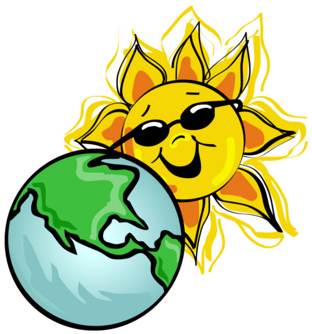


Joule Heating in the Thermosphere Caused by Large-Scale Field-Aligned Currents

Dimitar Danov [1], *Petko Nenovski* [2]

[1] *Space Research and Technology Institute (SRTI), Sofia, Bulgaria*
[2] *National Institute for Geophysics, Geodesy and Geography, Sofia, Bulgaria*

Abstract

The electromagnetic energy flux between the magnetosphere and ionosphere consists mainly of field-aligned currents (FAC), *Auroral Particle Precipitation* and wave processes. On other side, the neutral atmosphere (the thermosphere) can have significant influence on the ionospheric electrodynamics. *Joule Heating*, is the most thermodynamically important process dissipating energy from the magnetosphere to thermosphere.

While the electron concentration and electron temperature are caused mainly by ionization and heating processes due to the particle precipitation, the ion temperature disturbances are influenced strongly by Joule heating of the ions due to the electric field/field-aligned current in the polar ionosphere. As expected the ionospheric disturbances have appreciable magnitudes at the geomagnetic latitudes 68°-85° depending on the solar wind velocity and the IMF orientation. The thermospheric disturbances propagate to lower latitudes as traveling ionospheric disturbances (TID) and/or large-scale atmospheric gravity waves.

We suggest a new formula for the local Joile heating.

Introduction
Energy Balance in the Thermosphere

- ***Solar Radiation*** in the Extreme Ultraviolet part of the spectrum (10-100 nm) is the key energy source in the thermosphere on the day site.
- ***Joule Heating*** is the most thermodynamically important process dissipating energy from the magnetosphere
- ***Auroral Particle Precipitation*** is the second most important heat source in the lower thermosphere, after solar EUV energy;
- ***Sprites and Transient Luminous Events*** (TLEs) can reach altitudes of the ionospheric E-region, and can thus be important by possibly depositing large amounts of energy into the mesosphere and lower thermosphere.
- The main ***cooling agents*** in the thermosphere are CO_2 at 15 μm and NO at 5.3 μm together with chemical heating of various molecules(atomic oxygen is a player in most ***heating processes***)

A major component that is poorly defined among the above energy sources is **Joule heating** (at high- and mid-latitudes this can dominate over all other energy sources). To date, the techniques that were developed to estimate Joule heating produced wildly varying results.

Joule heating is the phenomenon in which the drift energy of ions in the thermosphere and in the high-latitude ionosphere turns into thermal and kinetic energy of neutrals. Joule heating is known to be one of the major energy sources of the upper atmosphere, in particular during solar storm times. Joule heating is considered to be the most thermodynamically important process dissipating energy from the magnetosphere. It is thought that its effects on the upper atmosphere are much more significant than Energetic and Auroral Particle Precipitation.

Methods for Calculating Joule Heating

- from the product of the electric field and the height-integrated current density, E•J;
- from the product of the height-integrated Pedersen conductivity and the square of the electric field, $\Sigma_P E^2$, where the height-integrated Pedersen conductivity is estimated from models;
- from the Poynting theorem, estimating the field-aligned Poynting flux,

$$S_{II} = \vec{b}.(\vec{E} \times (\vec{B} - \vec{B}_0)/\mu_0$$

, where $\boldsymbol{B_0}$ is the background magnetic field .

Data and assumptions

Field Aligned Currents measured on board of CHAMP satellite and ionosphere parameters measured by EISCAT UHF radar at Tromso were used. Solar Wind (SW) parameters were taken from Word Data Center. Measurements were performed in two time intervals from 9 to 13 UT on July 1, 2008 and from 20 to 24 UT on the same date.

