Introduction to the ionosphere

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Motivation- Question

Why do we start the Radar School with a lecture of the ionosphere?

Motivation- Answer 1

- The ionosphere affects the electromagnetic waves as they propagate in the ionosphere (that's how ionosphere was originally found).

Motivation- Answer 2

- By using radio waves, the properties of the ionosphere can be studied (utilizing e.g. ionosondes, riometers, incoherent radars and coherent radars).

- Neutral atmosphere

Atmospheric regions by temperature

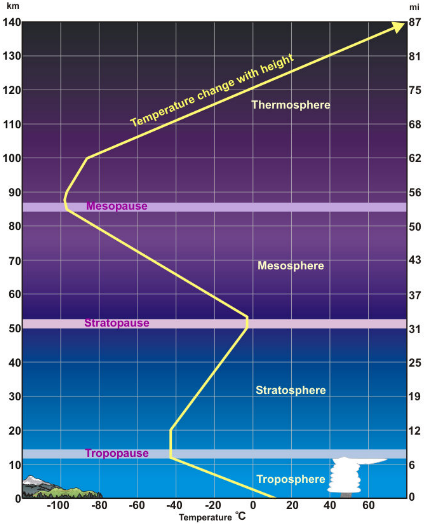


Figure : Atmospheric temperature profile.

- Troposphere is heated by the warm ground and the infrared radiation is emitted out radially => T decreases with height.
- Tropopause at 12–15 km, T_{min} $\sim$ -53° C.
- In the stratosphere, ozone (O_3) layer at 15 – 40 km absorbs solar radiation. Stratopause at 50 km with T_{max} $\sim$ 7° C.
- In the mesosphere heat is removed by radiation in infrared and visible airglow as well as by eddy transport. Mesopause close to 85 km with T_{min} $\sim$ -100° C.
- In thermosphere UV radiation is absorbed and it produces dissociation of molecules and ionization of atoms and molecules.

Thermospheric temperature

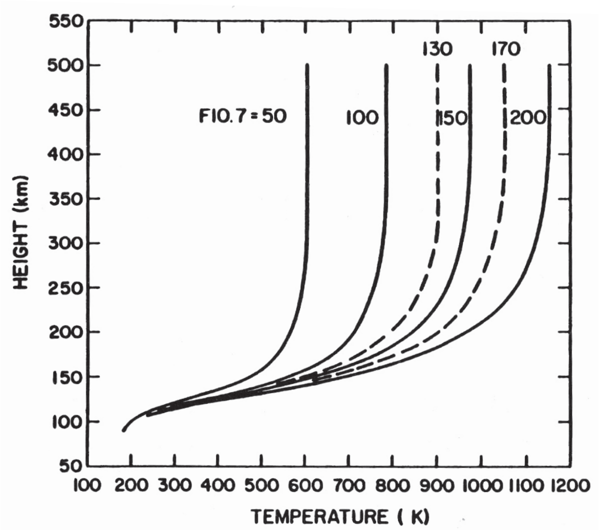


Figure : The variability in the thermospheric temperature for different values of the solar radio flux index $F_{10.7}$ in units of 10^{-22} $Wm^{-2}Hz^{-1}$ at 1 AU.

Atmospheric gas in a stationary state

Above to the surface of the Earth, the atmospheric pressure p and density n are given

$$p = p_0 \exp\left[-\int_{z_0}^{z} \frac{mg}{k_B T(z)} dz\right] = p_0 \exp\left[-\int_{z_0}^{z} \frac{dz}{H(z)}\right] \tag{1}$$

and

$$n = n_0 \frac{T_0}{T(z)} \exp\left[-\int_{z_0}^{z} \frac{dz}{H(z)}\right] \tag{2}$$

where p_0 and n_0 are values at a reference height z_0.
if the atmosphere is isothermal (T=constant), the scale height H

$$H = \frac{k_B T}{mg} \tag{3}$$

is independent of altitude and then the the hydrostatic equations are

$$p = p_0 \exp\left(-\frac{z - z_0}{H}\right), \; n = n_0 \exp\left(-\frac{z - z_0}{H}\right). \tag{4}$$

