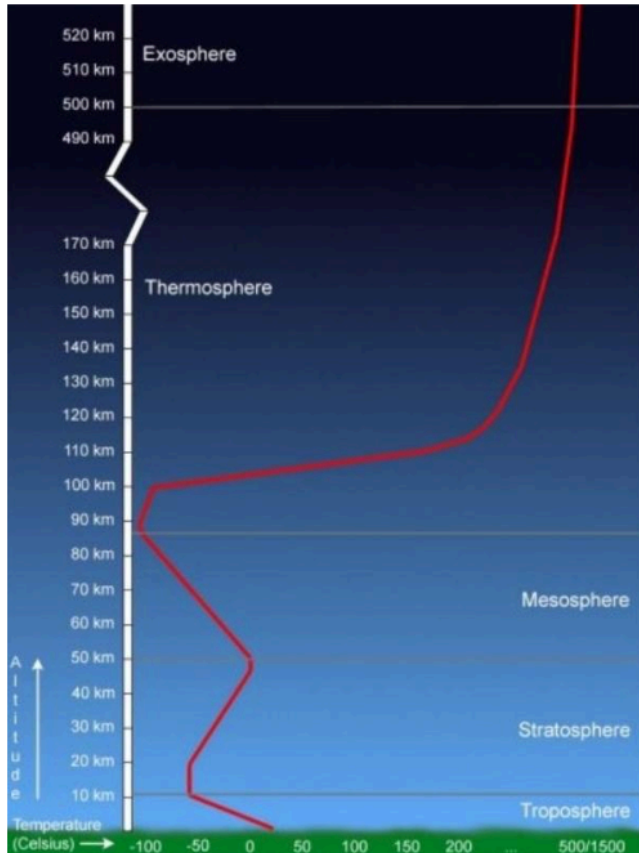


# Ionosphères planétaires (introduction)

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# Structure de l'atmosphère terrestre



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

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

Turbopause around the mesopause (90 km)

Higher atmospheric layer : the exosphere

# What about the density ?

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

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

For small arguments ( $r = R_0 + z$  and  $z \ll R_0$ ), one gets the usual exponential cutoff for the pressure with scale height  $H(z) = kT(z)/mg$

$$(nkT)(z) = (nkT)_0 \exp - \frac{mg}{kT(z)} z$$

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

For a constant  $H$ , 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.

# Chapman's ionization layer

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

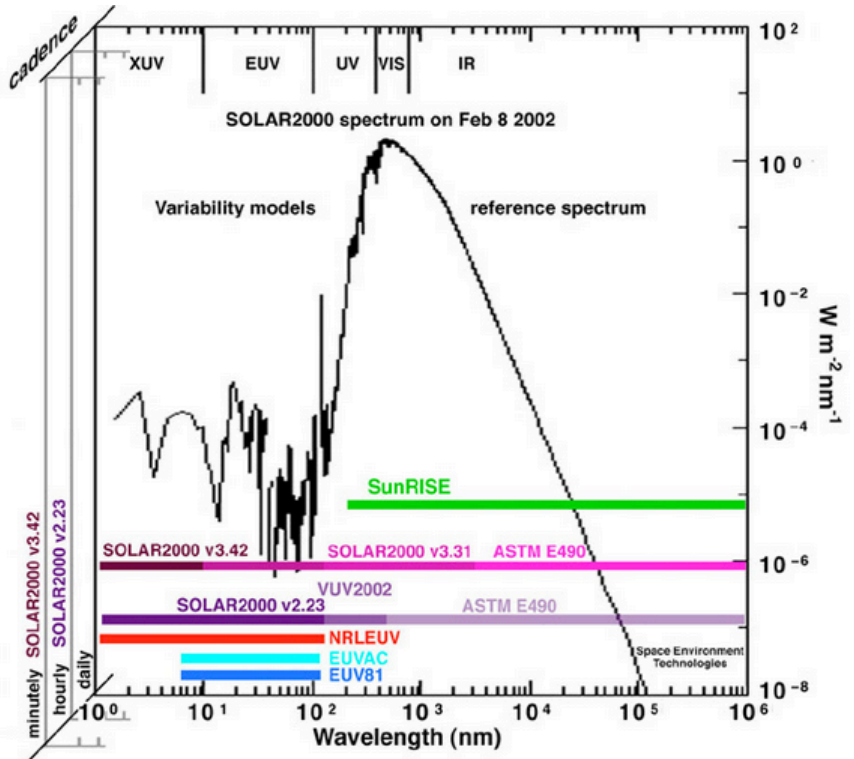
By S. CHAPMAN, M.A., D.Sc., F.R.S.

*Received July 7, 1930. Read November 7, 1930.*

*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 magnitude?

Simple atomic model (1 e- energy in Z=1 nucleus potential) :

$$W \sim \frac{\hbar^2}{2m_e r^2} - \frac{e^2}{4\pi\epsilon_0 r}$$

$dW/dr = 0$  gives Bohr's radius and energy at fundamental level

$$a_0 = \frac{\hbar^2 4\pi\epsilon_0}{m_e e^2}$$

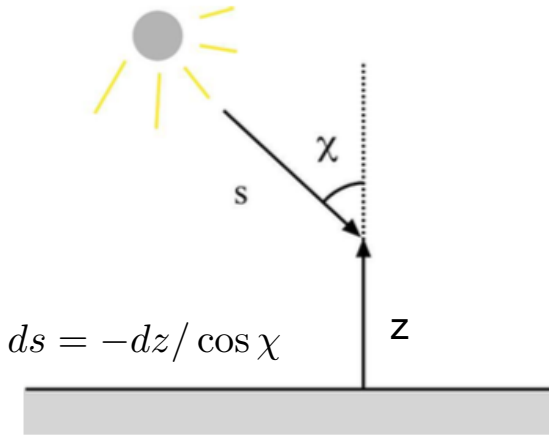
$$W_0 = \frac{m_e e^4}{8\epsilon_0^2 h^2}$$

With the well-known result :  $W_0 \simeq 13.6 \text{ eV}$   $\Rightarrow \lambda_0 = hc/W_0 \simeq 91 \text{ nm}$

UV flux ionises the atmosphere



# UV absorption along a ray of sunlight



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 ( $W/m^2$ ) 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  $\sigma$ , that depends only on the chemical properties of the specie considered – we will see later how to evaluate the order of magnitude of  $\sigma$ .