By $j_{II} = -\nabla \vec{J} = -\nabla.(\sum_P \vec{E}_\perp + \sum_H (\vec{b} \times \vec{E}))$ we make the assumption that changes in FAC lead to modification of the horizontal currents (in particular the Pedersen current $\vec{J}_P = \sum_P \vec{E}_\perp$)

By $Q(h) = \sigma_P E_\perp^2$ follows that Joule heating rate $\boldsymbol{Q(h)}$ reaches its peak where the $\boldsymbol{\sigma_P}$ has a maximum. The temperature increase $\boldsymbol{\Delta T(h)}$ should have a maximum at the same place because $\boldsymbol{Q(h)}$=C. $\boldsymbol{\Delta T(h)}$

FAC parameters are dependent on SW parameters $\boldsymbol{P}$, $\boldsymbol{B}_Y$ and $\boldsymbol{B}_Z$, but do not depend on IMF $\boldsymbol{B}_X$

Results

Geomagnetic activity was extremely quiet during the experimental days. Indeed, for the examined period the Kp index was 1 for the 09-12 UT interval and 0+ for the 21-24 UT interval. In particular, on 01 July, 2008 the interplanetary magnetic field (IMF) component B_X changed its magnitude between 5 and +4 nT, while the B_Y and B_Z variations were between 2 and +3 nT (for B_Y) and between -1 and +2 nT (for B_Z) (Fig. 2).

From Figure 2 and Figure 3 we can see that even minor disturbances in IMF $\boldsymbol{B}_Y$ and $\boldsymbol{B}_Z$ may cause strong medium-scale FAC. This has been also confirmed from other FAC measurements made aboard of CHAMP for the period June 30 to July 2, 2008 (similar IMF conditions).

However, other results from the conducted experiment are inconsistent to our preliminary assumptions. The temperature of the thermosphere has a local maximum slightly below the maximum of the electron concentration (h = 200-250 km). We expected it to coincide with the peak of the Pedersen conductivity. (h = 120-150 km)

Discussion

There are authors who starting from the linear relationship between *Pedersen conductivity* $\sigma_P = Ne^2\left[\frac{\nu_{in}}{m_i\left(\nu_{in}^2+\omega_i^2\right)}+\frac{\nu_e}{m_e\left(\nu_e^2+\omega_e^2\right)}\right]$ and the electron concentration ***N*** conclude that both peaks coincide. This conclusion is in fully agreement with the results from our measurements.

We do not agree with them because in the interval 80-400 km electron concentration increased to 10 times (top of Fig.4), while the frequency of collisions decreased more than 1000 times (see Figure 5).

Ionospheric conductivity profiles are shown in Figure 6. The model used is IRI2007, at the geographical coordinates of Tromso. We can see that σ_P reaches its maximum (~5.10^{-4} S/m) at 150 km altitude. On the same graph the parallel conductivity reaches 10^2 S/m in F layer (where is the maximum of electron concentration).

From all of this follows that the Joule heating <u>can not be</u> the reason for the observed local peak in the temperature profile.

To save Joule heating as a cause of heating in the ionosphere F layer, we propose a new formula. As folows: $Q_J = \vec{j}.\vec{E} = \sigma_P E_{\perp}^2 + \sigma_0 E_{\mathrm{II}}^2$ instead of used before $Q_J = \sigma_P E_{\perp}^2$. Making the new formula can be seen in Appendix.

Conclusions

Many aspects of the Joule heating process are not well characterized at all, and estimates of the energy deposition vary greatly depending on the calculation method.

The causal relationship of Joule heating to the thermosphere dynamics remains unresolved.

Acknowledgements

The EISCAT (UHF radar, Tromso) measurements on 30 June-02 July 2008 were supported by EISCAT Trans National Access (TNA) Program.
The authors thank Dr P. Ritter and Dr H. Luehr for providing CHAMP data.

