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 the ionosphere's existence was confirmed).

Invention of the ionosphere

- G. Marconi received the first trans-Atlantic radio signal (500 kHz, MF) in Newfoundland in 1901 sent from Cornwall, UK (Nobel Prize in Physics in 1909).
- O. Heaviside (UK) and A. Kennelly (USA) suggested independently in 1902, that the radio waves had been reflected by a layer of ionised gas (so-called Heaviside layer).
- Edward V. Appleton was awarded a Nobel Prize in 1947 for his work related to radiowave propagation in the ionosphere.
- The term ionosphere was taken into use about 1932.

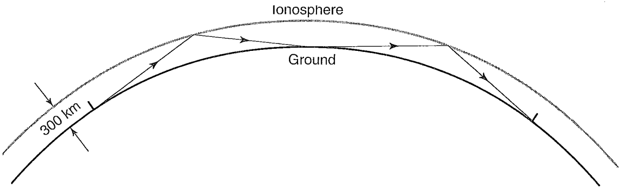


Figure: Long distance propagation of MF signal by multiple hops between the ionosphere and the ground.

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

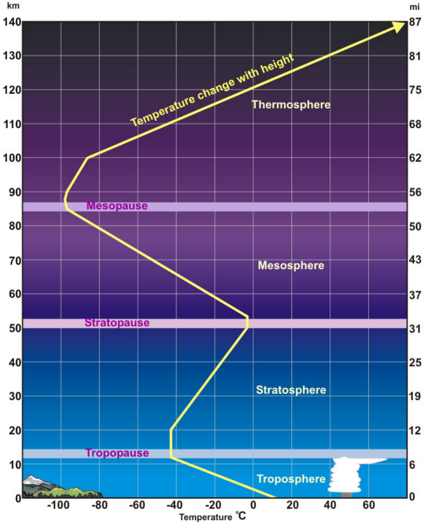


Figure: Atmospheric temperature profile.

- 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

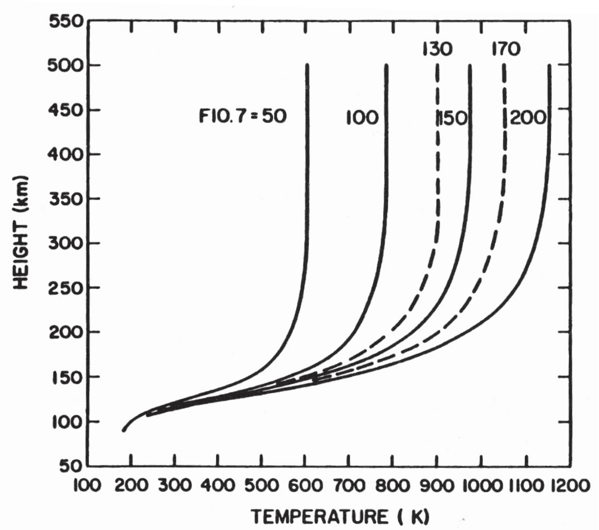


Figure: The variability in the thermospheric temperature for different values of the solar radio flux index $F_{10.7}$ in units of 10^{-22} $\mathrm{Wm}^{-2}\mathrm{Hz}^{-1}$ at 1 AU.

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 composition

- Above about 100 km altitude, each molecular species distribute with height independently of the other species, according to its own scale height => At great altitudes light molecular species dominate.