Atmospheric regions by composition

1. The homosphere is the region below about 100 km altitude, where all gas constituents are fully mixed; i.e. the relative concentrations of different molecular species are independent of height. This is caused by turbulent mixing of the air.
2. The turbopause is the upper boundary of the homosphere at an altitude of about 100 km.
3. The heterosphere is the region above the homosphere. In the absence of atmospheric turbulence, each molecular species distribute with height independently of the other species (according to its own scale height)=> At great altitudes light molecular species dominate.

Composition in the heterosphere

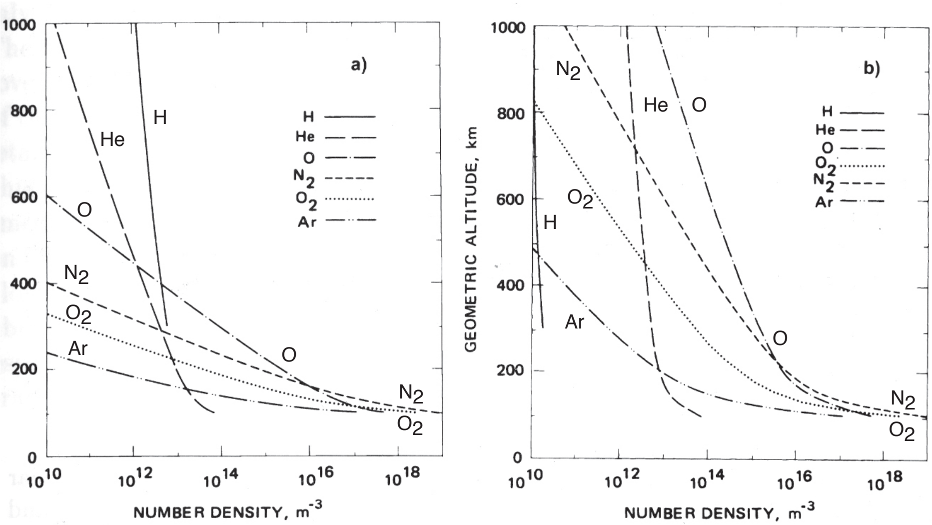


Figure : Atmospheric composition during (a) solar minimum and (b) solar maximum (U.S. Standard atmosphere, 1976).

- Ionosphere

  In the solar wind plasma, and in many parts of the magnetosphere the ionization degree is 100%.

  What is the maximum ionization degree in the atmosphere?

- Ionosphere

  At maximum 1‰ of the neutral atmosphere is ionized.

Ionospheric regions

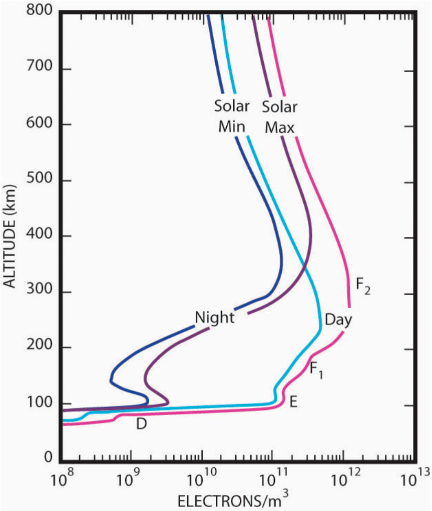


Figure : Typical ionospheric electron density profiles.

Ionospheric regions and typical daytime electron densities:

- D region: 70–90 km, $n_e = 10^8$–10^{10} m^{-3}
- E region: 90–150 km, $n_e = 10^{10}$–10^{11} m^{-3}
- F region: 150–1000 km, $n_e = 10^{11}$–10^{12} m^{-3} .