Appendix

Ohm's law for the ionosphere (commonly accepted representation)

$$\vec{j} = \hat{\sigma}.\vec{E} \ldots where \ldots \hat{\sigma} = \begin{bmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix}$$

where

σ_0 – *paralel conductivity*

σ_P – *Pedersen conductivity*

σ_H - *Hall conductivity*

$$\sigma_0 = Ne^2 \left(\frac{1}{m_i \nu_i} + \frac{1}{m_e \nu_e} \right)$$

where

$$\sigma_P = Ne^2 \left[\frac{\nu_i}{m_i\left(\nu_i^2 + \omega_i^2\right)} + \frac{\nu_e}{m_e\left(\nu_e^2 + \omega_e^2\right)} \right]$$

$$\sigma_H = Ne^2 \left[\frac{|\omega_e|}{m_e\left(\nu_e^2 + \omega_e^e\right)} - \frac{\omega_i}{m_i\left(\nu_i^2 + \omega_i^2\right)} \right]$$

where

N :electron density

m_i : mean Ion mass

ω_e : electron cyclotron frequency

$\nu_e = \nu_{en} + \nu_{ei}$ $\quad \nu_i = \nu_{in}$

ν_{ei} : electron - ion collision frequency

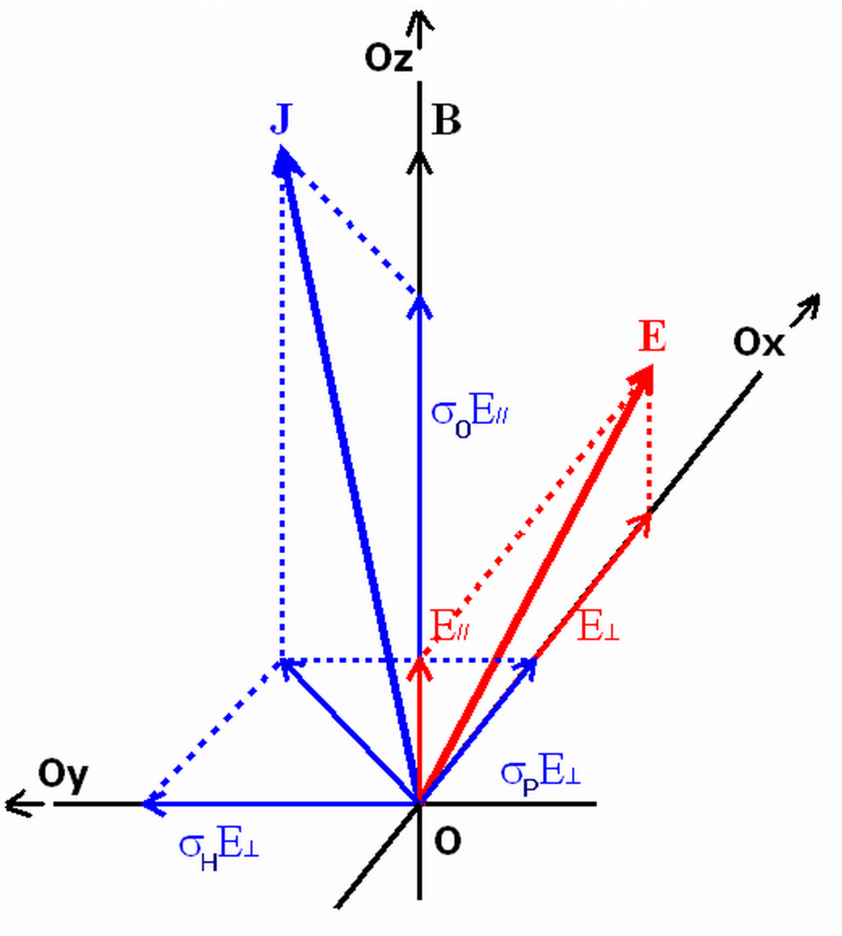
e :a bare electric charge $1.602 \mathrm{x} 10^{-19}$ C

m_e : electron mass (9.109x10^{-31} kg

ω_i : mean ion cyclotron frequency

ν_{en} : ion - neutral collision frequency

ν_{in} : mean ion - neutral collision frequency



It should be noted that the above equations are written in a very special coordinate system (look left).