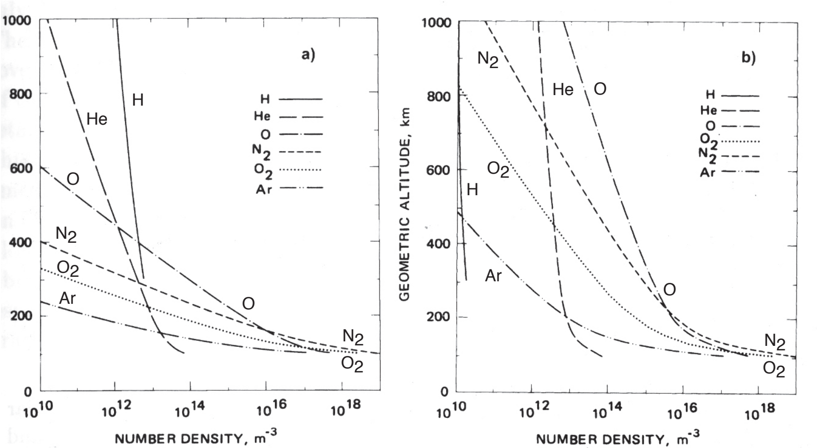


Figure: Atmospheric composition during (a) solar minimum and (b) solar maximum (U.S. Standard atmosphere, 1976).

- Ionosphere

  In the solar corona, solar wind and in 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

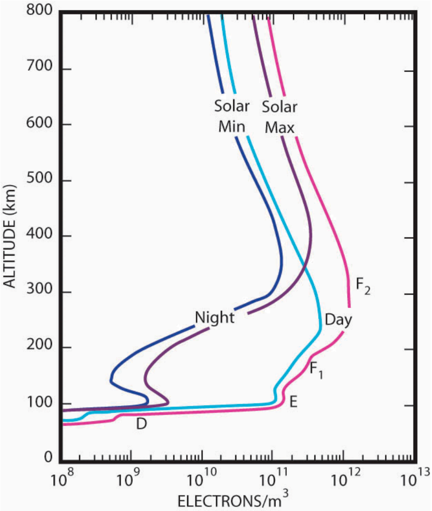


Figure: Typical ionospheric electron density profiles.

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

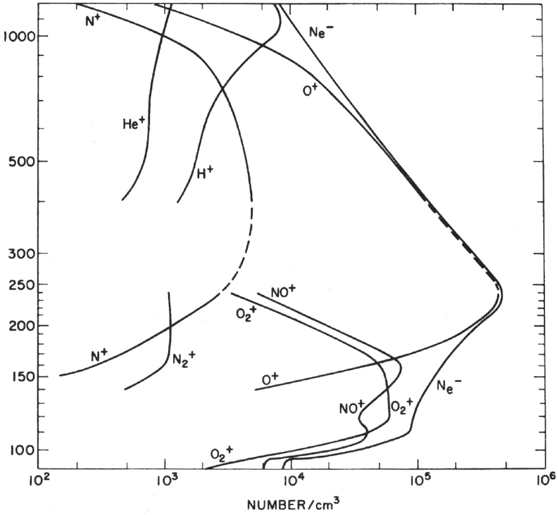


Figure: Daytime solar minimum ion profiles.

- 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

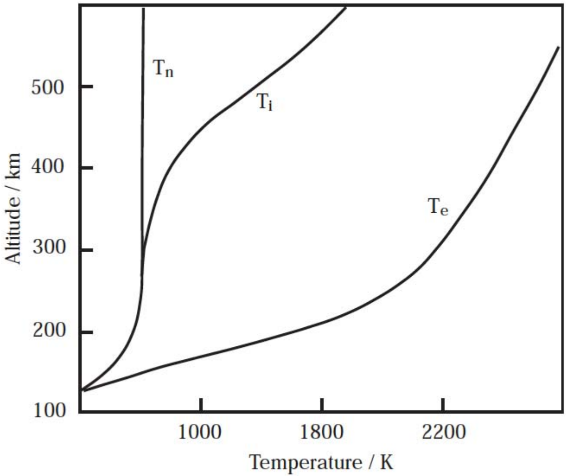


Figure: An example of neutral (Tn), ion (Ti) and electron (Te) temperature profiles.