Ionosphere has great variability:

- Solar cycle variations (in specific upper F region)
- Day-night variation in lower F, E and D regions
- Space weather effects based on short-term solar variability (lower F, E and D regions)

Ion composition

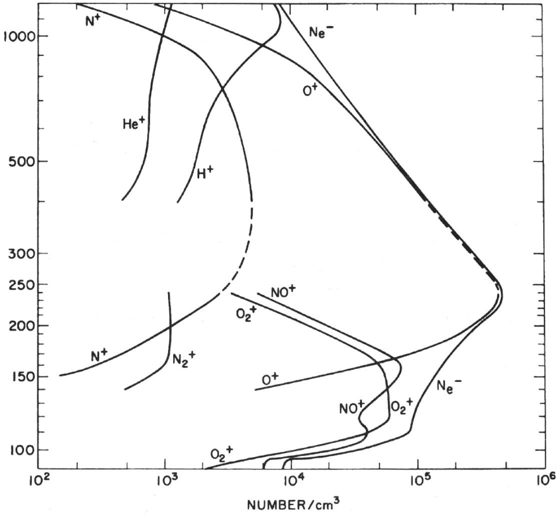


Figure : Daytime solar minimum ion profiles.

- O^+ dominates around F region peak and H^+ starts to increase rapidly above 300 km.
- NO^+ and O_2^+ are the dominant ions in E and upper D regions (Ion chemistry: e.g. $N_2^+ + O \longrightarrow NO^+ + N$).
- D-region (not shown) contains positive and negative ions (e.g. O_2^-) and ion clusters (e.g. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$).

Ionospheric temperatures

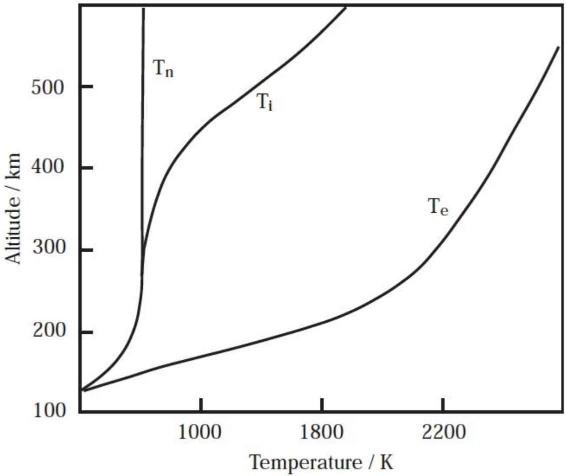


Figure : An example of neutral (Tn), ion (Ti) and electron (Te) temperature profiles.

Dynamics of the ionosphere

The important equations for ions (number density n_i) and electrons (number density n_e) in the ionosphere are the continuity equations:

$$\frac{\partial n_{i,e}}{\partial t} + \nabla \cdot (n_{i,e}\mathbf{v}_{i,e}) = q_{i,e} - l_{i,e}, \tag{5}$$

where q is the production rate per unit volume and l the loss rate per unit volume; and the momentum equations:

$$n_i m_i \left(\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \mathbf{v}_i \;=\; n_i m_i \mathbf{g} + e n_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \nabla p_i - n_i m_i \nu_i (\mathbf{v}_i - \mathbf{u}) \tag{6}$$

$$n_e m_e \left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla \right) \mathbf{v}_e \;=\; n_e m_e \mathbf{g} - e n_e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e - n_e m_e \nu_e (\mathbf{v}_e - \mathbf{u}) \tag{7}$$

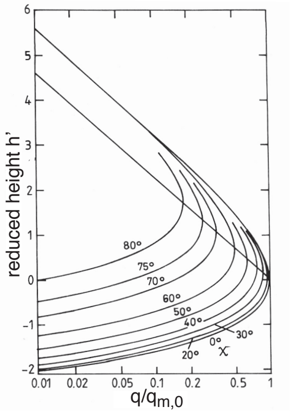
where **E** is electric field, **B** is magnetic induction, p_i and p_e are the pressures of the ion and electron gas, and the ion-neutral and electron-neutral collision frequencies are denoted by ν_i and ν_e, respectively.