# 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  $1/35 \text{ eV}^{-1}$  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 ?

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

The production rate  $Q_e$  is expressed in terms of  $z_m$  and  $Q_{em}$

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

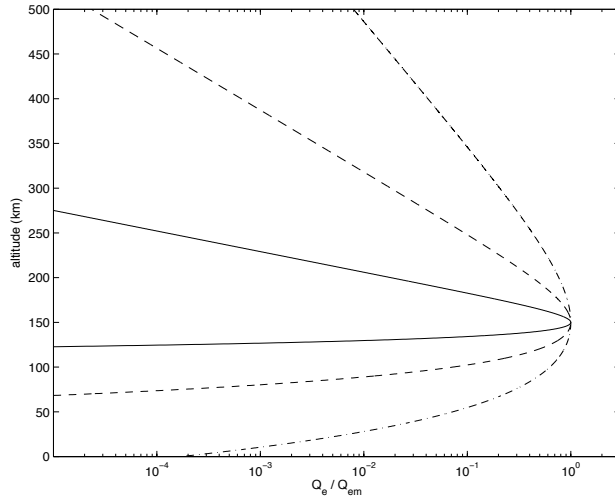
$$\text{where } y = (z - z_m)/H$$

+ Intensity profile ?

# Chapman's production function

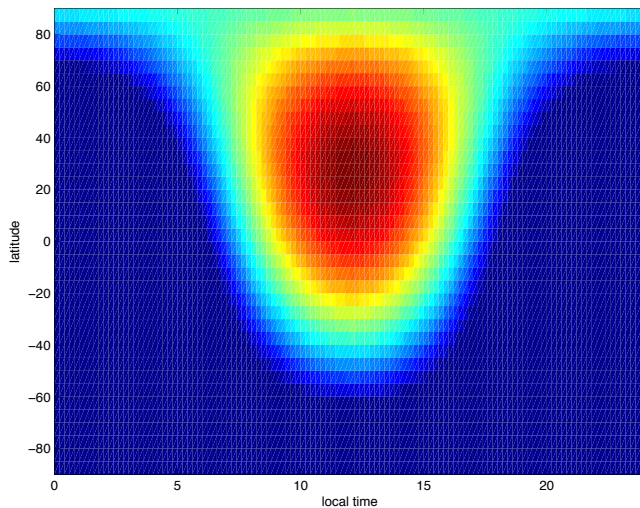
$$Q_e = Q_{em} \exp [1 - y - \exp(-y)]$$

For  $z_m = 150$  km  
 $H = 10, 30, 60$  km.

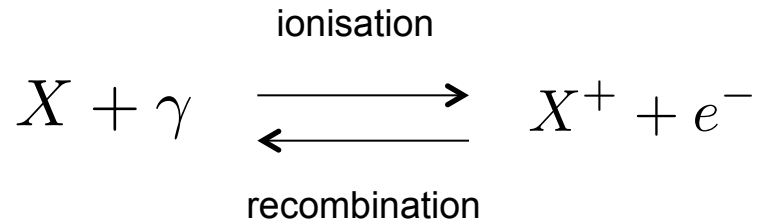


Cosinus of zenith angle in  $(\phi, \theta)$  plane  
For solar declination angle  $\delta = -25^\circ$

$$\cos \chi = \sin \delta \cos \theta + \cos \delta \sin \theta \cos \phi$$



# Ionization/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 :

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

$$\begin{aligned} &= 2.6 \times 10^{-22} \text{ m}^2 \\ &(\text{for } W_0 = 13,6\text{eV}) \end{aligned}$$

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

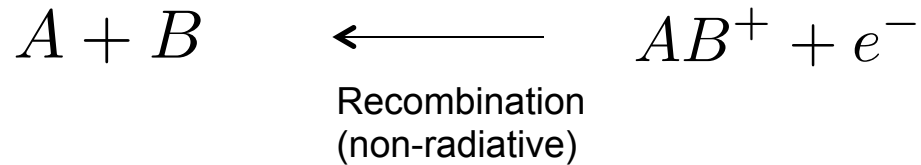
$$\begin{aligned} &= 3.4 \times 10^{-24} \text{ m}^2 \\ &(\text{for } T = 1000 \text{ K}) \end{aligned}$$

# Airglow



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

# Dissociative Recombination



Order of magnitude of the cross section :

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

$$\longrightarrow \sigma_{rec} \simeq \pi \left( \frac{\hbar}{m_e v_e} \right)^2 = 2.7 \times 10^{-18} \text{ m}^2$$

(for T = 1000 K)

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

Dominant processes in Earth's atmosphere :

$$\begin{aligned} \text{O}_2^+ + e &\rightarrow \text{O} + \text{O} \\ \text{N}_2^+ + e &\rightarrow \text{N} + \text{N} \end{aligned}$$

(cf document part 5.7 for more reactions typical of Earth's ionosphere)

# 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  $Q_e$  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  $Q_e$  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	$\sim 0$	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 <sub>2</sub>	1.9
Earth	1.0	1.0	1.0	1.0	1.0	N <sub>2</sub>	1.0
Mars	1.5	0.107	0.53	1	$< 10^{-6}$	CO <sub>2</sub>	1.3
Jupiter	5.2	318.	11.2	2.4	$2.0 \times 10^4$	H <sub>2</sub>	2.9
Saturn	9.5	95	9.4	2.3	$5.8 \times 10^2$	H <sub>2</sub>	5.8
Uranus	19	14.5	4.0	1.4	48	H <sub>2</sub>	3.1
Neptune	30	17.1	3.9	1.3	28	H <sub>2</sub>	2.2
Pluto	39	0.0022	0.18	0.16		N <sub>2</sub>	5

Notes: The mean heliocentric distance  $d$ , mass  $M$ , equatorial radius  $R$ , rotation rate  $\Omega$  and magnetic moment  $\mu \simeq (4\pi/\mu_0) B_0 R^3 \text{ A m}^2$  ( $B_0$  is the planet's magnetic field amplitude at equator) are normalised to the Earth's values, respectively equal to  $d_{\oplus} \simeq 1.5 \times 10^{11} \text{ m}$  (1 AU),  $M_{\oplus} \simeq 6. \times 10^{24} \text{ kg}$ ,  $R_{\oplus} \simeq 6.4 \times 10^6 \text{ m}$ ,  $\Omega_{\oplus} \simeq 7.3 \times 10^{-5} \text{ rad s}^{-1}$  and  $\mu_{\oplus} \simeq (4\pi/\mu_0) 7.9 \times 10^{15} \text{ A m}^2$ . 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  $H_{\oplus} \simeq 8 \times 10^3 \text{ m}$ .

