Ionosphères planétaires (introduction)

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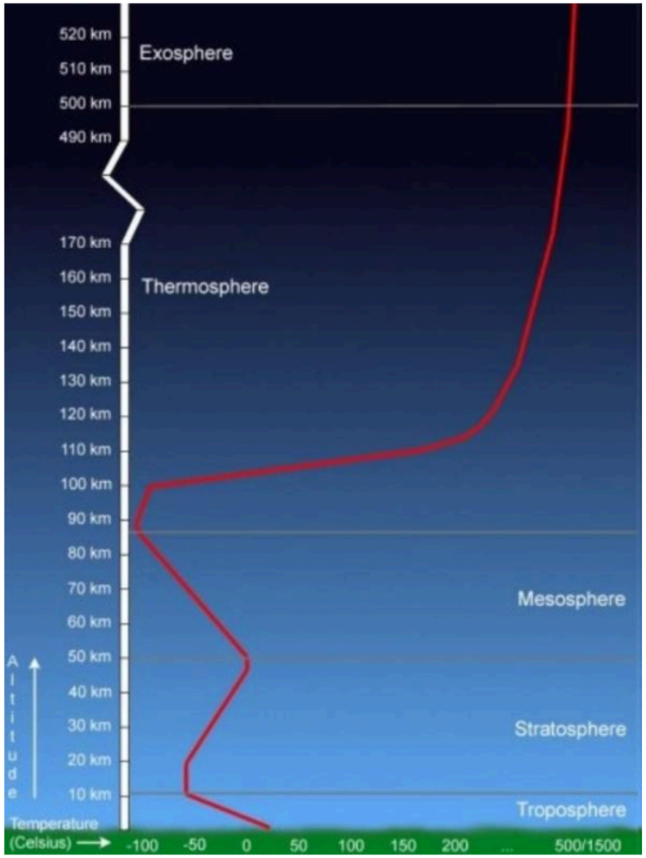
Structure of Earth's atmosphere



Temperature gradients determined by IR radiation from Earth (low altitude Troposhere)

And from photochemical reactions at higher altitudes (Ozone-oxygene cycle in the Stratosphere, Photoionisation in the thermosphere) that produce an inversion of the temperature gradient.

Turbopause & homopause around the mesopause (90 km)

Higher atmospheric layer : the exopshere

What about the density ?

Assumption : hydrostatic equilibrium (neglection of v_z component of the atmospheric fluid velocity field)

$$-\frac{d}{dr}p - nm\frac{GM}{r^2} = 0 \quad \Rightarrow \quad (nkT)(r) = (nkT)(r = R_0)\exp\left(-\int_{R_0}^{r}\frac{m}{kT(r)}\frac{GM}{r^2}dr\right)$$

(Evaporation if T(r) decreases slower than 1/r !!!)

For small arguments (r = R0 + z and z<<R0), one gets the usual exponential cutoff for the pressure with scale height H =kT / mg

We obtain the usual (Boltzmann) exponential stratification of the density of the isothermal atmosphere

$$\Rightarrow \quad n(z) = n_0 \exp - \frac{mgz}{kT}$$

Note : Cutoff scale depends on the chemical specie through the mass : chemical stratification if no mixing process (heterosphere)

What about collisions ?

Now that we've got a density profile, we can have a look at the collisionality of the gas.

Mean free path of a molecule/atom at altitude z : $\lambda(z) = 1/(\sigma n(z))$

Physical processes in d/dz are controlled by collisions when the mean free path is much smaller than the variations scales of the parameters along z. That is, when the Knudsen number is much smaller than 1.

$$K_n = \lambda(z)/H(z) \ll 1$$

In the opposite case, the gas is non-collisional (neutral particles trajectory are to a good approximation « ballistic » trajectories of free particles in the gravitational field force)

Exobase defined at Kn = 1.

Q : What is the altitude of the exobase on Earth ?

The Earth's geocorona seen from the Moon

121 nm

A conductive layer in the atmosphere ?

1901 : Marconi « crosses the Atlantic » with a radio transmission at 300 kHz

1902 : Kennelly & Heaviside : reflection on an ionized atmospheric layer ?

1920-25 : Development of long distance radio communication with short waves (<30 MHz)

1925 : First experimental proof of an ionized layer and its height by phase comparison of 2 signals (ground and reflected)

1931 : Chapman presents its theory for the formation of an « ionosphere » from solar UV radiation effect.

Spatial distribution of the ionospheric plasma

Continuity equation (conservation of the number of particles) :

$$\frac{\partial}{\partial t} n_e + \nabla n_e v_e = Q_e - R_e$$

The steady state is given by equilibrium between particles mobility and local creation/loss of charged particles

$$\nabla n_e v_e = Q_e - R_e$$

Transport phenomena

Local (chemical) phenomena

Chapman's ionization layer

THE ABSORPTION AND DISSOCIATIVE OR IONIZING EFFECT OF MONOCHROMATIC RADIATION IN AN ATMOSPHERE ON A ROTATING EARTH

By S. CHAPMAN, M.A., D.Sc., F.R.S.

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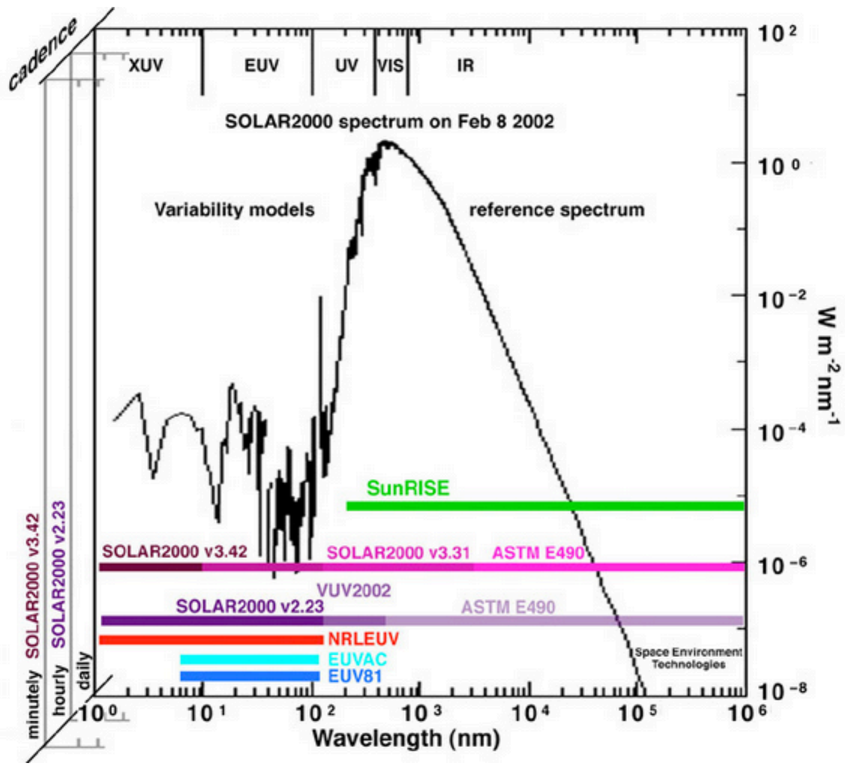
ABSTRACT. The absorption of monochromatic radiation from the sun in an atmosphere of which the density varies exponentially with height is considered; the energy of the radiation, or a definite fraction of it, is supposed to dissociate or ionize the air, and the dissociation products are supposed to recombine with one another only, and not to diffuse away from the element in which they were formed. The resulting distribution of density of the dissociation products is determined, a constant recombination coefficient being assumed, while account is taken of the variation in rate of dissociation due to the earth's rotation. The results are illustrated by numerous diagrams, showing the density of the dissociation-products as a function of height, time, latitude and season.

What happens when solar's UV flux irradiates the exponentially stratified atmosphere ?

Solar photon flux



Ionisation energy order of magntiude?