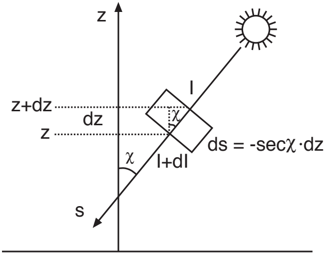
Ionization source: solar radiation

Chapman production function by using a height variable $h' = h - \ln \sec \chi$:

$$q(\chi, h') = q_{m,0} \cos \chi \cdot \exp \left[1 - h' - e^{-h'} \right] ,$$

where χ is the solar zenith angle and $h = (z - z_{m,0})/H$, where H is the atmospheric scale height.





- With larger zenith angle χ, the peak of ionization rate rises in altitude and decreases by a factor $\cos \chi$.

Ionization source: particle precipitation (electrons)

- High-energy electrons deposit the energy at lower altitudes.

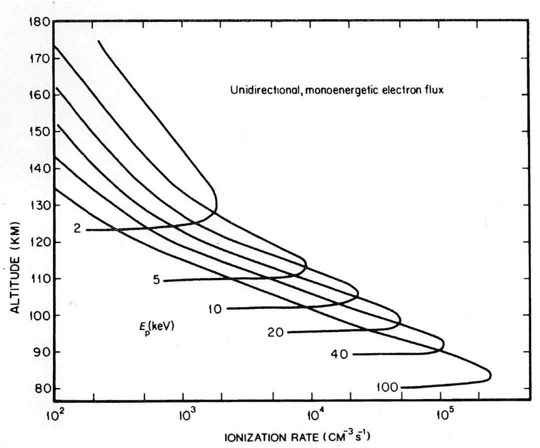


Figure : Ionization rate for monoenergetic electrons with energies 2–100 keV.

Ionization source: particle precipitation (protons)

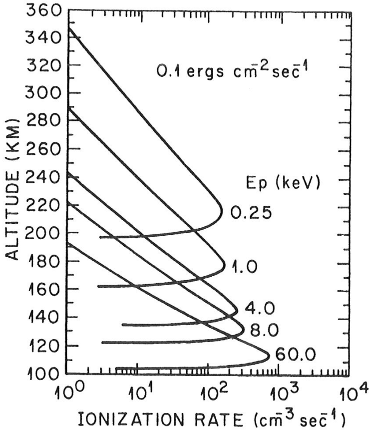


Figure : Ionization rate for monoenergetic protons with energies 0.25–60 keV (Rees, 1982).

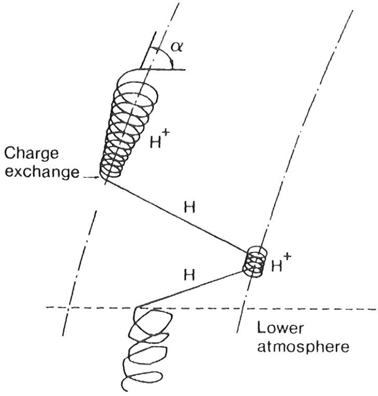


Figure : Protons may make charge exchange with neutral hydrogen.

Ionosphere at high, middle and low latitudes

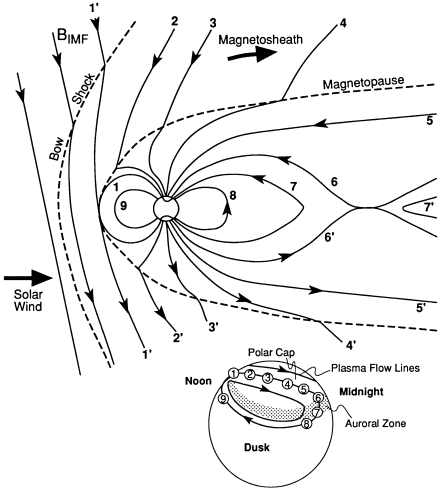


Figure : IMF coupling to the magnetosphere.