D'autres paramètres :

- Terre :  $n_0 = 2 \times 10^{25} \text{ m}^{-3}$ .  $T = 300 \text{ K}$ .
- Venus :  $n_0 = 10^{27} \text{ m}^{-3}$ .  $T = 700 \text{ K}$ .
- Mars :  $n_0 = 2 \times 10^{23} \text{ m}^{-3}$ .  $T = 200 \text{ K}$ .

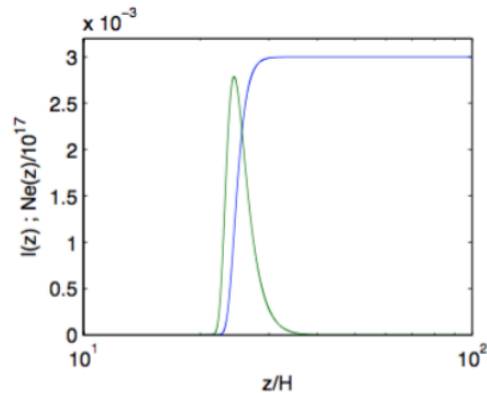


Figure : Flux UV et densité électronique pour des paramètres typiques de la Terre.

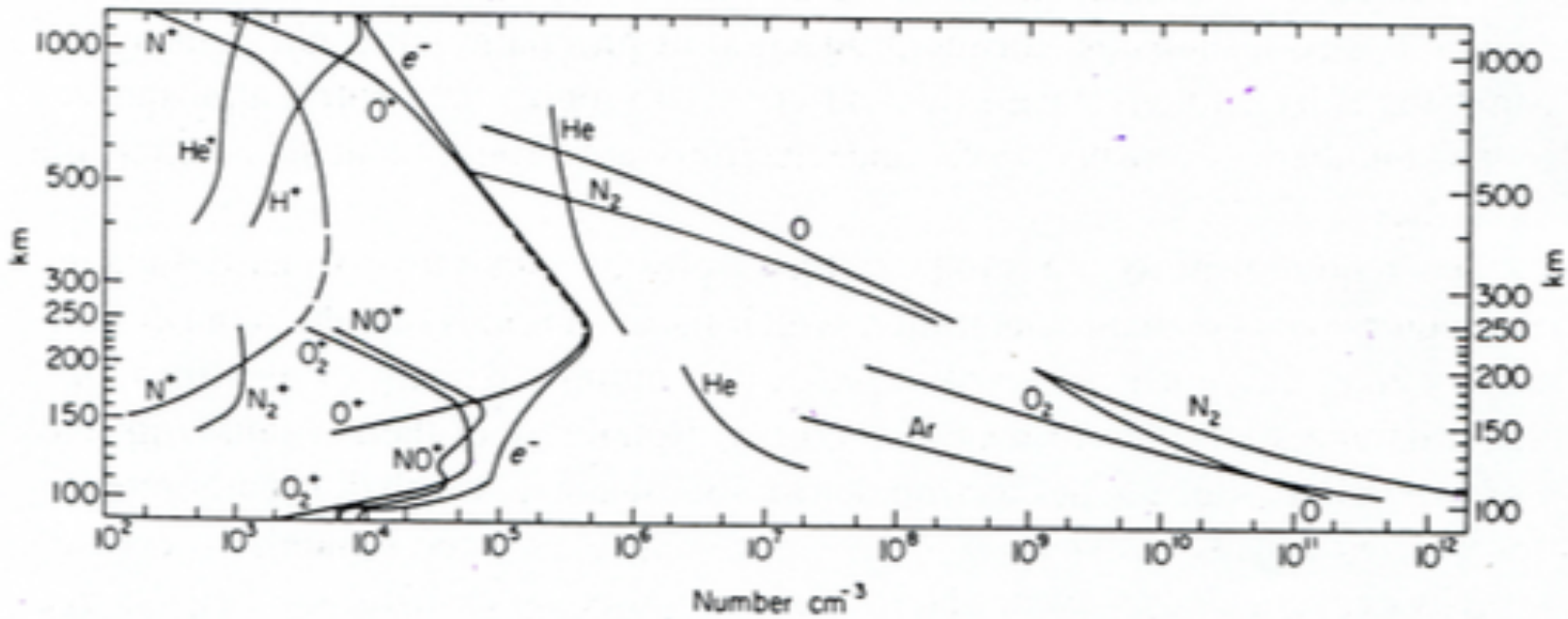
Solar ionizing UV flux at 1 AU :