Bohr's atom:

$$H = \frac{n^2\hbar^2}{2m_e r^2} - \frac{Ze^2}{r}$$

dH = 0 => Bohr's radius and energy (at fundamental level n=1) :

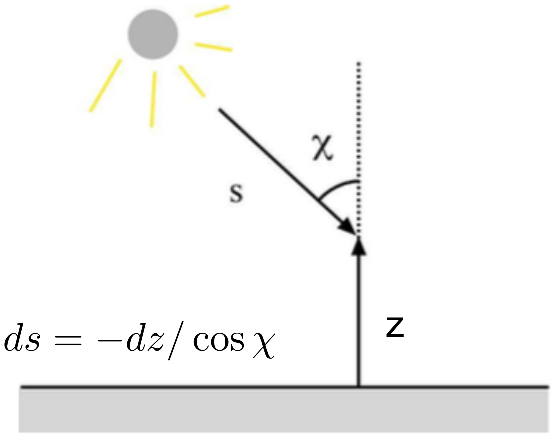
$$a_0 = \frac{\hbar^2}{Zm_e e^2} \qquad W_0 = Z^2\frac{m_e e^4}{2\hbar^2} = \frac{Z^2}{2}\alpha^2 m_e c^2$$

With the well-known result : $W_0 \simeq 13.6 \times Z^2 \text{ eV}$

$$\lambda_0 = hc/W_0 \simeq 91/Z^2 \text{ nm}$$

UV radiation is ionizing

UV absorption along a ray of sunlight



$ds = -dz/\cos\chi$

Number of photons absorbed along ds :

$$N(s+ds) = N(s) \times (1 - ds/\lambda_{ph}(z))$$

So the equation in terms of I(z) reads :

$$\frac{dI}{dz} = \frac{I}{\lambda_{ph}(z)\cos\chi}$$

So the intensity (W/m2) altitude profile of the UV flux can be expressed in terms of the neutral number density

$$I(z) = I(\infty)\exp\left(-\int_z^{\infty} \sigma n(z)\frac{dz}{\cos\chi}\right)$$

Where we introduced the photoionisation cross section σ, that depends only on the chemical properties of the specie considered – we will see later how to evaluate the order of magnitude of σ.

Photoelectrons production rate

Assumptions : the number of ions (or equivalently of e-) produced by unit time at altitude z is proportional to dI/ds, with a proportionality constant C (around 1/35 eV^{-1} in the air).

Neutral density always much larger than ion density (so one can use the exponential profile for n(z))

$$Q_e = -C\frac{dI}{ds} = C\sigma n(z)I(z)$$

What is the maximum production rate and at which altitude does it occur ?

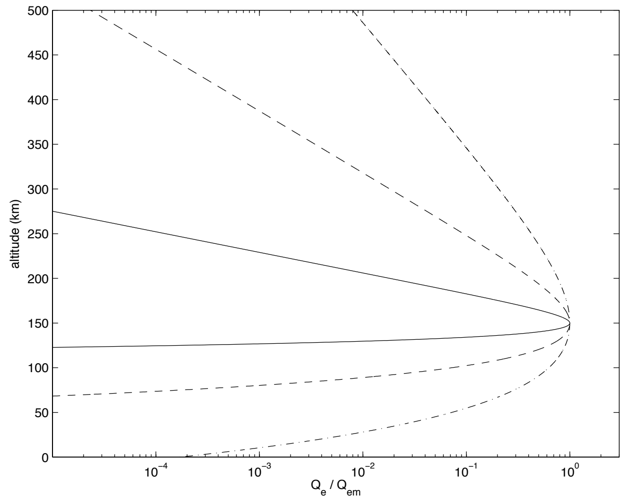
$$dQ_e = 0 \Rightarrow z_m = H \ln \frac{\sigma H n_0}{\cos\chi}$$ and $$Q_{em} = \frac{CI(\infty)\cos\chi}{\exp(1)H}$$

The production rate Qe is expressed in terms of zm and Qem

$$Q_e = Q_{em} \exp\left[1 - y - \exp(-y)\right]$$

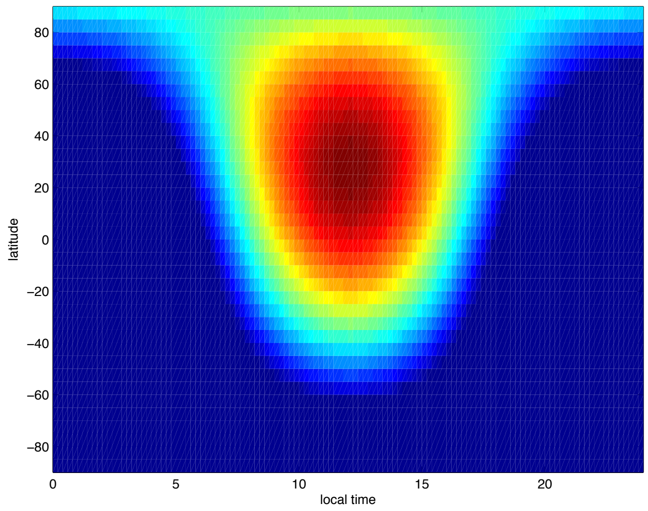
where $y = (z - z_m)/H$

Chapman's production function



$$Q_e = Q_{em} \exp\left[1 - y - \exp(-y)\right]$$

For zm = 150 km
H = 10, 30, 60 km.



Cosinus of zenith angle in (φ,θ) plane
For solar declination angle δ = 23.44°

$$\cos\chi = \sin\delta \cos\theta_{lat} + \cos\delta \sin\theta_{lat} \sin H.$$

Radiative Recombination

ionisation

$$X + h\nu \rightleftarrows X^+ + e^-$$

recombination

Order of magnitude of the cross sections :

1)Be close « enough » from the atom/molecule : $\delta x \sim \hbar / p$

2)Probability to emit/absorb a photon while close enough : $P \sim \alpha^3$

Hence the cross sections for photoionisation and radiative recombination :

$$\sigma_{ph} \simeq 10 \left(\frac{\hbar c}{W_0} \right)^2 \alpha^3$$

= 2.6 x 10^{-22} m^2
(for W_0 = 13,6eV)

$$\sigma_{rec} \simeq 10 \left(\frac{\hbar}{m_e v_e} \right)^2 \alpha^3$$

= 3.4 x 10^{-24} m^2
(for T = 1000 K)

Dissociative Recombination

$$A + B \longleftarrow AB^+ + e^-$$

Recombination
(non-radiative)

Order of magnitude of the cross section :

1)Be close « enough » from the atom/molecule : $\delta x \sim \hbar/p$

$$\Rightarrow \quad \sigma_{rec} \simeq \pi \left(\frac{\hbar}{m_e v_e} \right)^2$$

= 2.7 x 10^{-18} m^2
(for T = 1000 K)

Much more efficient recombination process ! (but needs presence of molecular ions)

Dominant processes in Earth's atmosphere :

$$O_2^+ + e \rightarrow O + O$$
$$N_2^+ + e \rightarrow N + N$$

Airglow

Radiative+dissociative recombination causes (a part of) the phenomenon of airglow (very faint, but limiting for ground based optical astronomy)

Ionospheric electron density

Electron number conservation : $$\frac{\partial}{\partial t}n_e + \nabla n_e v_e = Q_e - R_e$$

In steady state, and neglecting vertical motion, one simply has local equality of creation and recombination rates.

$$Q_e = R_e = \beta n_e n_i = \beta n_e^2$$

We expressed Qe previously (Chapman's production function). The recombination coeff. depends on the recombination cross-section as :

$$\beta = \sigma_{rec} v_e$$

So the electron density at an altitude z depends on Qe and the local temperature, through

$$n_e = \sqrt{Q_e/\beta}$$

Some numbers…

Table 7.1 *Some basic characteristics of the Moon and the planets (rounded up to a few per cent)*

	$d/d_\oplus$	$M/M_\oplus$	$R/R_\oplus$	$\Omega/\Omega_\oplus$	$\mu/\mu_\oplus$	Atmosphere	$H/H_\oplus$
Moon	1.00	0.0122	0.27	0.036	~ 0	Na	20
Mercury	0.39	0.055	0.38	0.017	$3-6\times 10^{-4}$	Na	8
Venus	0.72	0.81	0.95	0.0041	$< 10^{-5}$	CO_2	1.9
Earth	1.0	1.0	1.0	1.0	1.0	N_2	1.0
Mars	1.5	0.107	0.53	1	$< 10^{-6}$	CO_2	1.3
Jupiter	5.2	318.	11.2	2.4	2.0×10^{4}	H_2	2.9
Saturn	9.5	95	9.4	2.3	5.8×10^{2}	H_2	5.8
Uranus	19	14.5	4.0	1.4	48	H_2	3.1
Neptune	30	17.1	3.9	1.3	28	H_2	2.2
Pluto	39	0.0022	0.18	0.16		N_2	5

Notes: The mean heliocentric distance d, mass M, equatorial radius R, rotation rate Ω and magnetic moment $\mu \simeq (4\pi/\mu_0)\, B_0 R^3$ A m^2 (B_0 is the planet's magnetic field amplitude at equator) are normalised to the Earth's values, respectively equal to $d_\oplus \simeq 1.5\times 10^{11}$ m (1 AU), $M_\oplus \simeq 6.\times 10^{24}$ kg, $R_\oplus \simeq 6.4\times 10^{6}$ m, $\Omega_\oplus \simeq 7.3\times 10^{-5}$ rad s^{-1} and $\mu_\oplus \simeq (4\pi/\mu_0)\, 7.9\times 10^{15}$ A m^2. The last two columns indicate the main constituent of the atmosphere, and its approximate scale height $H \simeq k_B T/mg$ (with m the mass of the main constituent and $g = MG/R^2$), normalised to the Earth's value $H_\oplus \simeq 8\times 10^{3}$ m.