- High-latitude ionosphere (polar cap, cusp, auroral oval): intense electric fields mapping from the magnetosphere, particle precipitation, effects of magnetospheric substorms.
- Mid-latitude ionosphere: occasionaly high-latitude electric fields may penetrate to mid-latitudes, effects of magnetic storms.
- Low-latitude and equatorial ionosphere: very small electric fields, high day-time conductivities due to solar radiation. Equatorial electrojet close to the magnetic equator.

Characteristics of D region

- Small electron densities, large neutral densities
- Complex chemistry including ion production and recombination processes, also transport, that are not fully understood

SIC model positive ions

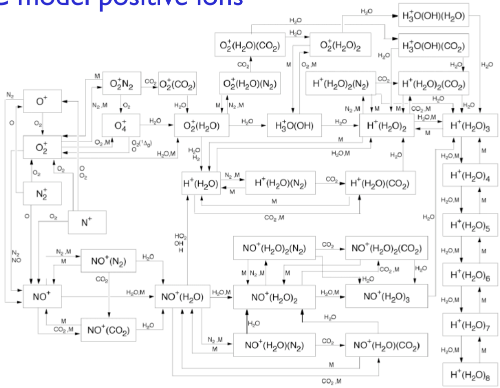


Figure : Sodankyla Ion Chemistry model (SIC), positive ions.

Characteristics of D region

- Small electron densities, large neutral densities
- Complex chemistry including ion production and recombination processes, also transport, that are not fully understood

SIC model negative ions

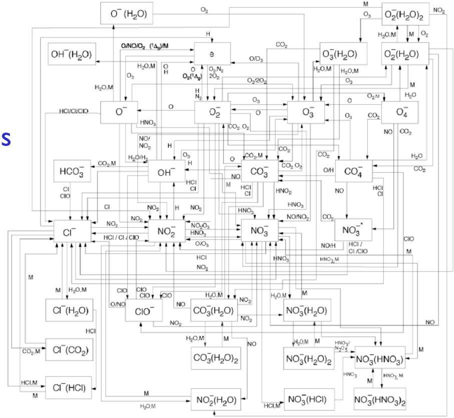


Figure : Sodankyla Ion Chemistry model (SIC), negative ions.

Characteristics of E region

- Due to different collision and gyro frequencies for ions and electrons, electrical conductivities maximize in the E region
- At high latitdes, conductivities may be greatly enhanced due to auroral particle precipitation.
- Horizontal currents flow in the E region, when the electric field and the conductivities are non-zero.

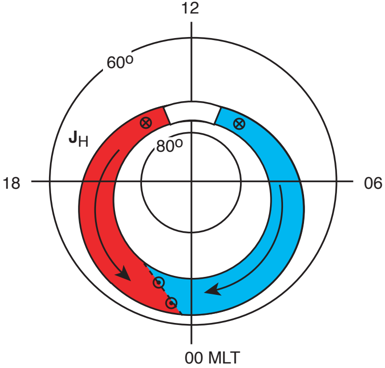


Figure : Hall currents within the auroral oval: eastward electrojet (red) and

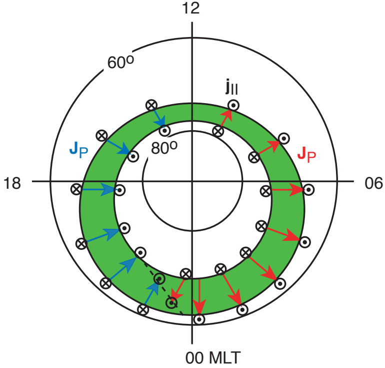


Figure : Pedersen and field-aligned currents within the auroral oval.

Characteristics of F region

- Maximum electron densities occur at F-region maximum (h$\sim$ 300 km).
- Collisions with neutrals become sparse both for ions and electrons, hence both species drift with the same convection velocity of $\mathbf{v} = \mathbf{E}x\mathbf{B}/B^2$.
- Ambipolar diffusion becomes important.
- At high latitudes, ion outflows may take place and field-aligned currents flow.