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

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

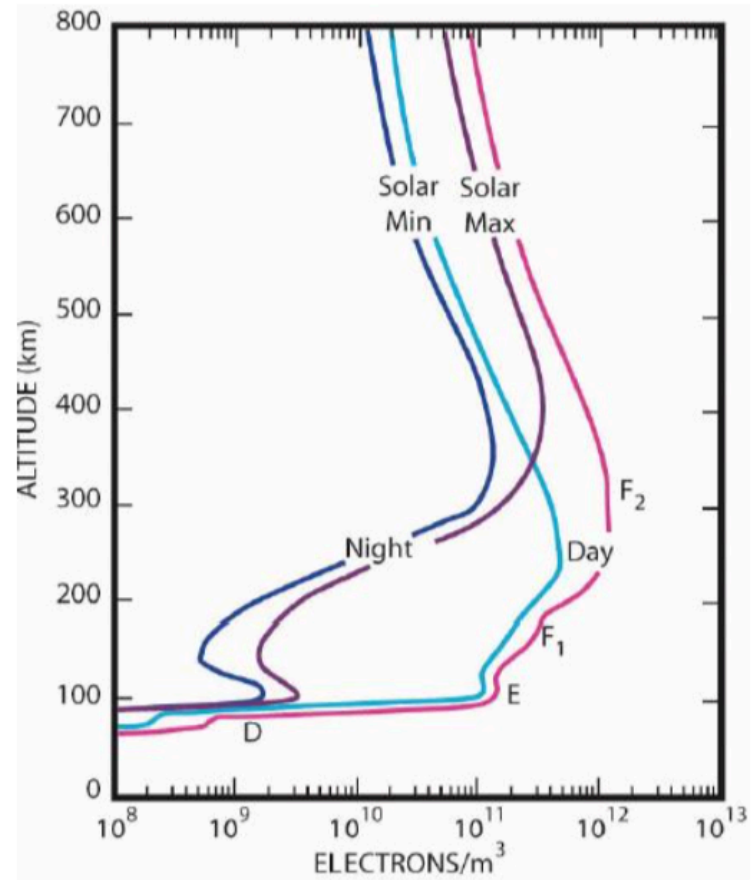
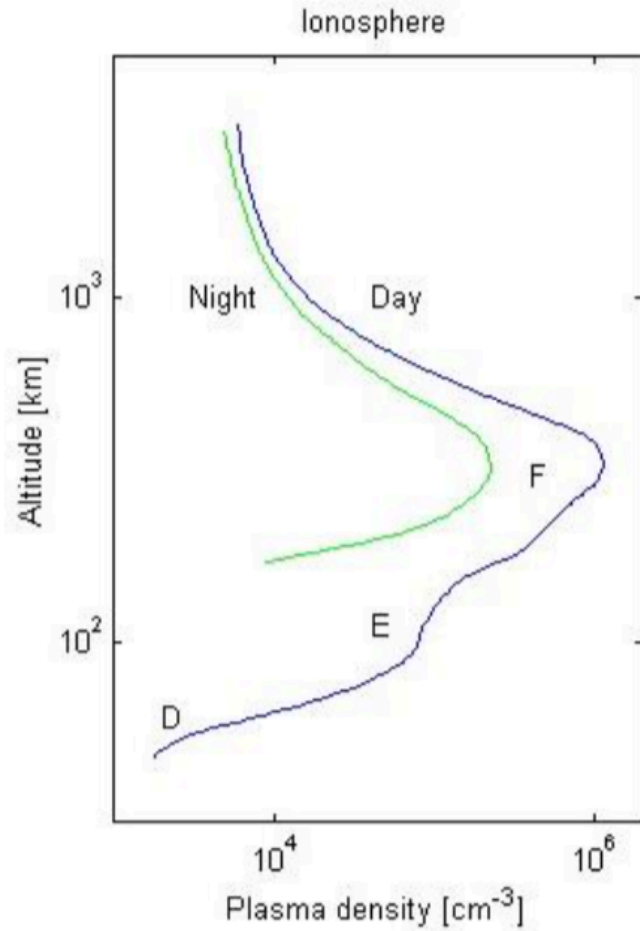


# Some numbers...



Chemical stratification

# Zoology of Earth's ionosphere



# Layers of Earth's ionosphere

## Below 90 km : **D Layer**

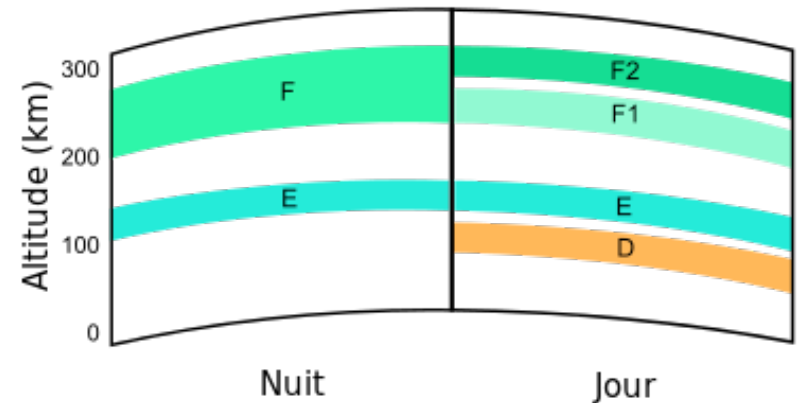
- Predominant composition : polyatomic ions ( $\text{NO}^+$ ,  $\text{O}_2^+$ ,  $\text{N}_2^+$ )
- Weakly ionised, high electron-neutral collision rates (absorption of radio waves)
- High recombination rates
- Disappears mostly entirely at night

## Between 90-150 km : **E Layer**

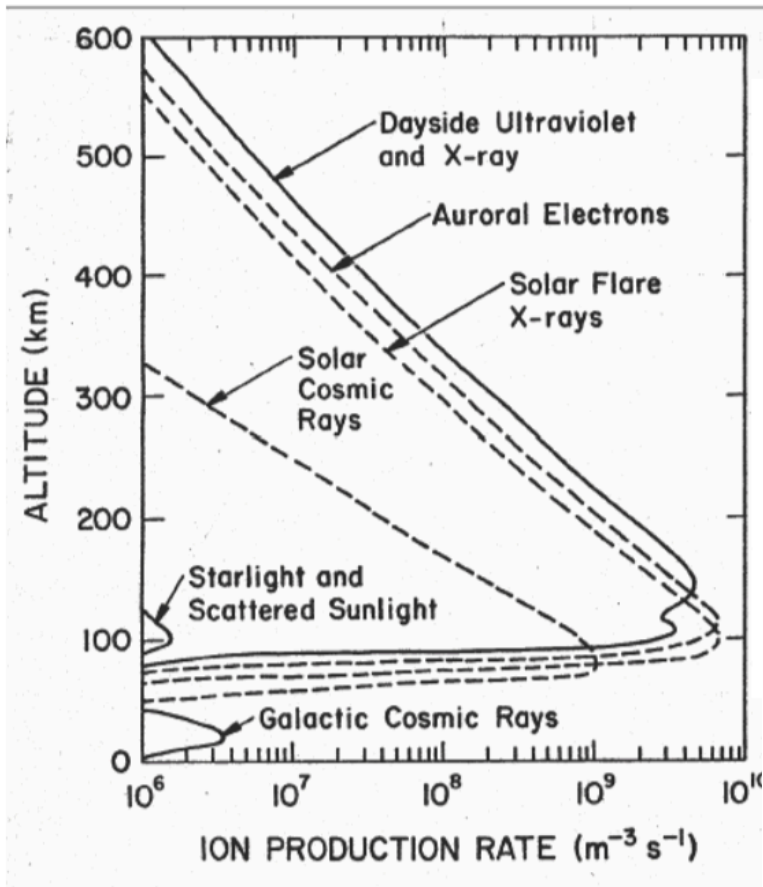
- Predominant composition :  $\text{NO}^+$  and  $\text{O}_2^+$
- Survives during night