D'autres paramètres :

— Terre : $n_0 = 2\times 10^{25}\text{m}^{-3}$. T = 300 K.

— Venus : $n_0 = 10^{27}\text{m}^{-3}$. T = 700 K.

— Mars : $n_0 = 2\times 10^{23}\text{m}^{-3}$. T = 200 K.

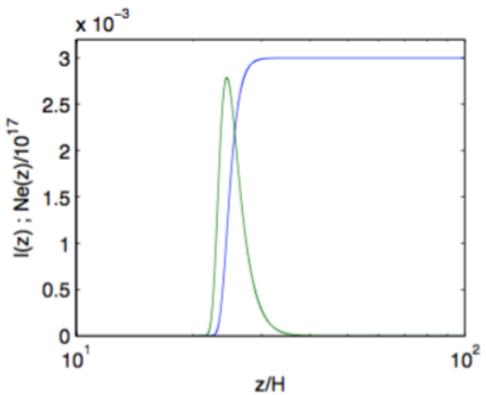


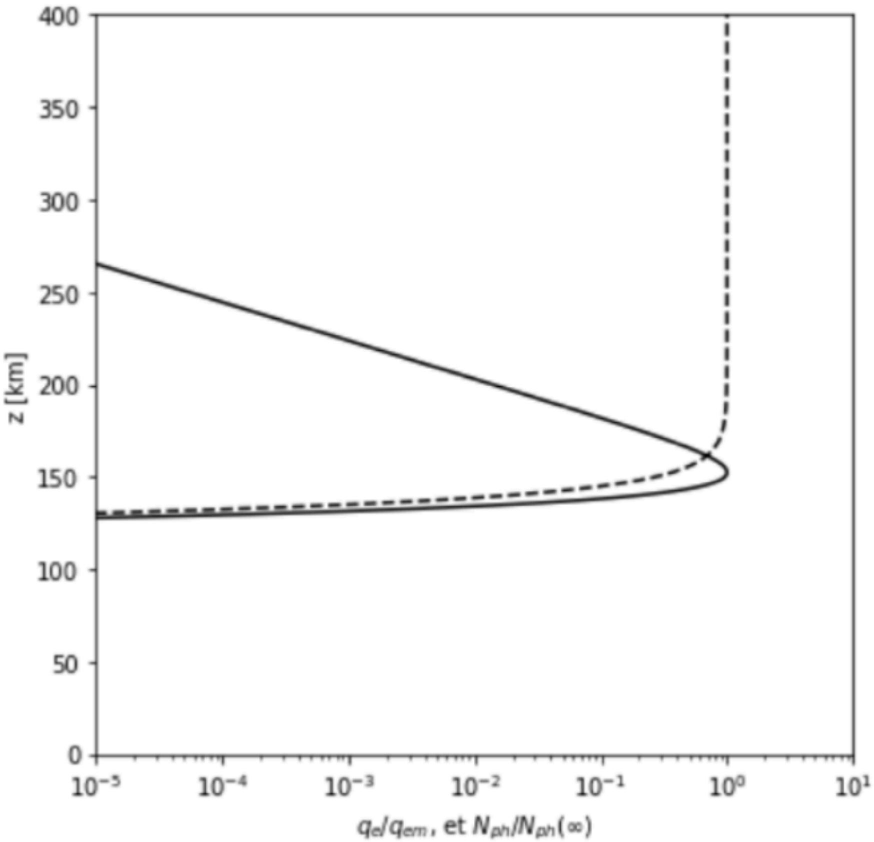
Figure : Flux UV et densité électronique pour des paramètres typiques de la Terre.

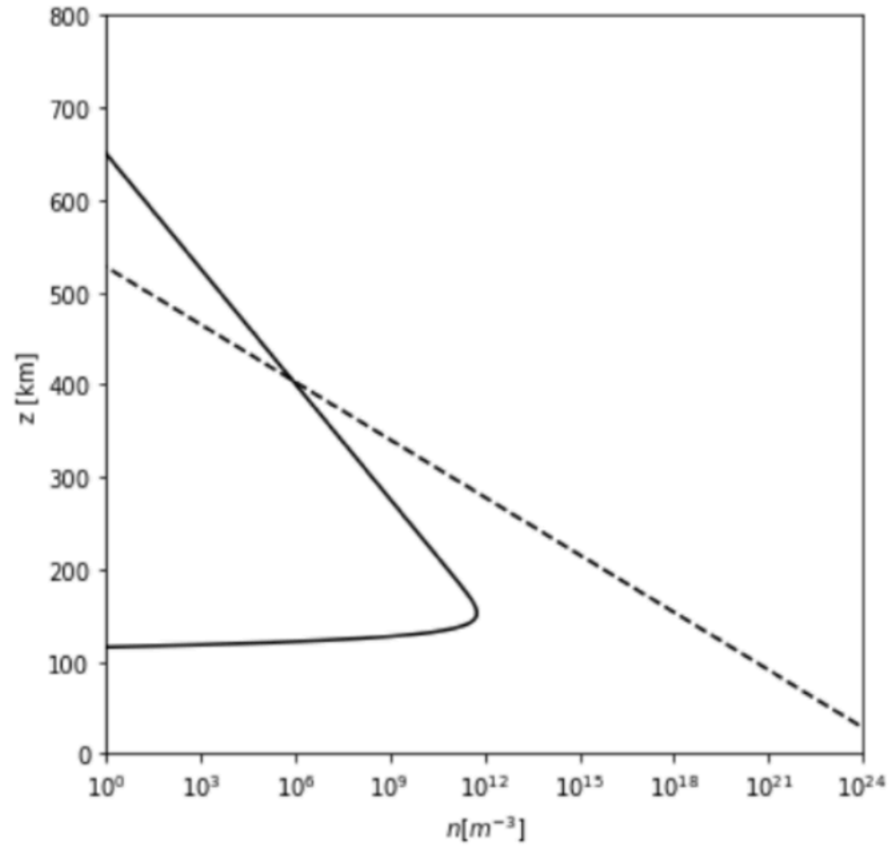
Solar ionizing UV flux at 1 AU :

$$I_0 \sim 3\times 10^{-3}\ \text{W.m}^{-2}.$$

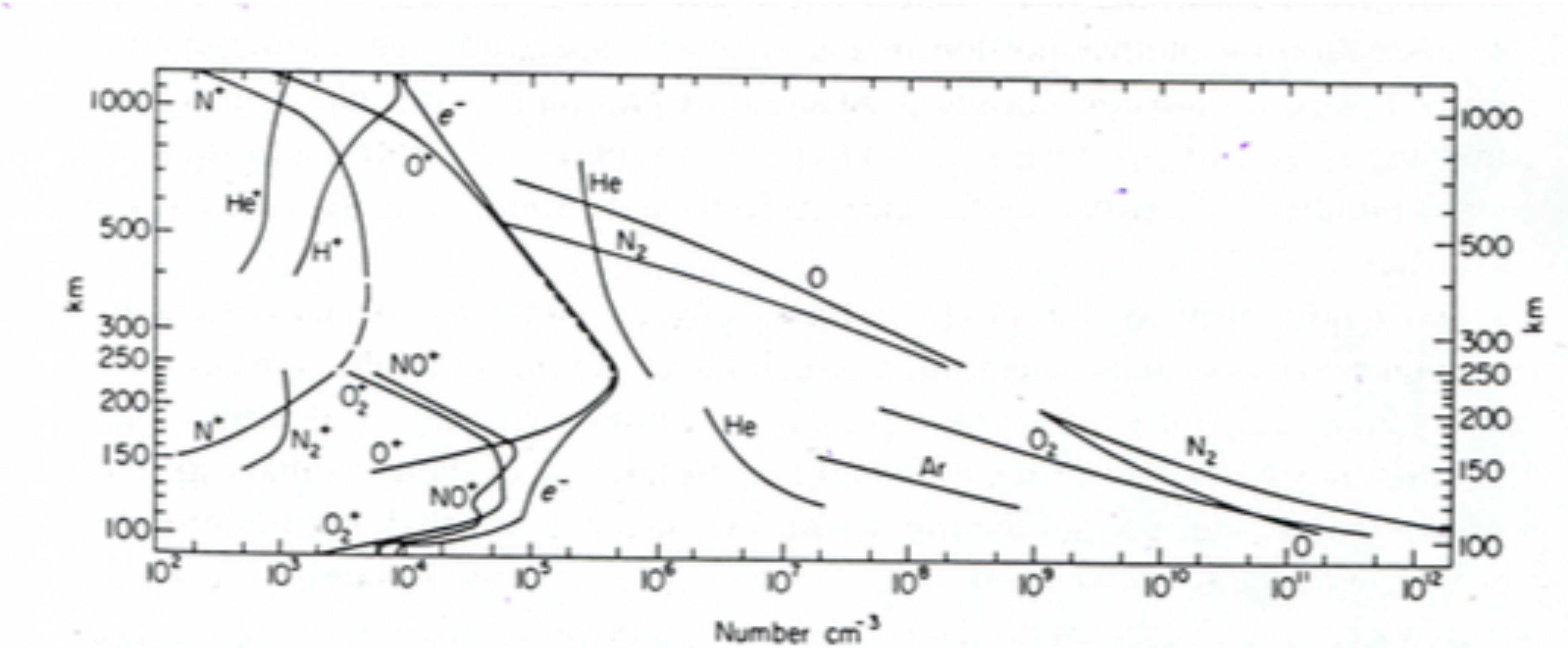
Q: estimate the relevant parameters for different planets in the solar system on the basis of Chapman's model.

