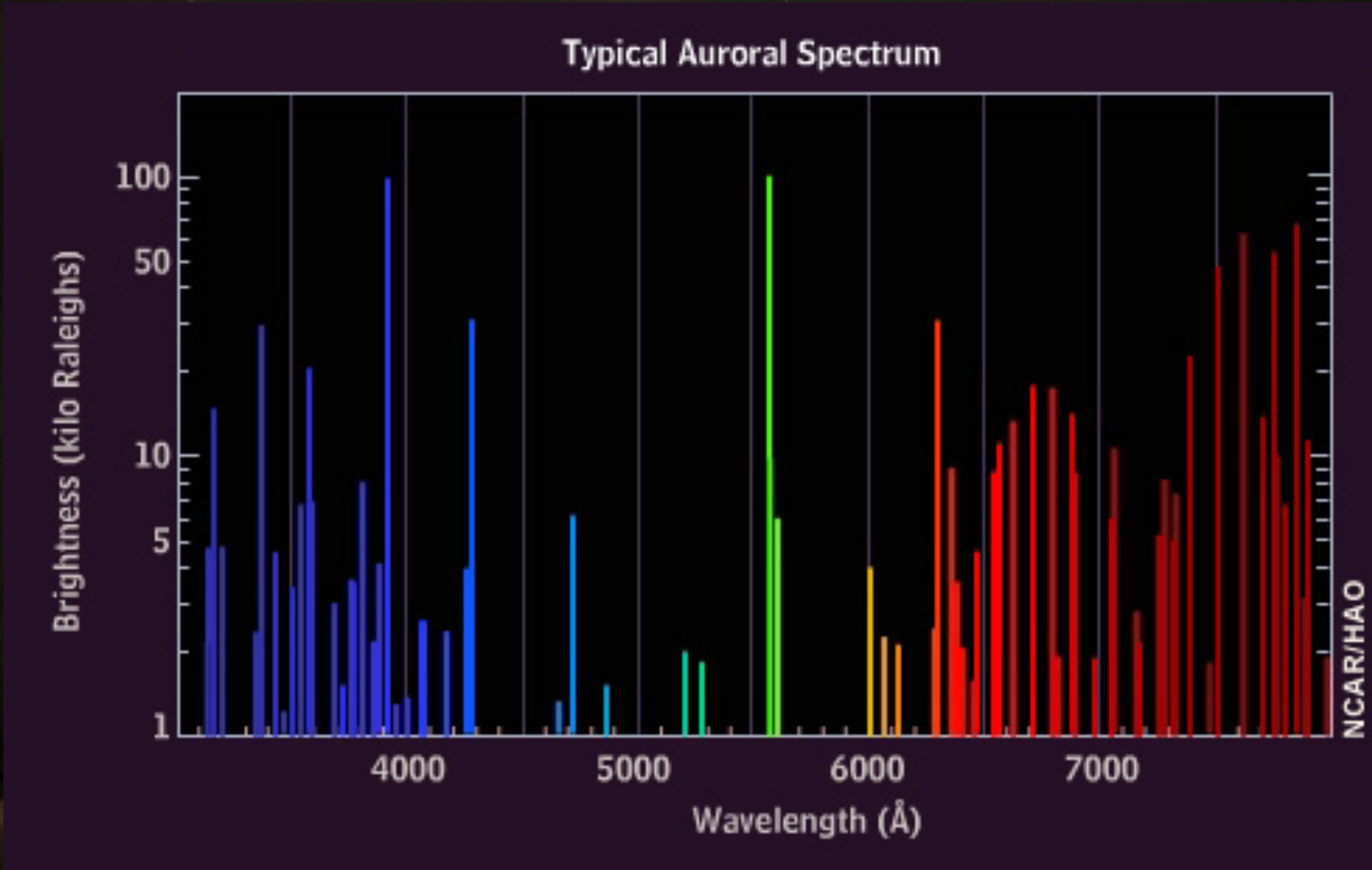

Tom Eklund

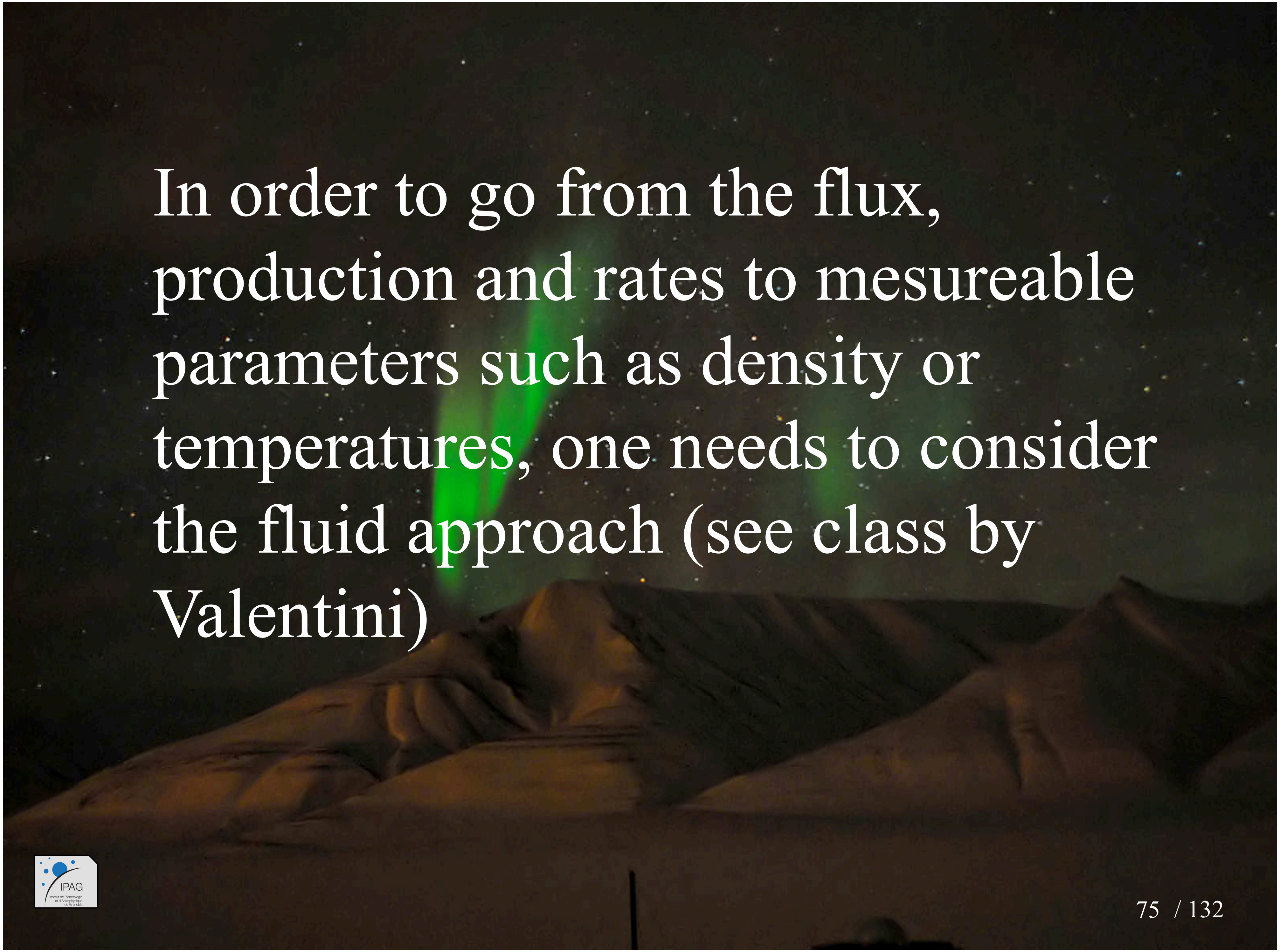

Tom Eklund



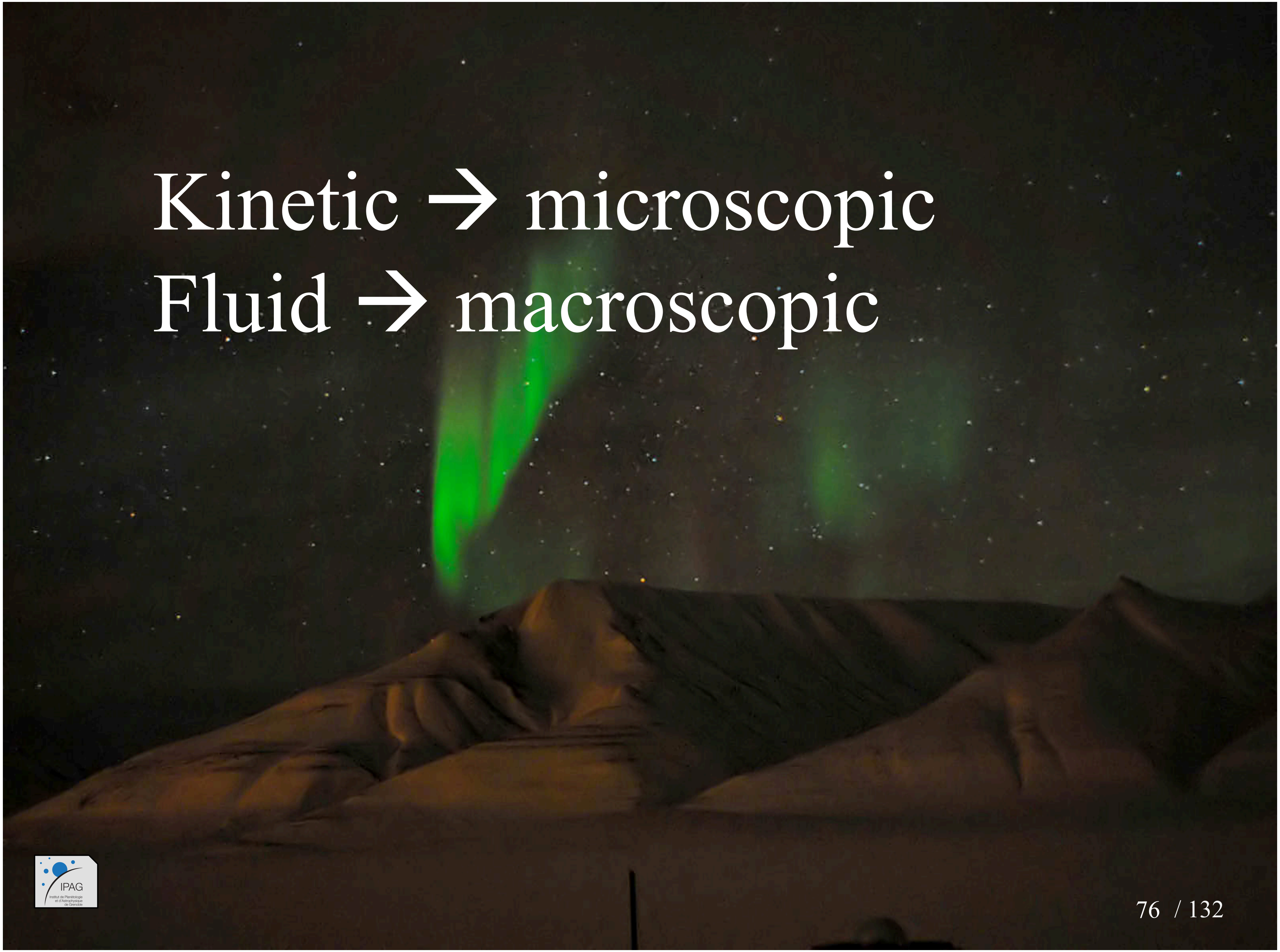


..\..\..\Jean\images\Aurores_et_rayonnement\films\Thomas_Ulich_20020119_20.mov


Typical Auroral Spectrum
Brightness (kilo Raleighs)
100
50
10
5
1
4000
5000
6000
7000
Wavelength (Å)
NCAR/HAO



In order to go from the flux, production and rates to mesureable parameters such as density or temperatures, one needs to consider the fluid approach (see class by Valentini)



Kinetic → microscopic
Fluid → macroscopic

Kinetic → distribution function

Fluid → integral of the distribution function

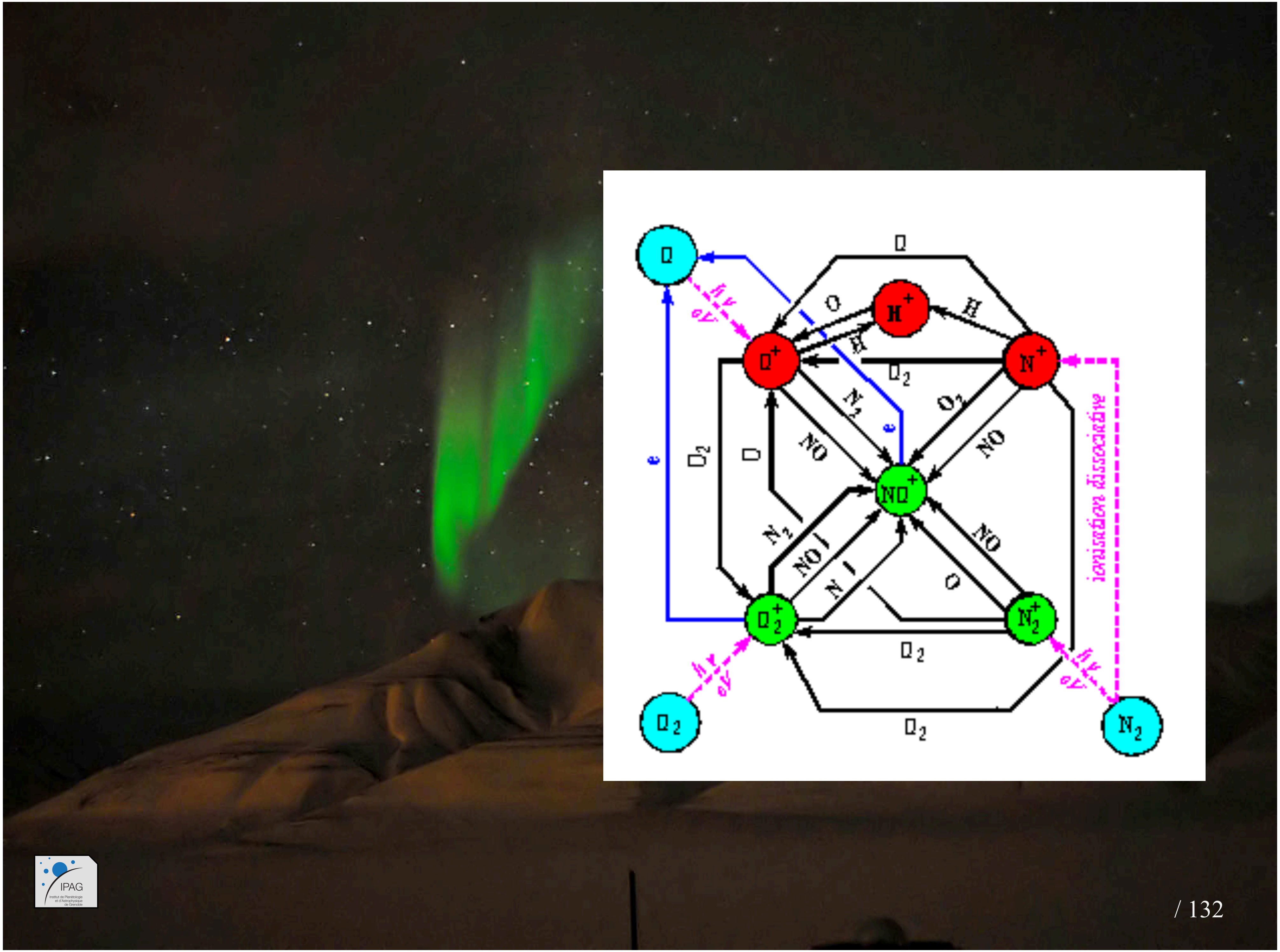
Boltzmann fluid equations:

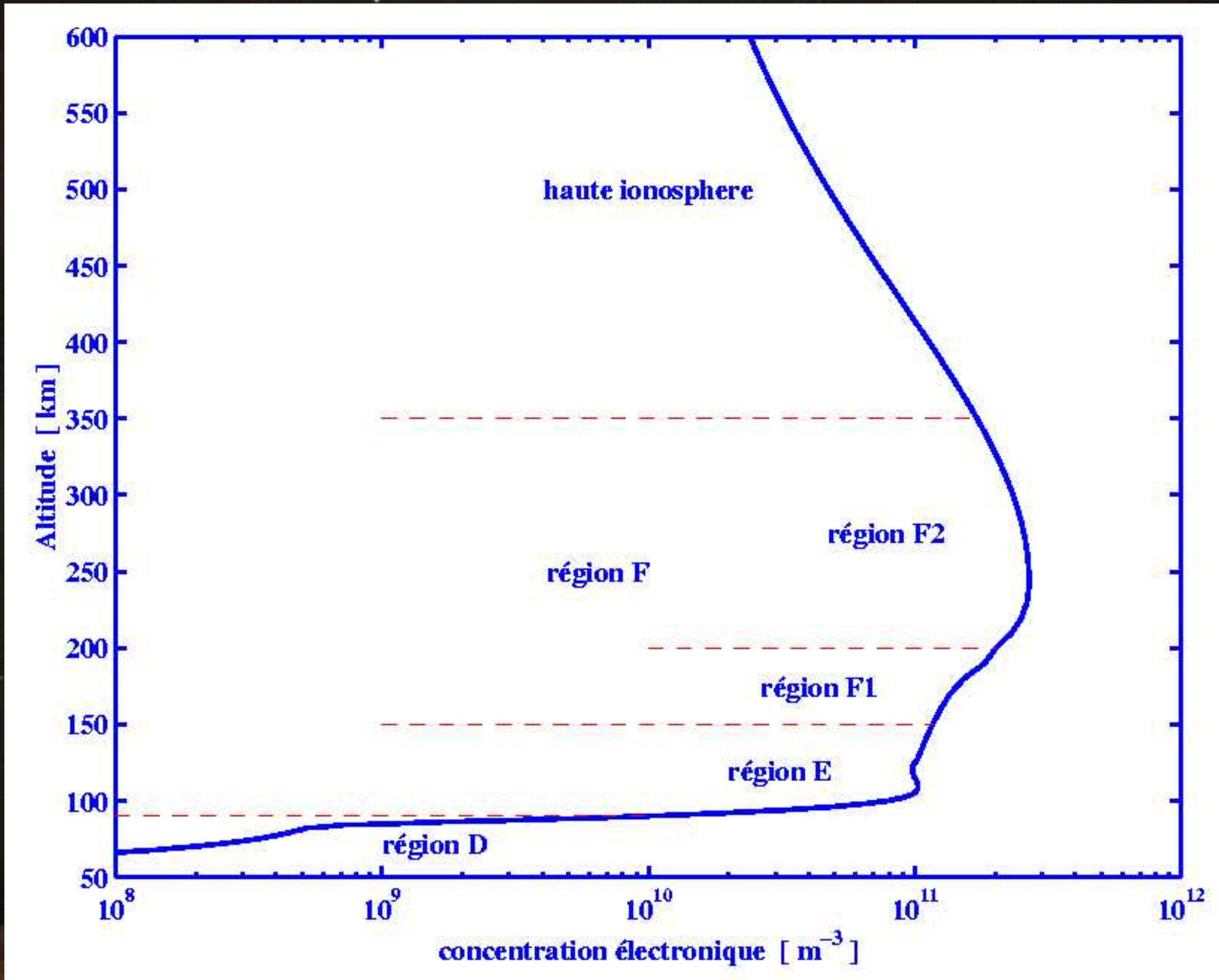
Integrals of the kinetic equation over $v^a dv$

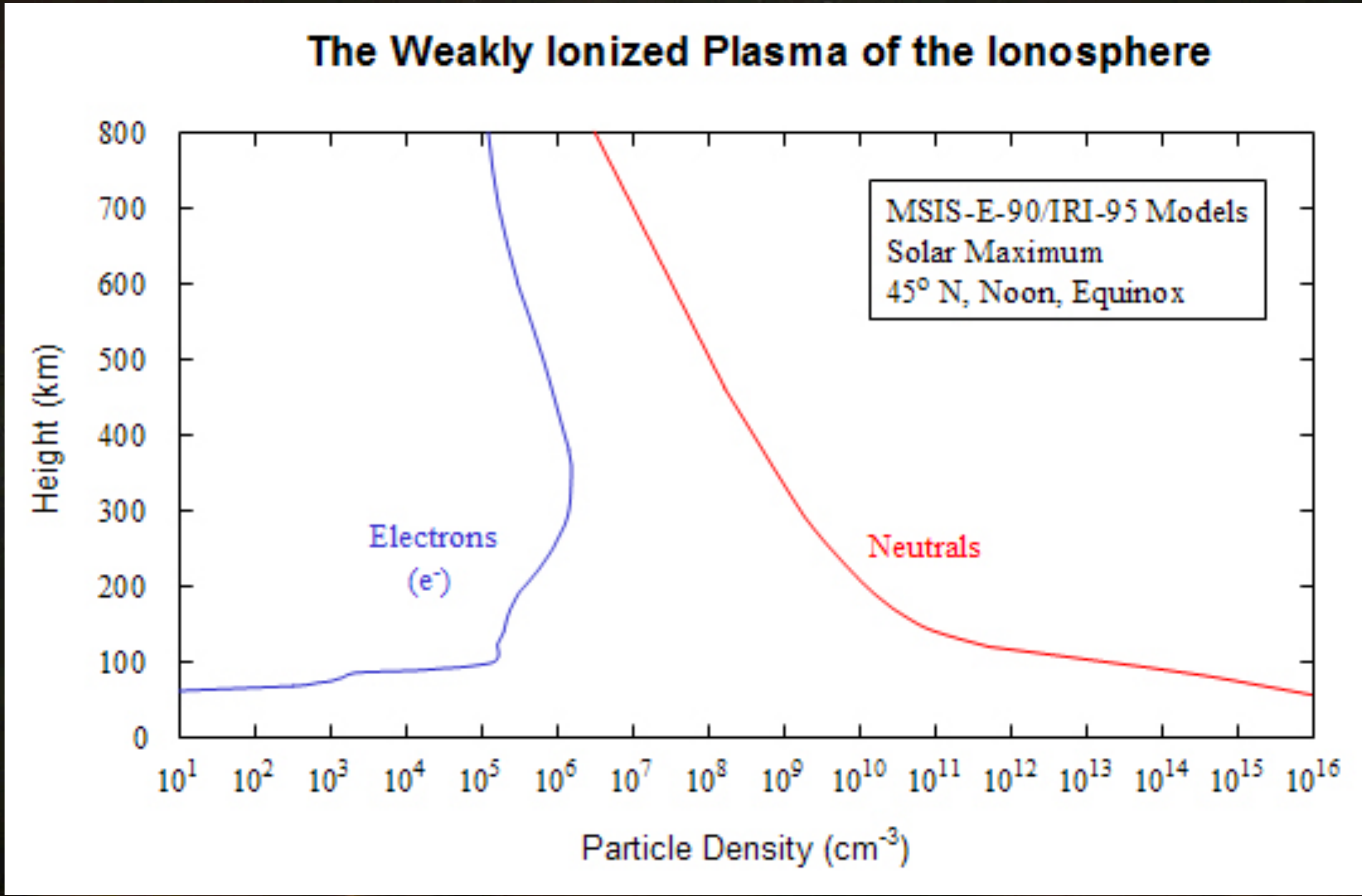
Oth order momentum = continuity equation
1st order momentum = force equation
2^{d} order momentum = energy equation
3^{d} order momentum = heat flux equation