## Above 150 km to 600 km : **F Layer**

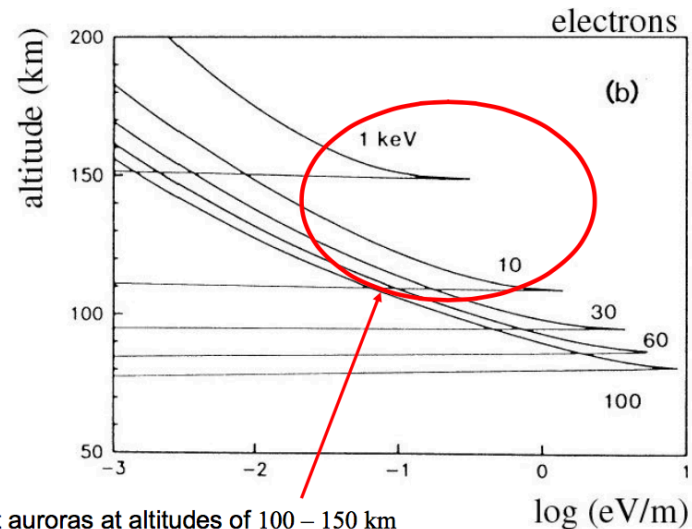
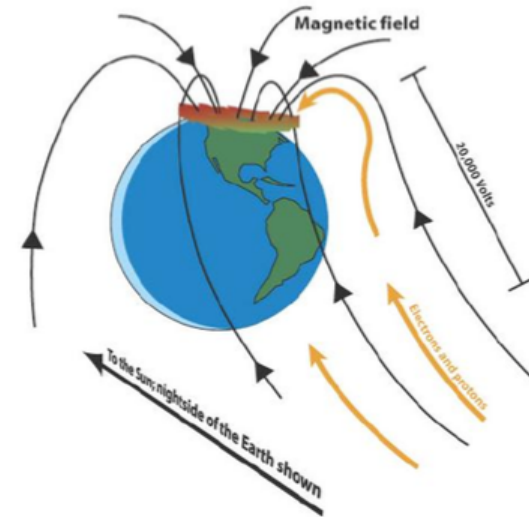
- Atomic ions ( $\text{O}^+$   $\text{N}^+$ )
- High electron density ( $10^6 \text{ cm}^{-3}$ )
- Fluctuates a lot with solar activity



# Other sources of ionisation

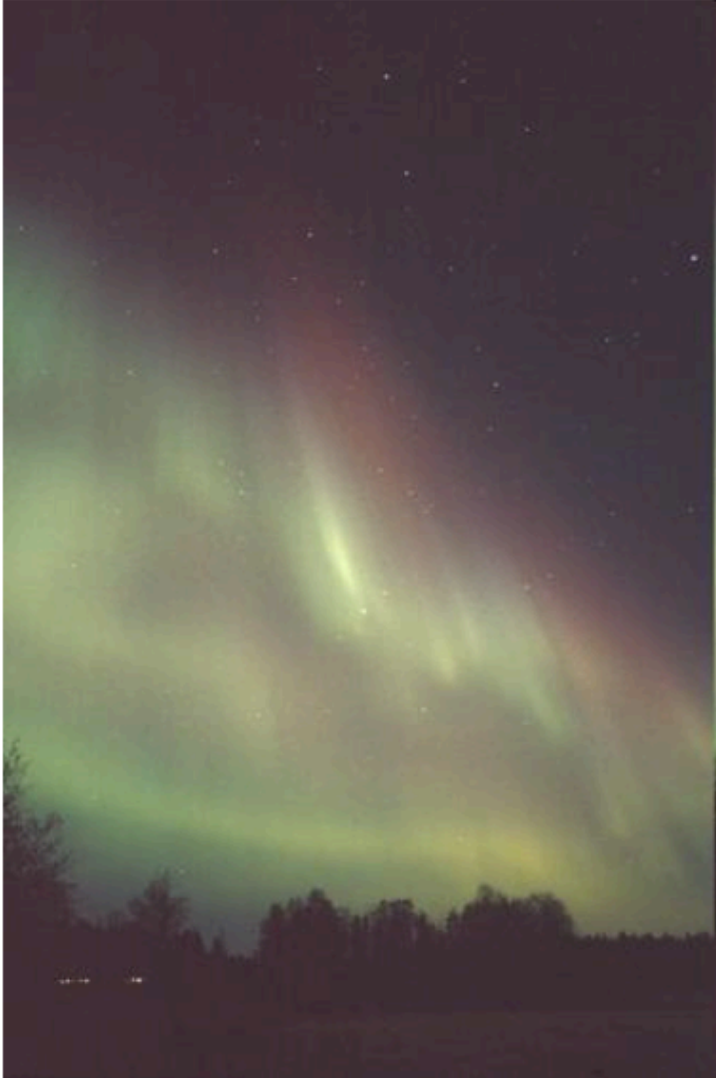


Auroral : very fluctuating but important source of ionization at the Earth's poles