Ionisation of an isohthermal N_2 atmosphere



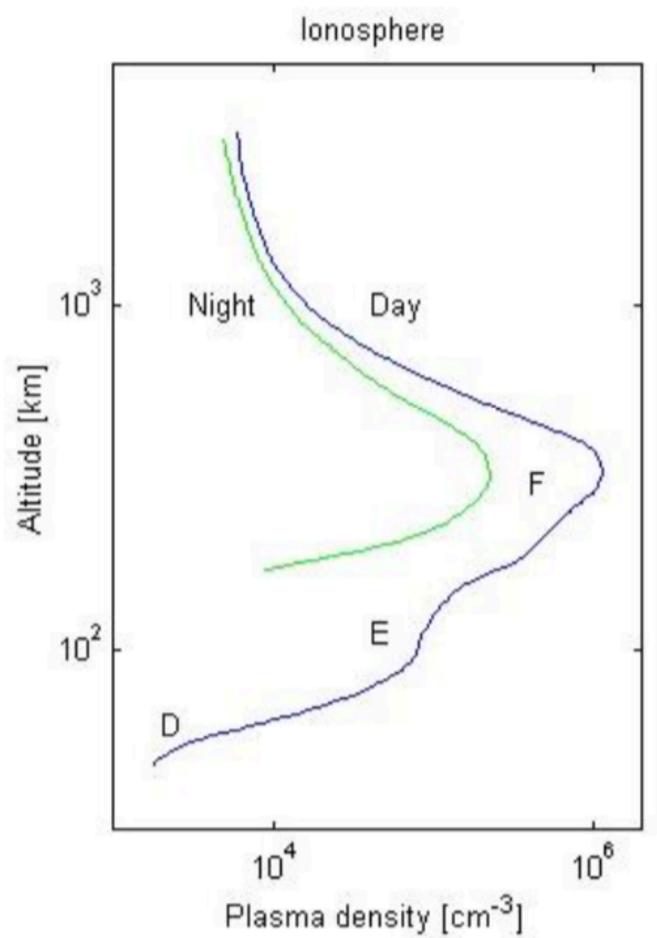


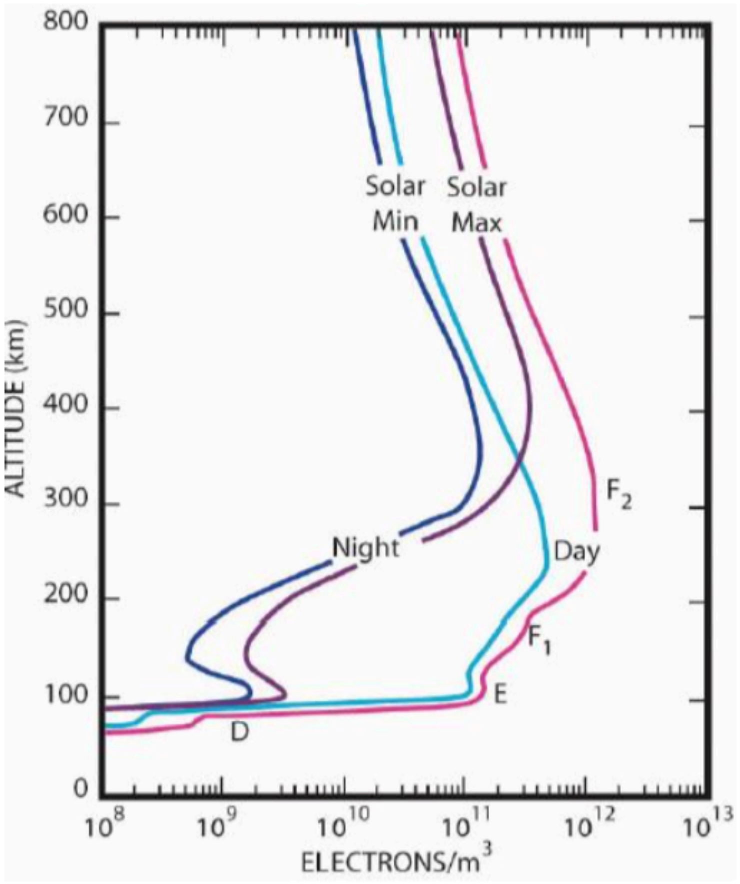
Some numbers…



Chemical stratification

Zoology of Earth's ionosphere





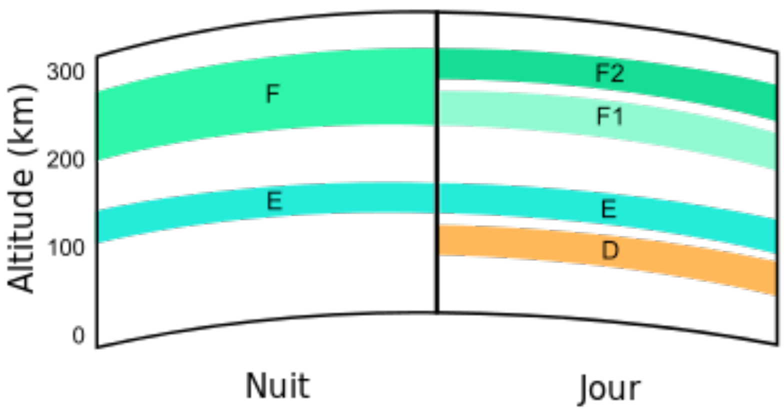
Layers of Earth's ionosphere

Below 90 km : D Layer

- Predominant composition : polyatomic ions (NO+, O2+, N2+)
- Weakly ionised, high electron-neutral collision rates (absorption of radio waves)
- High recombination rates
- Disapears mostly entierly at night

Between 90-150 km : E Layer

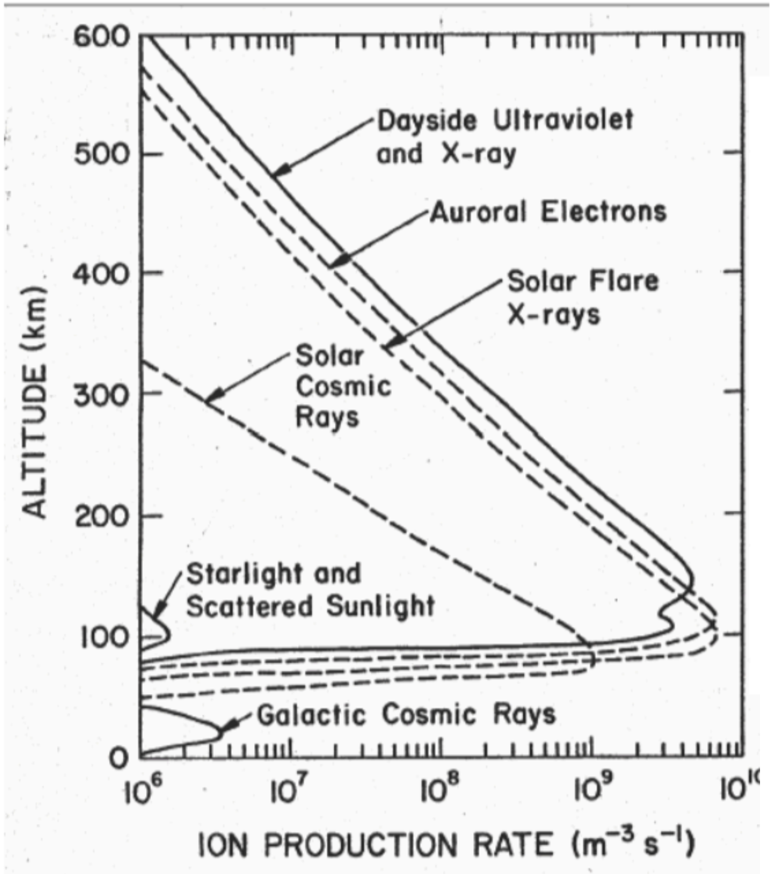
- Predominant composition : NO+ and O_2+
- Survives during night