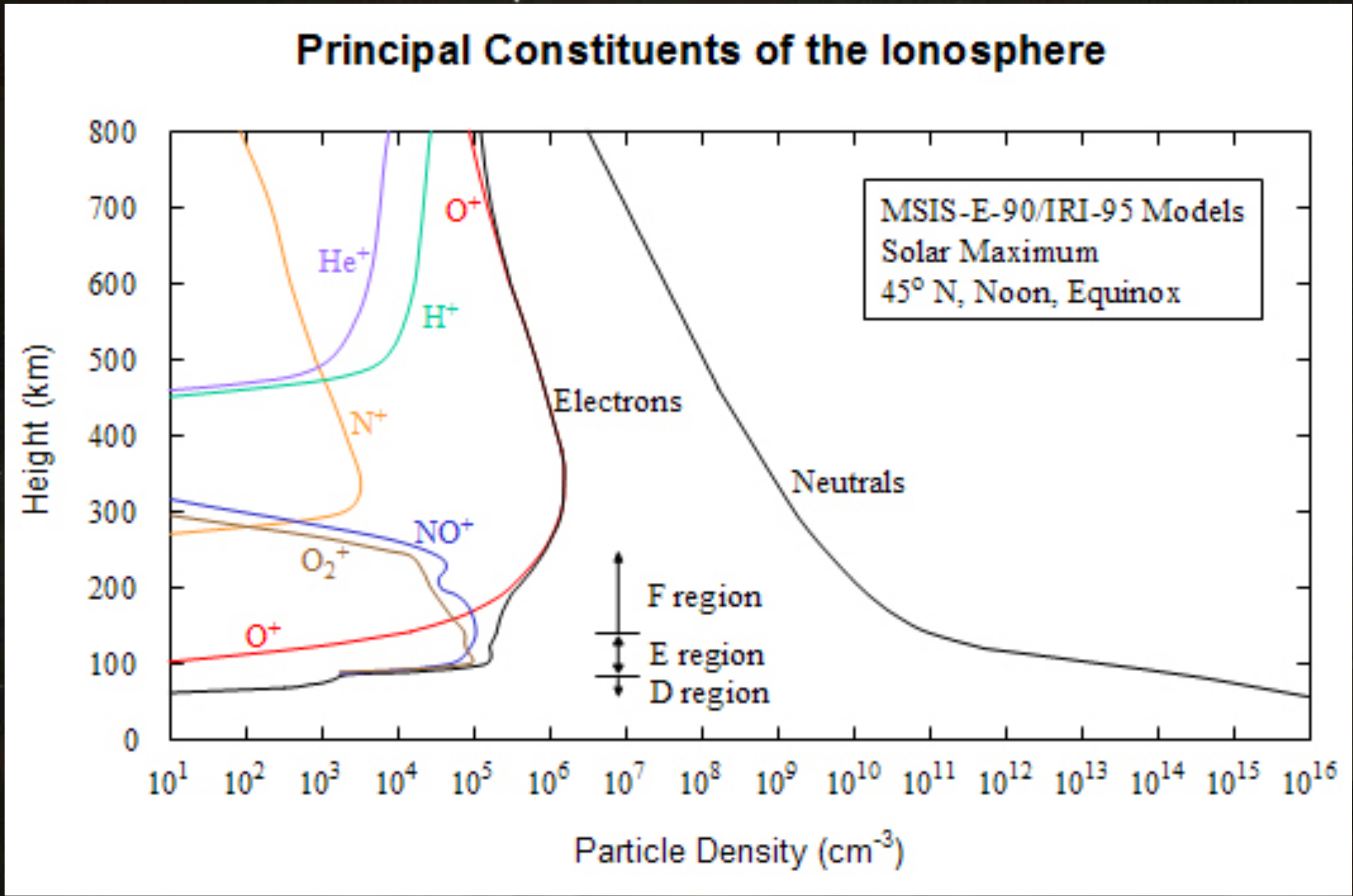
The distribution function is a maxwellian for thermal particles :

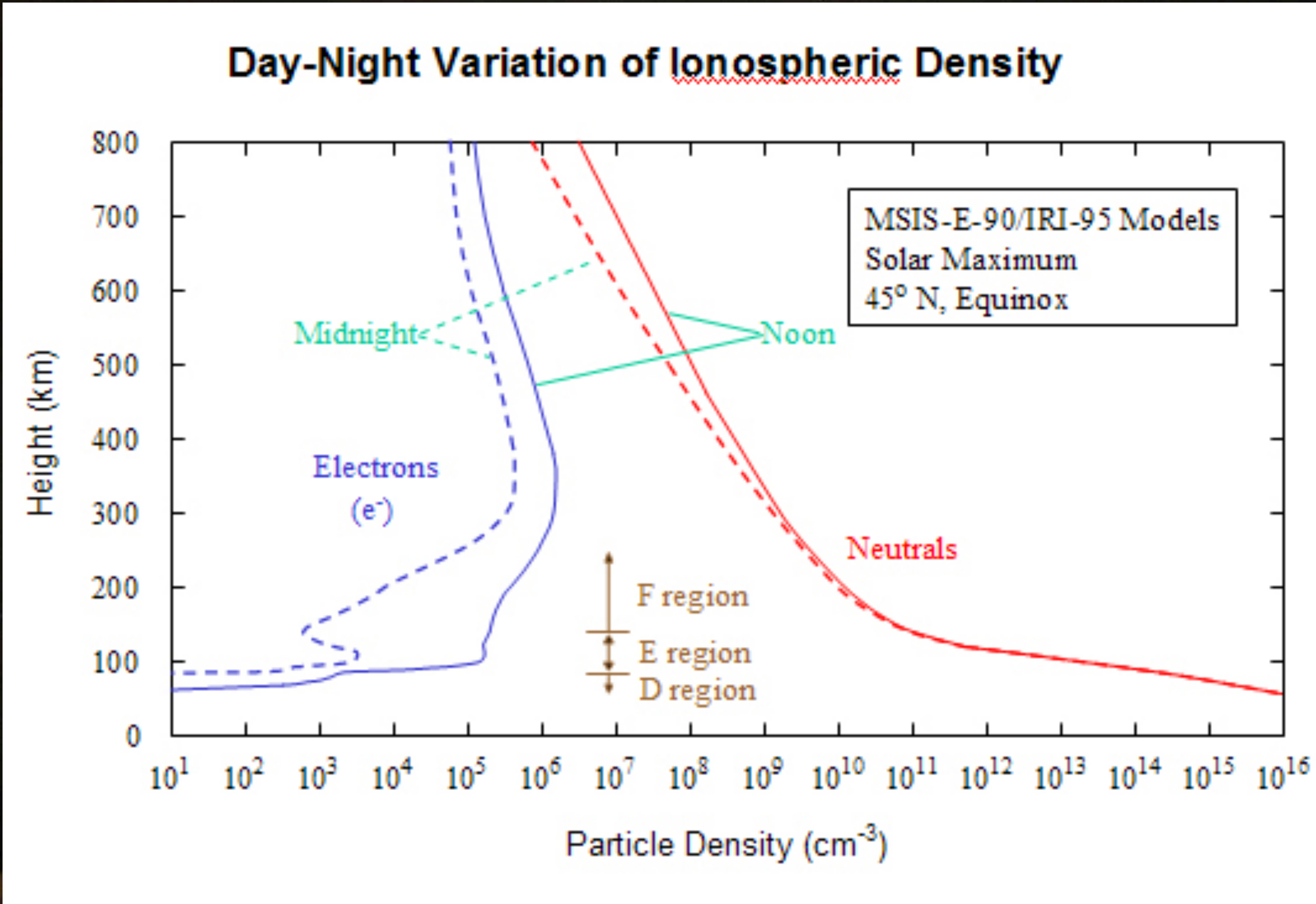
Oth order momentum $\rightarrow$ densities (scalars)
1st order momentum $\rightarrow$ velocities (vectors)
2^{d} order momentum $\rightarrow$ temperatures (scalars)
3^{d} order momentum $\rightarrow$ heat flux (vectors)

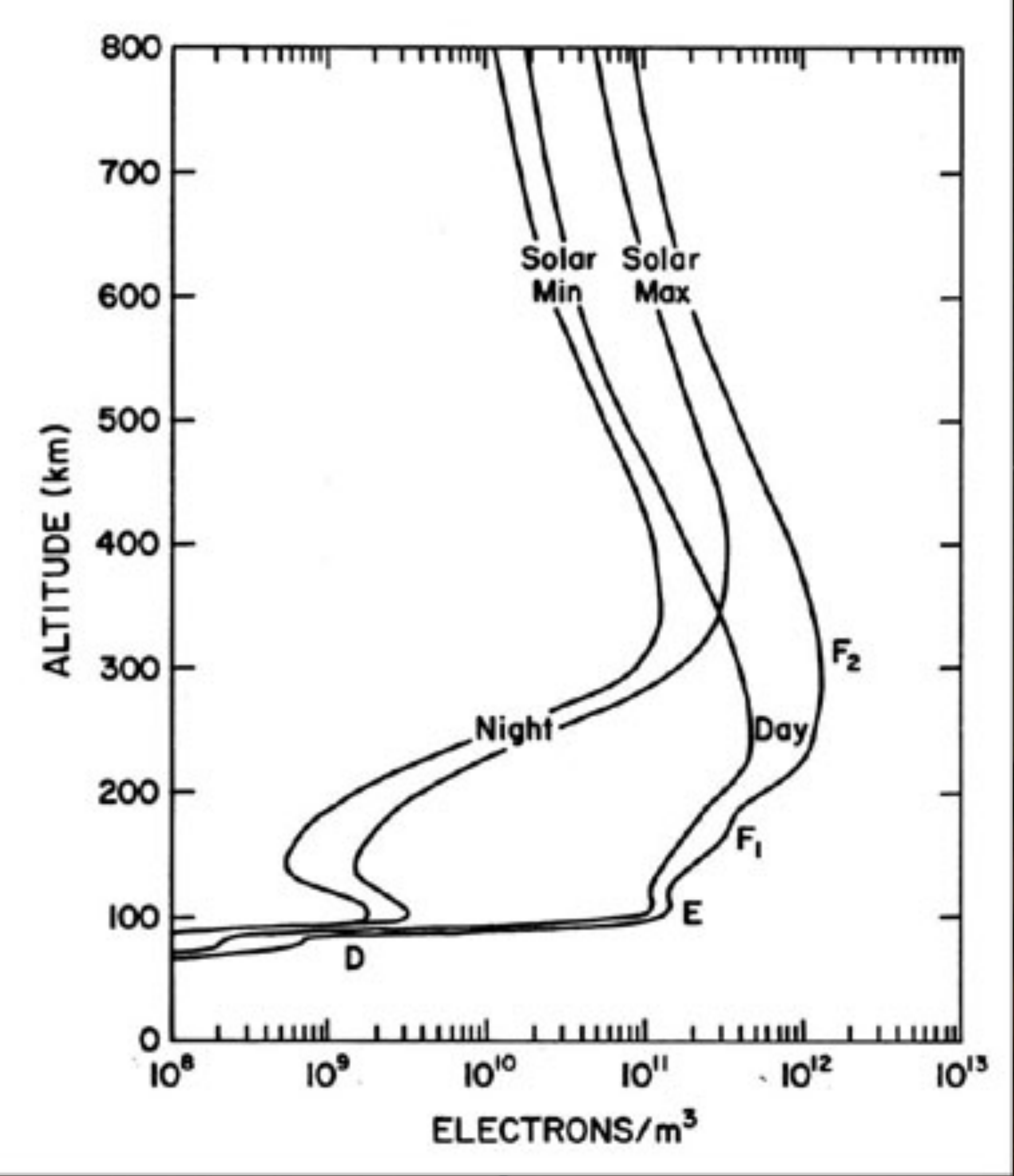

O
O
H+
H
O
H
O+
N+
O2
N2
O2
NO
NO
e
e
O2
O
NO+
N2
NO
N
NO
O
O2+
N2+
O2
O2
O2
N2
hν
eV
hν
eV
hν
eV
ionisation dissociative


haute ionosphere
région F2
région F
région F1
région E
région D
Altitude [km]
concentration électronique [m^{-3}]
600
550
500
450
400
350
300
250
200
150
100
50
10^8
10^9
10^{10}
10^{11}
10^{12}

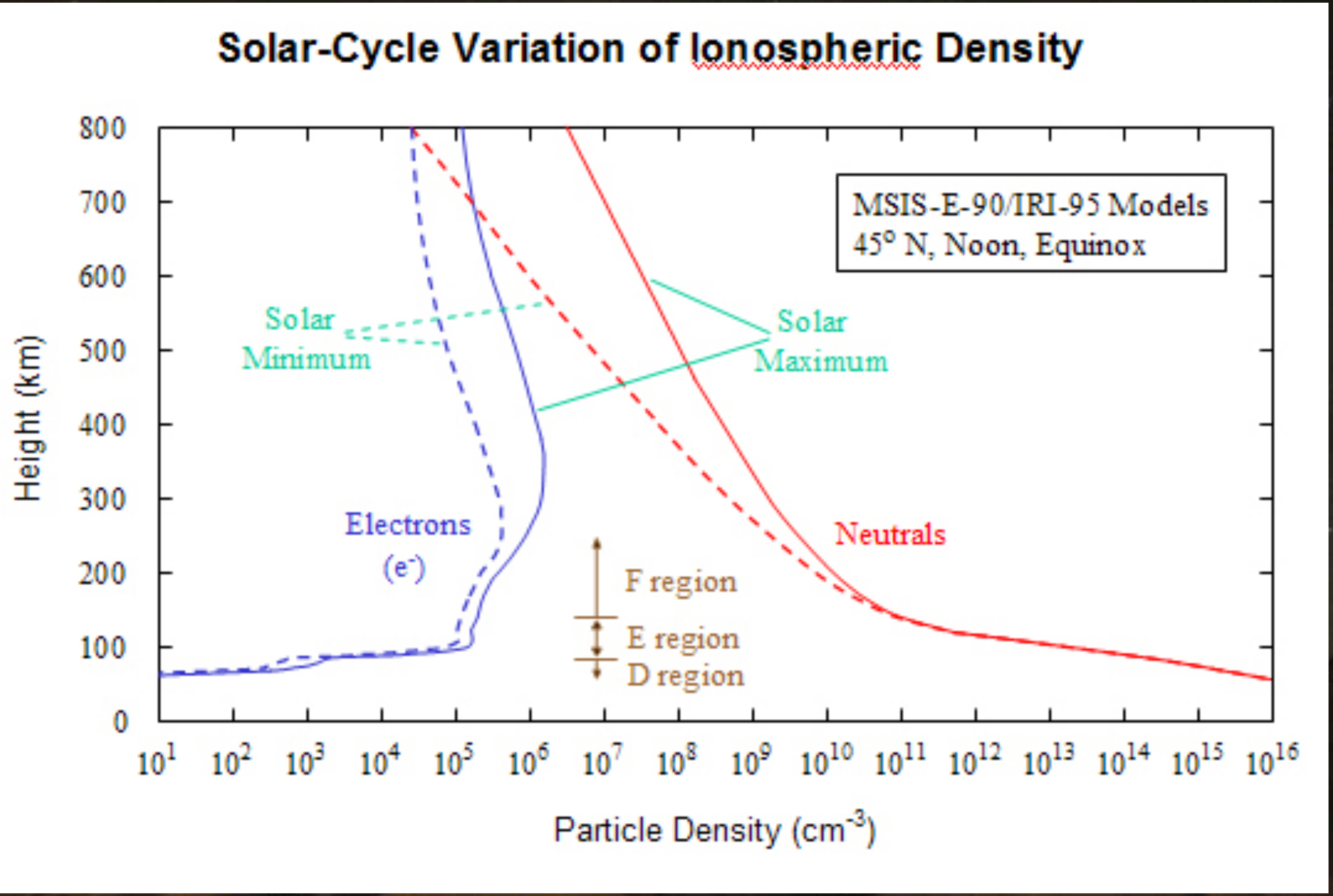

The Weakly Ionized Plasma of the Ionosphere
MSIS-E-90/IRI-95 Models
Solar Maximum
45° N, Noon, Equinox
Height (km)
800
700
600
500
400
300
200
100
0
Electrons
(e⁻)
Neutrals
10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶
Particle Density (cm⁻³)


Principal Constituents of the Ionosphere
MSIS-E-90/IRI-95 Models
Solar Maximum
45° N, Noon, Equinox
Height (km)
Particle Density (cm-3)
He+
H+
O+
N+
NO+
O2+
Electrons
Neutrals
F region
E region
D region
800
700
600
500
400
300
200
100
0
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16


Day-Night Variation of Ionospheric Density
Height (km)
800
700
600
500
400
300
200
100
0
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}
Particle Density (cm^{-3})
MSIS-E-90/IRI-95 Models
Solar Maximum
45° N, Equinox
Midnight
Noon
Electrons
(e^-)
Neutrals
F region
E region
D region

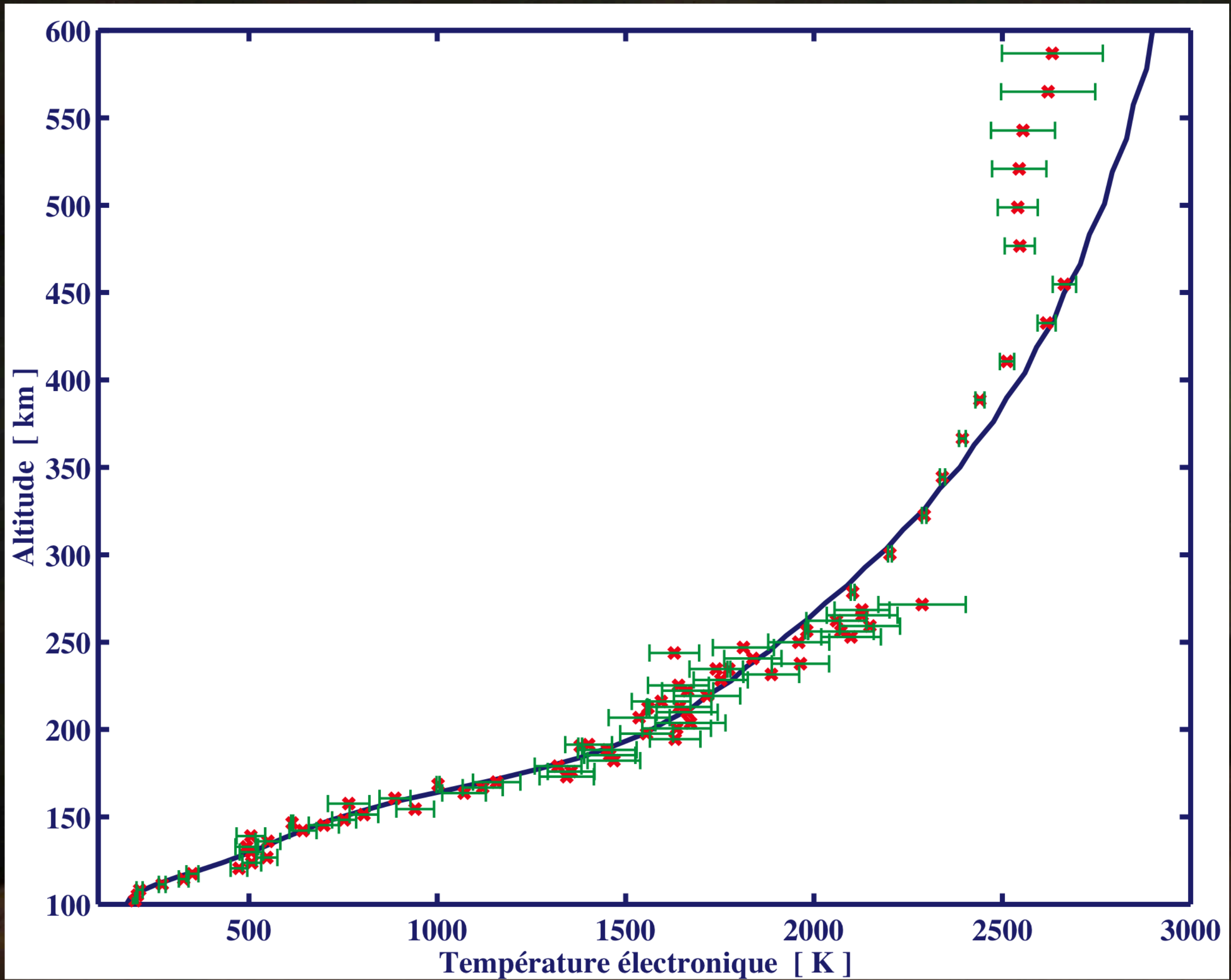


ALTITUDE (km)
ELECTRONS/m^3
Solar Min
Solar Max
Night
Day
F_2
F_1
E
D
0
100
200
300
400
500
600
700
800
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}

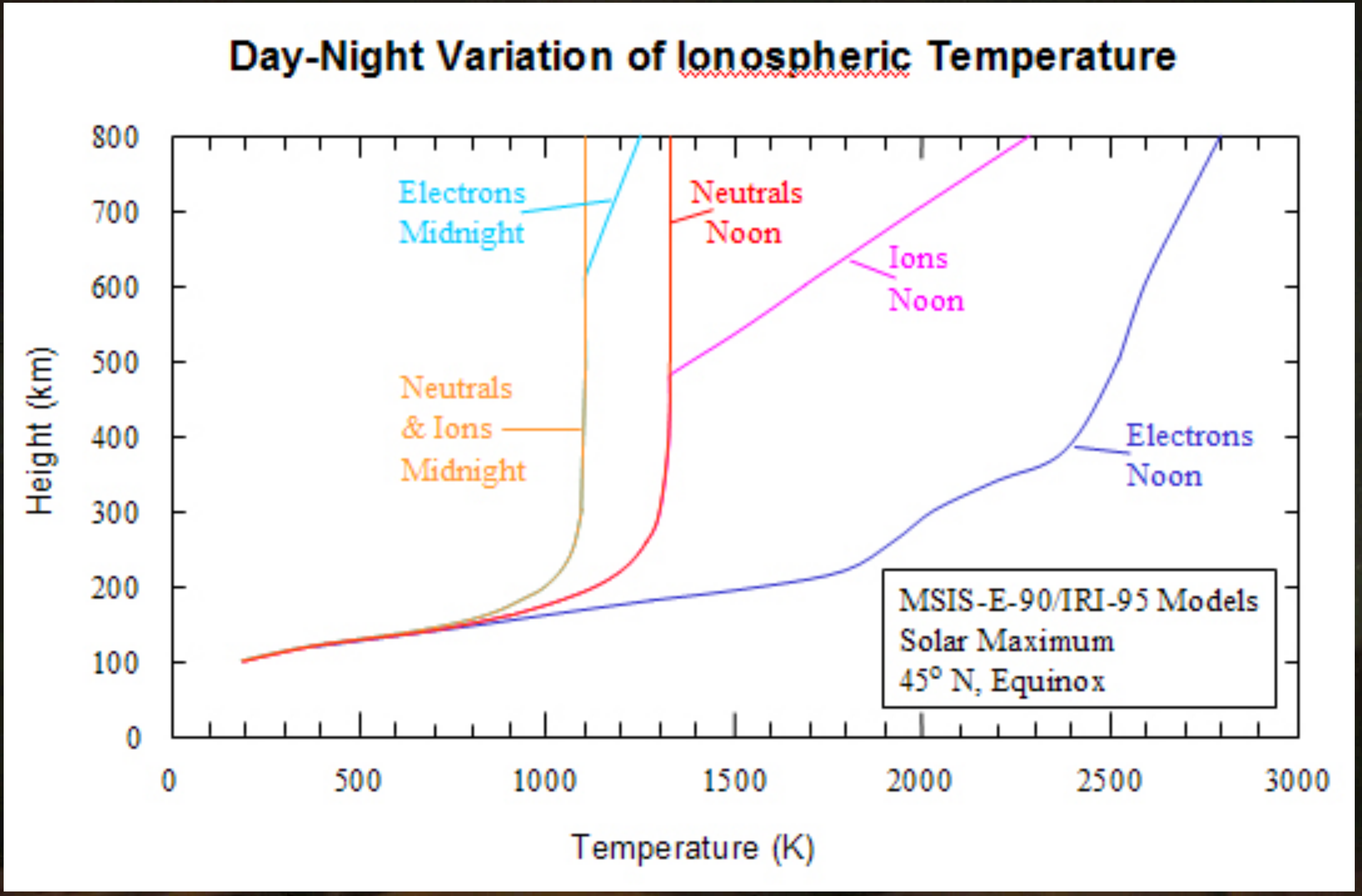


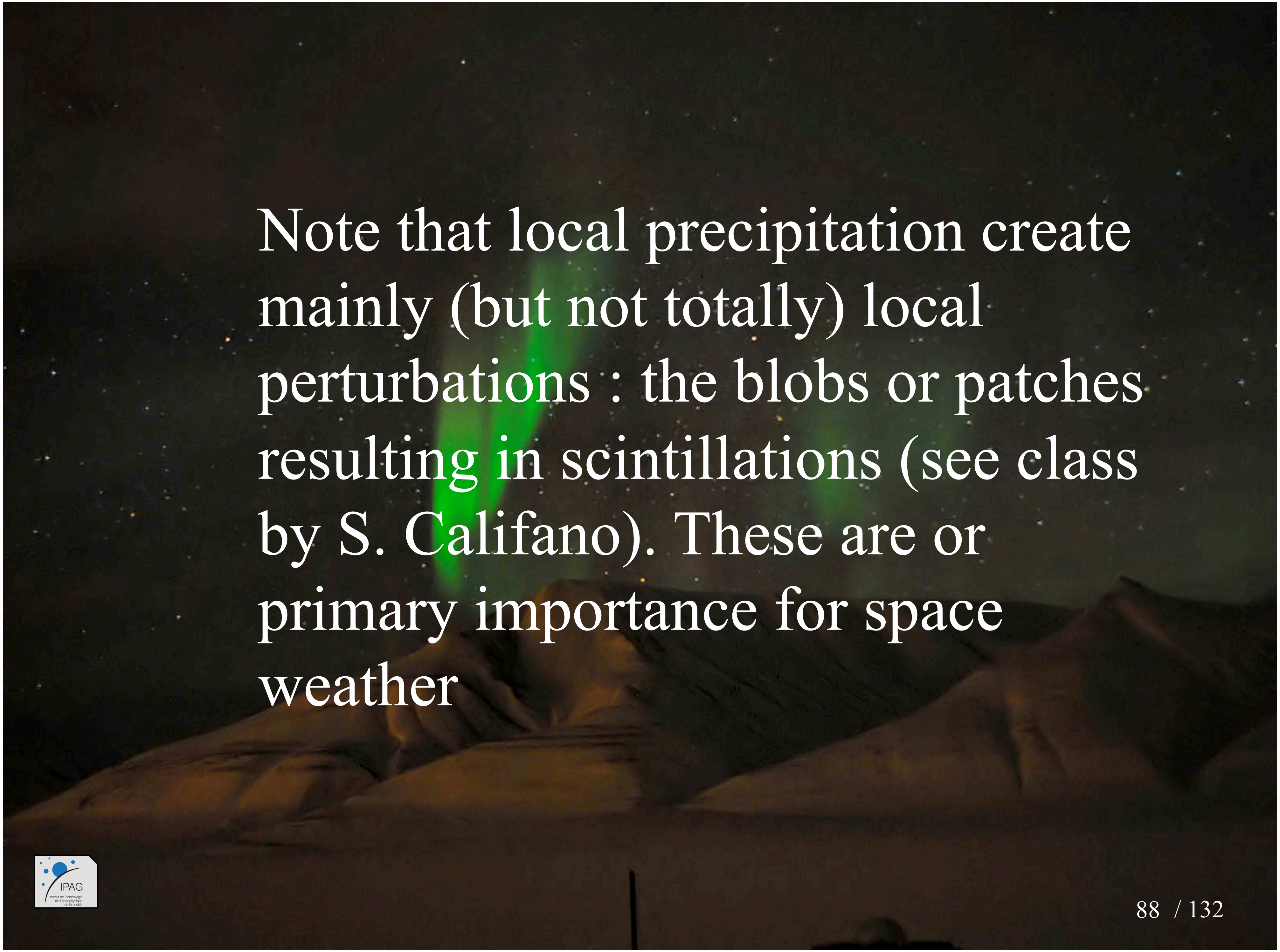
Solar-Cycle Variation of Ionospheric Density
MSIS-E-90/IRI-95 Models
45° N, Noon, Equinox
Solar Minimum
Solar Maximum
Electrons (e-)
Neutrals
F region
E region
D region
Height (km)
Particle Density (cm-3)
800
700
600
500
400
300
200
100
0
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16