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 equation:

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

where $\mathbf{v}_{i,e}$ is the ion or electron velocity, q is the production rate per unit volume and l the loss rate per unit volume; and the momentum equations:

$$\begin{aligned} n_i m_i \left(\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla\right)\mathbf{v}_i &= n_i m_i \mathbf{g} + e n_i(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \nabla p_i - n_i m_i \nu_i(\mathbf{v}_i - \mathbf{u}) \quad (6) \\ n_e m_e \left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right)\mathbf{v}_e &= n_e m_e \mathbf{g} - e n_e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e - n_e m_e \nu_e(\mathbf{v}_e - \mathbf{u}) \quad (7) \end{aligned}$$

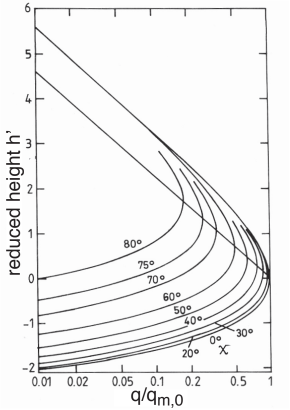
where **E** is electric field, **B** is magnetic induction, p_i and p_e are the pressures of the ion and electron gas, and the ion-neutral and electron-neutral collision frequencies are denoted by ν_i and ν_e, respectively. By solving these equations, we can obtain e.g. the electrical conductivities of the ionosphere.

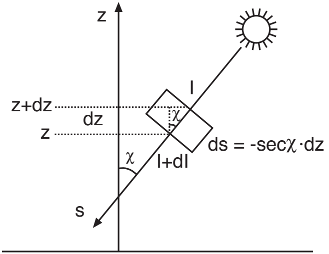
Ionization source: solar radiation

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

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

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: electron precipitation

- Higher energy electrons deposit the energy at lower altitudes.

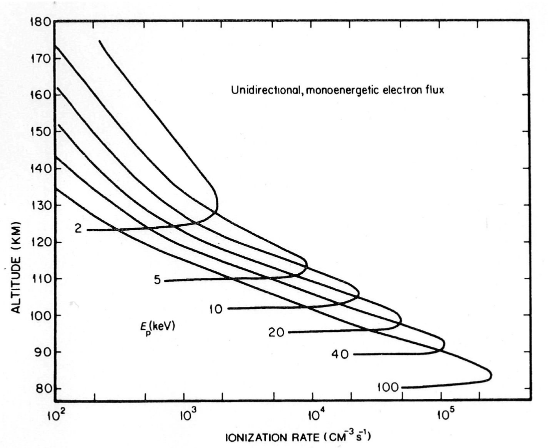


Figure: Ionization rate for monoenergetic electrons with energies 2–100 keV.

Ionization source: proton precipitation

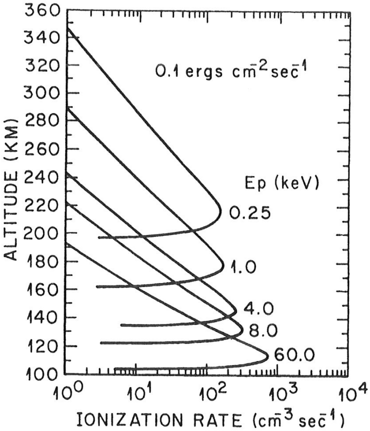


Figure: Ionization rate for monoenergetic protons with energies 0.25–60 keV (Rees, 1982).

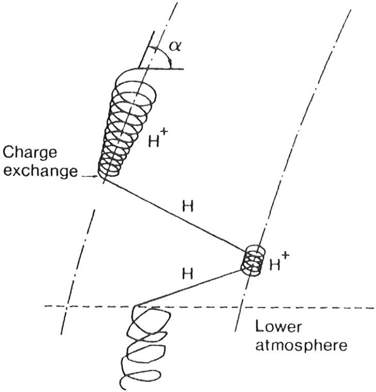


Figure: Protons may make charge exchange with neutral hydrogen.

Ionization loss

Electrons may recombine directly with positive ions to make neutral atoms or molecules in the radiative recombination

$$X^{+} + e \longrightarrow X + h\nu \tag{8}$$

which leads to a production of a photon.
Another possibility is dissociative recombination of a diatomic ions according to the reaction

$$XY^{+} + e \longrightarrow X + Y \ . \tag{9}$$

The conservation laws are more easily satisfied by this reaction which produces two neutral atoms.