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

# 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



Kiruna receiver

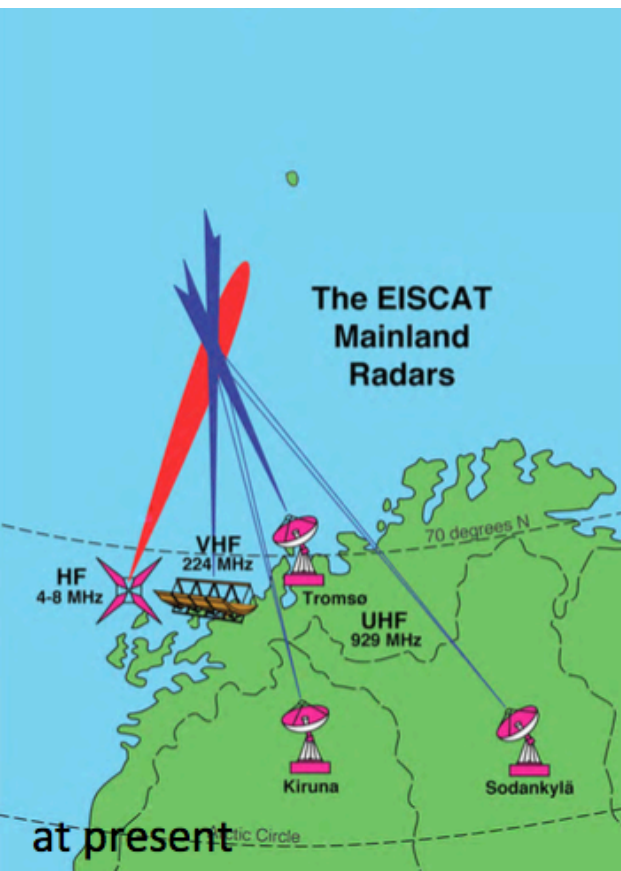
# EISCAT Incoherent Scatter Radars

Transmit High Power Radio & Receive Faint Signal

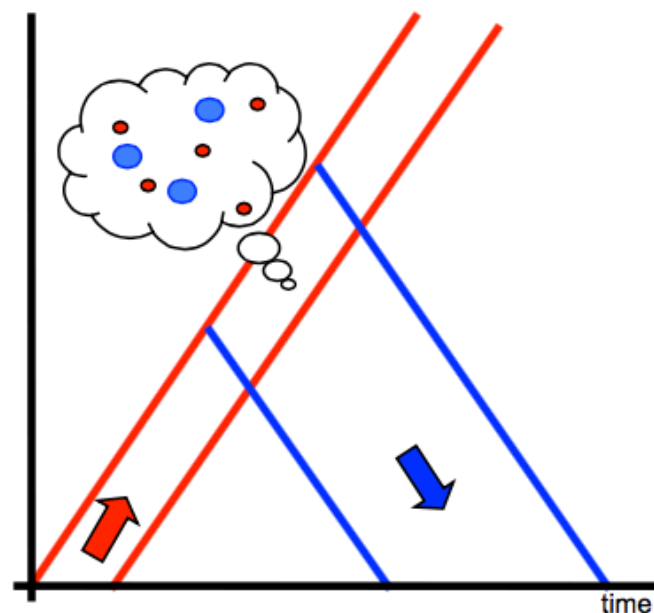
derive from data:  
 electron density  
 electron temperature  
 ion density  
 ion temperature

(..... meteors, PMSE)

*Electrons scatter the radio wave:*



at present



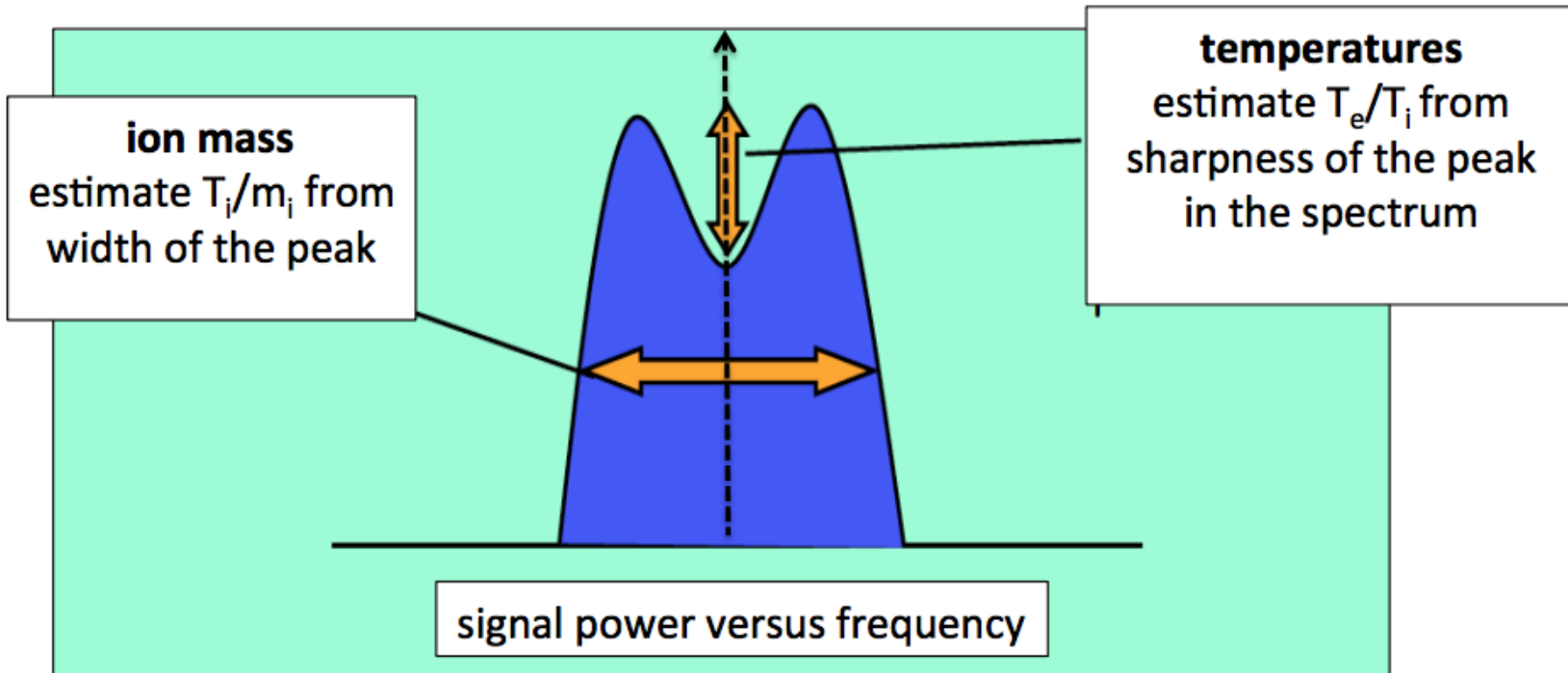
high power  
radio pulse 2 MW

sensitive receiver  
signal  $10^{-18}W$

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

# Some parameters found from scatter spectrum:

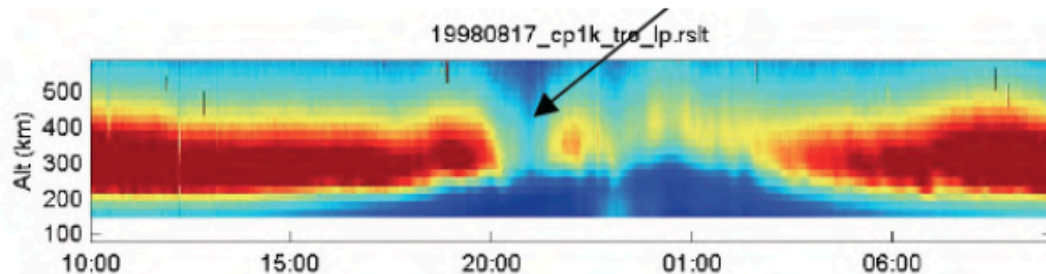
**electron density** (= ion) density from integrated back scattered signal  
**ion velocity** from Doppler shift of frequency  
altitude of scattered volume from time lag