Temperatures

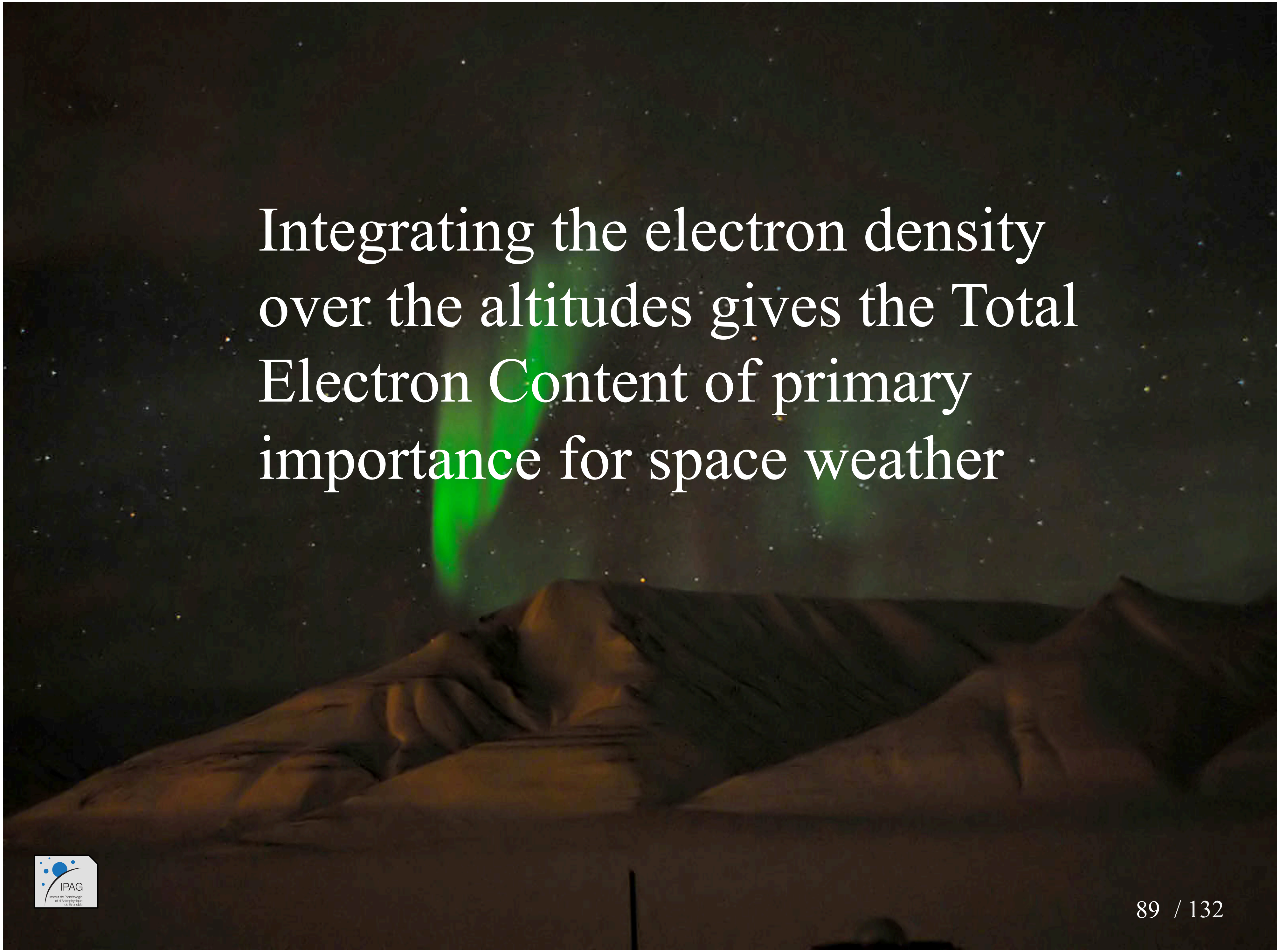


T electrons:
1500 K to
3000 K

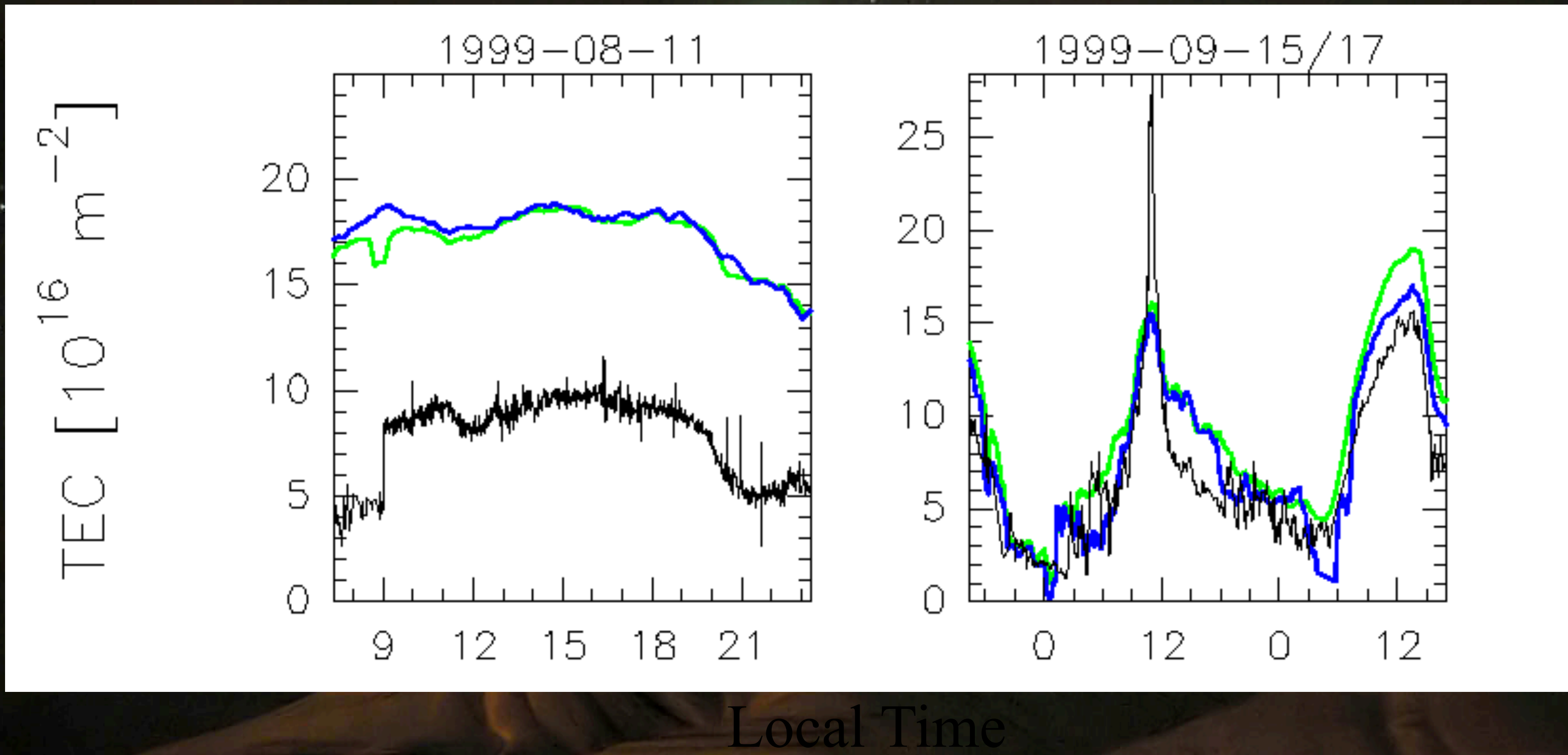

Day-Night Variation of Ionospheric Temperature
Electrons Midnight
Neutrals Noon
Ions Noon
Neutrals & Ions Midnight
Electrons Noon
MSIS-E-90/IRI-95 Models
Solar Maximum
45° N, Equinox
Height (km)
Temperature (K)
0
100
200
300
400
500
600
700
800
0
500
1000
1500
2000
2500
3000

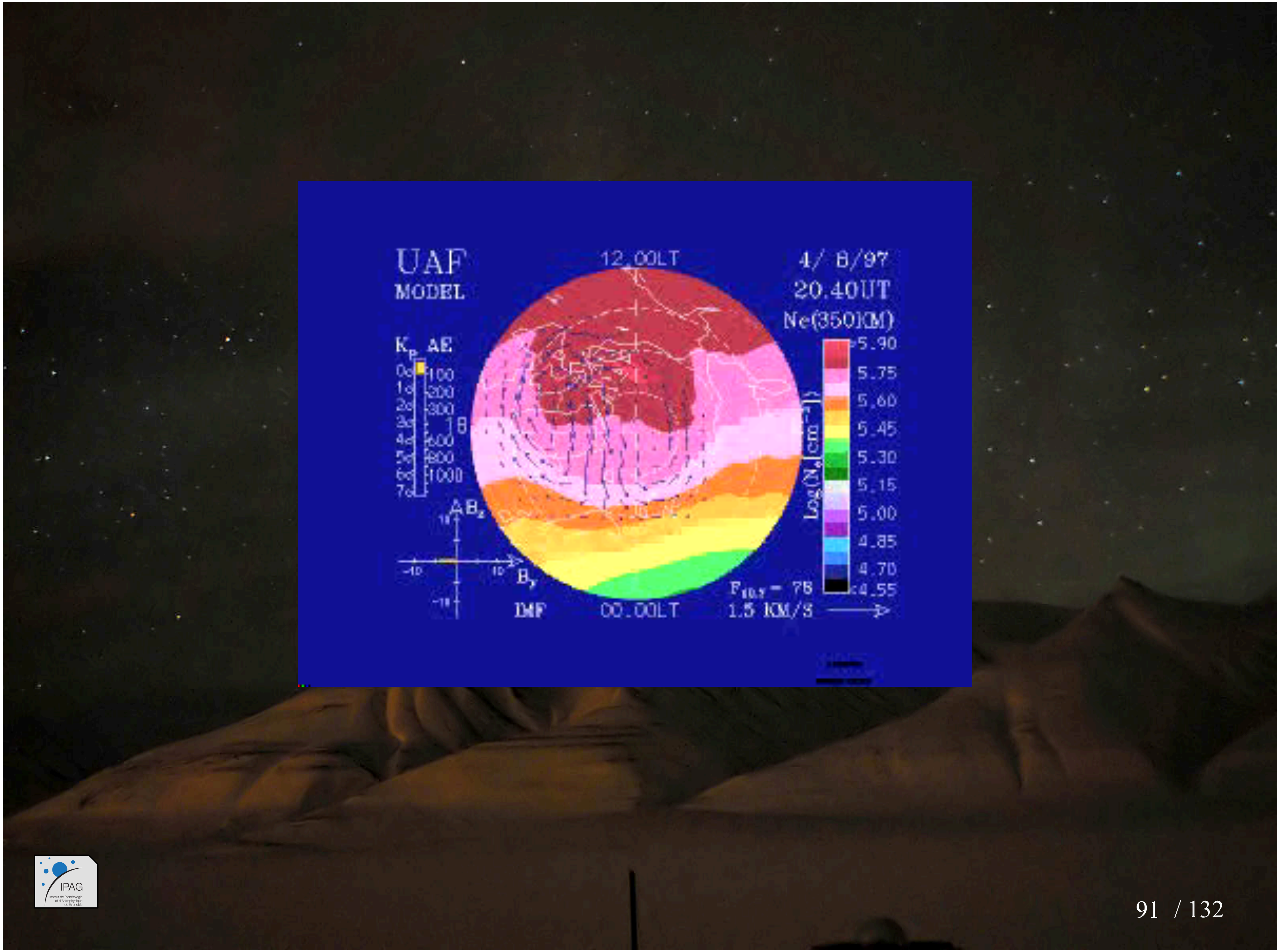


Note that local precipitation create mainly (but not totally) local perturbations : the blobs or patches resulting in scintillations (see class by S. Califano). These are or primary importance for space weather

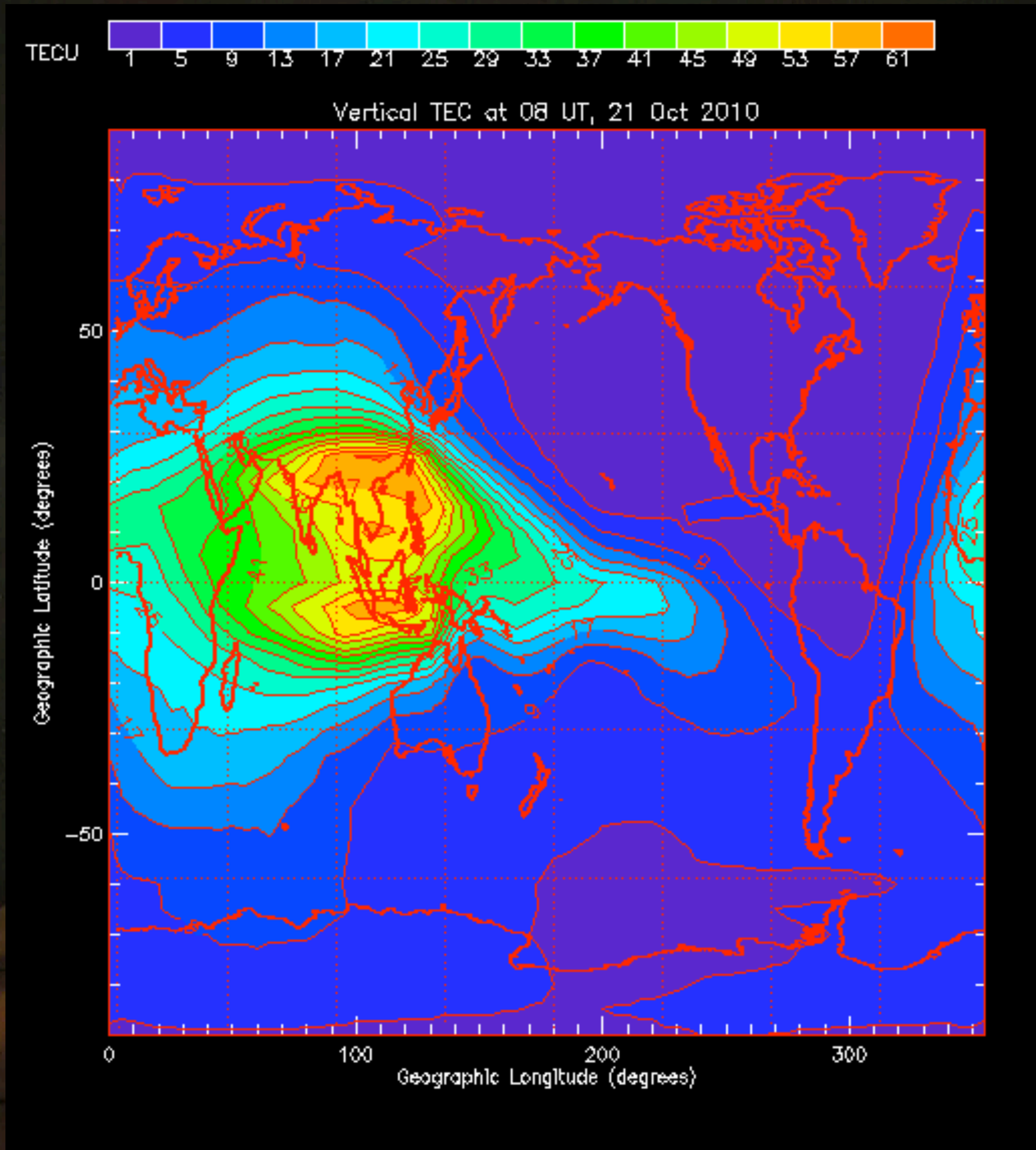


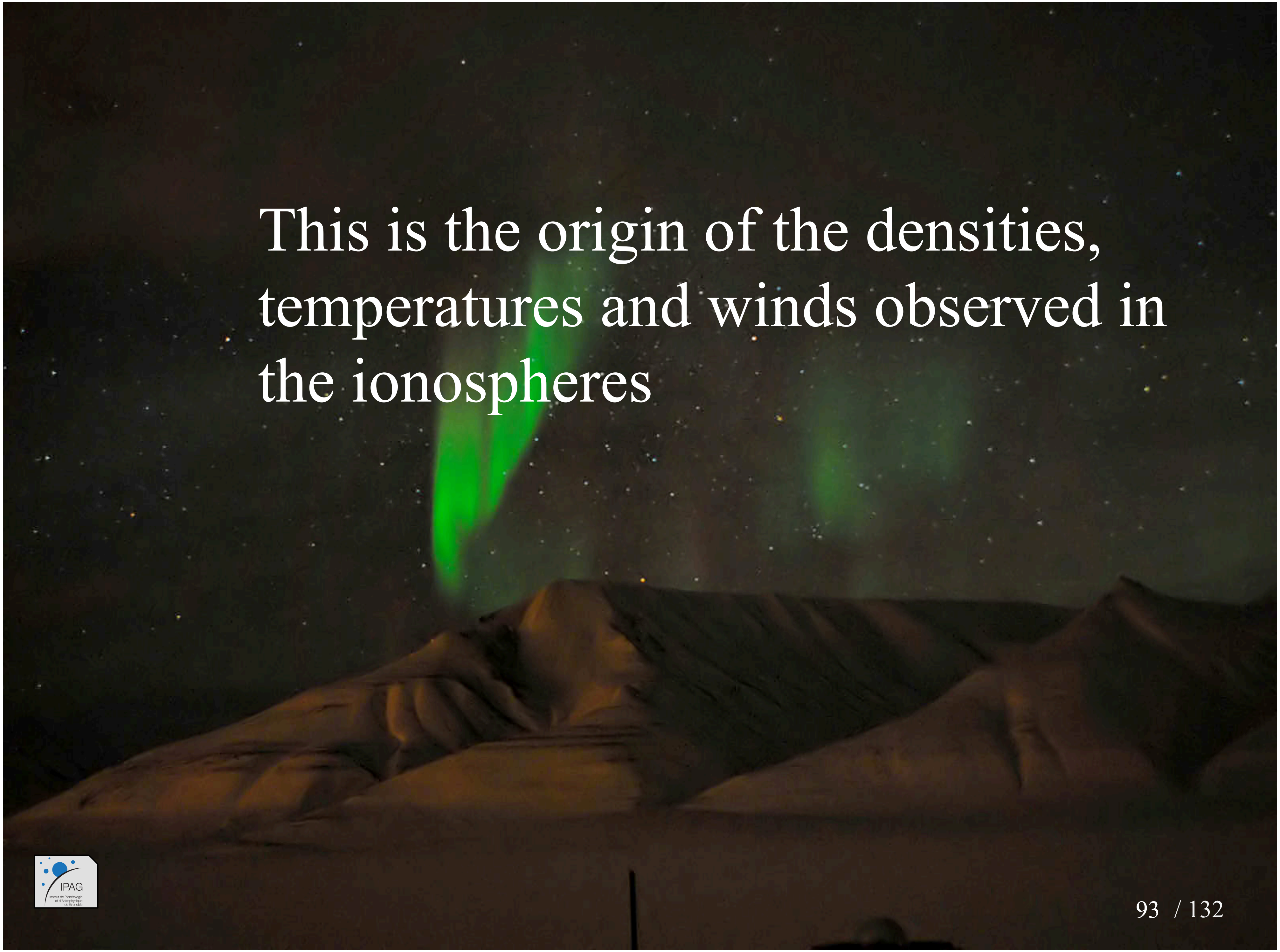
Integrating the electron density over the altitudes gives the Total Electron Content of primary importance for space weather

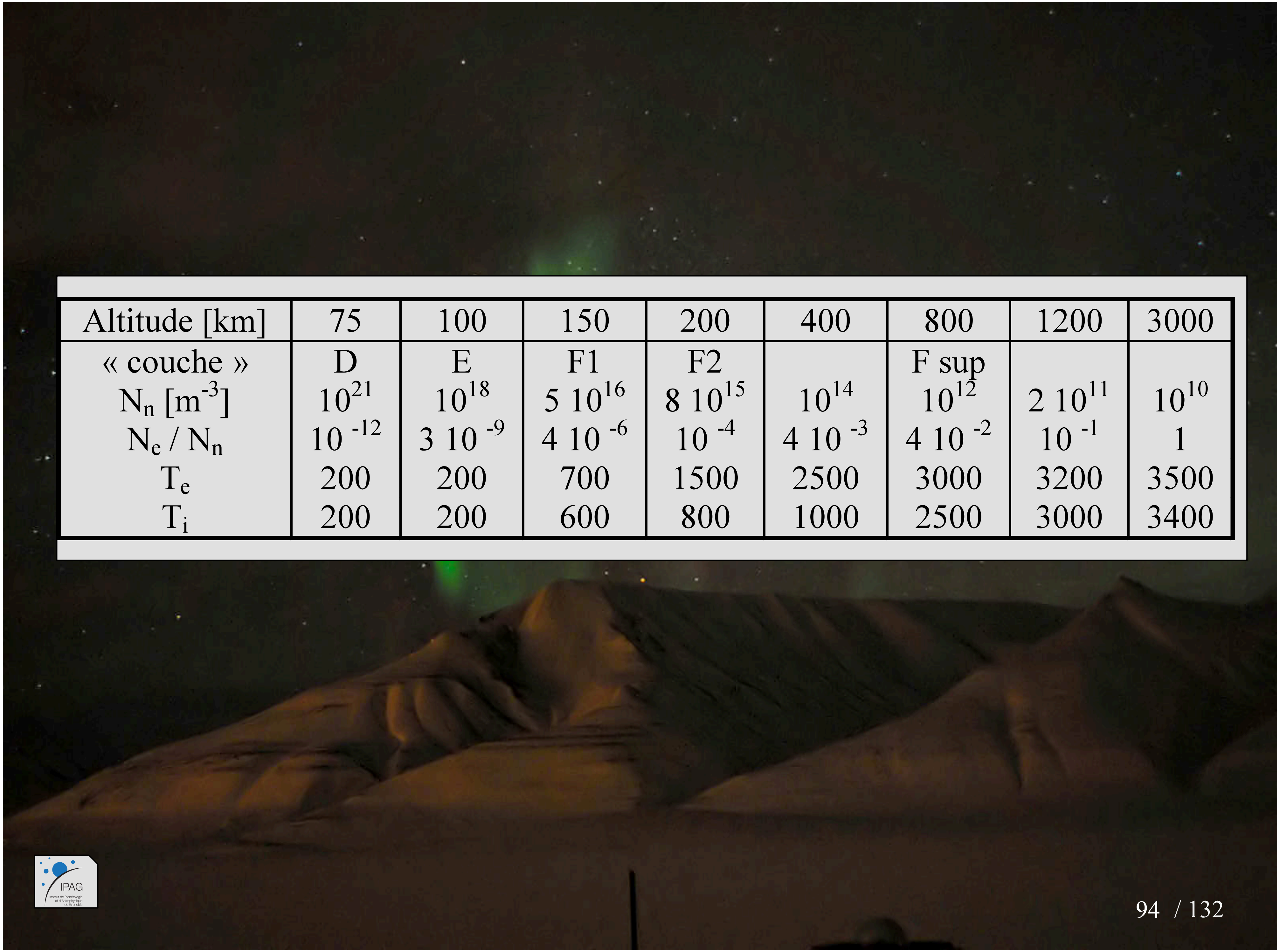

1999-08-11
1999-09-15/17
TEC [10^{16} m^{-2}]
Local Time



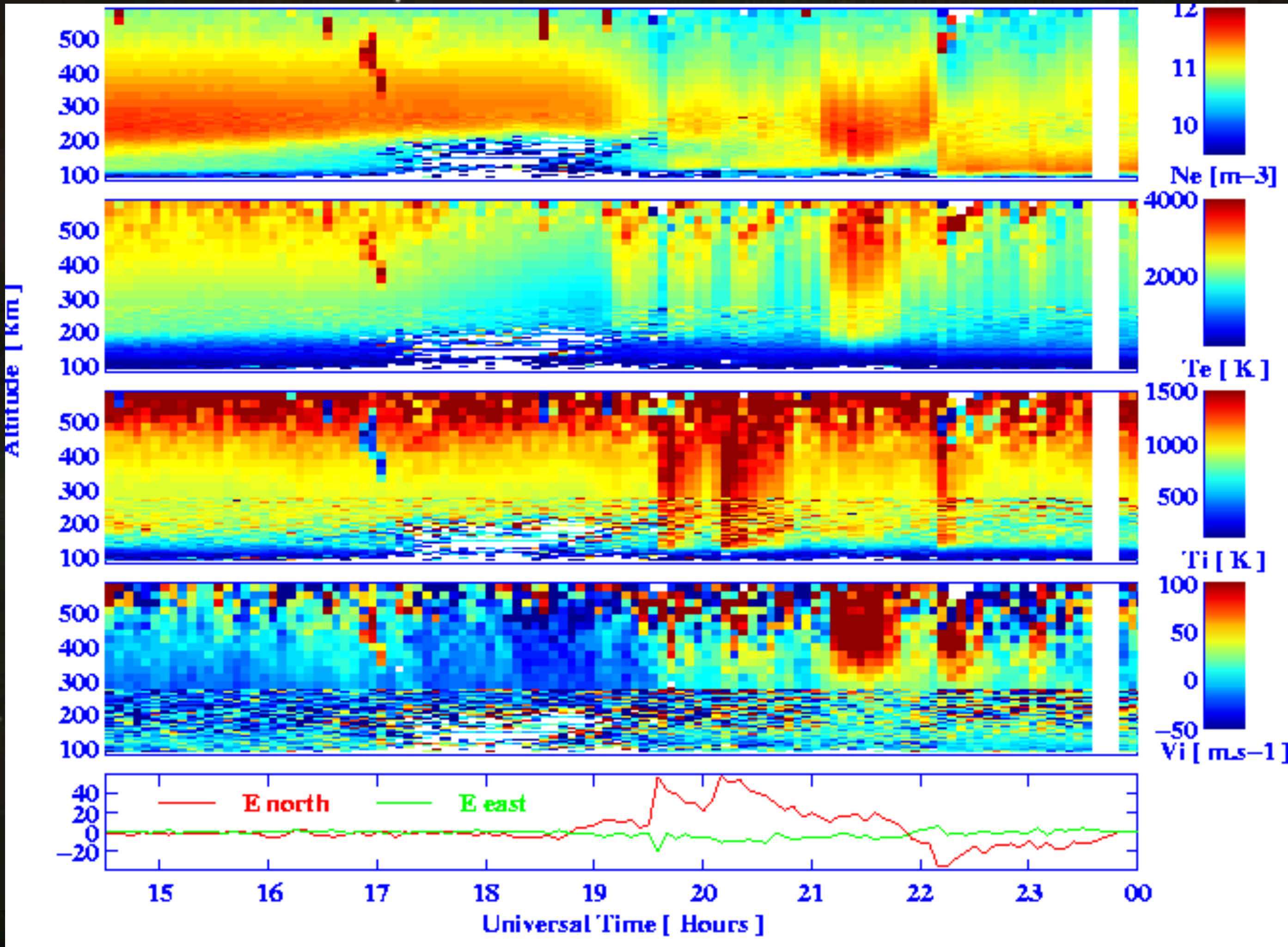
UAF
MODEL
12.00LT
4/ 8/97
20.40UT
Ne(350KM)
Kp AE
5.90
5.75
5.60
5.45
5.30
5.15
5.00
4.85
4.70
4.55
IMF
00.00LT
1.5 KM/S