Recombination time constants depend greatly on altitude and background conditions. In the E region the recombination time is order of seconds to tens of seconds and in the F region even hours.

High latitudes: Auroral oval and the polar cap

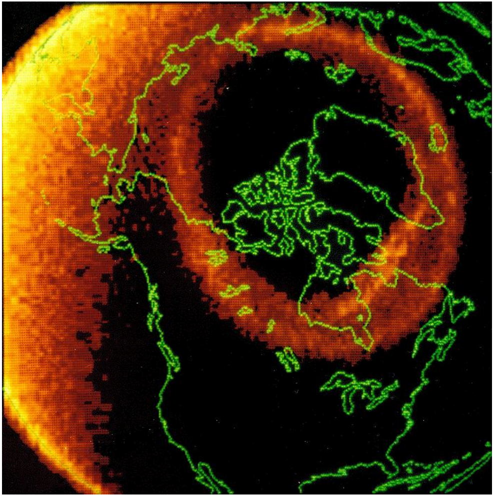


Figure: The instantaneous auroral oval in visible light measured by the DE-1 satellite at an altitude of 20 000 km. The auroral ovals (one for each hemisphere) are luminous bands centered near 67° MLAT at magnetic midnight and near 77° MLAT near noon. The polar cap is located inside the oval.

Ionosphere at high, middle and low latitudes

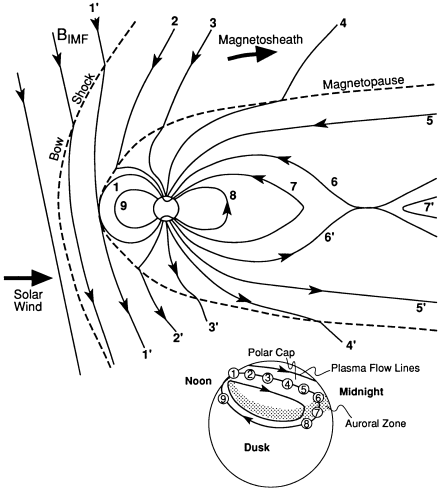


Figure: IMF coupling to the magnetosphere.

- 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 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.

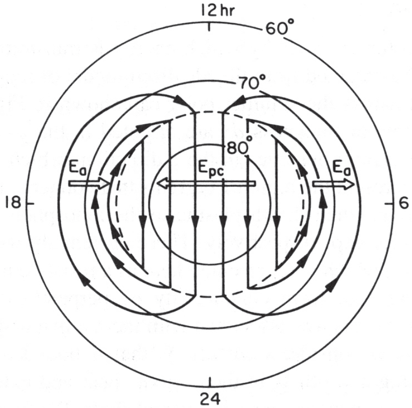


Figure: Plasma convection in the northern high latitude ionosphere and associated convection electric fields.

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.

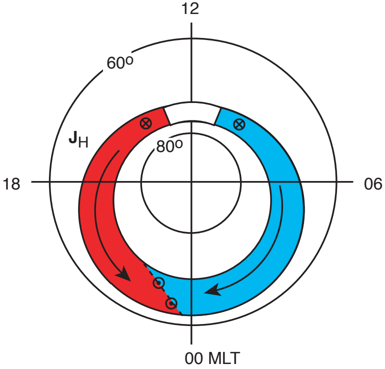


Figure: Hall currents within the auroral oval: eastward electrojet (red) and westward electrojet (blue).

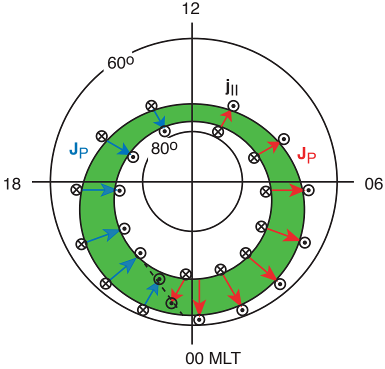


Figure: Pedersen and field-aligned currents within the auroral oval.