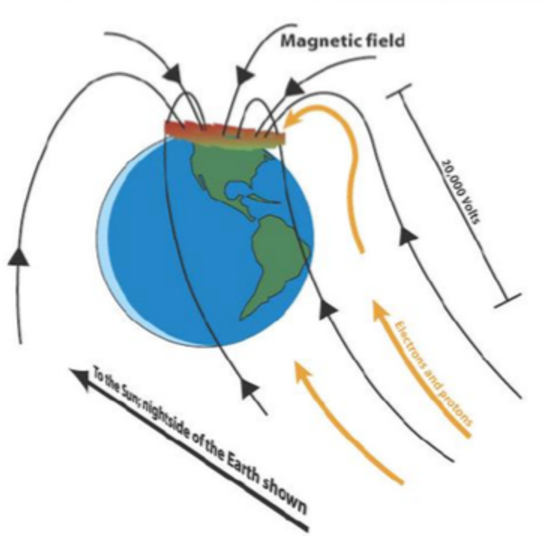


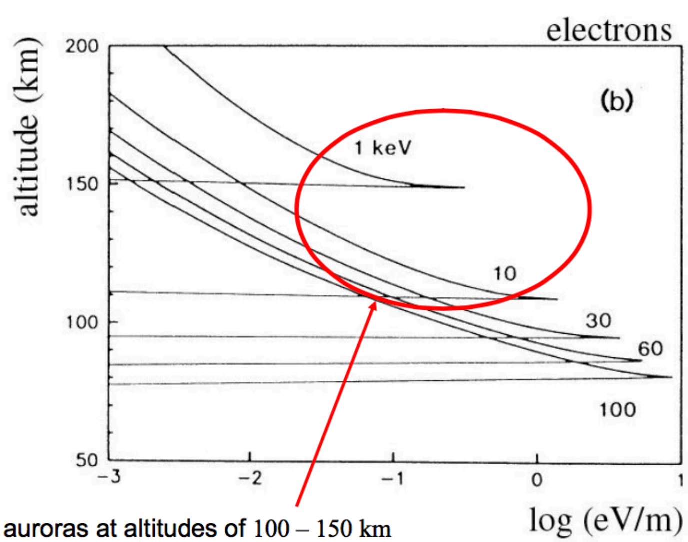
Above 150 km to 600 km : F Layer

- Atomic ions (O+ N+)
- High electron density (10^6 cm^{-3})
- Fluctuates a lot with solar activity

Other sources of ionisation





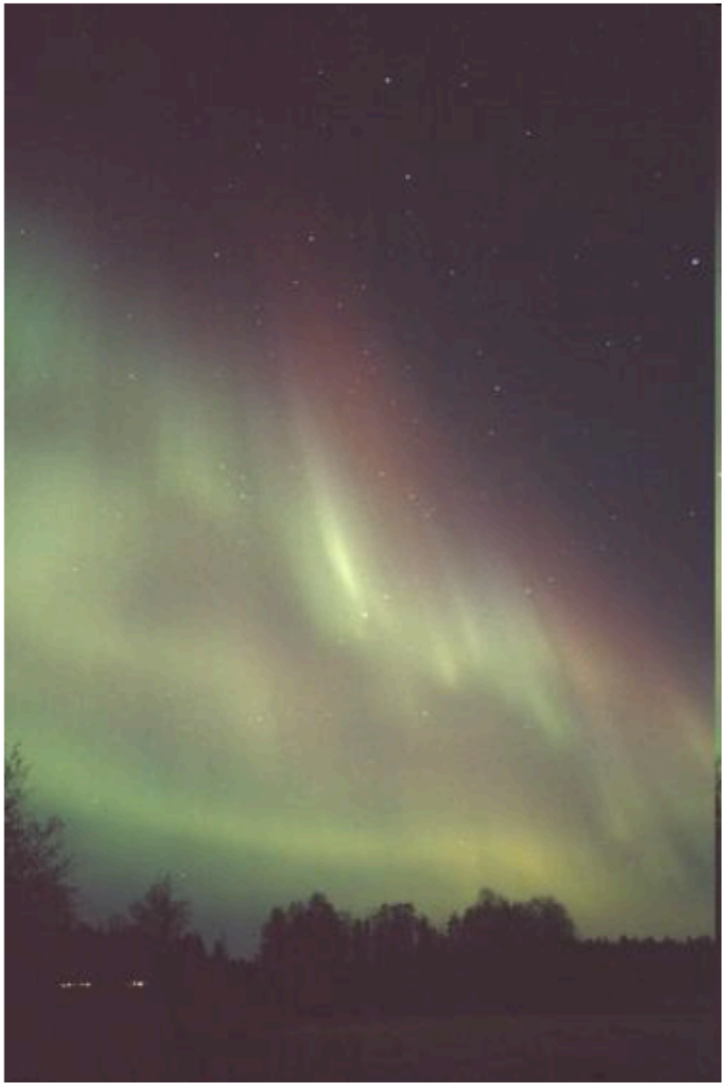


Auroral e-: very fluctuating but important source of ionization at the Earth's poles

Most auroras at altitudes of 100 – 150 km
→ created mainly by 1 – 10-keV electrons