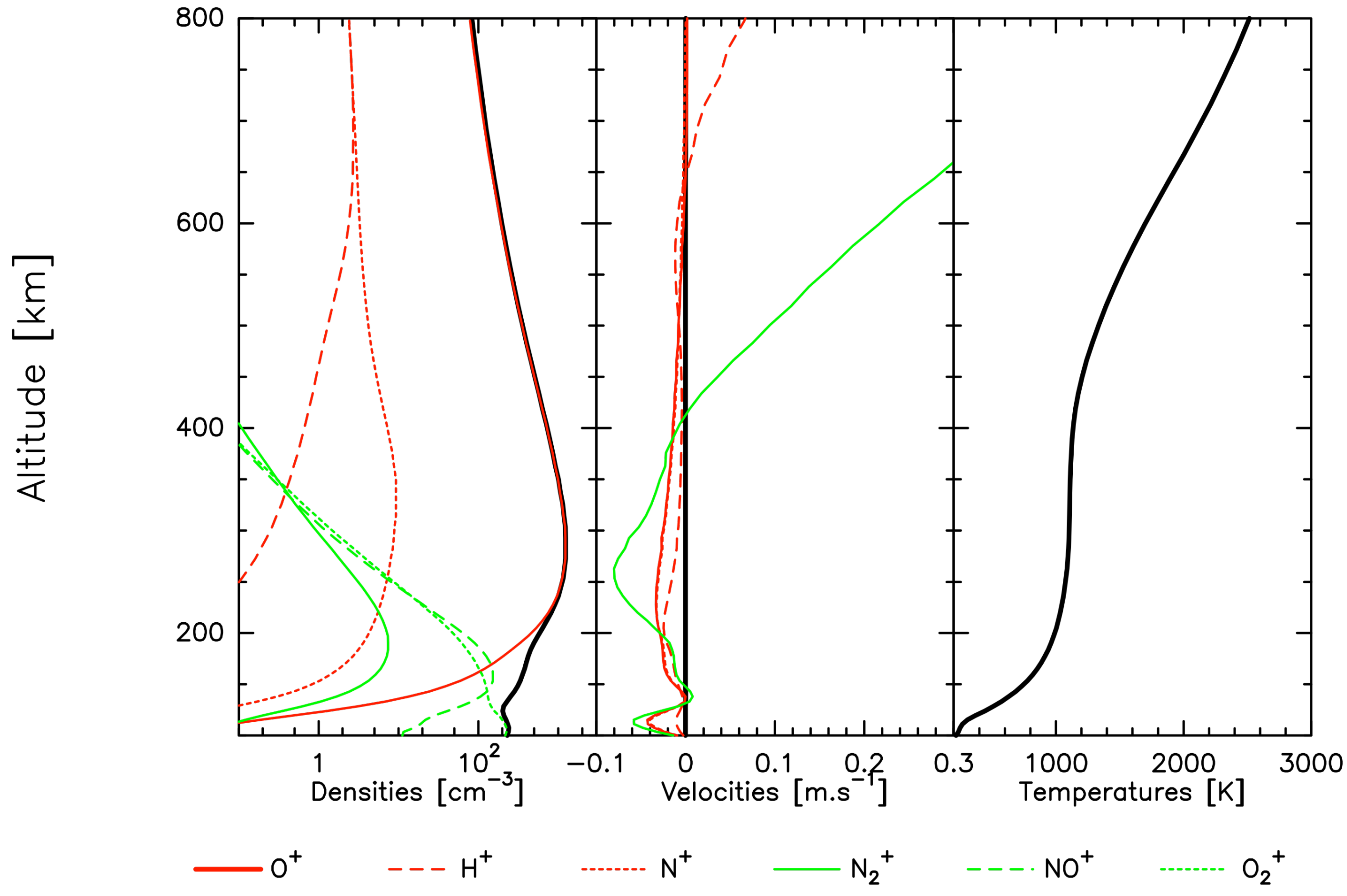

TECU
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61
Vertical TEC at 08 UT, 21 Oct 2010
Geographic Latitude (degrees)
50
0
−50
0
100
200
300
Geographic Longitude (degrees)


This is the origin of the densities, temperatures and winds observed in the ionospheres



Altitude [km]	75	100	150	200	400	800	1200	3000
« couche »	D	E	F1	F2		F sup		
N_n [m^{-3}]	10^{21}	10^{18}	$5\ 10^{16}$	$8\ 10^{15}$	10^{14}	10^{12}	$2\ 10^{11}$	10^{10}
N_e / N_n	10^{-12}	$3\ 10^{-9}$	$4\ 10^{-6}$	10^{-4}	$4\ 10^{-3}$	$4\ 10^{-2}$	10^{-1}	1
T_e	200	200	700	1500	2500	3000	3200	3500
T_i	200	200	600	800	1000	2500	3000	3400


Altitude [km]
500
400
300
200
100
12
11
10
Ne [m-3]
4000
2000
Te [K]
1500
1000
500
Ti [K]
100
50
0
-50
Vi [m.s-1]
40
20
0
-20
E north
E east
15
16
17
18
19
20
21
22
23
00
Universal Time [Hours]



Altitude [km]
800
600
400
200
1
10^2
Densities [cm^-3]
−0.1
0
0.1
0.2
0.3
Velocities [m.s^-1]
1000
2000
3000
Temperatures [K]
O+
H+
N+
N2+
NO+
O2+

Sources of variations of the thermosphere :

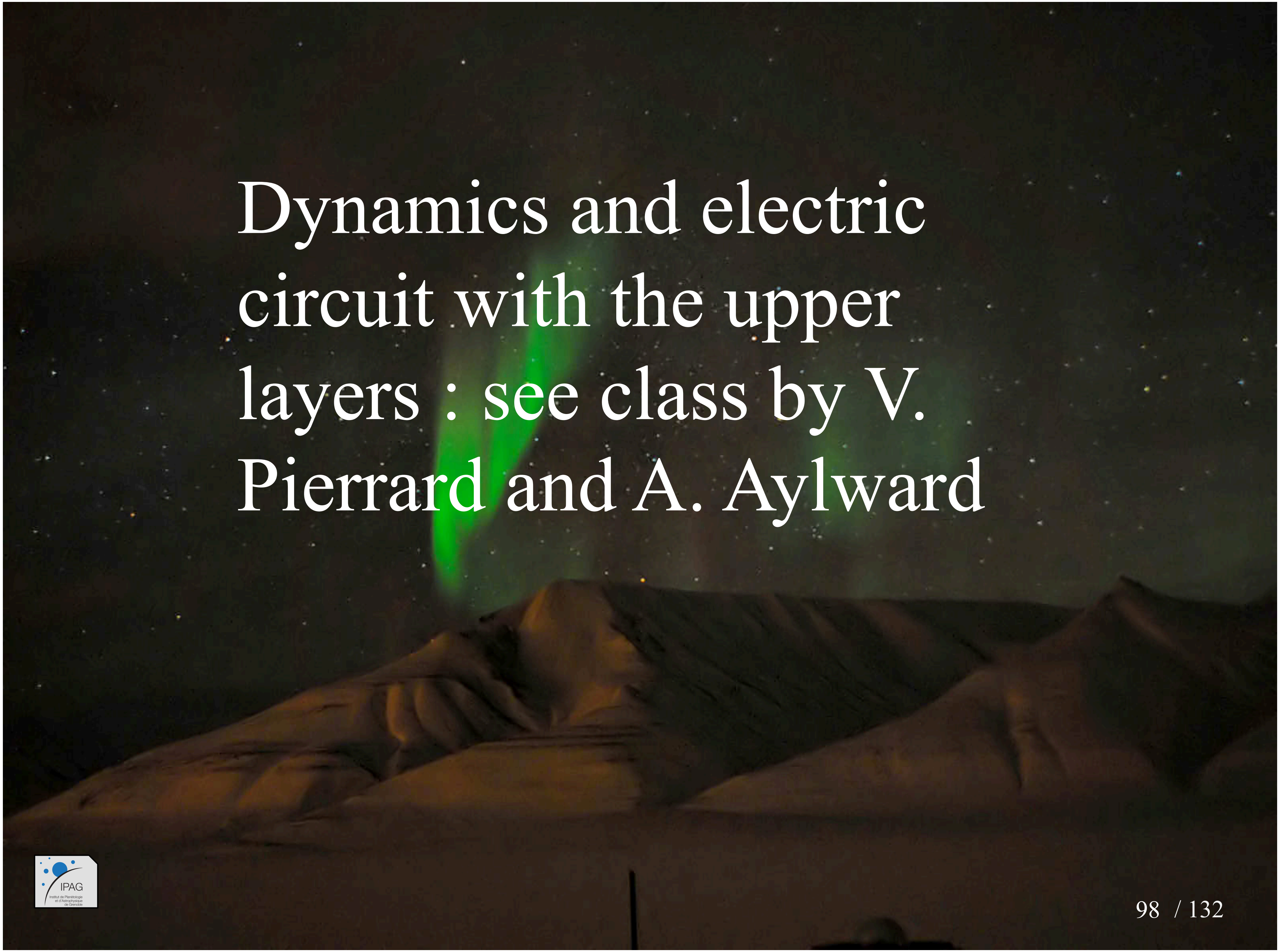
- X rays and EUV fluxes
- Particle precipitation
- E fields

Physical processes involved :

- photo-absorption
- particle collisions
- Joule heating
- frictional heating

Result (amongst other phenomena) in rapid variations and creations of small scale disturbances

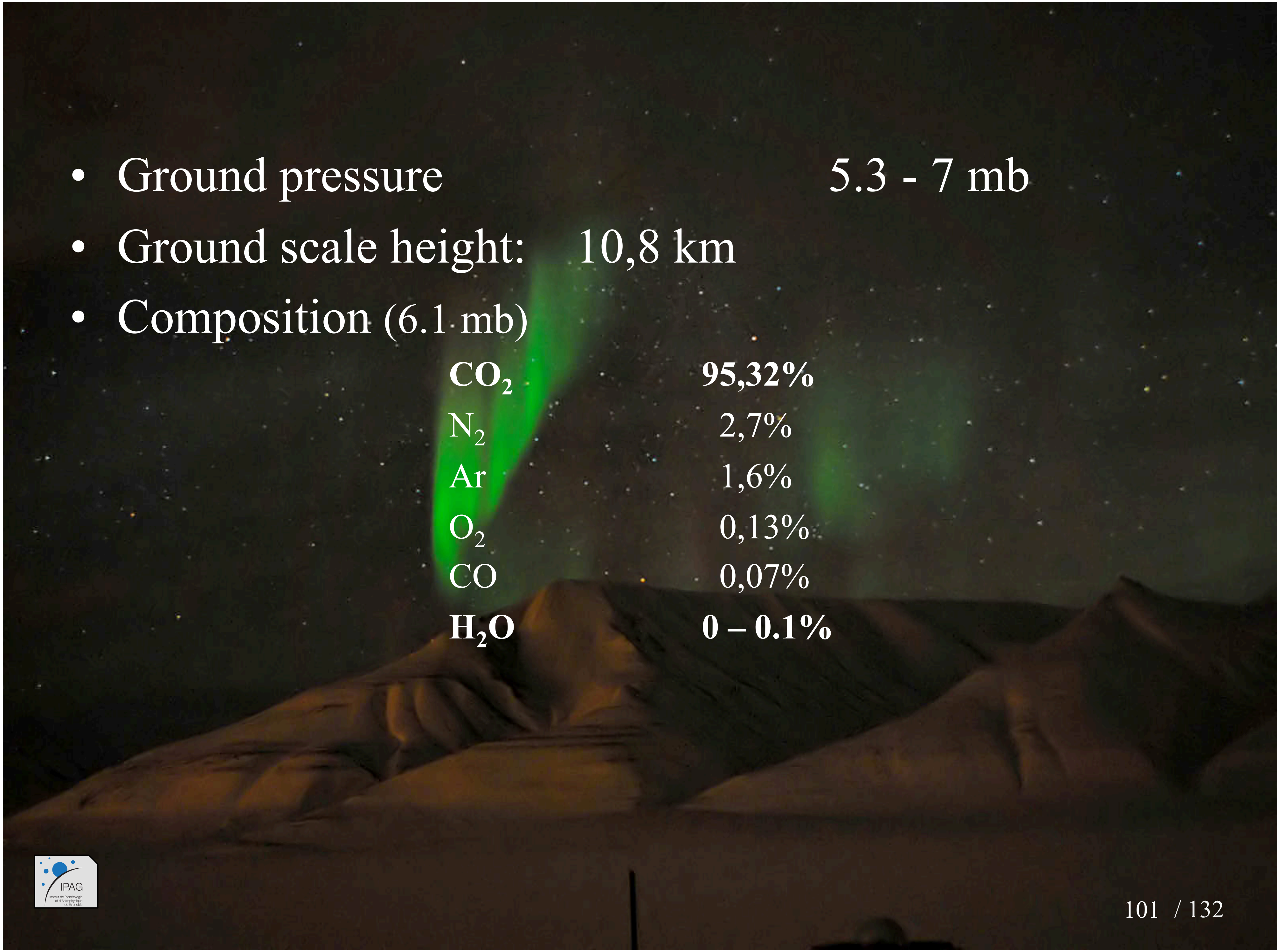
Result (amongst other phenomena) in a dilatation of the thermosphere (density may increase by a factor of 10 at the altitude of the International Space Station)



Dynamics and electric circuit with the upper layers : see class by V. Pierrard and A. Aylward

What about the other planets?

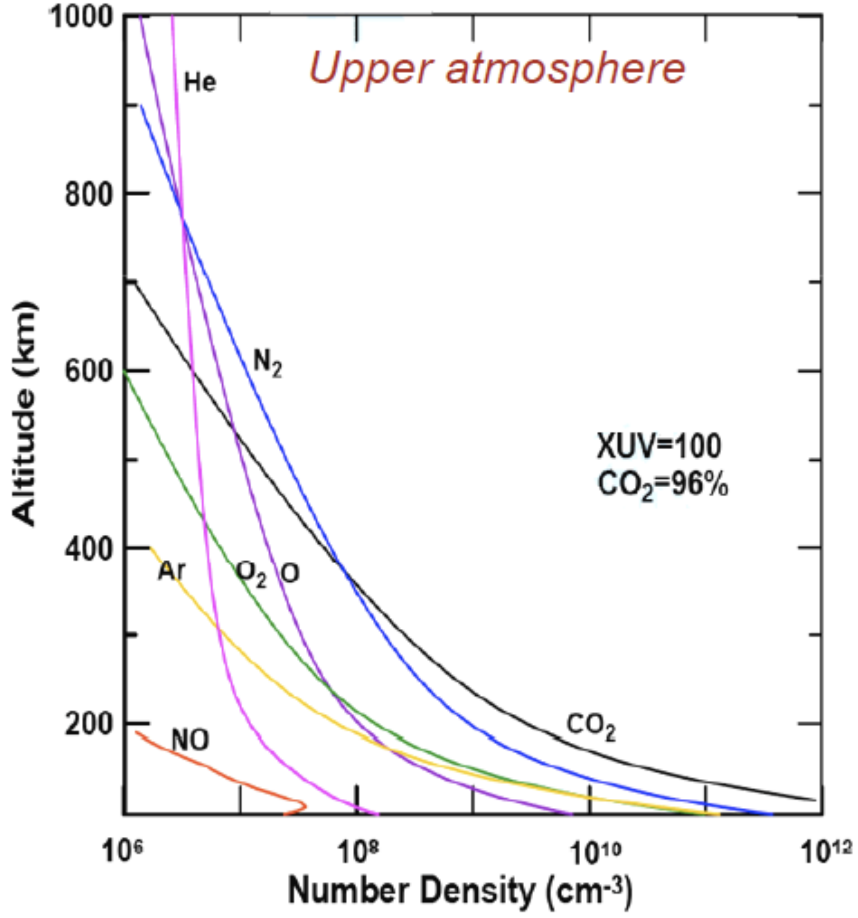

An example of a planet
without a magnetic field :
Mars…
IPAG



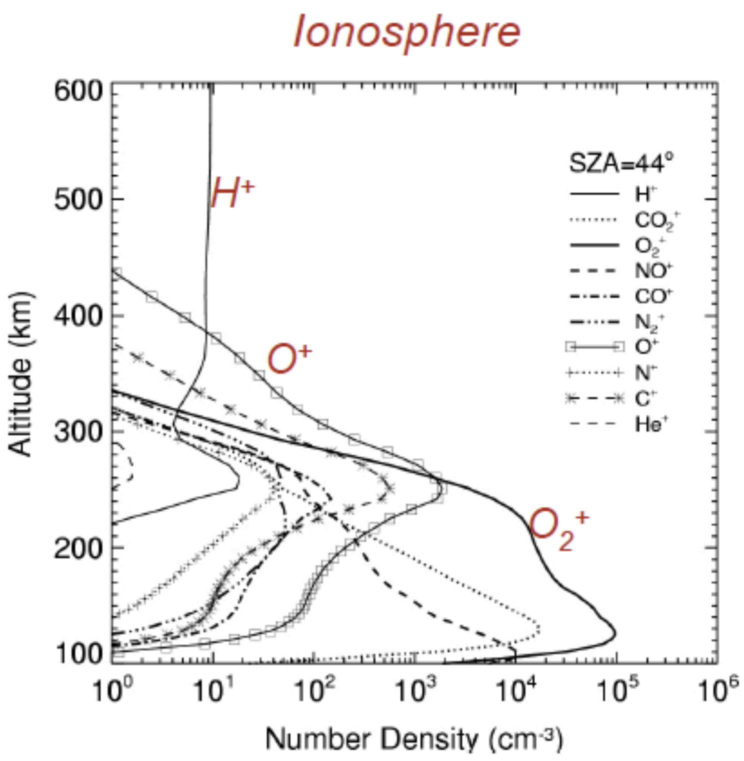
- Ground pressure 5.3 - 7 mb
- Ground scale height: 10,8 km
- Composition (6.1 mb)

CO_2	**95,32%**
N_2	2,7%
Ar	1,6%
O_2	0,13%
CO	0,07%
H_2O	**0 – 0.1%**

IPAG



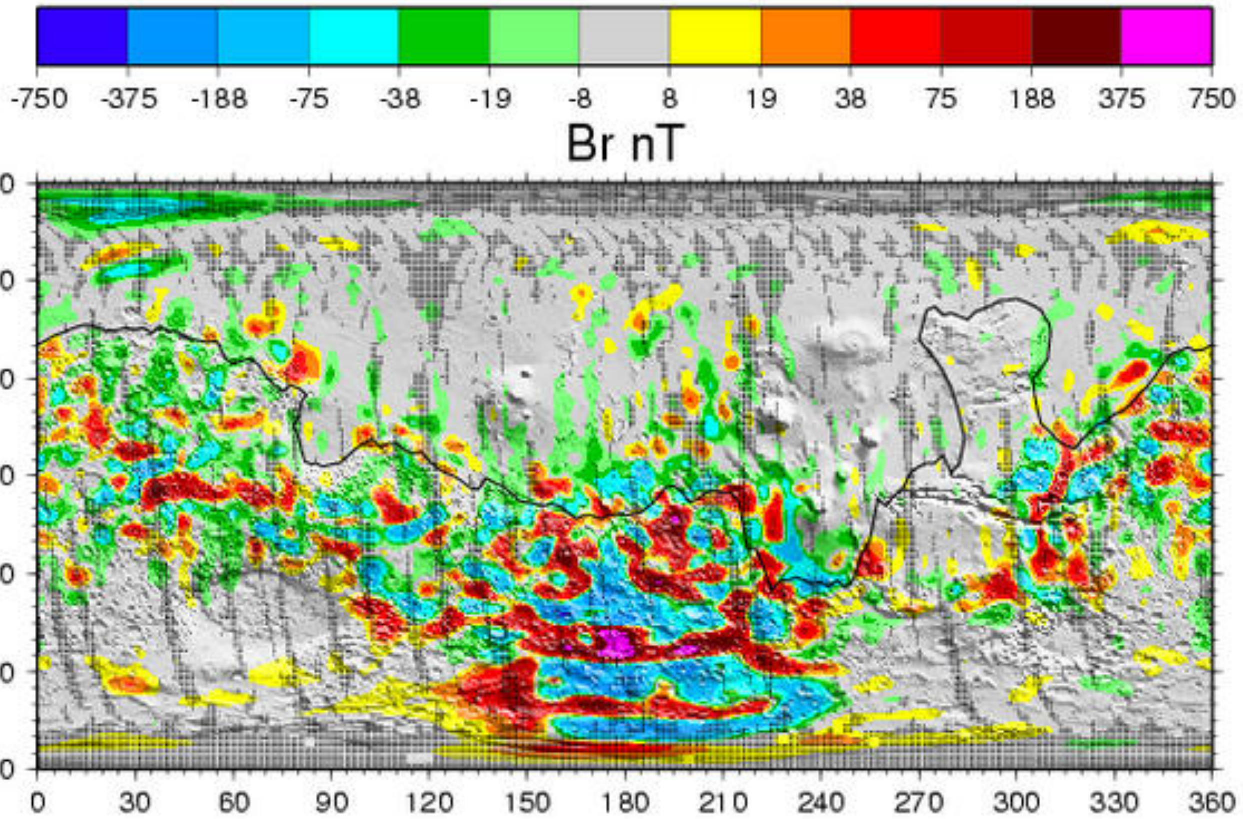
(Shinagawa and Cravens, 1989)