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

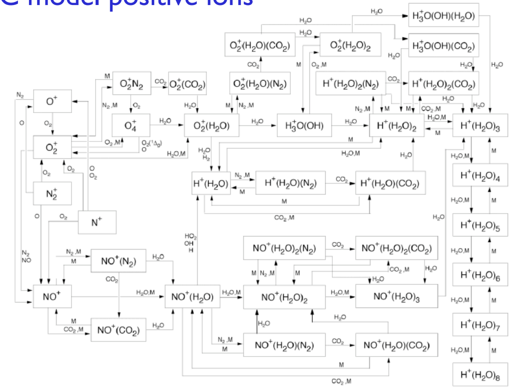


Figure: Sodankyla Ion Chemistry model (SIC), positive ions.

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

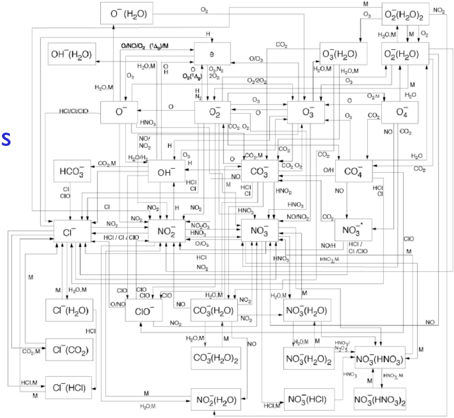
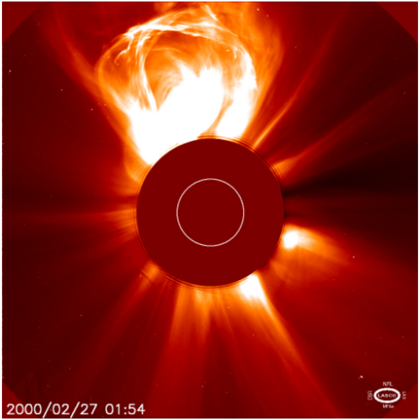


Figure: Sodankyla Ion Chemistry model (SIC), negative ions.

Space Weather conditions affect the ionosphere

- Coronal mass ejections (CMEs) are huge explosions of plasma and magnetic field from the Sun's corona.
- High-speed streams (HSSs) originate from the coronal holes on the Sun and last for several days.
- CMEs are more common during sunspot maxima and HSSs during the declining phase of the solar cycle.



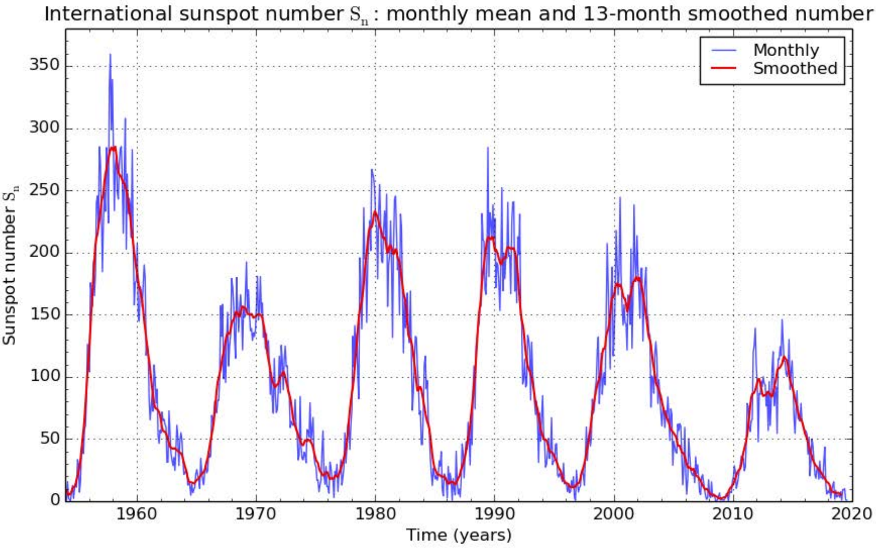
- Both CMEs and HSSs may produce geomagnetic substorms and storms that are associated with auroras and intense high-latitude electric fields.
- One crucial factor for production of geomagnetic effects is the direction of the Interplanetary Magnetic Field (IMF) that should have a southward direction (Bz negative).
- Geomagnetic disturbance level is monitored e.g. by the 3-h Kp index (0-9) or by the AE index.