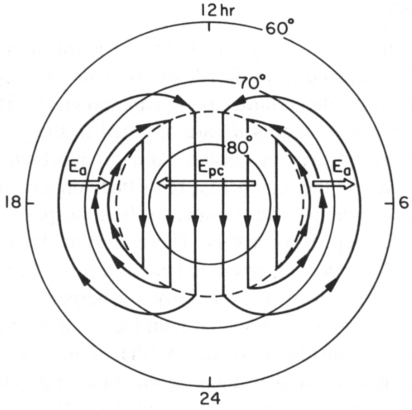
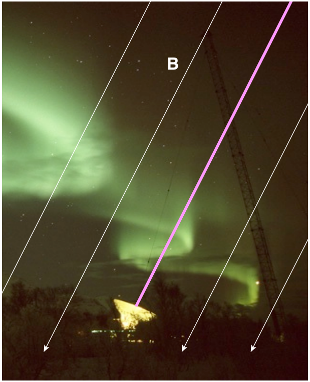
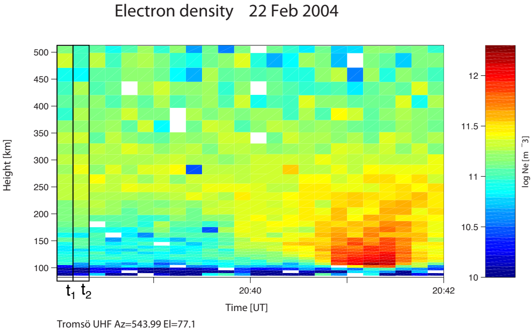


Figure : Plasma convection in the northern high latitude ionosphere and associated convection electric fields.

How measurement is turned into a plot for a single-beam radar

- EISCAT radar beam width is narrow, about 0.5°.
- Typical look direction is along the external magnetic field **B**. Then each analysed raw data dump (typically 5 s - 1 min) gives one altitude profile of analysed parameters, like Ne, Te, Ti or Vi.
- Sometimes elevation scans or azimuth scans are made.





Example of 24-h high-latitude measurement

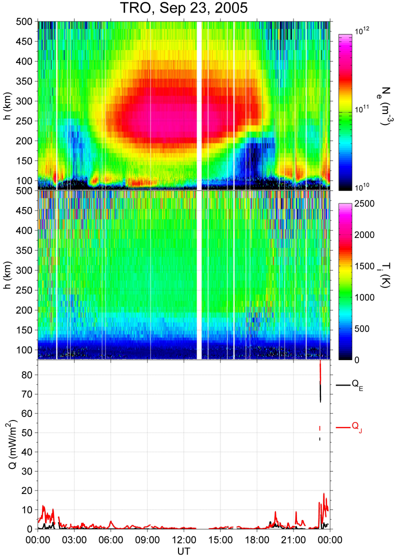


Figure : EISCAT Tromso UHF radar measurement: Ne (top), Ti (middle) and Joule heating (bottom). Note the high dayside F-region electron densities. High E-region densities in the evening-night-morning time are associated with particle precipitation.

Some ionospheric phenomena: Sporadic-E layers

- Sporadic-E (Es) layers are thin (a few km) layers of high Ne in the E region.
- They can be formed by the wind shear mechanism or the electric field mechanism.
- The basic process behind both of them is that plasma is compressed into a thin layer. The electric field mechanism is efficient at high latitudes, but at mid and low latitudes the wind shear is the main mechanism.
- The ions that form the layer must be metallic ions, which have high enough life times so that they can be compressed before they recombine.

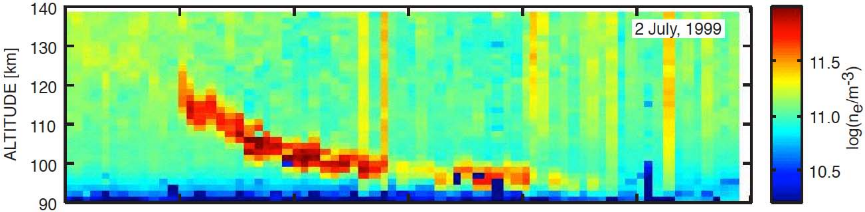


Figure : Es-layer measured by the EISCAT Svalbard radar (duration about 1.5 h).