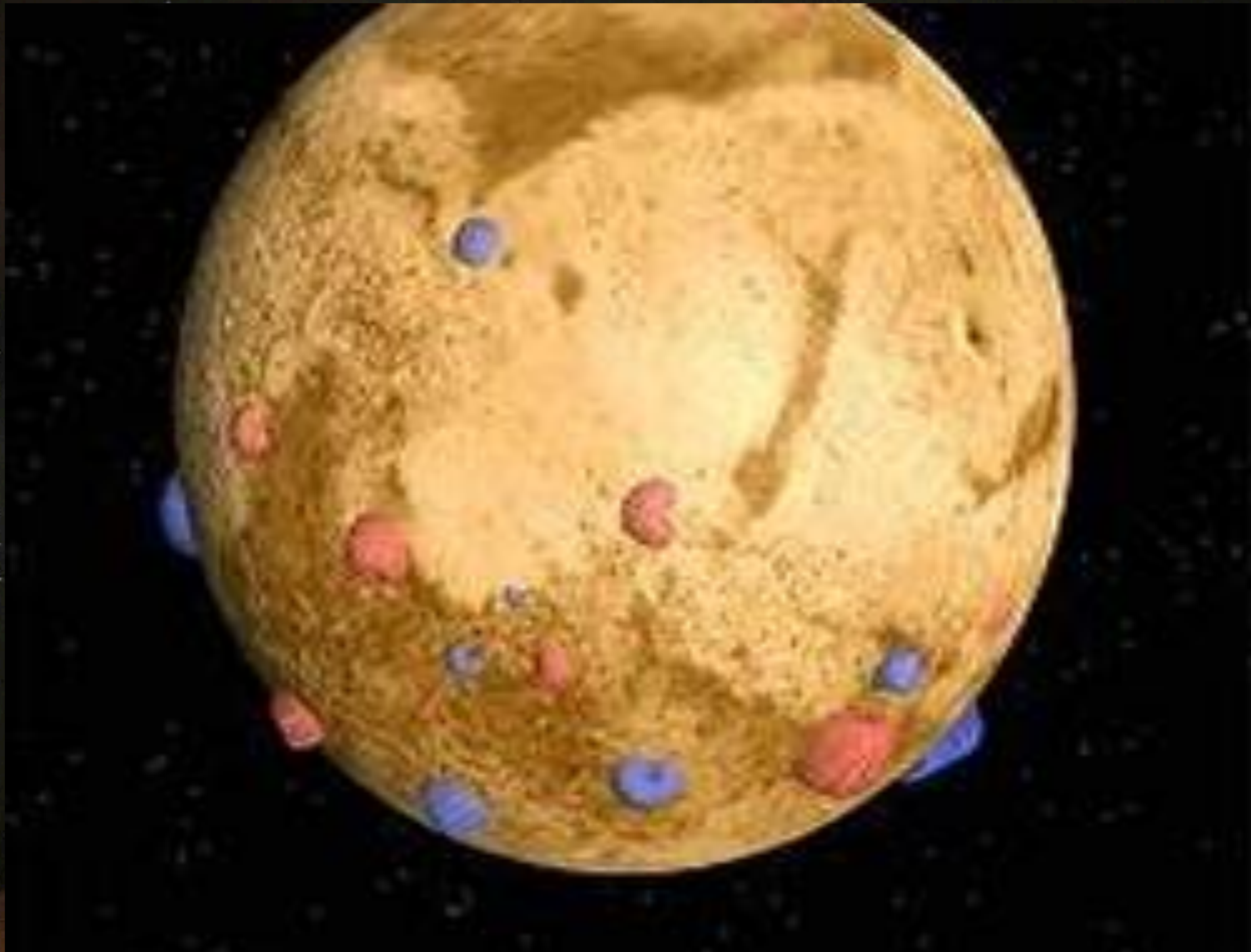


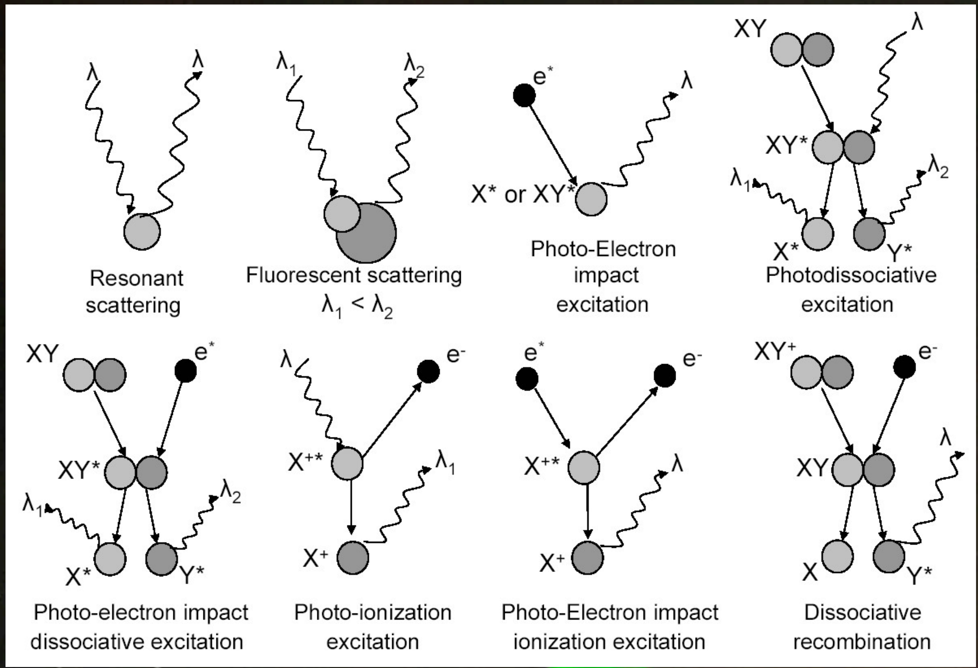
(Terada et al, 2009)

Le champ magnétique recalculé à 200 km

(les zones sans données au-dessous de 200 km sont grisées)

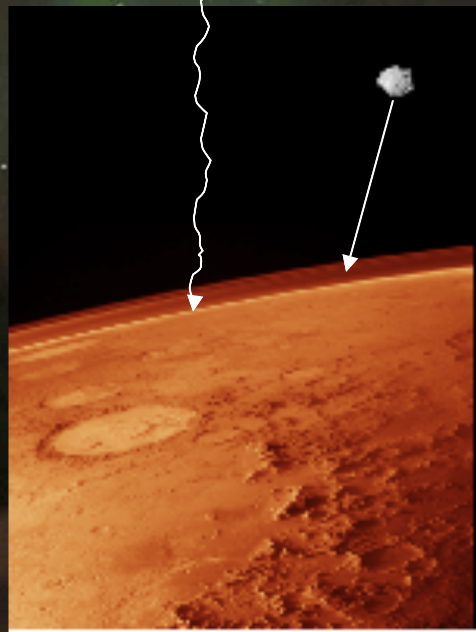






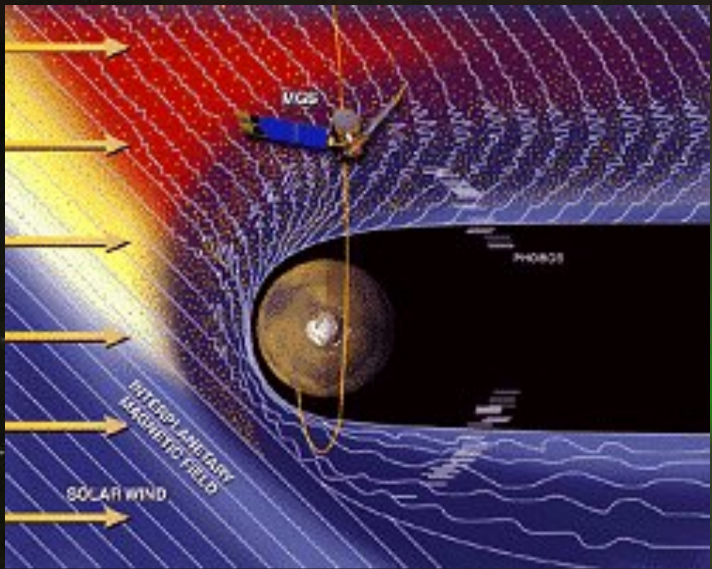
There are several origins for the martian ionosphere and its glow

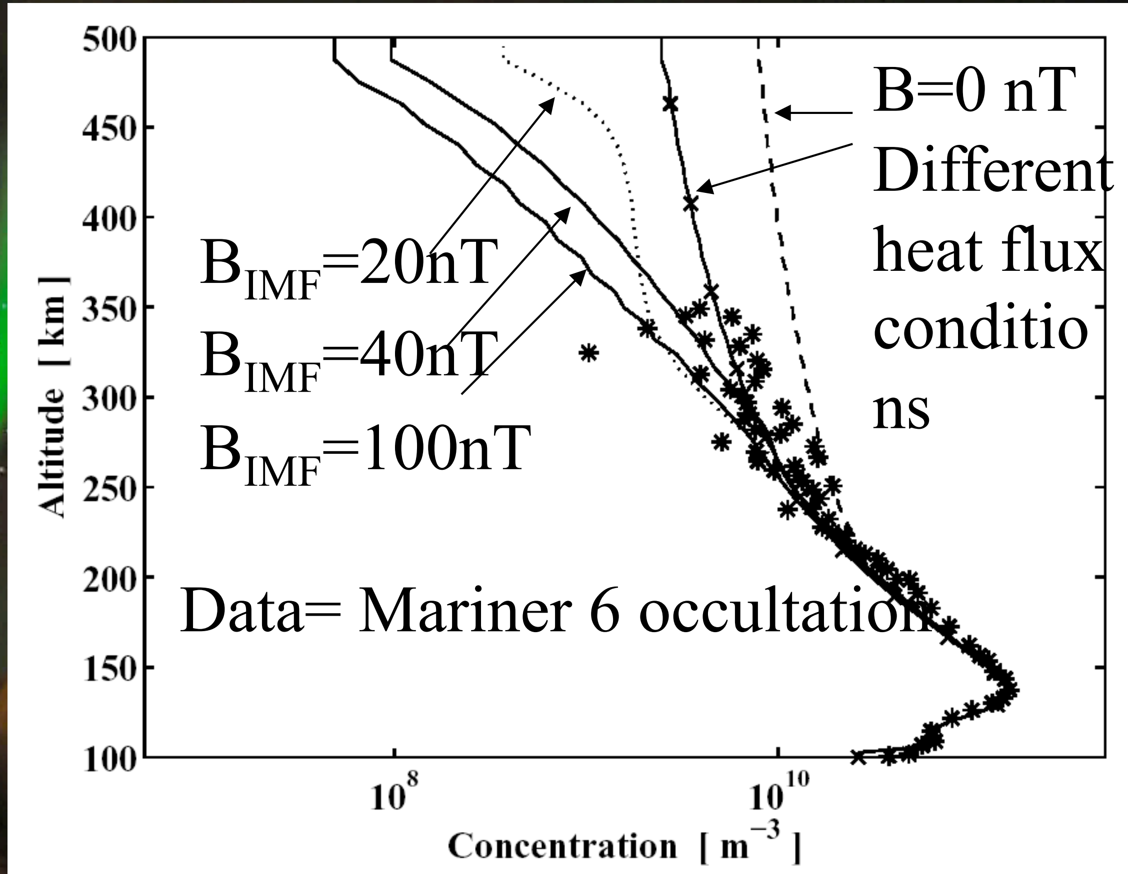
Cosmic rays

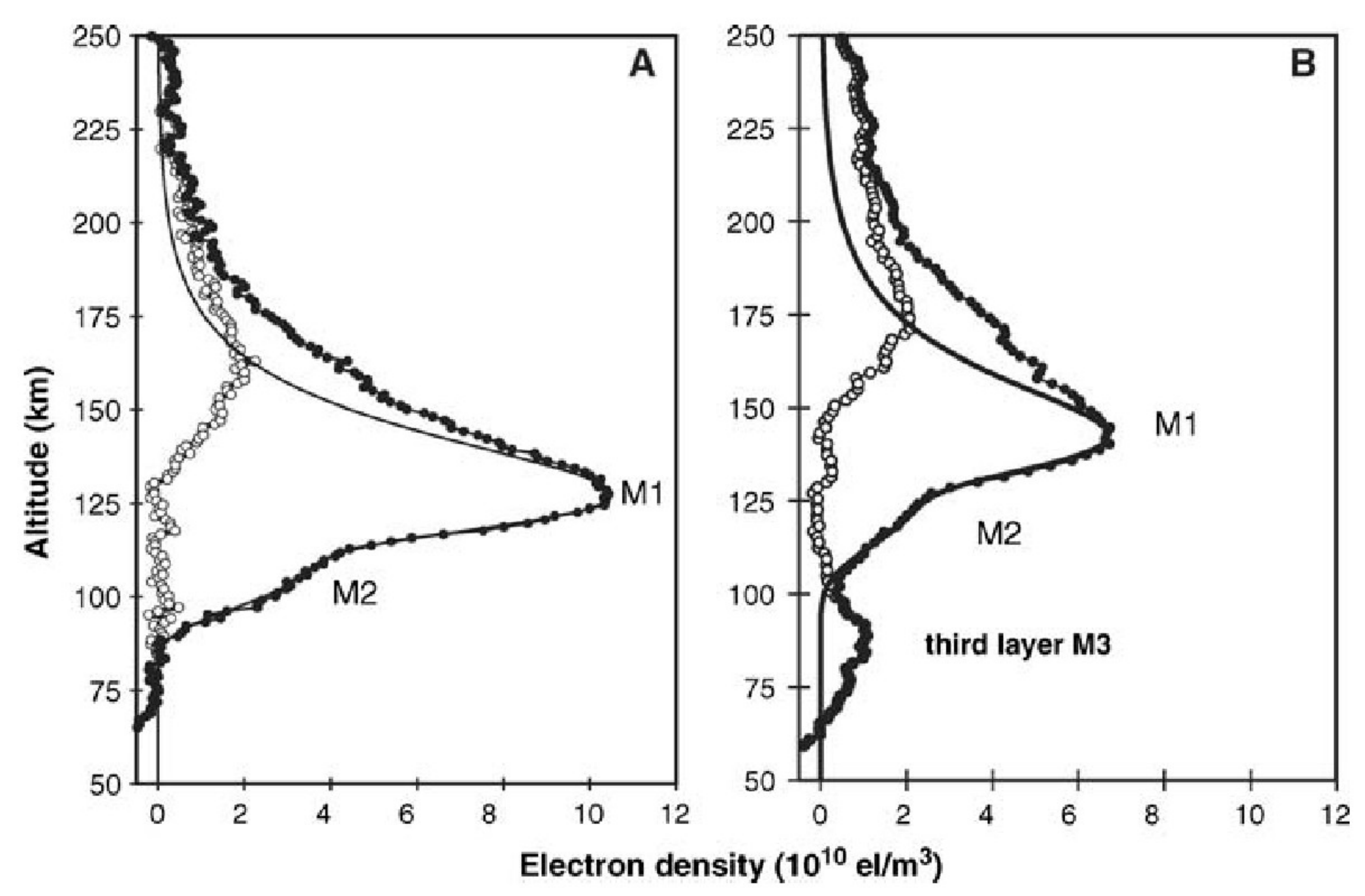


Meteoritic ablation

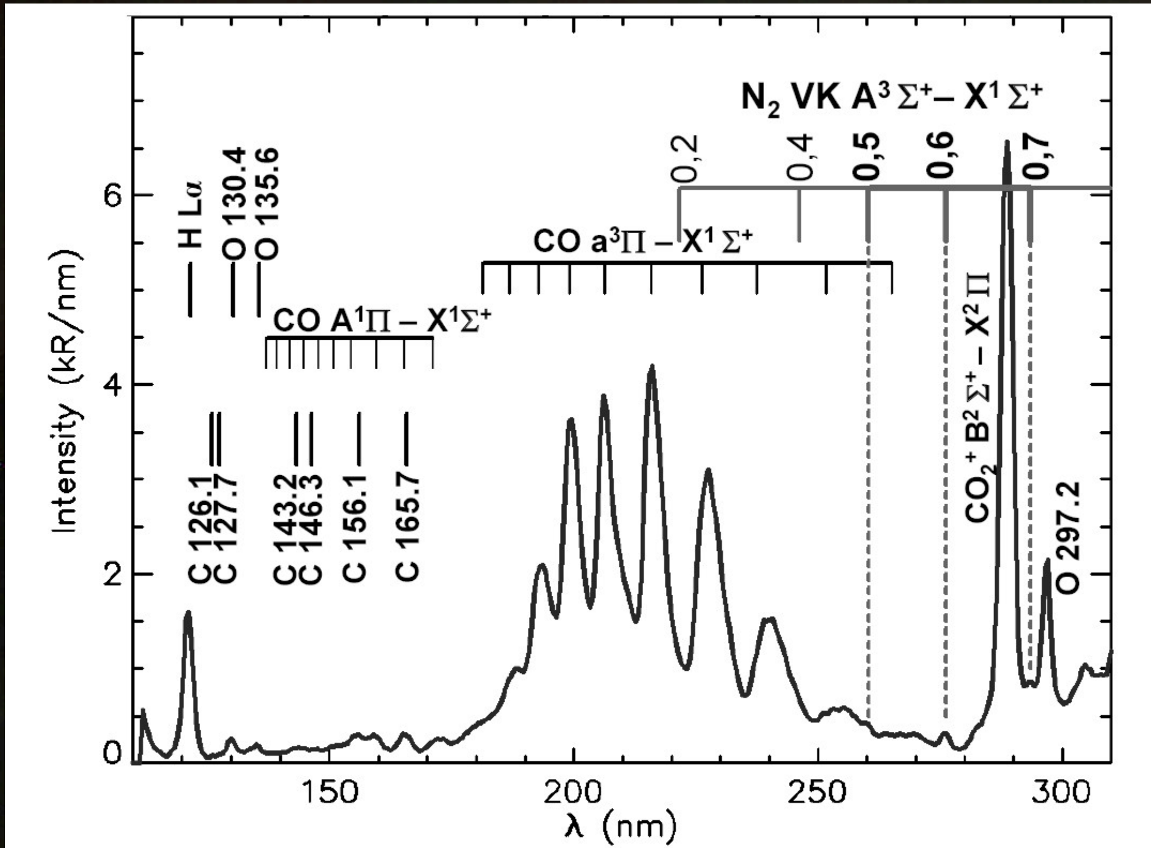
Since there is no global martian magnetic field, the interaction with the IMF is of first importance in the case of Mars.



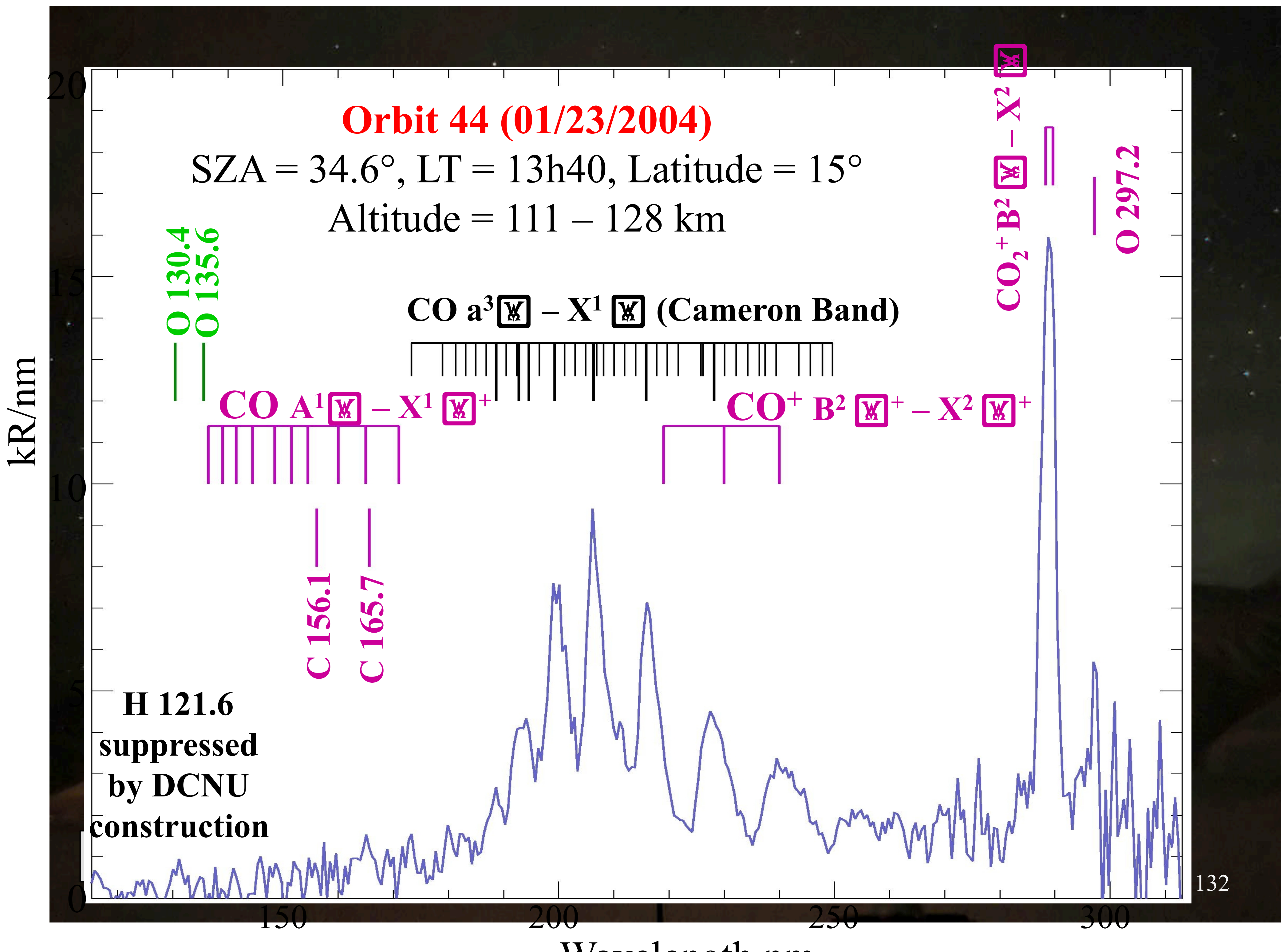




MARSIS, Pätzold et al., Science, 2005



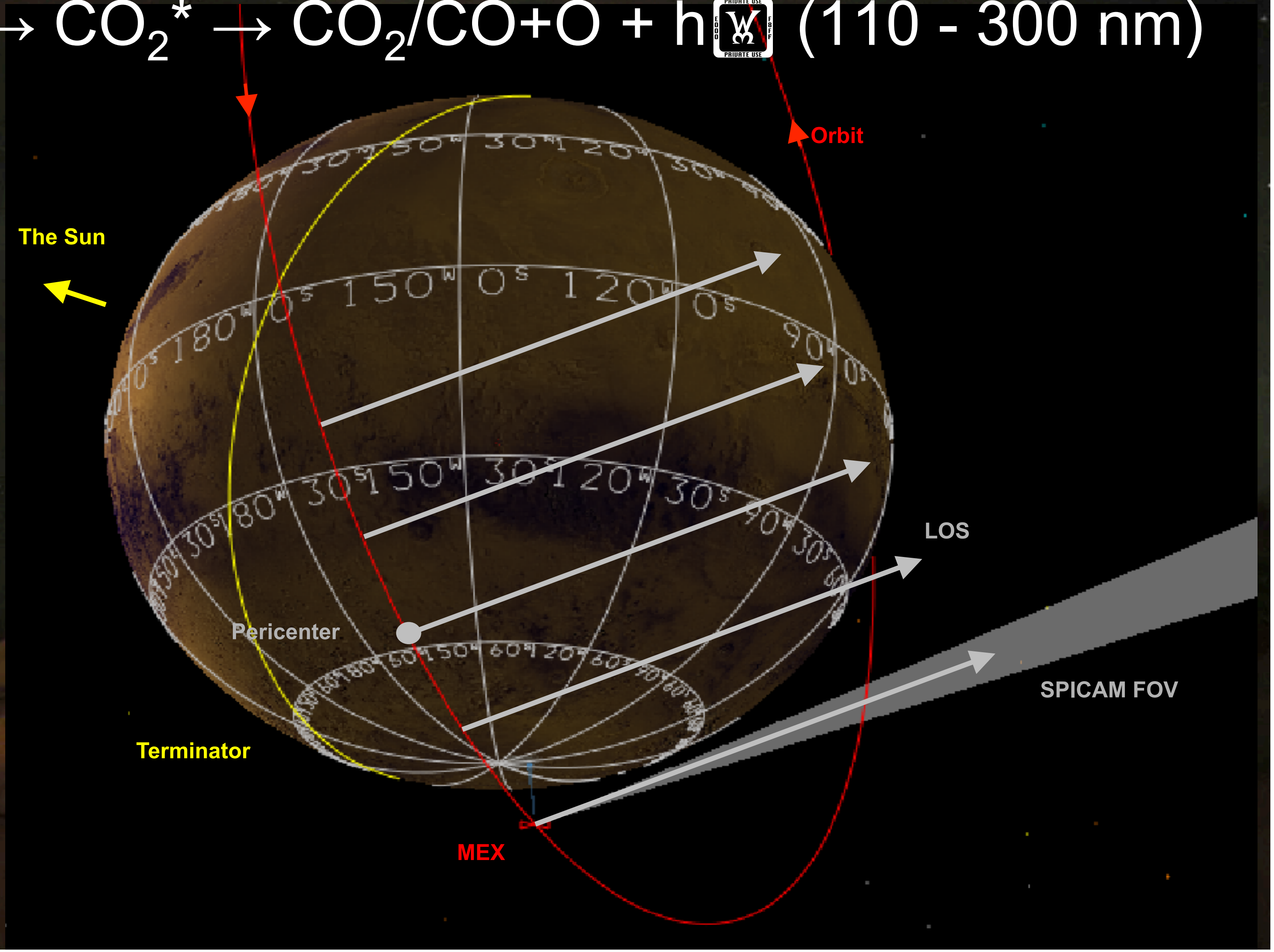
Leblanc et al., 2005


Orbit 44 (01/23/2004)
SZA = 34.6°, LT = 13h40, Latitude = 15°
Altitude = 111 – 128 km
O 130.4
O 135.6
CO a3 – X1 (Cameron Band)
CO A1 – X1 +
CO+ B2 + – X2 +
CO2+ B2 – X2
O 297.2
C 156.1
C 165.7
H 121.6
suppressed
by DCNU
construction
kR/nm
20
15
10
5
0
150
200
250
300
Wavelength nm