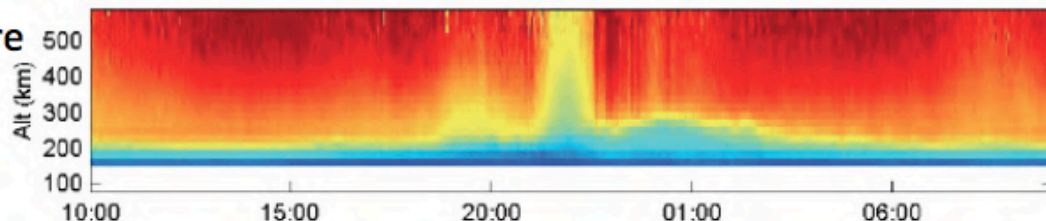
# EISCAT data - a typical summer day

nightside minima in  $N_e$  (and  $T_e$ )

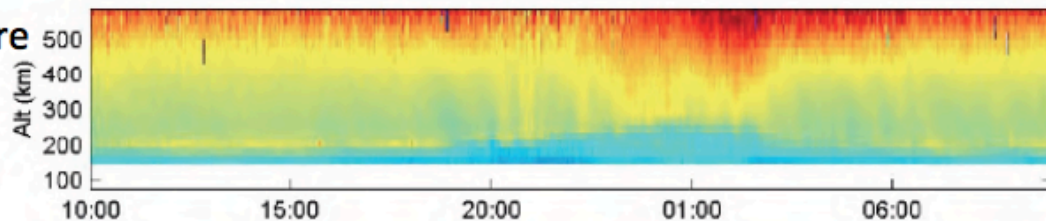
electron density



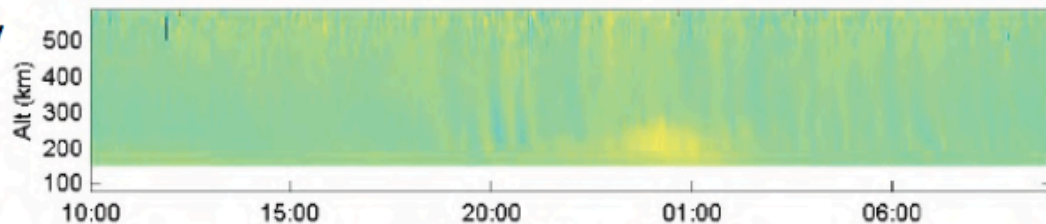
electron temperature



ion temperature



ion velocity

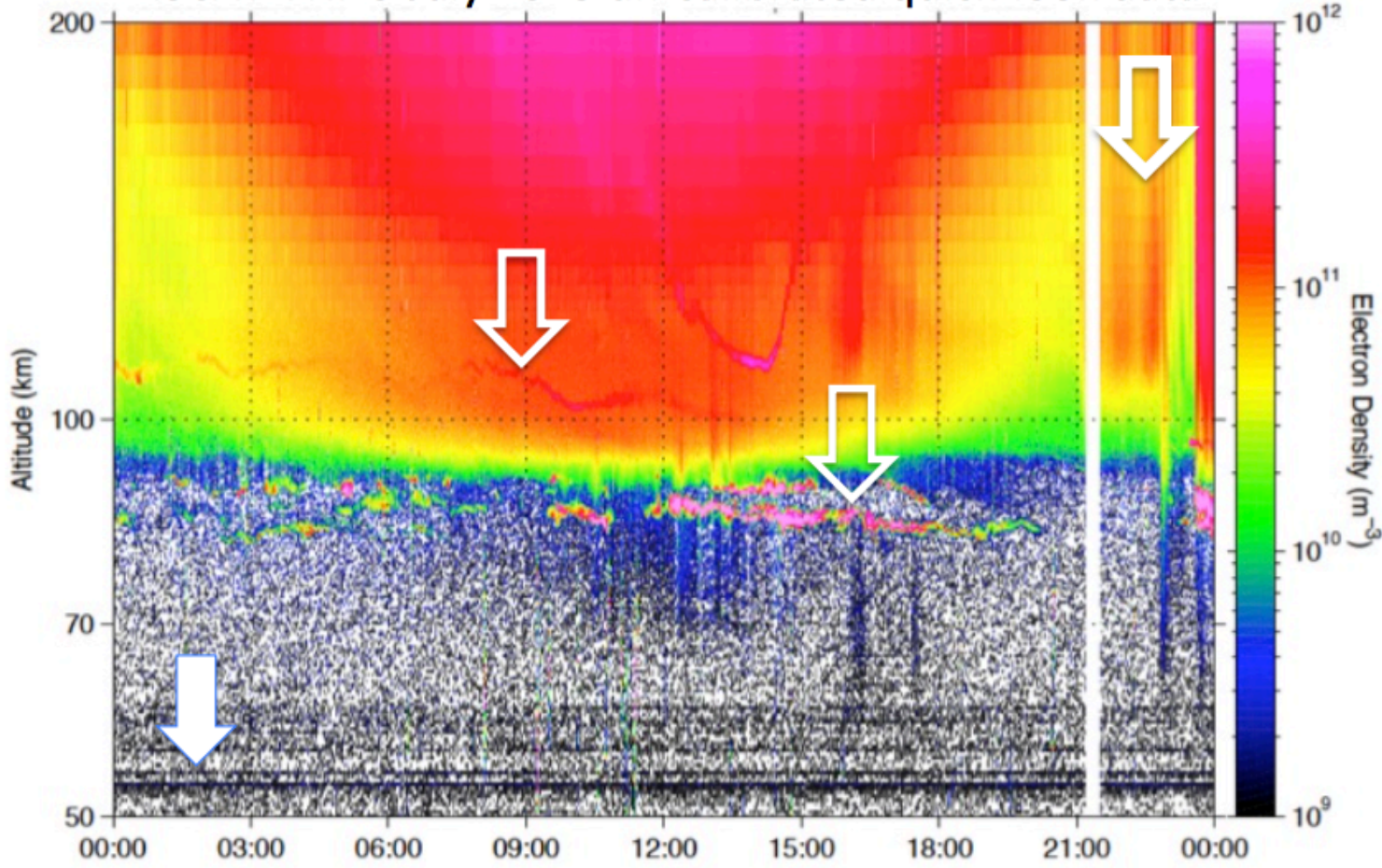


Universal Time (hours)