However **Ohm's law for the ionosphere** is not dependent on the choice of coordinate system.

Let we rewrite Ohm's law for the ionosphere as follows:

$$\vec{j} = \hat{\sigma}.\vec{E} = \begin{bmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix} \bullet \begin{bmatrix} E_\perp \\ 0 \\ E_{II} \end{bmatrix} = \begin{bmatrix} \sigma_P E_\perp & \sigma_H E_\perp & \sigma_0 E_{II} \end{bmatrix}$$

Local *Joule heating rate* **is equal to the scalar product of *current density* and the *electric field*, therefore.**

$$Q(h) = \vec{j}.\vec{E} = \begin{bmatrix} \sigma_P E_\perp & \sigma_H E_\perp & \sigma_0 E_{II} \end{bmatrix} \bullet \begin{bmatrix} E_\perp \\ 0 \\ E_{II} \end{bmatrix} = \sigma_P E_\perp^2 + \sigma_0 E_{II}^2$$

What we wanted to prove. We got the new formula.

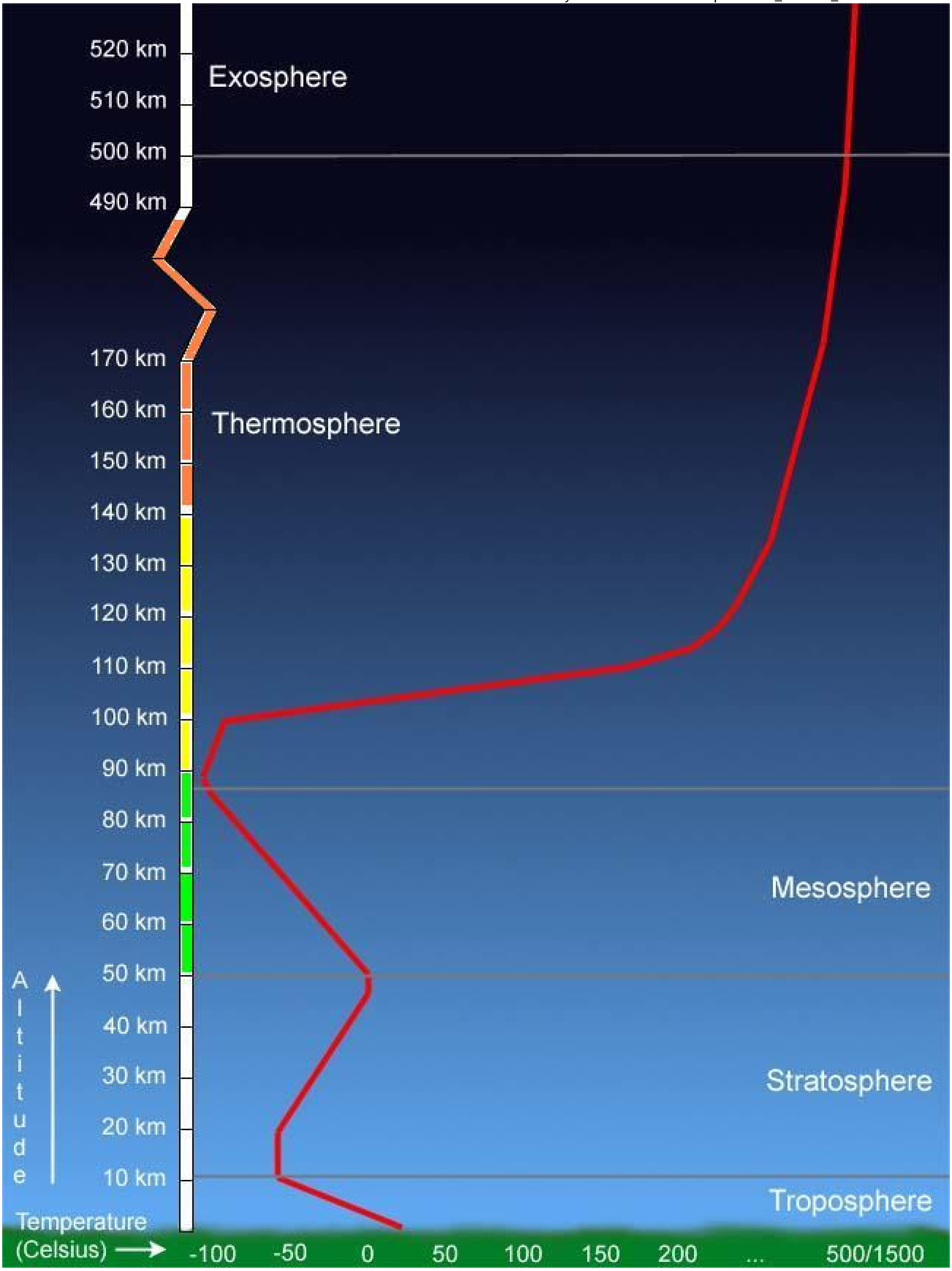


Figure 1. Temperatures climb sharply in the lower thermosphere (below 200 to 300 km altitude), then level off and hold fairly steady with increasing altitude above that height. Solar activity strongly influences temperature in the thermosphere. The thermosphere is typically about 2000 C hotter in the daytime than at night, and roughly 5000C hotter when the Sun is very active than at other times. Temperatures in the upper thermosphere can range from about 5000 C to 2 0000 C or higher.