Credit : F. Mottez

Auroras…

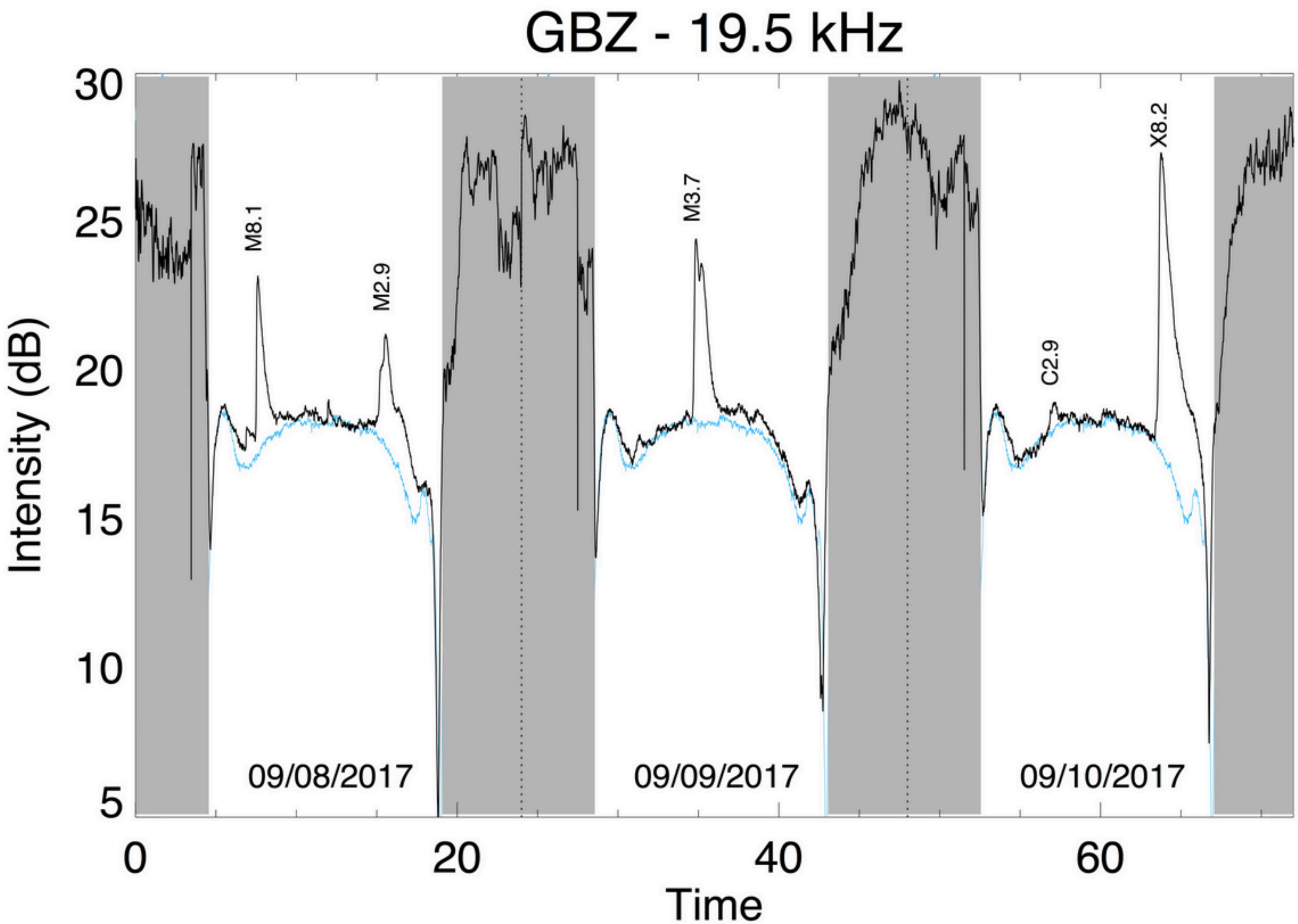


230 km
Red color at 630 nm
Electrons hitting atomic Oxygen

110 km
green color at 557.7 nm
Electrons hitting atomic Oxygen

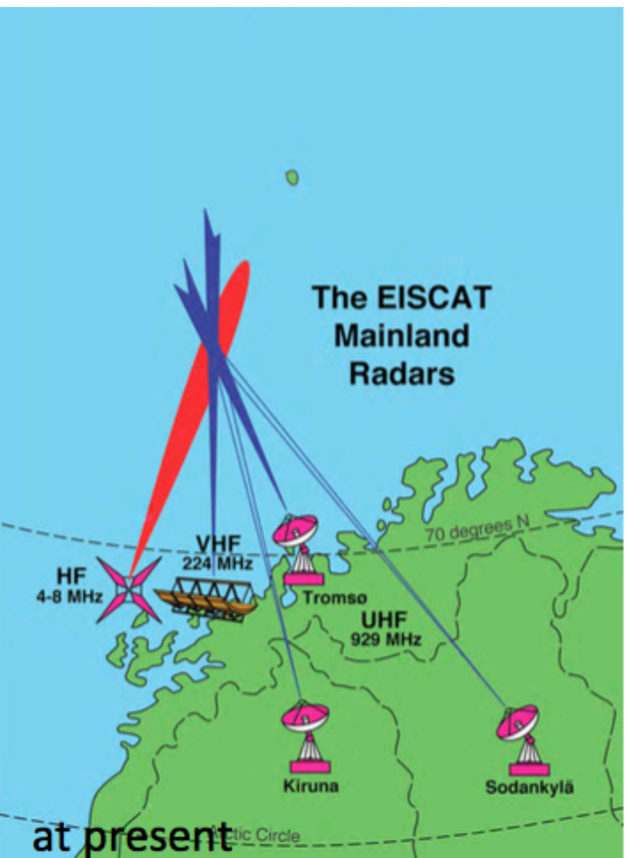
90 km
purple color at 427.8 nm
Electrons hitting Nitrogen molecules

Radio reflection on D/F layer



Credit : C. Briand et al.

Kiruna receiver



EISCAT Incoherent Scatter Radars

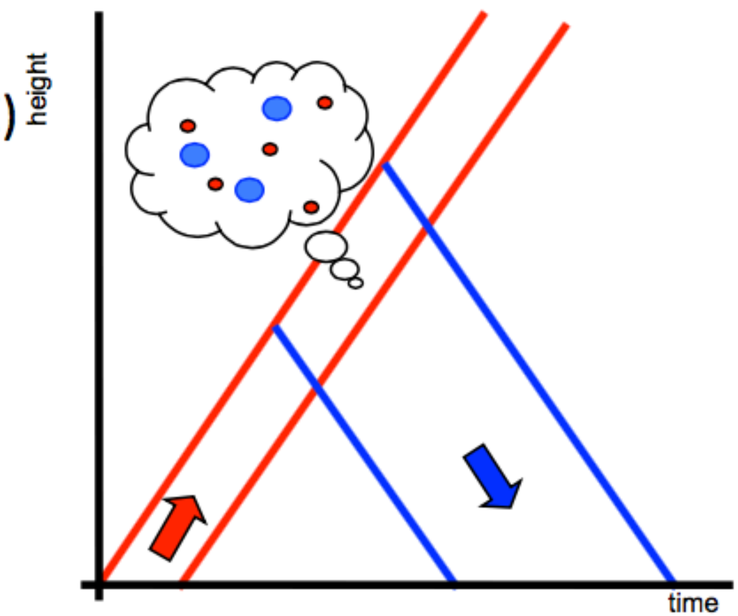
Transmit High Power Radio & Receive Faint Sig

derive from data:
electron density
electron temperature
ion density
ion temperature

(….. meteors, PMSE)

observe scattering at electrons
electron oscillations “damped”
by ions(& charged dust)

Electrons scatter the radio wave:



high power
radio pulse 2 MW

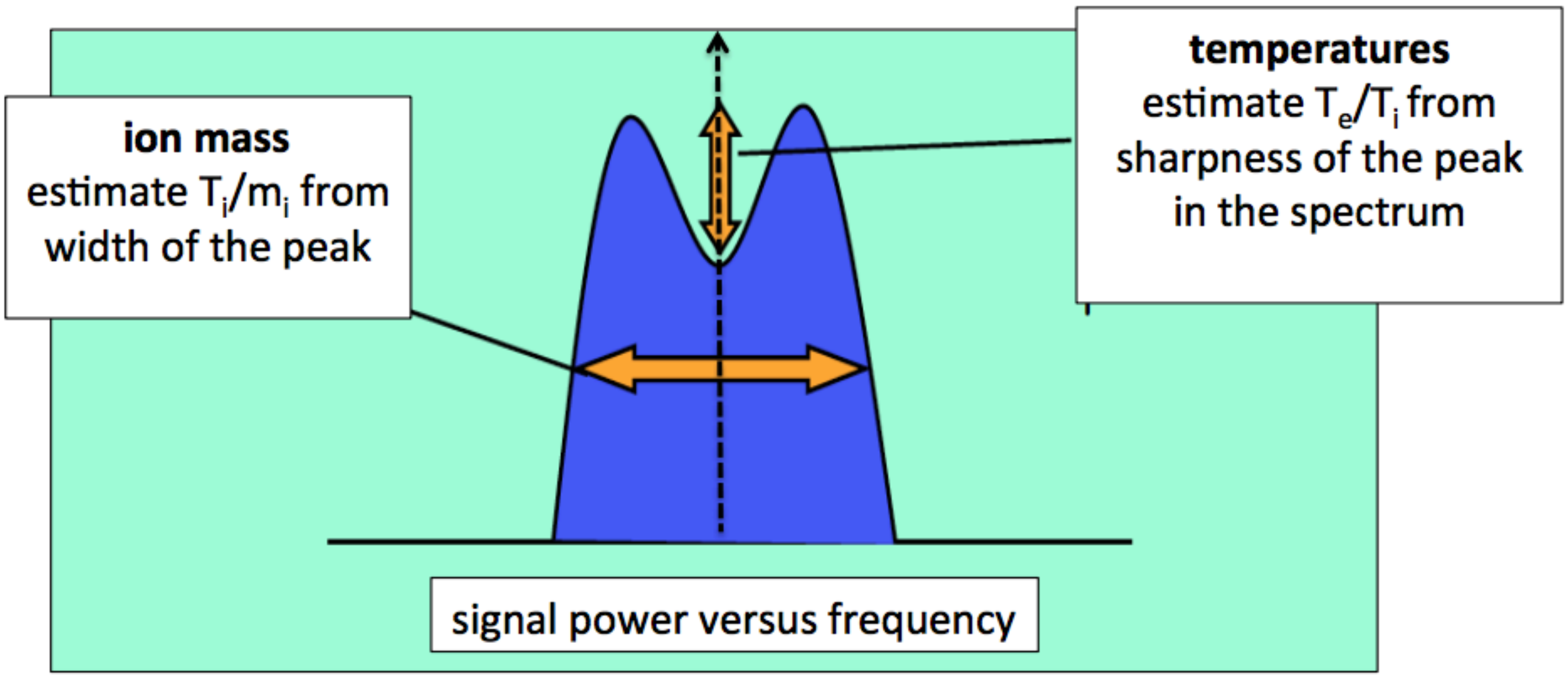
sensitive receiver
signal 10^{-18}W

Some parameters found from scatter spectrum:

electron density (= ion) density from integrated back scattered signal

ion velocity from Doppler shift of frequency

altitude of scattered volume from time lag



EISCAT data - a typical summer day

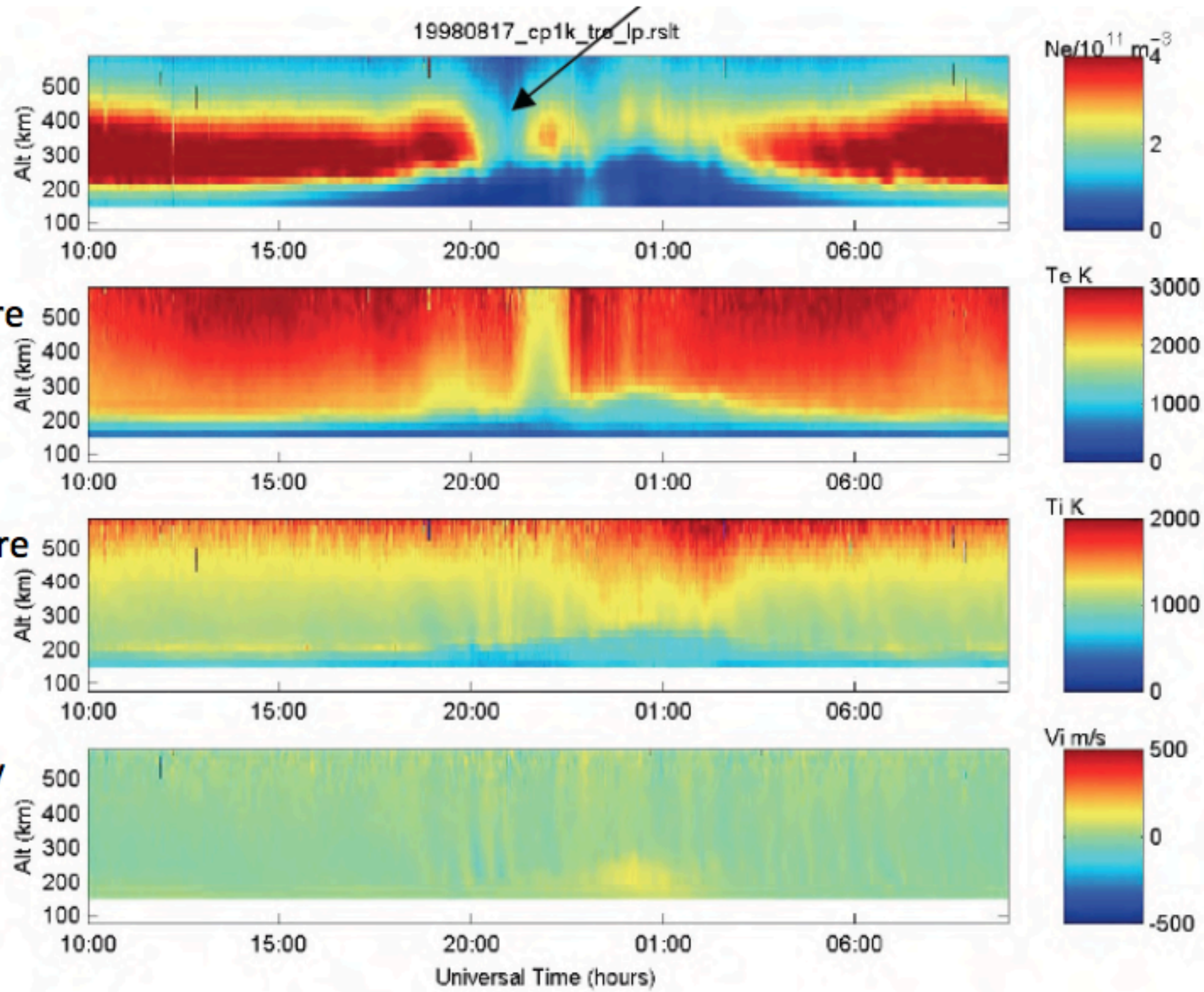
nightside minima in N_e (and T_e)