SPICAM discovery of a Martian Aurora

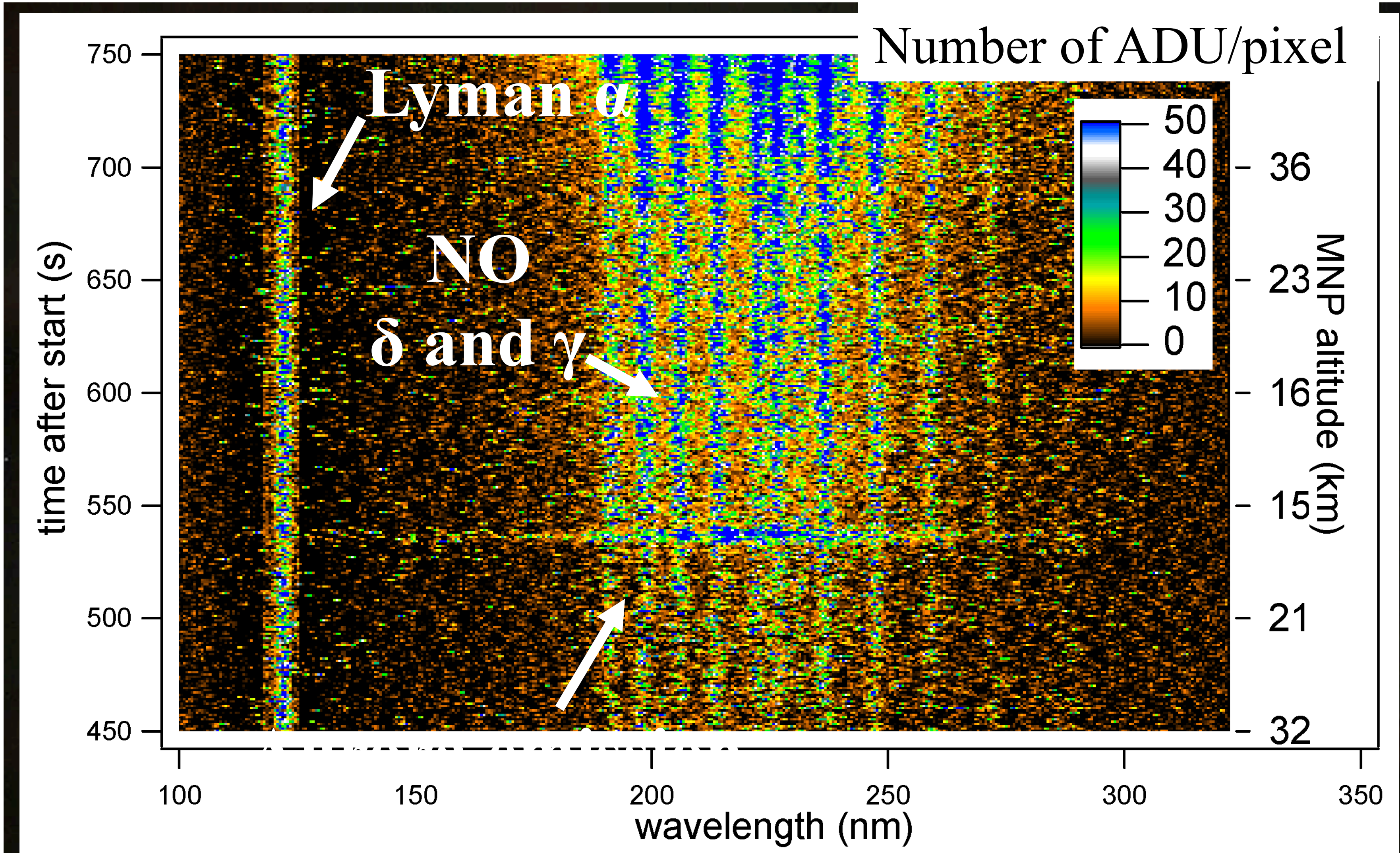
Charge particle precipitation into Mars' atmosphere

$CO_2 + e \rightarrow CO_2^* \rightarrow CO_2/CO + O + h\nu$ (110 - 300 nm)



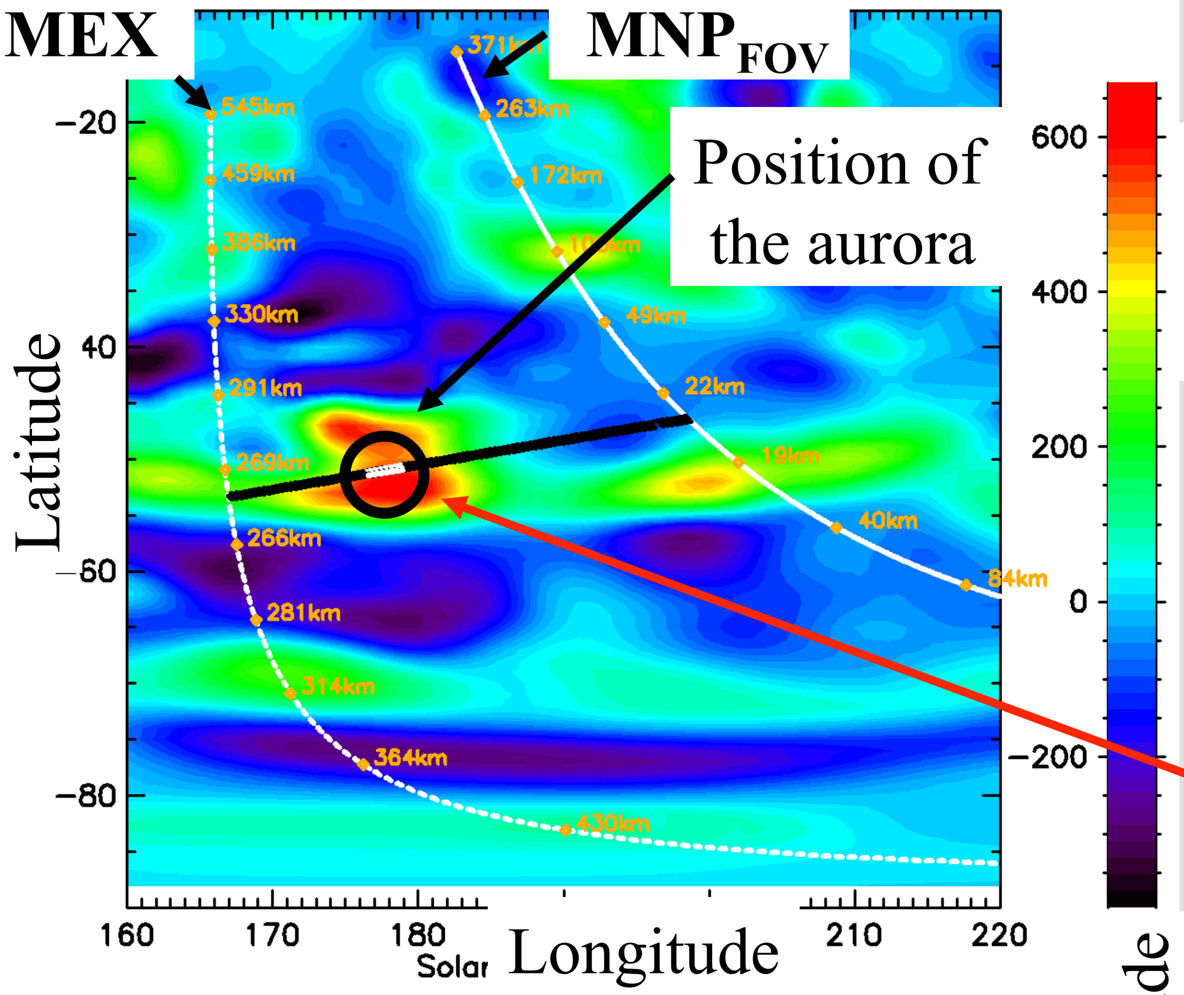
Bertaux et al. Nature, 435, 790-794, 2005

Orbit 716, 08/11/2004



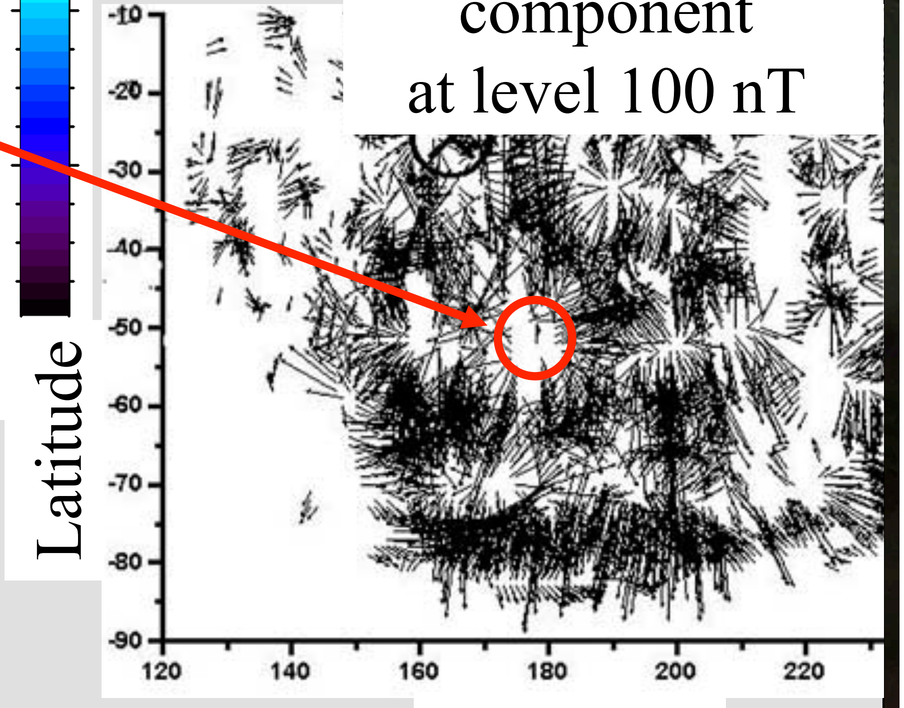
Aurora emission lasts ~ 7 seconds
= 7 successive integrations

From Purucker et al. (2000)



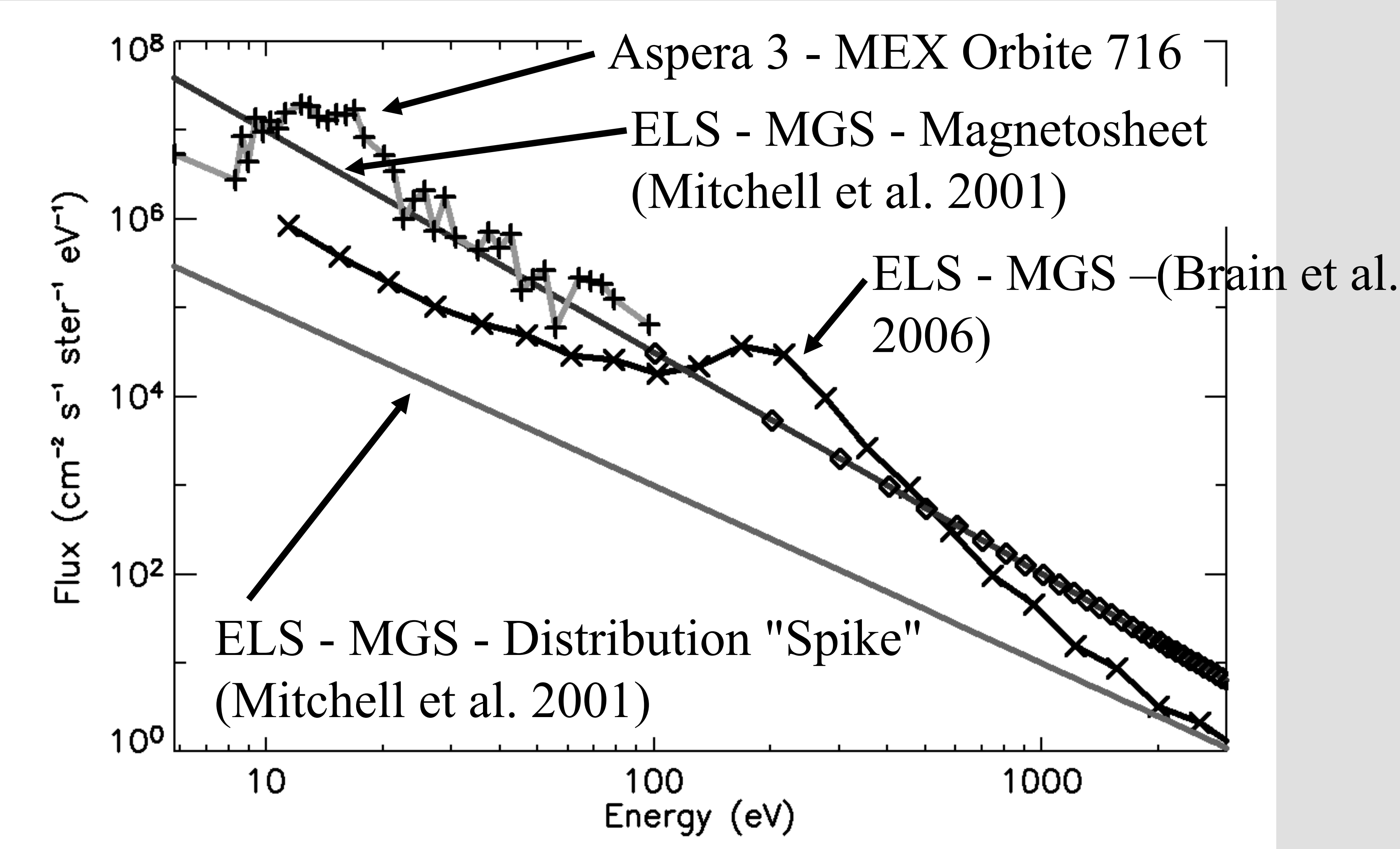
Crustal radial component (nT) at 400 km

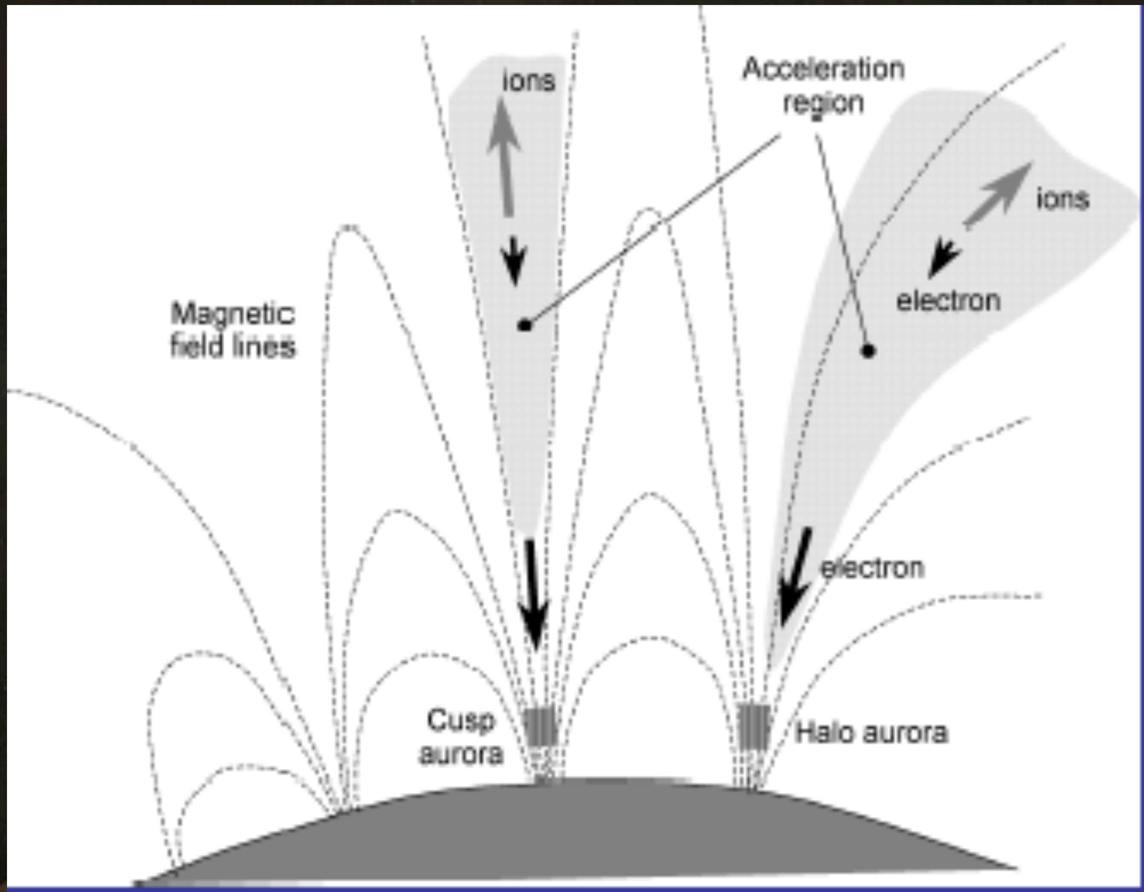
Crustal horizontal component at level 100 nT



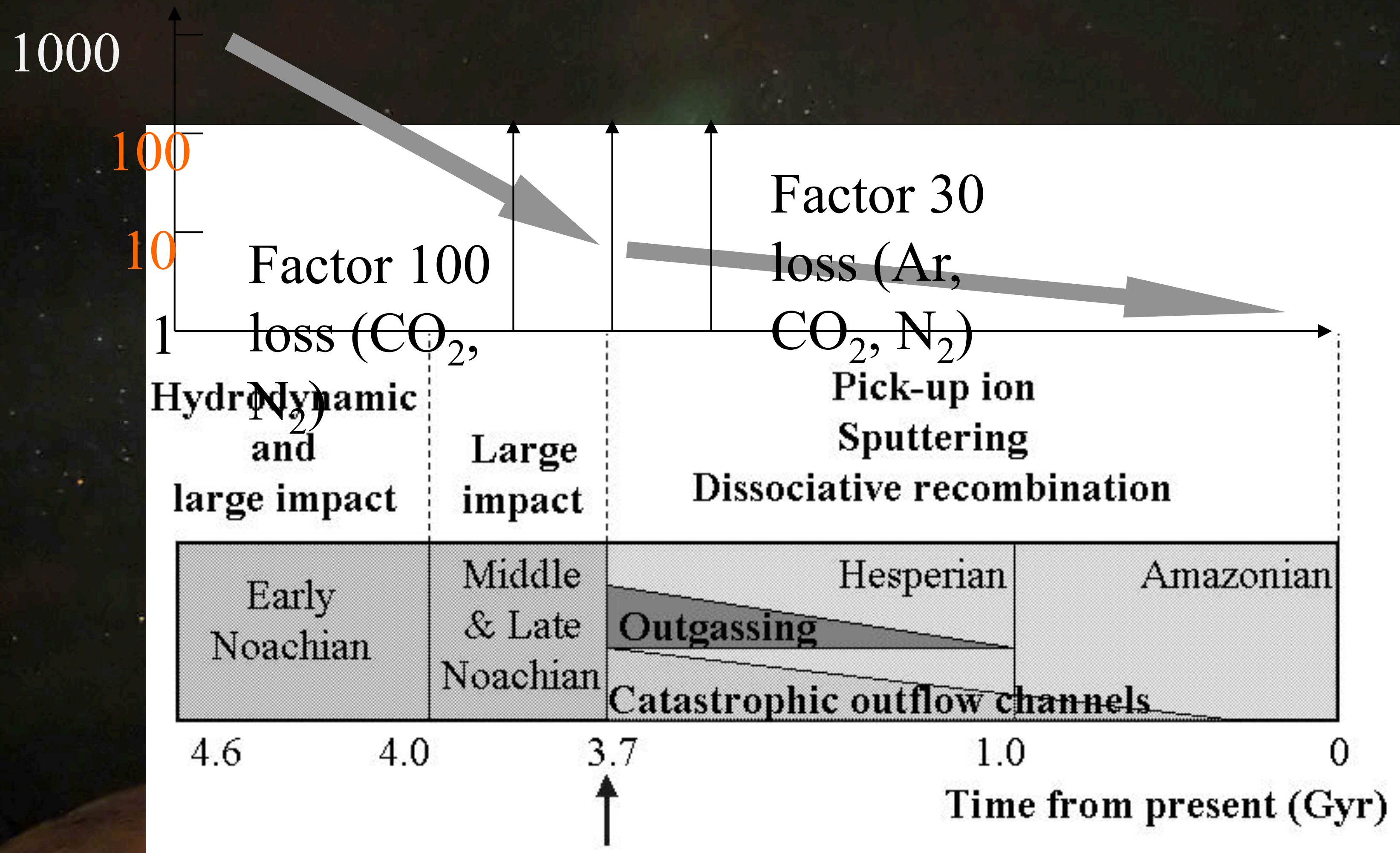
Aurora emission corresponds to an open field line region

From Krimskyi et al. (2002)

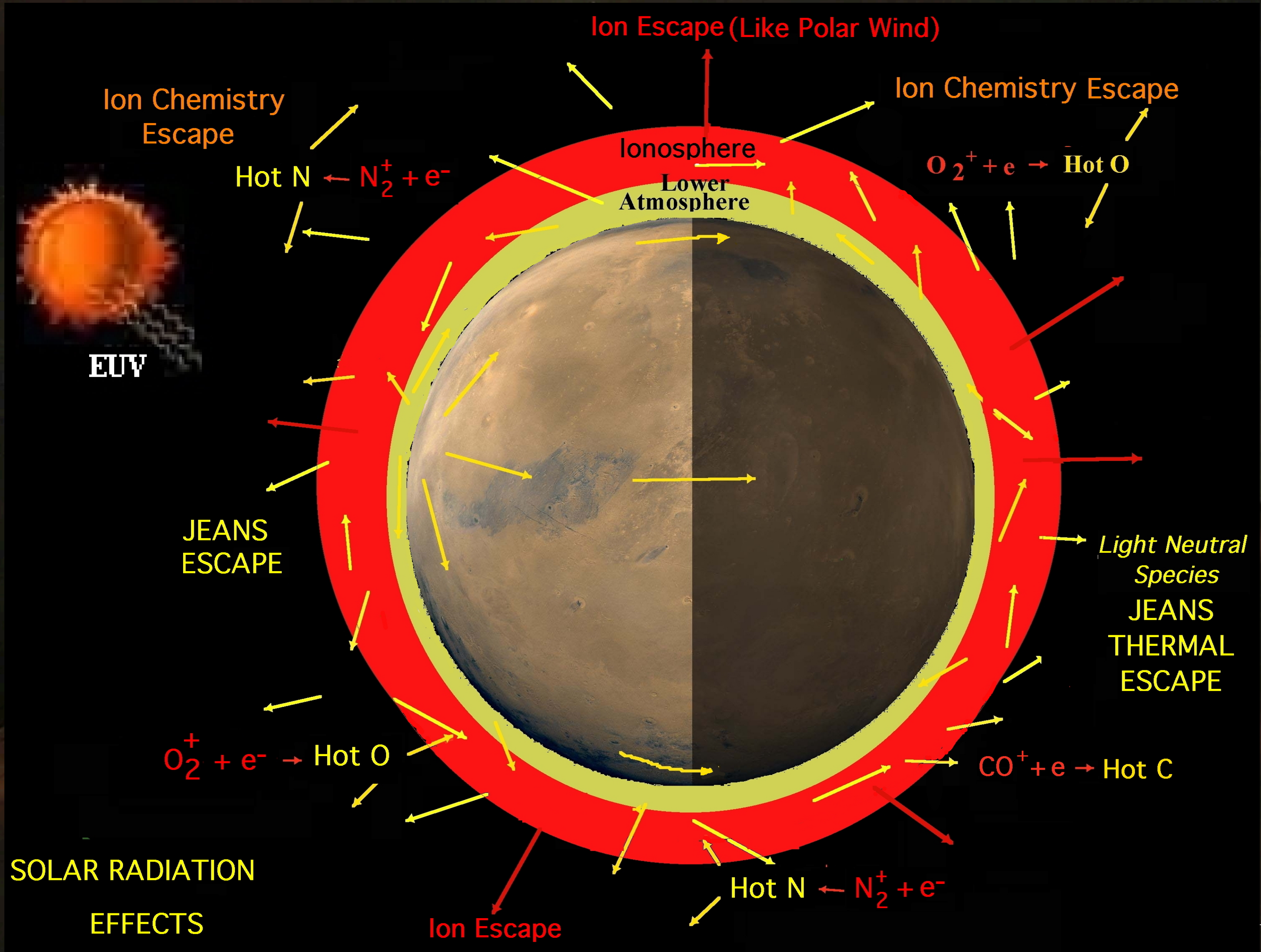

Aspera 3 - MEX Orbite 716
ELS - MGS - Magnetosheet
(Mitchell et al. 2001)
ELS - MGS –(Brain et al.
2006)
ELS - MGS - Distribution "Spike"
(Mitchell et al. 2001)
Flux (cm⁻² s⁻¹ ster⁻¹ eV⁻¹)
10⁸
10⁶
10⁴
10²
10⁰
10
100
1000
Energy (eV)


ions
Acceleration region
ions
electron
Magnetic field lines
electron
Cusp aurora
Halo aurora