Figure: CME leaving the Sun measured by the SOHO satellite, with the Sun (inner circle) behind the occulting disc.

Magnetospheric substorms

When the IMF B_z turns toward south (i.e. in the GSM coordinate system it becomes negative, a lot of solar wind energy can enter the Earth's magnetosphere via dayside magnetic reconnection process (see the video).

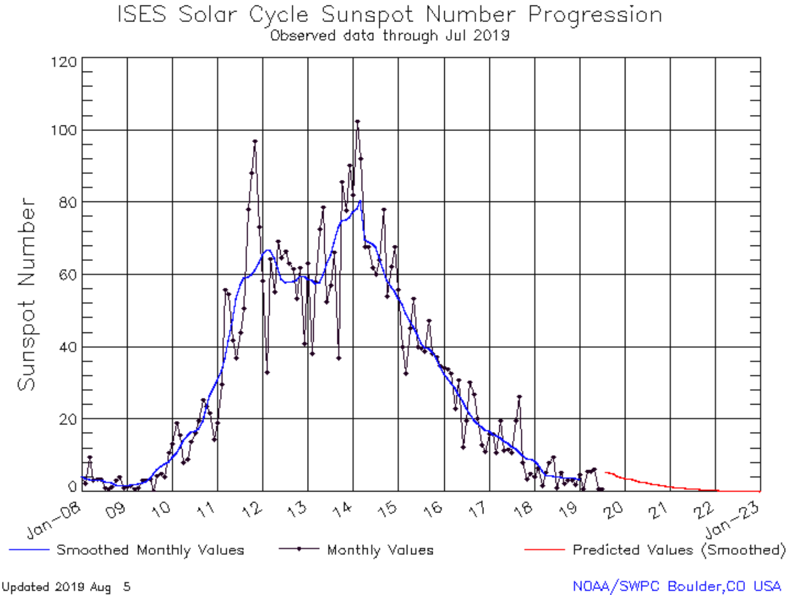
11-year cycle of solar activity



SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2019 August 1

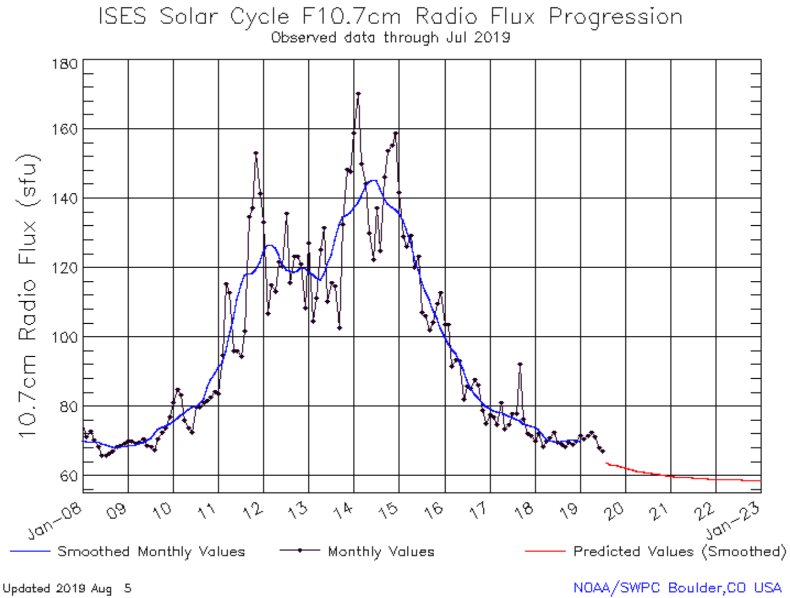
Current solar activity, sunspot number

- We are close to the end (minimum) the current solar cycle (SC) 24.