Some ionospheric phenomena: Equatorial fountain effect

- A small eastward daytime electric field is present in the ionosphere above the magnetic equator.
- In the F region, this electric field creates an $\mathbf{E} \times \mathbf{B}/B^2$ drift and since the magnetic field points northwards, the drift is upwards.
- The electric field can lift the F region plasma to very high altitudes, where recombination is slow.
- The plasma hoisted by the electric field to great heights starts to flow down along the geomagnetic field lines to higher latitudes under the forces of gravity and pressure gradients => *fountain effect*.

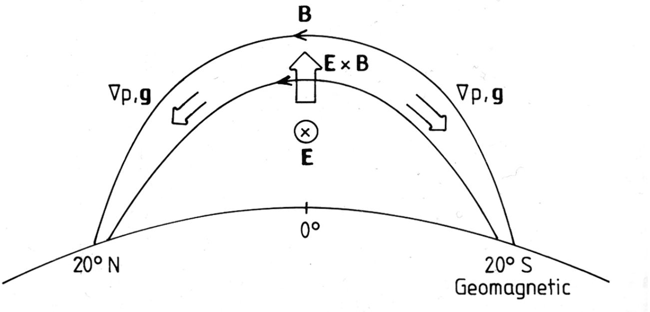


Figure : Schematic figure of the equatorial fountain effect (Kelley, 2003).

Some ionospheric phenomena: Equatorial fountain effect

- The result is that Ne in the equatorial F-region is smaller than on both sides of the equator => *equatorial anomaly*

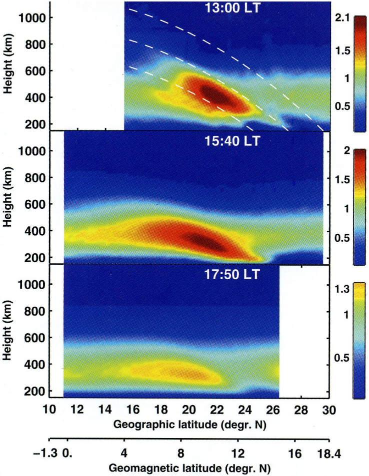


Figure : Electron densities measured by satellite radiotomography.

IS radars and the global ionosphere

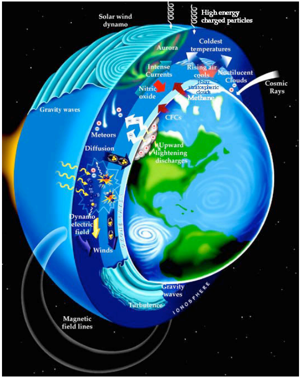


Figure : Global phenomena.

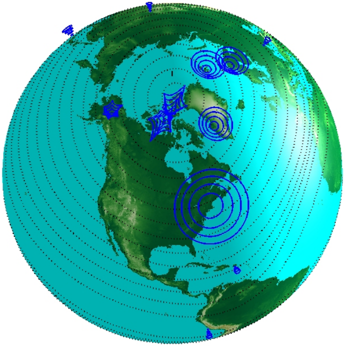


Figure : Global IS radars (figure by C. Heinselman).

Literature

- Brekke, A.: *Physics of the Upper Atmosphere*, John Wiley & Sons, 1997.
- Hunsucker, R. D. and J. K. Hargreaves, *The High-Latitude Ionosphere and its Effects on Radio Propagation*, Cambridge University Press, 2003.
- Kelley, M. C.: *The Earth's Ionosphere*, Academic Press, 1989.
- R. W. Schunk and A. F. Nagy, *Ionospheres – Physics, Plasma Physics, and Chemistry*, Cambridge University Press, 2000.
- H. Risbeth and O. K. Garriot: *Introduction to Ionospheric Physics*, Academic Press, 1969.