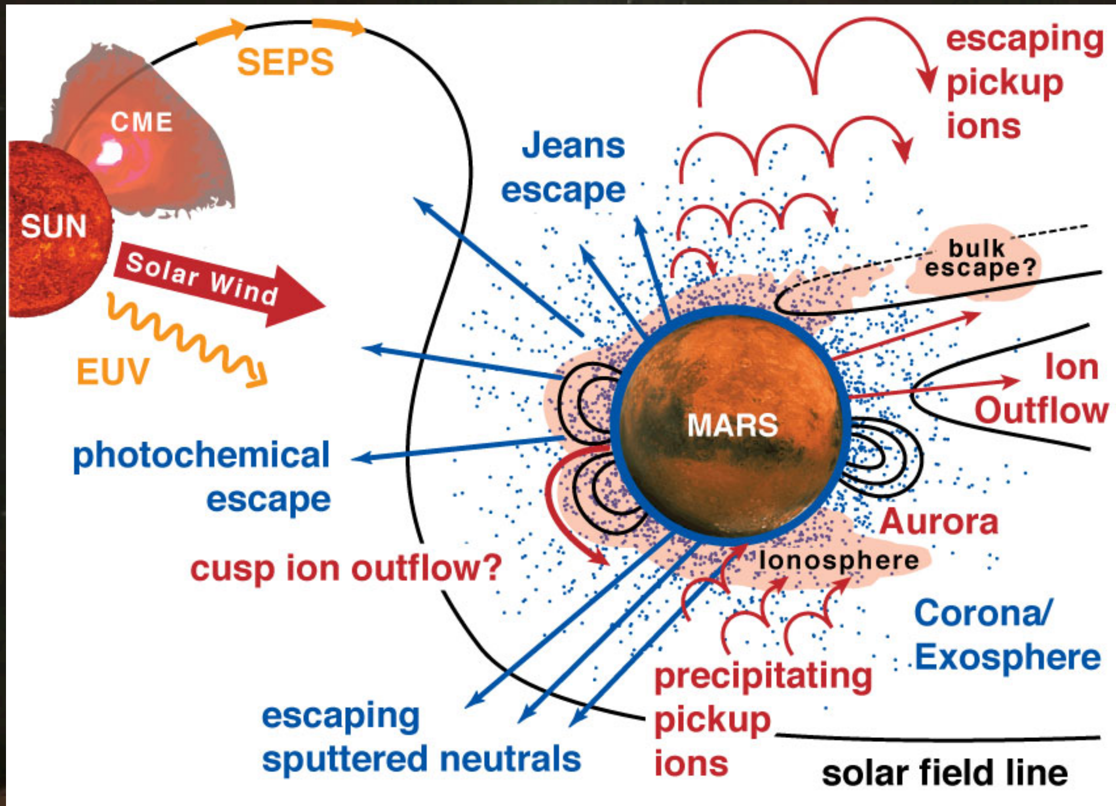
Possible chronological scheme



Solar EUV Driven Escape
Without Solar Wind and Magnetic Fields



Solar Wind and Magnetic Fields Expands the Escape Scenarios



• Absence of intrinsic magnetic field exposes parts of atmosphere to solar wind/IMF - driven escape

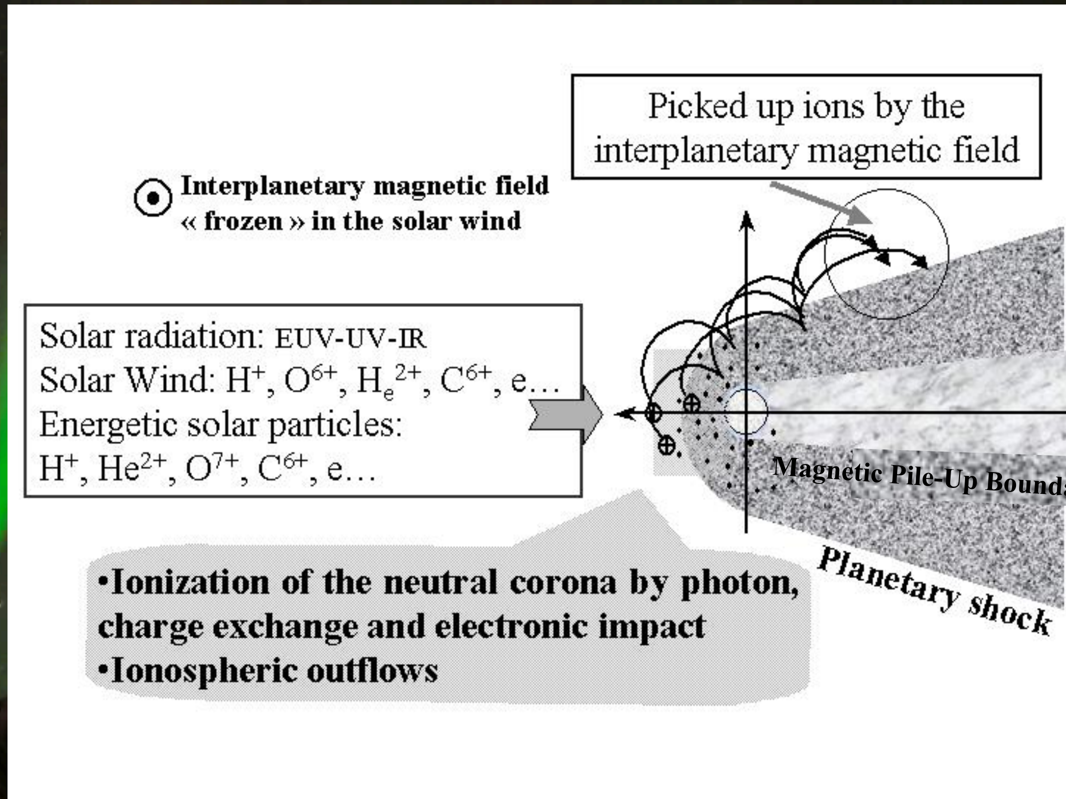
•Remanent magnetic field regions with aurora may have wave-driven loss processes

Escape to space by sputtering

Sputtering is possible only in the absence of a global magnetic field.

Sputtering is strongly non-linear with solar EUV flux :

[illegible]$_{sput}$ [illegible] [illegible]$_{EUV}^{8}$

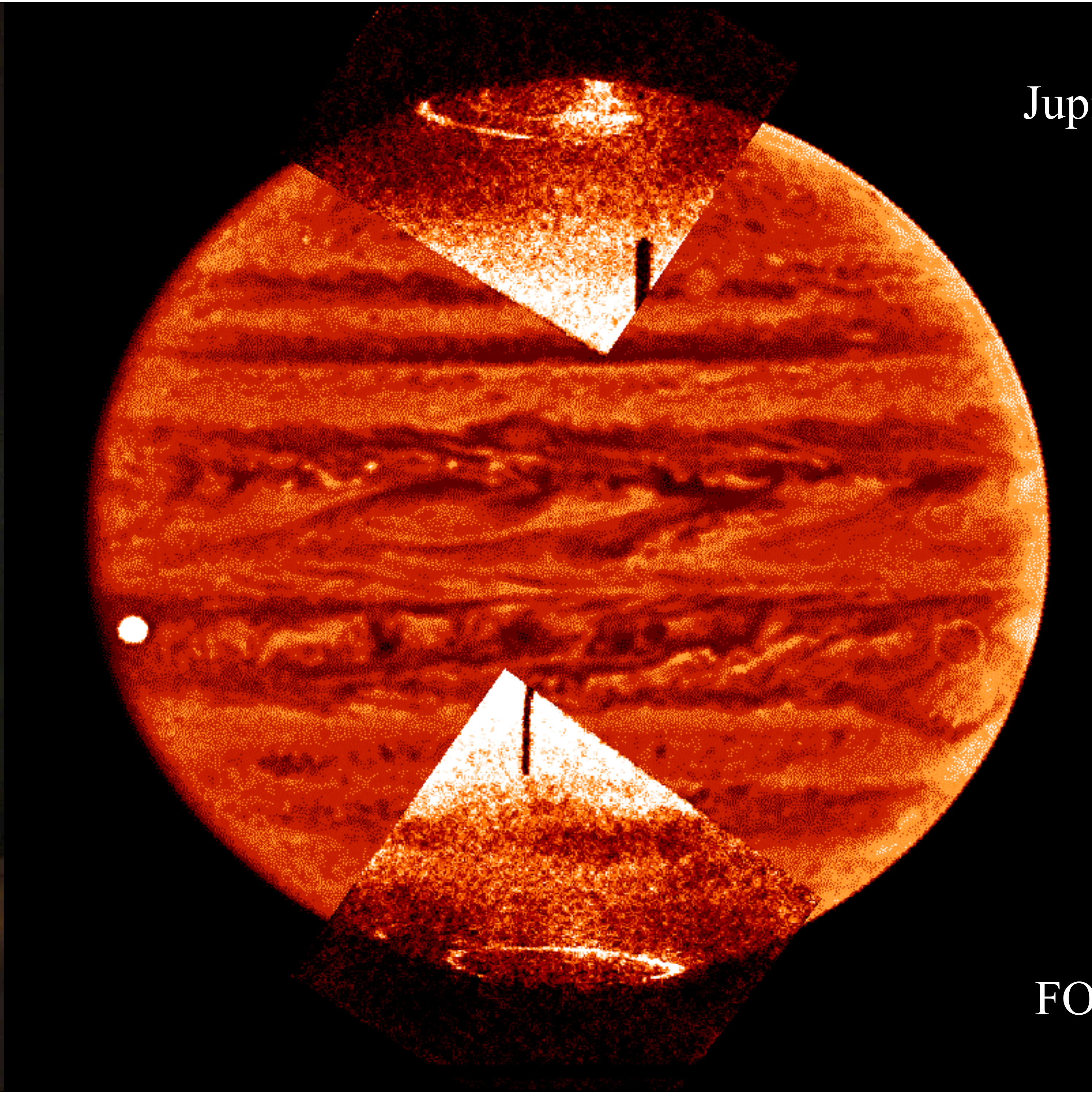


Present	-2.5 Gyr	-3.5 Gyr	reference
$5\ 10^{23}$	$1.4\ 10^{26}$	$1.8\ 10^{27}$	Leblanc and Johnson (2002)
$3\ 10^{24}$	$7\ 10^{26}$	$7\ 10^{27}$	Kass and Yung (1995, 1996)
$7\ 10^{23}$	$1.6\ 10^{26}$	$4.2\ 10^{27}$	Luhmann et al. (1992)