electron density

electron temperature

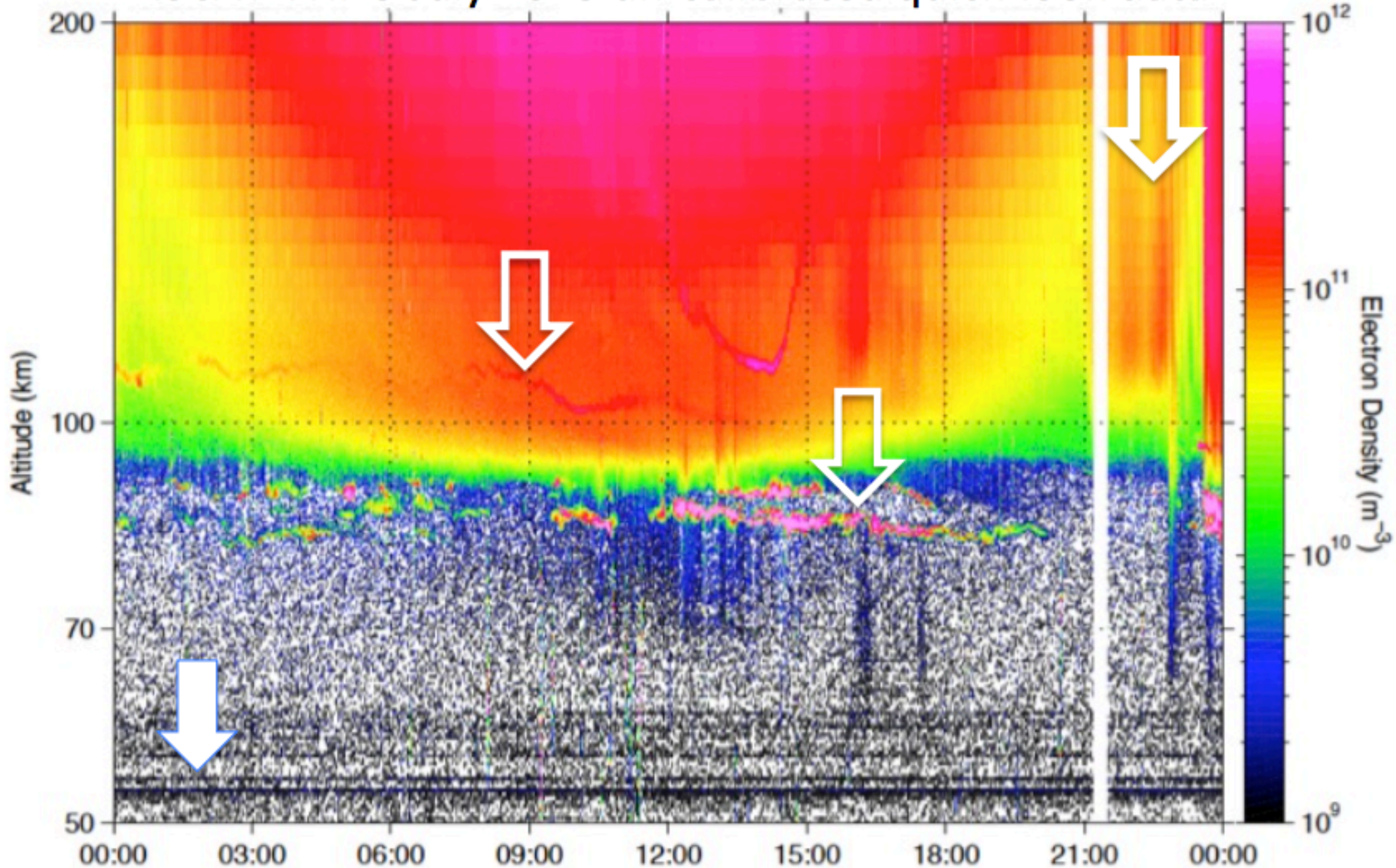
ion temperature

ion velocity



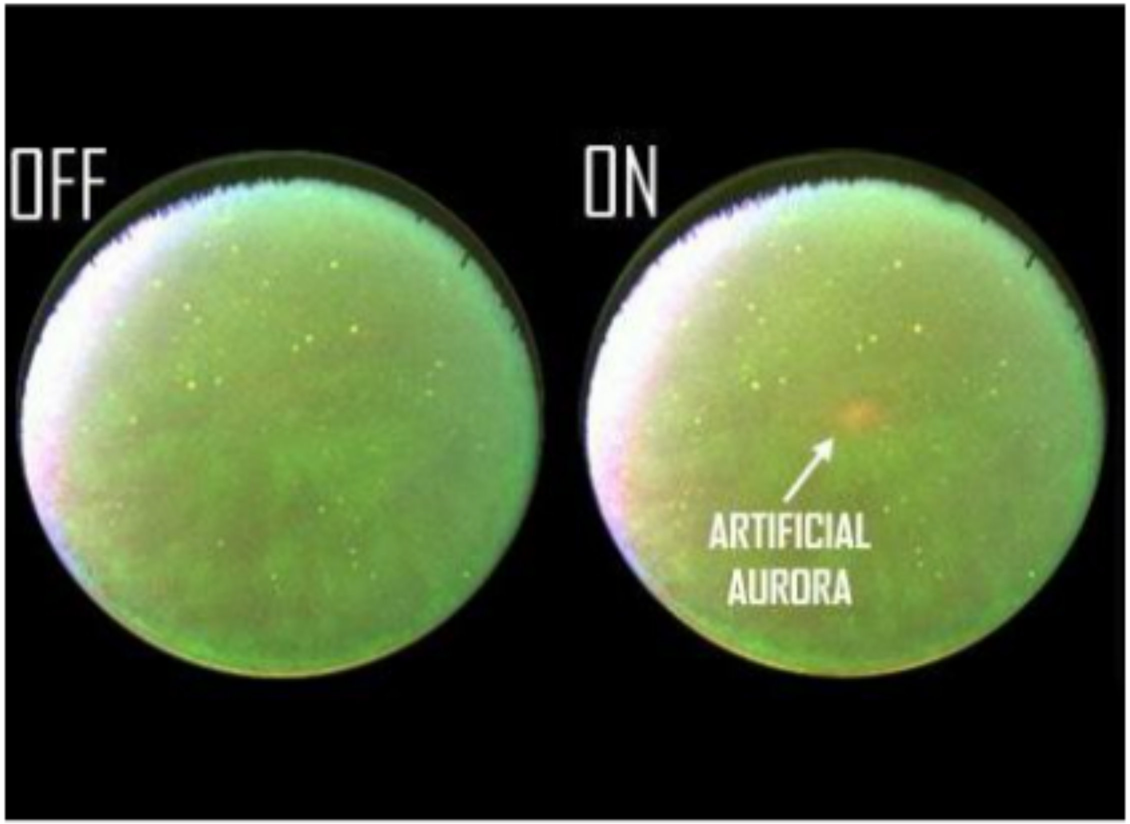
Standard Analysis of one day of observations:

EISCAT VHF 9 July 2013 un-calibrated quick-look data



Electron densities above 100 km - Sporadic E-layers (metallic ions)
Precipitation events of high energy protons - Polar Mesospheric Summer Echoes (PMSE)
Radar reflections at the ground (¨ground clutter¨)

Ionospheric heating



F-layer e- accelerated enough to excite O- ions (630 nm)
(Tromsø HF transmitter)

Ambipolar motion & electric field

$$0 = m_i \mathbf{g} - \frac{1}{n_i}\nabla(n_i k T_i) + e\mathbf{E} + e\mathbf{v}_i \times \mathbf{B} - m_i \nu_i \mathbf{v}_i$$

$$0 = m_e \mathbf{g} - \frac{1}{n_e}\nabla(n_e k T_e) - e\mathbf{E} - e\mathbf{v}_e \times \mathbf{B} - m_e \nu_e \mathbf{v}_e$$

Plasma steady-state 1st order motion eq.

$$\frac{\partial}{\partial t}\rho + \nabla \cdot \mathbf{j} = 0$$

Charge conservation

Then we use 2 main hypothesis :

1) No horizontal gradients
2) Quasi-neutrality

⇒ $n_e \simeq n_i$ and $v_{ez} \simeq v_{iz}$ (from j_z =0)

Ambipolar motion & electric field

Equation along the z direction :

$$0 = -m_i g - \frac{1}{n}\frac{\partial}{\partial z}(nkT_i) + eE_z + e(v_{ix}B_y - v_{iy}B_x) - m_i \nu_i v_z$$

$$0 = -m_e g - \frac{1}{n}\frac{\partial}{\partial z}(nkT_e) - eE_z - e(v_{ex}B_y - v_{ey}B_x) - m_e \nu_e v_z$$

Weak field assumption ($eB/m_i v_i << 1$), negleting electron mass and summing, one obtains the ambipolar flow and electric field expressions

$$v_A = -\frac{1}{m_i \nu_i}\left(m_i g + \frac{1}{n}\frac{\partial nk(T_e + T_i)}{\partial z}\right)$$

$$E_A = -\frac{1}{en}\frac{\partial nkT_e}{\partial z}$$

Plasma scale height

Given that $v_A << g/v_i$, one has

$$\frac{\partial nk(T_e+T_i)}{\partial z}+nm_i g=0$$

So in a simple isothermal model, the plasma scale height is twice the neutral scale height

$$H=\frac{k(T_e+T_i)}{m_i g}=2H_n$$

The reason for that is the effect of the electric field due to the electron mobility (e- would tend to have a much higher H, so electroneutrality hypothesis imposes an E that keeps everything together)

$$E_{PR}=-\frac{1}{en}\frac{\partial nkT_e}{\partial z}\simeq\frac{m_i g}{2e}$$

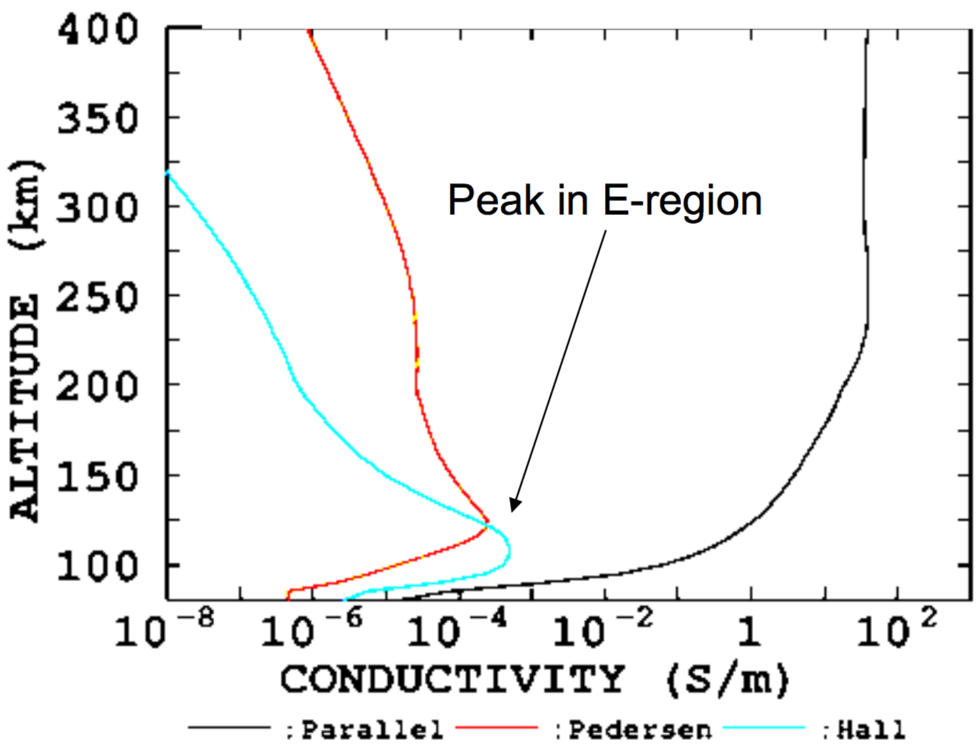
Ionospheric conductivity and currents

Conductivity tensor of a magnetized collisional plasma :

$$\sigma_P = \frac{e}{B}\left(\frac{n_i r_i}{1+r_i^2} - \frac{n_e r_e}{1+r_e^2}\right)$$

$$\sigma_H = \frac{e}{B}\left(\frac{n_i}{1+r_i^2} - \frac{n_e}{1+r_e^2}\right)$$

$$\sigma_\parallel = \frac{e}{B}\left(\frac{n_i}{r_i} - \frac{n_e}{r_e}\right) \sim \frac{n_e e^2}{m_e \nu_{en}}.$$



$$\vec{\mathbf{J}}_\perp = \sigma_P \vec{\mathbf{E}}_\perp + \sigma_H \vec{\mathbf{E}} \times \vec{\mathbf{b}}$$

$$\vec{\mathbf{J}}_\parallel = \sigma_\parallel \vec{\mathbf{E}}_\parallel$$

Ionospheric currents