Current solar activity, F10.7cm solar radio flux

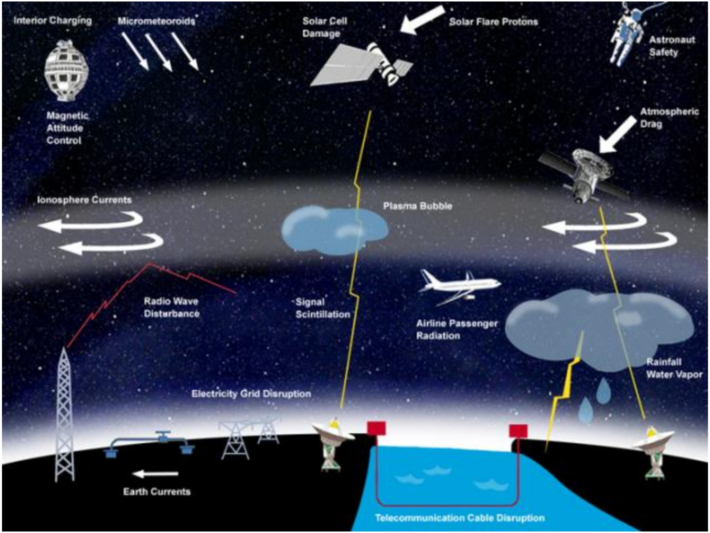
- F10.7 index follows closely the sunspot number.



Motivation, Broader view - Question

What kind of Space Weather disturbances can take place in the geospace environment?

Space Weather disturbances



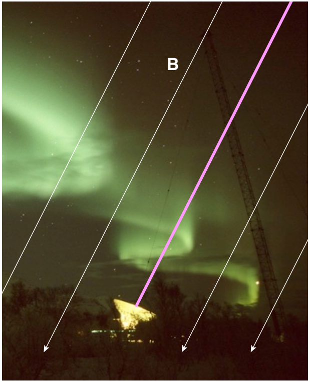
Suggestion, to be done during your own radar experiment

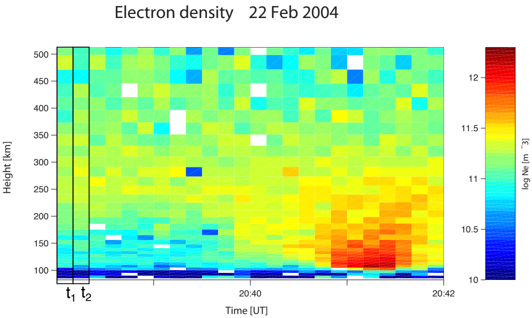
Check the solar wind and geomagnetic acitivity conditions from http://www.spaceweather.com/:

- Solar wind speed (average value is 350 km/s, varies between 270 km/s to over 1000 km/s in extreme cases)
- Sunspot number and Solar Radio Flux F10.7 index
- Whether any X-ray flares have taken place from the Sun (X and M scale flares are the largest and second largest events)
- IMF Bz value and direction
- Kp index

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 or antenna is pointed at low elevation.