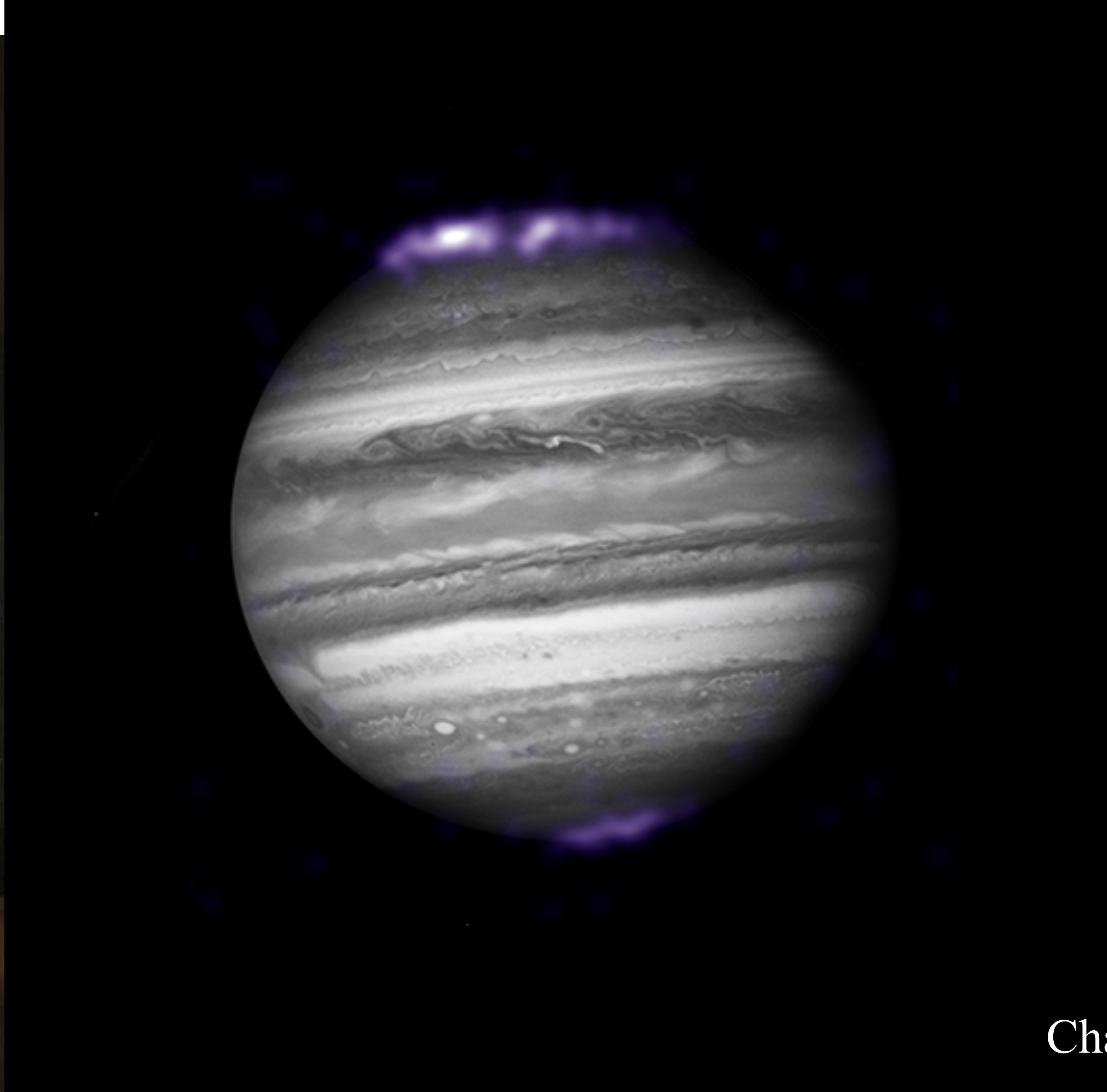
Values given in O atoms s^{-1}

Magnetized planets : the gazeous planets…

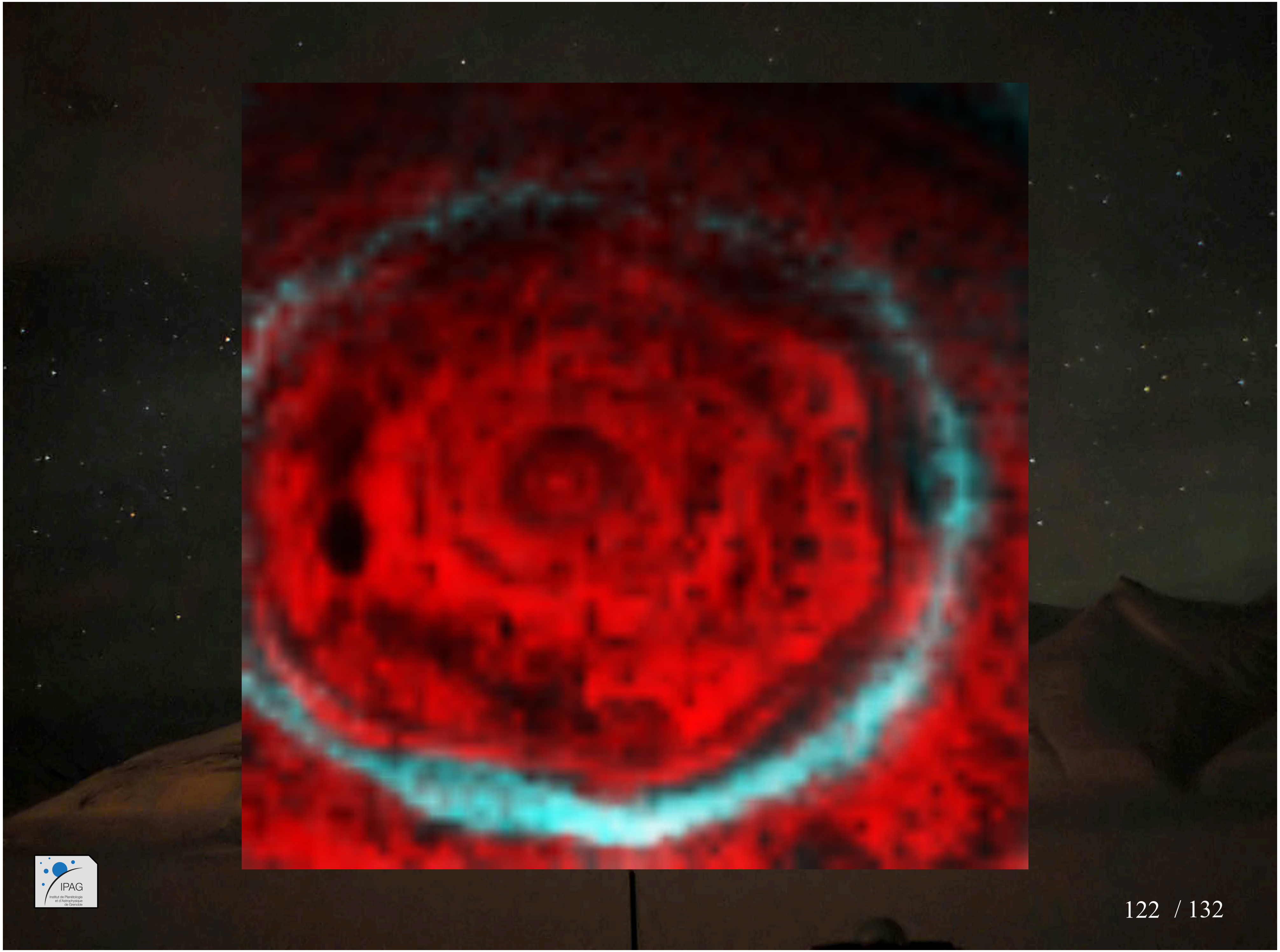
Jupiter



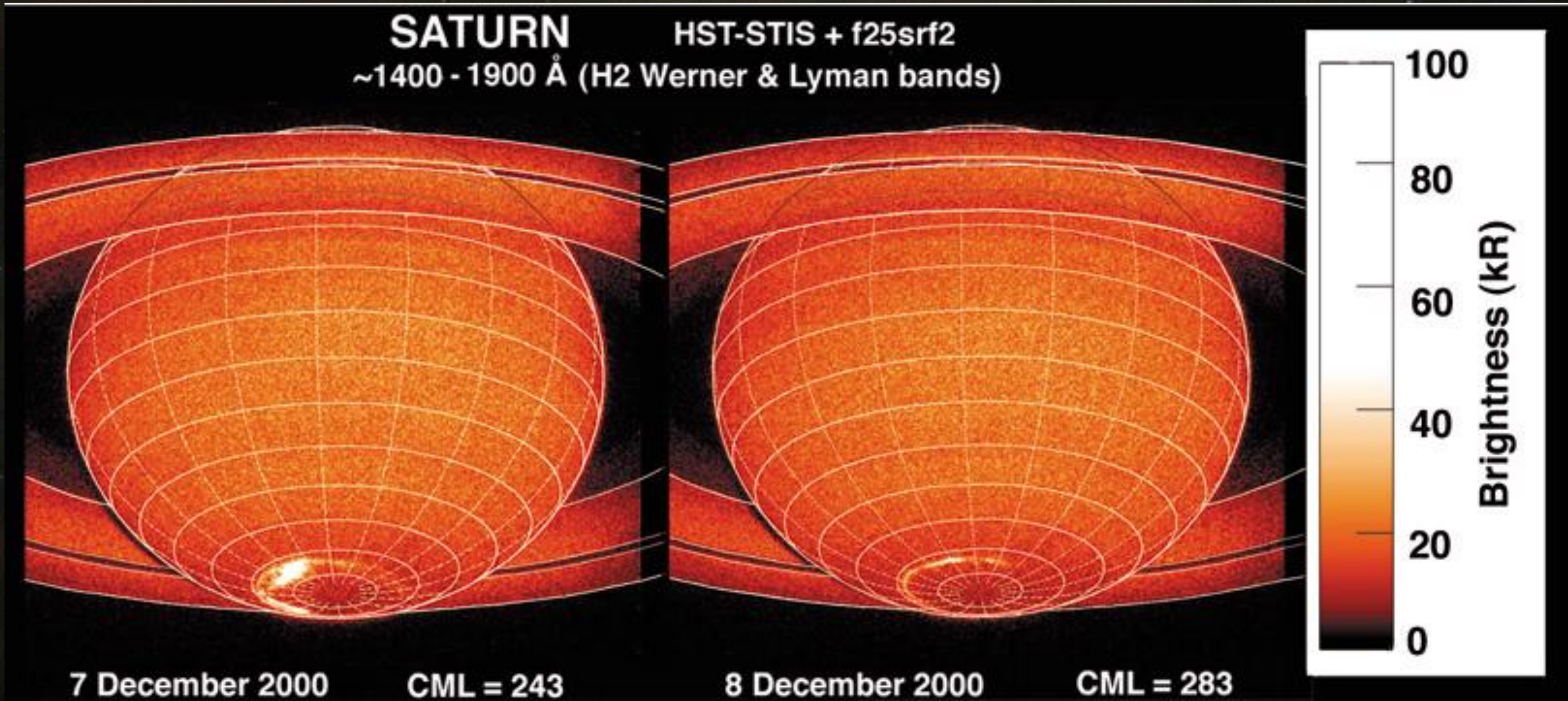
FOC

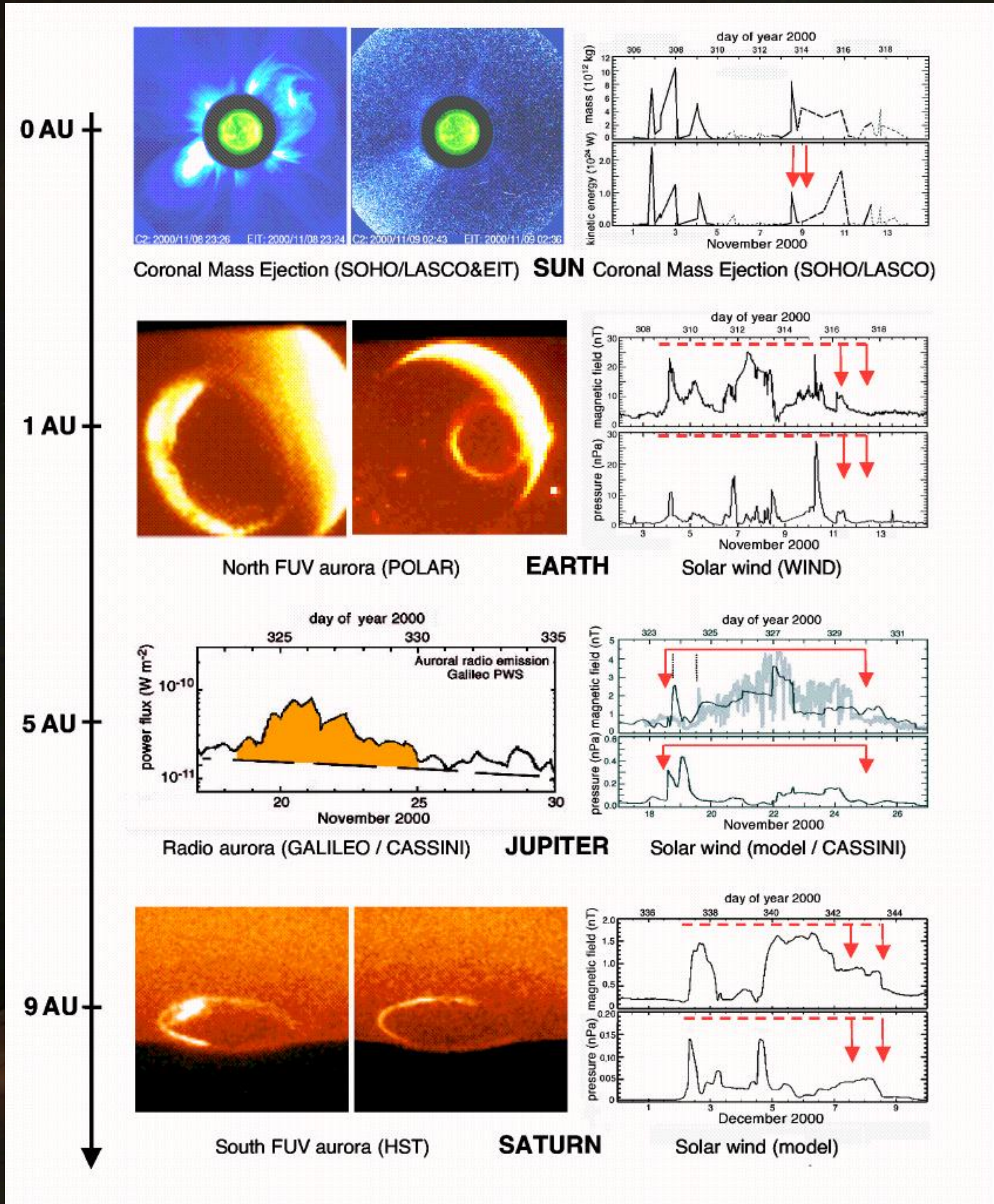


Chandra



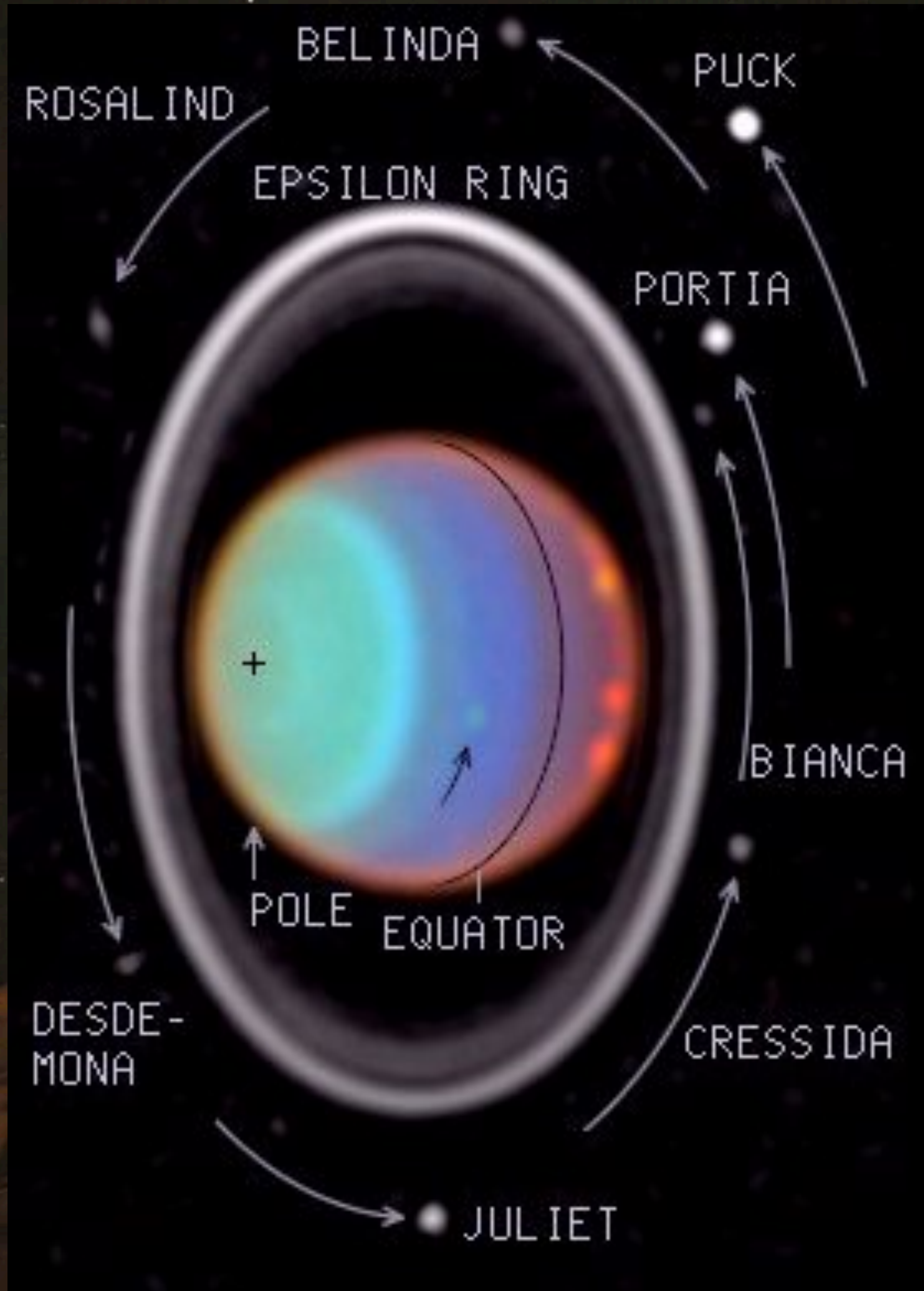
Saturn

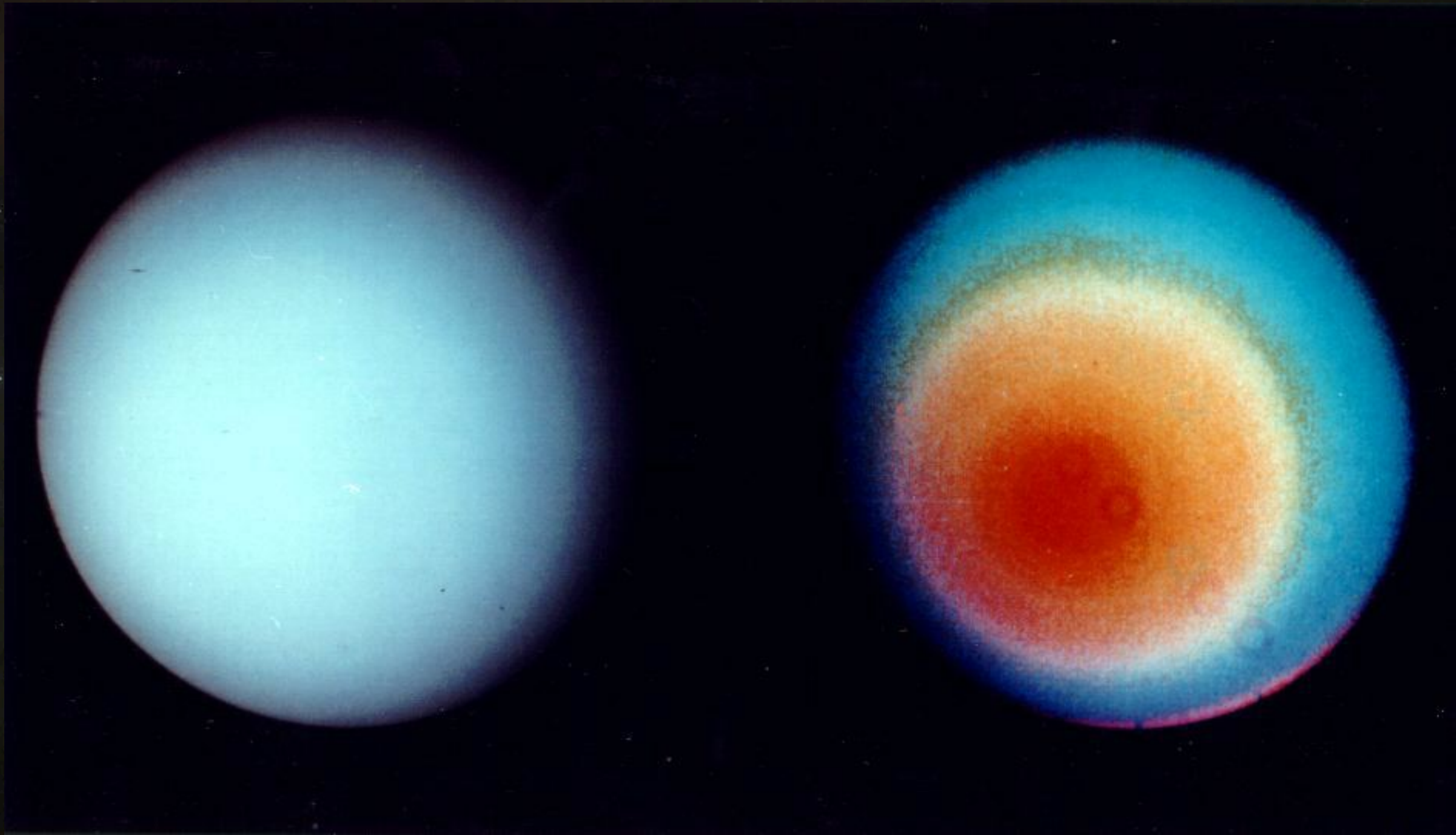

SATURN
HST-STIS + f25srf2
~1400 - 1900 Å (H2 Werner & Lyman bands)
100
80
60
40
20
0
Brightness (kR)
7 December 2000
CML = 243
8 December 2000
CML = 283



Prangé et al., nature, 2001

Uranus


BELINDA
PUCK
ROSALIND
EPSILON RING
PORTIA
BIANCA
POLE
EQUATOR
DESDE-
MONA
CRESSIDA
JULIET



Jupiter

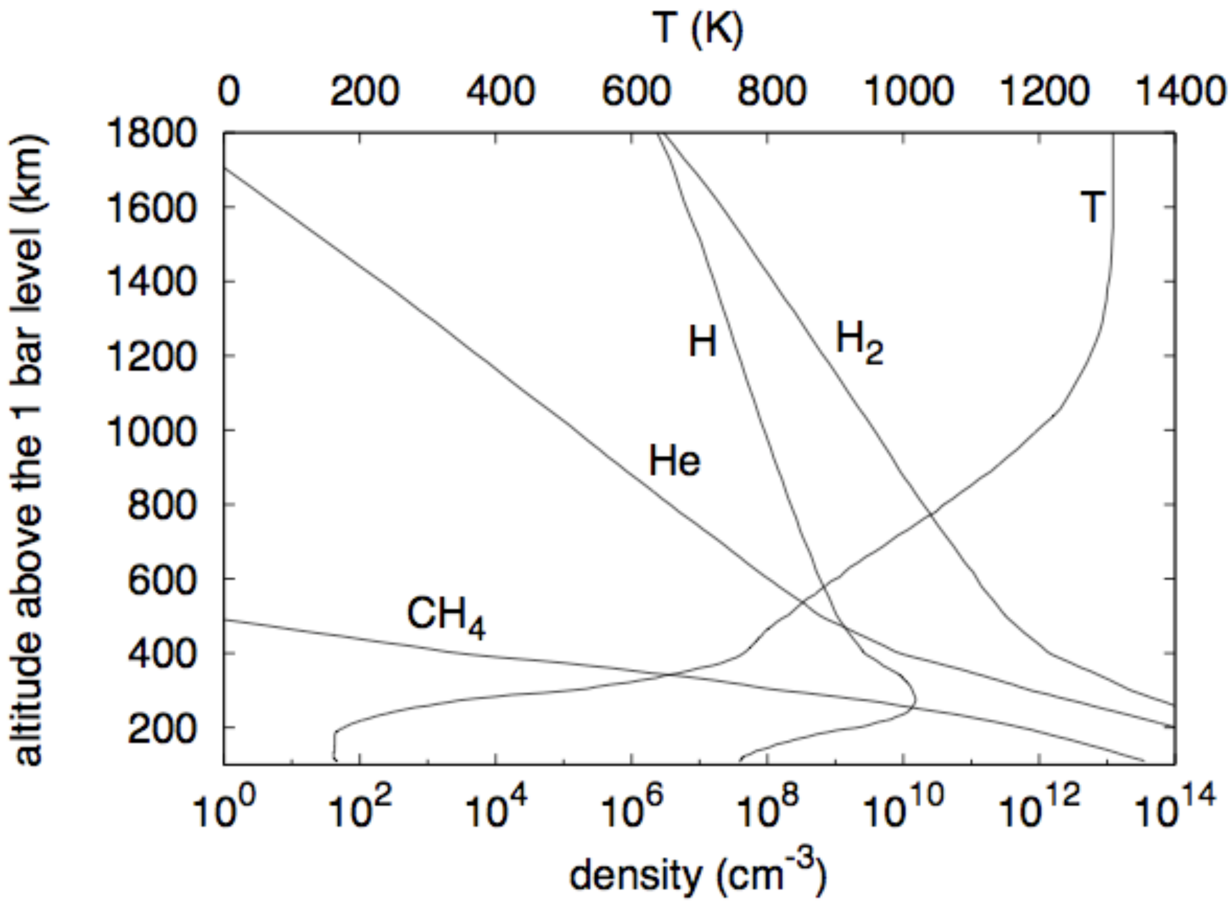


Fig. 1: Composition and temperature profiles in the atmosphere of a discrete aurora, after Grodent & Gérard (2001).

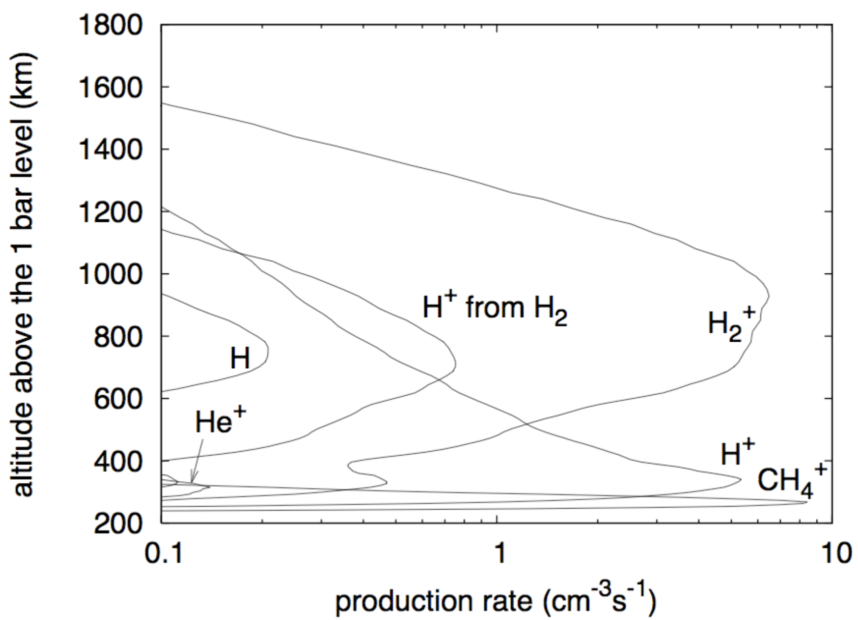


Fig. 2: Photoionization rates for a solar zenith angle of 70° and F10.7= 100.

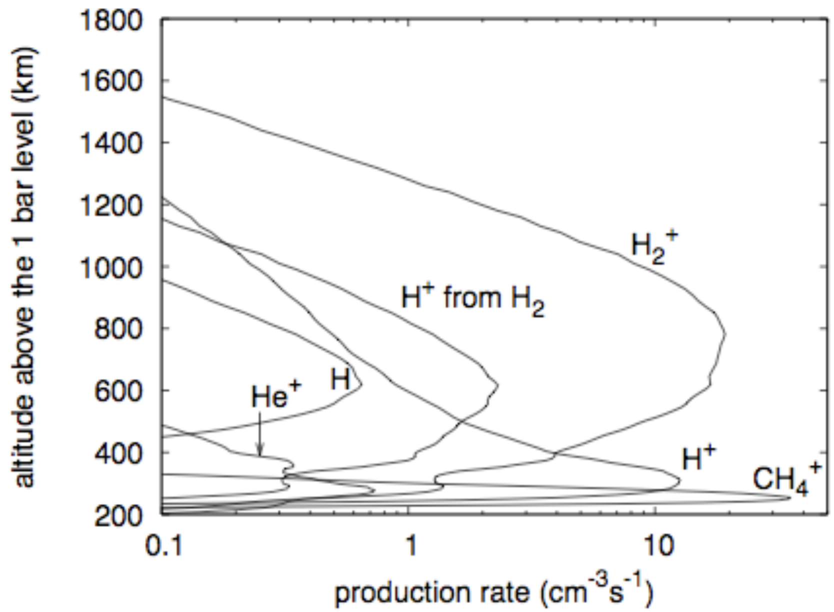


Fig. 4: Photoionization rates for a solar zenith angle of 0° and F10.7=100.

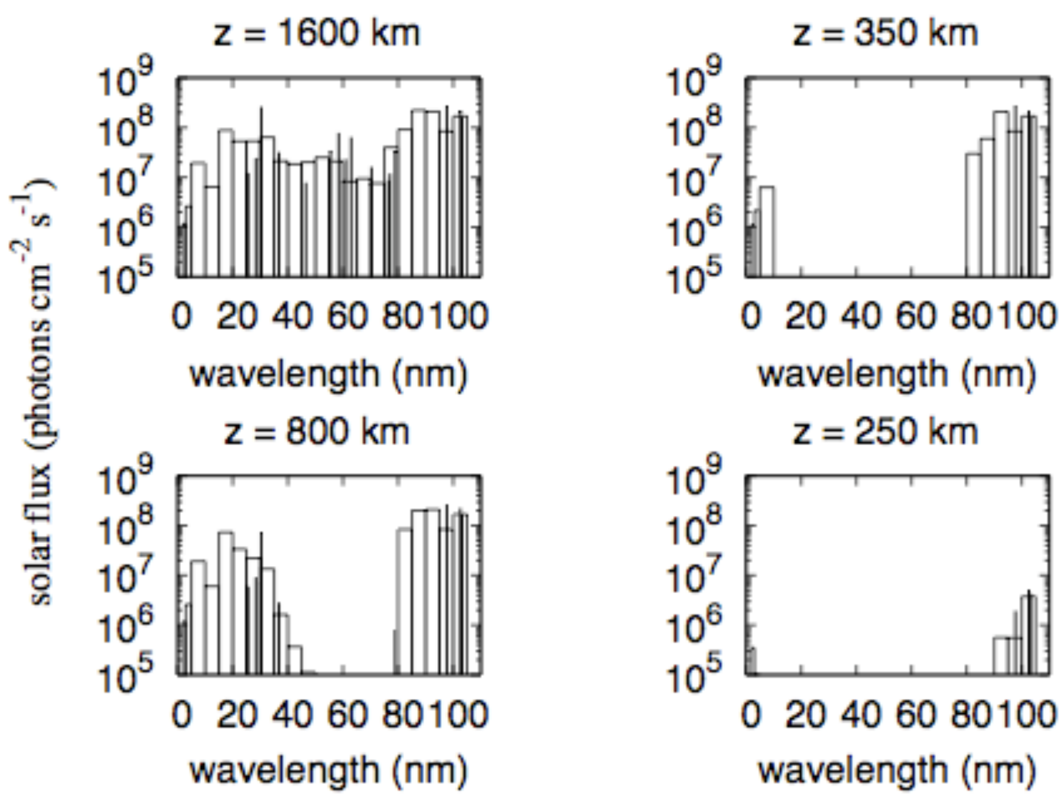


Fig. 3: Penetration of the solar UV flux in the atmosphere of Jupiter for a solar activity of F10.7=100 and a solar zenith angle of 70° .

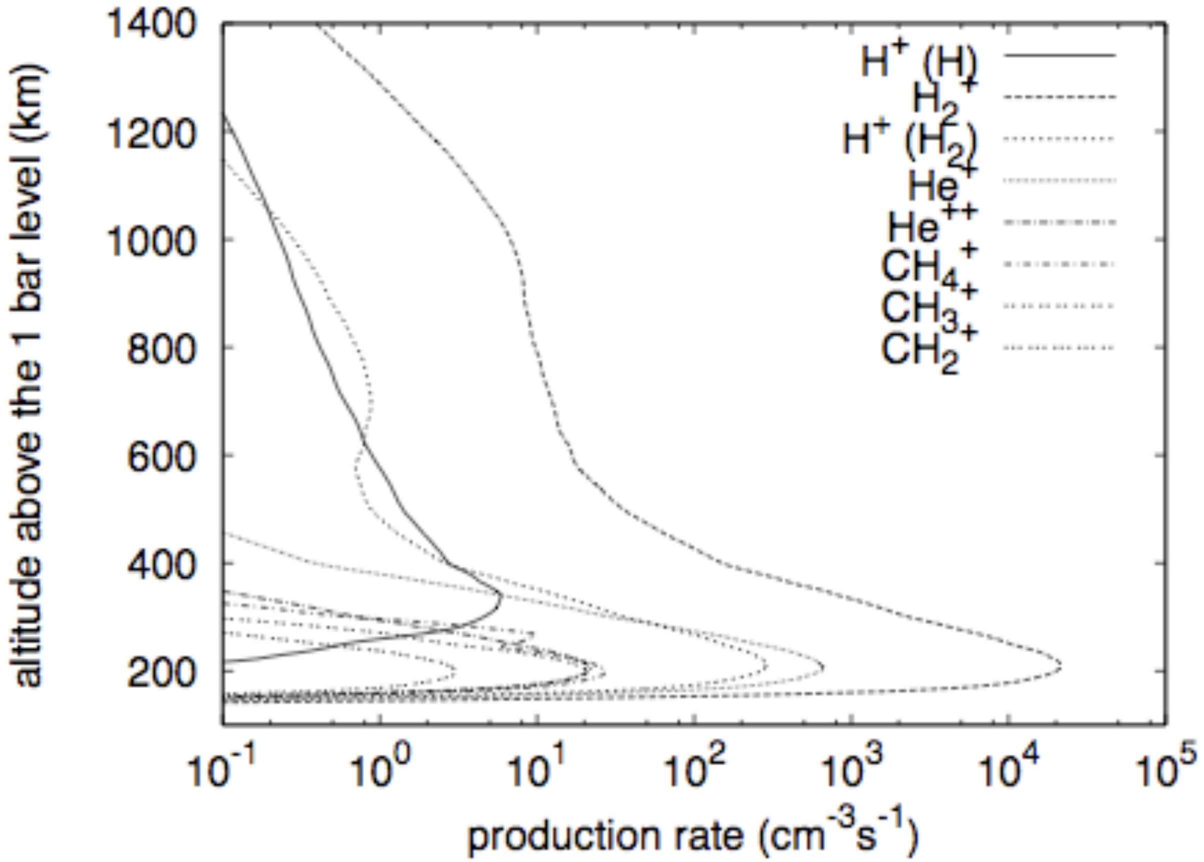


Fig. 5: Ionization rates for maxwellian precipitations of 50 keV

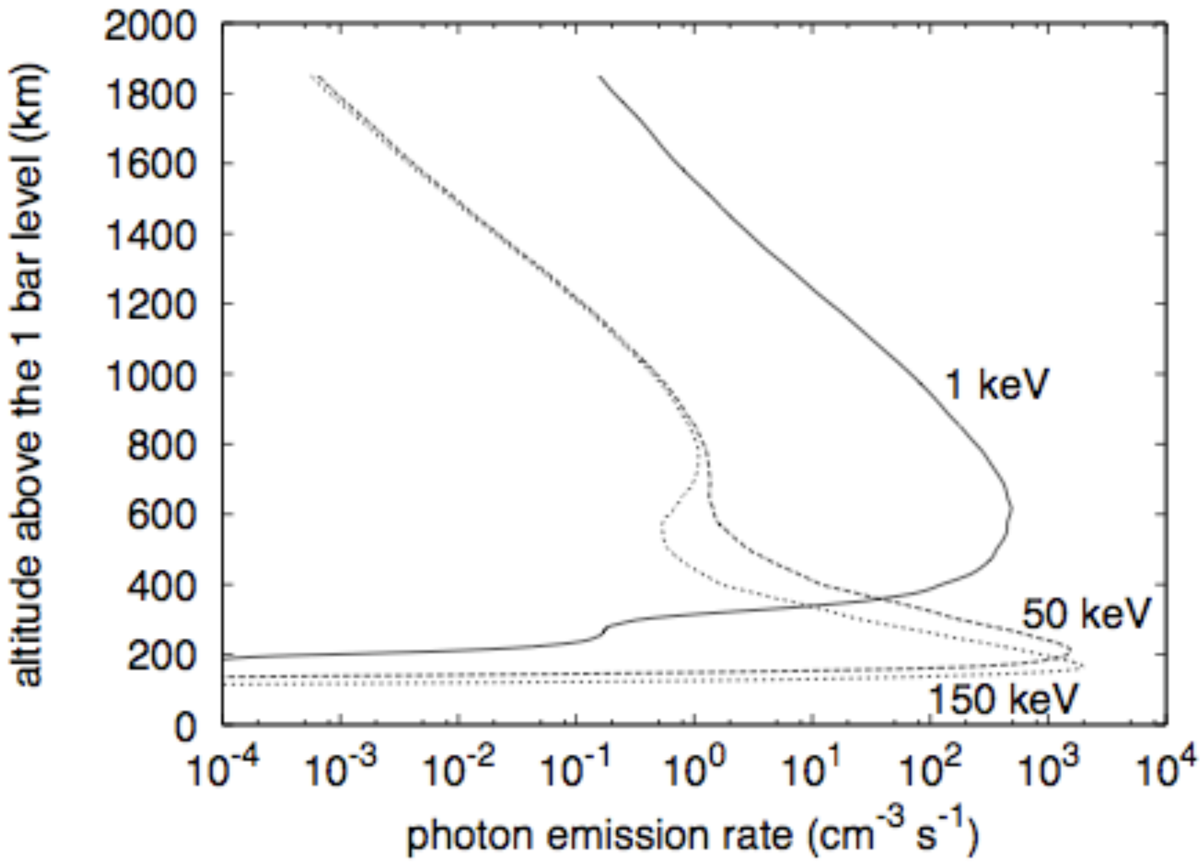


Fig. 9: Emission rate of Lyman Alpha photons, a low solar illuminance (F10.7 = 100, solar zenith angle of 70 °) and maxwellian precipitations of 1 keV, 50 keV and 150 keV

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IPAG