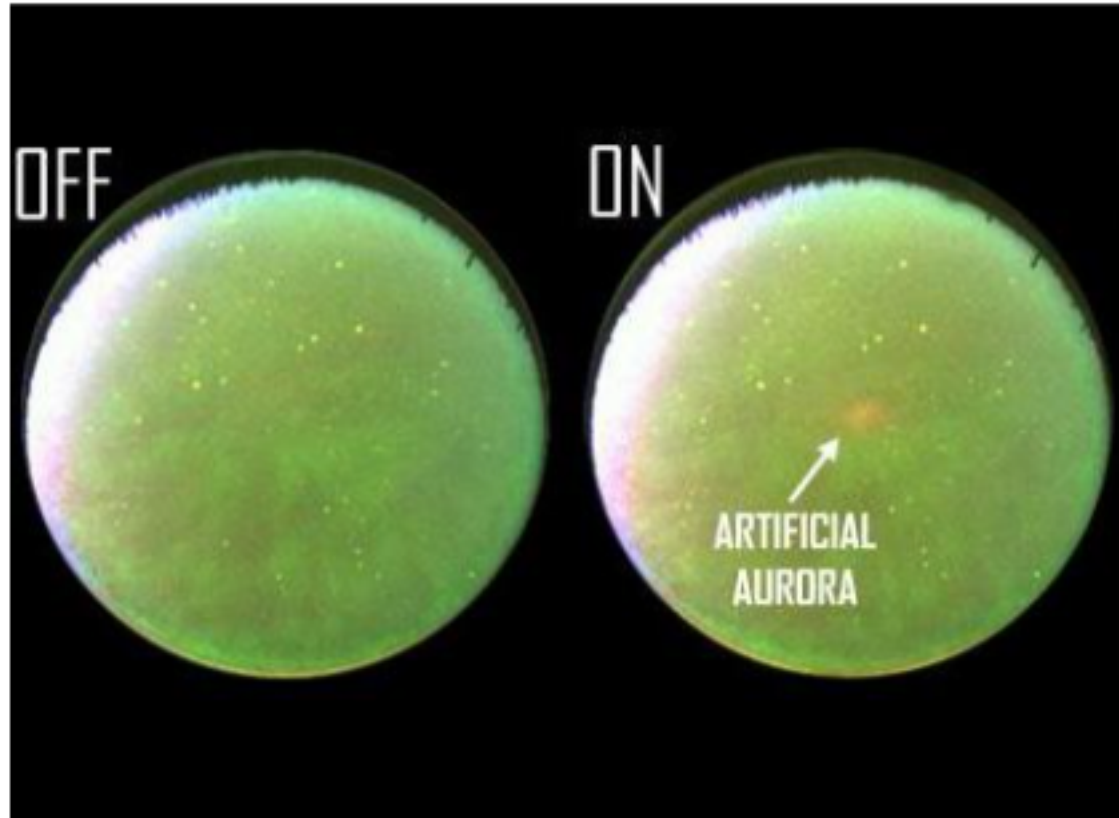
# Standard Analysis of one day of observations:

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.

$$\frac{\partial}{\partial t} \rho + \nabla \cdot \mathbf{j} = 0 \quad \text{Charge conservation}$$

Then we use 2 main hypothesis :

- 1) No horizontal gradients
- 2) Quasi-neutrality



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

# 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 ( $eB/m_i v_i \ll 1$ ), neglecting 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  $v_A \ll g/v_i$ , 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 :

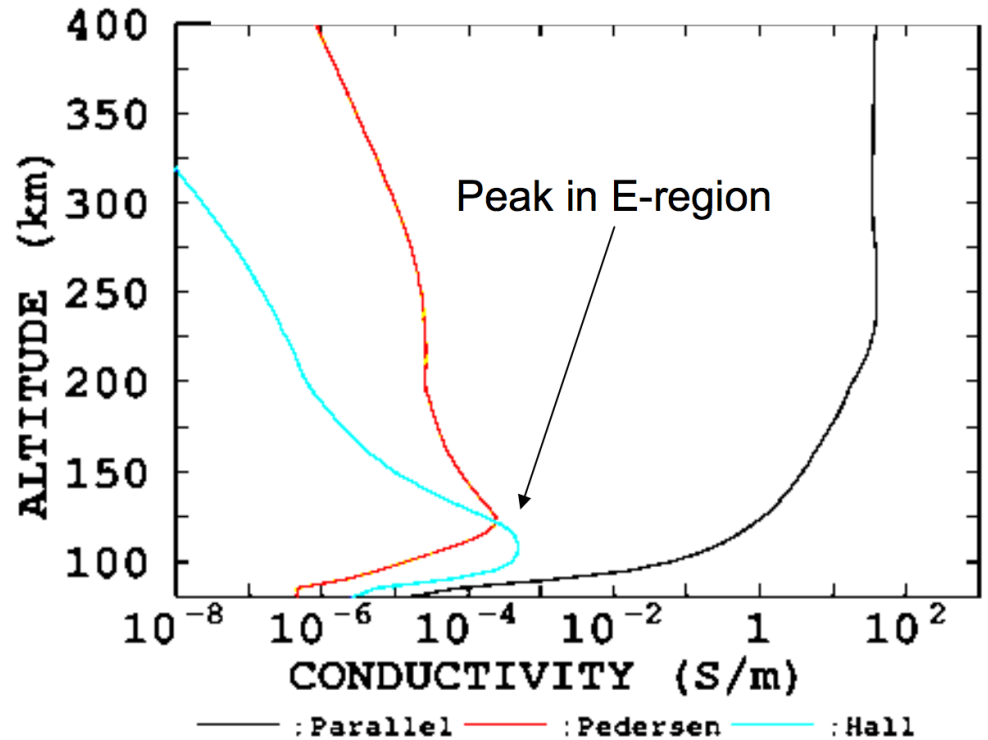
$$\sigma_P = \frac{e}{B} \left( \frac{n_i r_i}{1 + r_i^2} - \frac{n_e r_e}{1 + r_e^2} \right)$$

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

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

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

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



# Ionospheric currents