Electron density 22 Feb 2004

Tromsö UHF Az=543.99 El=77.1

Example of 24-h high-latitude measurement

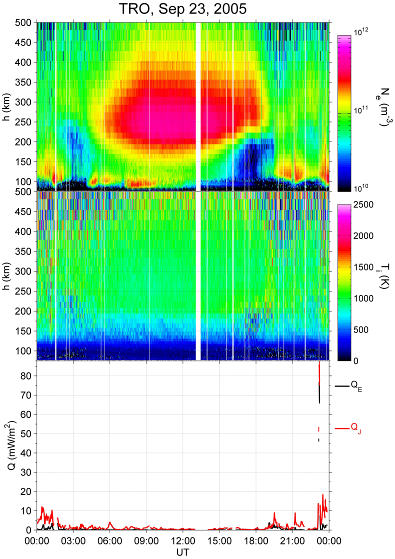
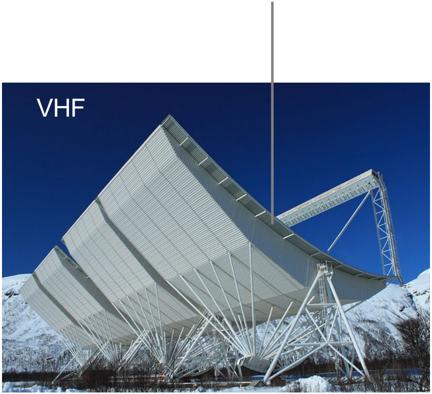
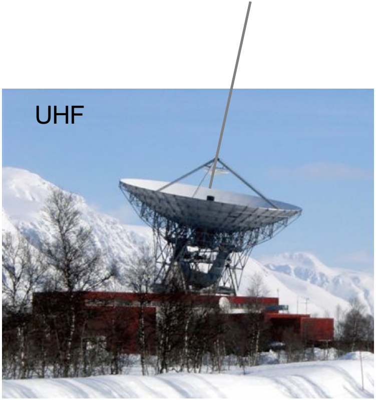


Figure: EISCAT Tromso UHF radar measurement: Ne (top), Ti (middle) and Joule heating (bottom). Note the high dayside F-region electron densities. High E-region densities in the evening-night-morning time are associated with particle precipitation.

EISCAT radars in Tromso

- In Tromso (67° MLAT) we have the VHF radar that can be pointed from the vertical toward low elevation ($\sim 30^\circ$) north and the fully steerable UHF radar (can be pointed also along **B**). In addition, KIR and SOD receivers can make tristatic (vector) measurements with the VHF radar from a selected altitude (typically in the F region).





EISCAT radar on Svalbard (ESR)

- On Svalbard (75° MLAT) the UHF radar has two antennas, the fixed 42m-diameter antenna pointing along **B** (almost vertically upward) and the fully steerable 32m antenna.

IS radars and the global ionosphere

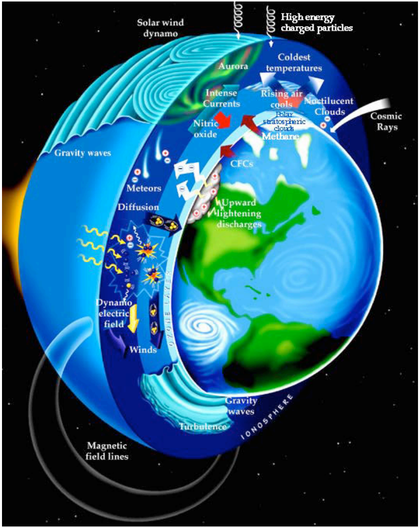


Figure: Global phenomena.

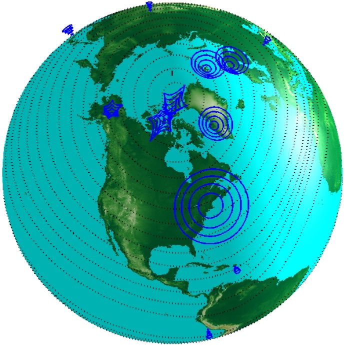


Figure: Global IS radars (figure by C. Heinselman).

Notice

Please notice that all the figures and diagrams shown in this Introduction are SCHEMATIC and reality is much more complex. The plasma may not convect in the direction you assumed, the plasma parameters will contain a lot of variability (and you probably don't know if that is of spatial or temporal origin), there might be a lot happening that you (or anyone else) don't have a clue of... That's why we still need to make research of the dynamics of the ionosphere!

Task (solution given tomorrow morning)

Based on your groups previous experience, try to guess to which phenomena the following plots are related. Labels "UHF" and "VHF" refer to Tromsø radars (67 MLAT) and "ESR" to EISCAT Svalbard radar (75 MLAT). Pay attention to the radar antenna mode, which are the following:

A Azimuth and elevation scan
B Elevation scan along meridian
C Field-aligned (along the external magnetic field)
D Field-aligned
E Field-aligned
F Vertical

Literature

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