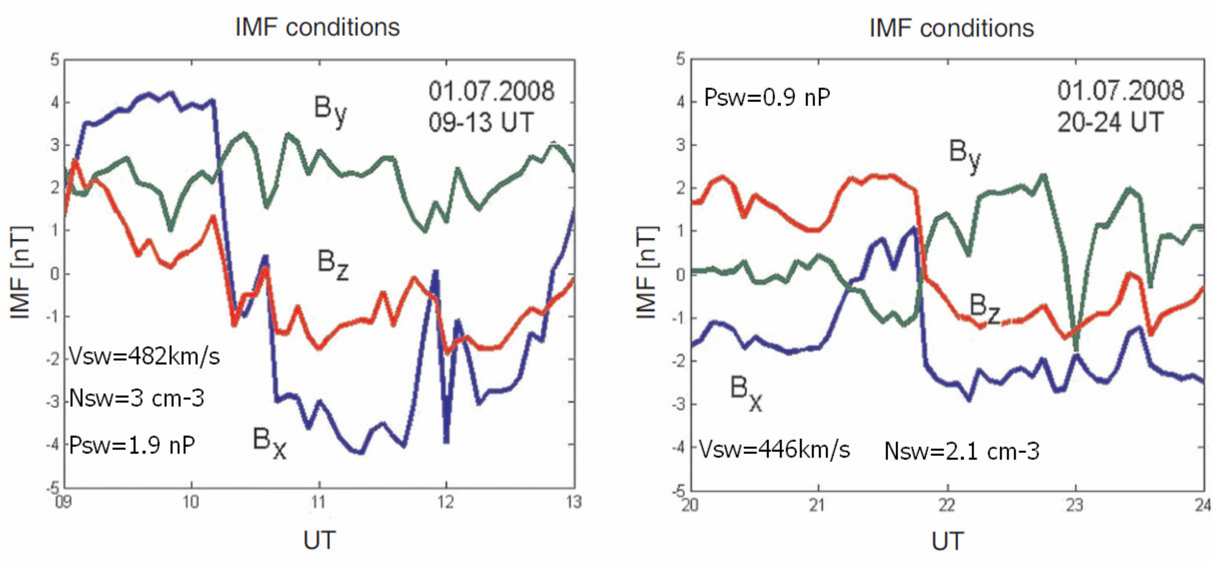


Figure 2. IMF conditions during the experiment

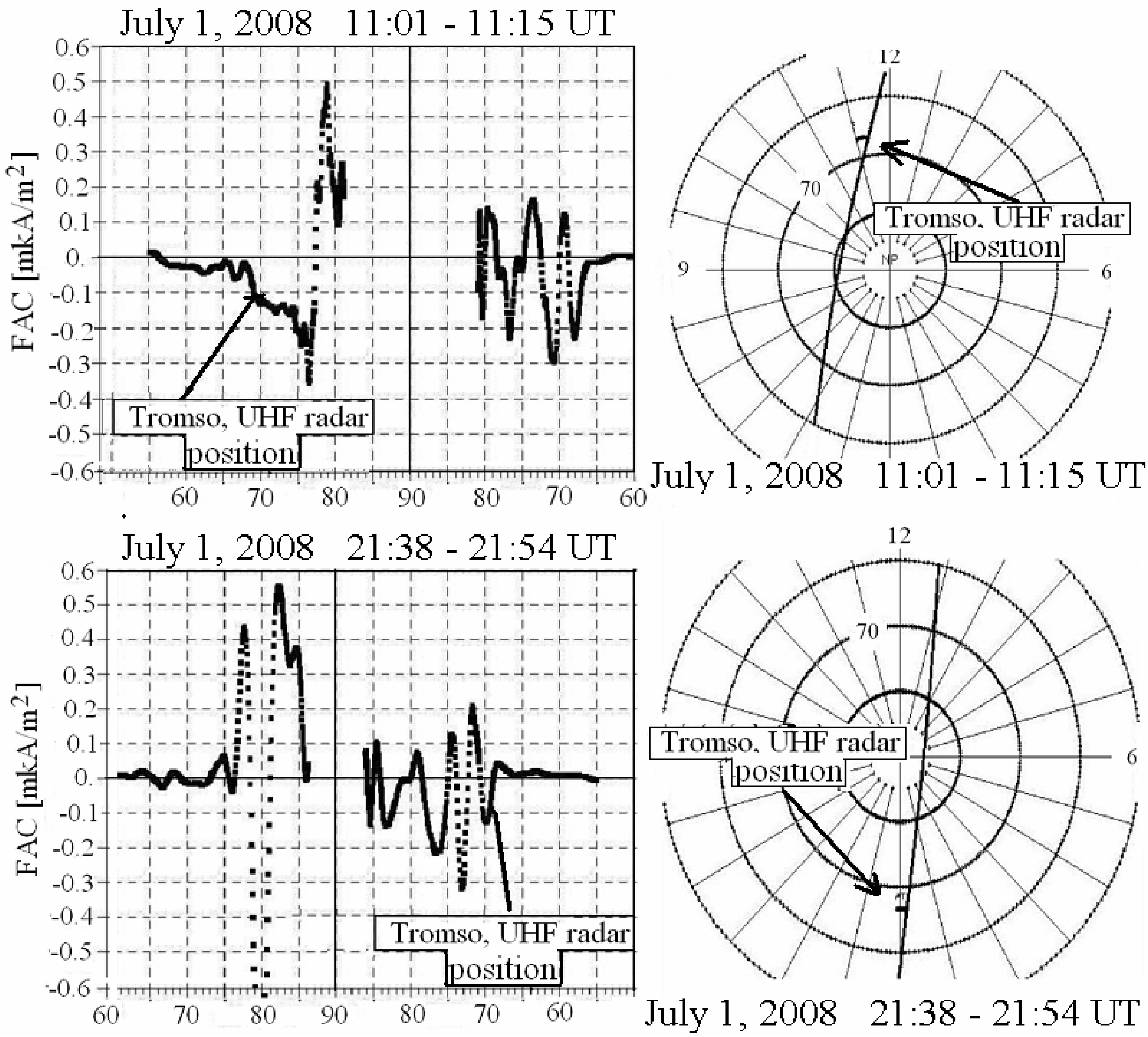


Figure 3. On the left, CHAMP data of the field-aligned currents (FACs) in the Northern hemisphere are shown. On the right the CHAMP orbit crossing Tromso on 01.07. 2008 (evening session) is depicted

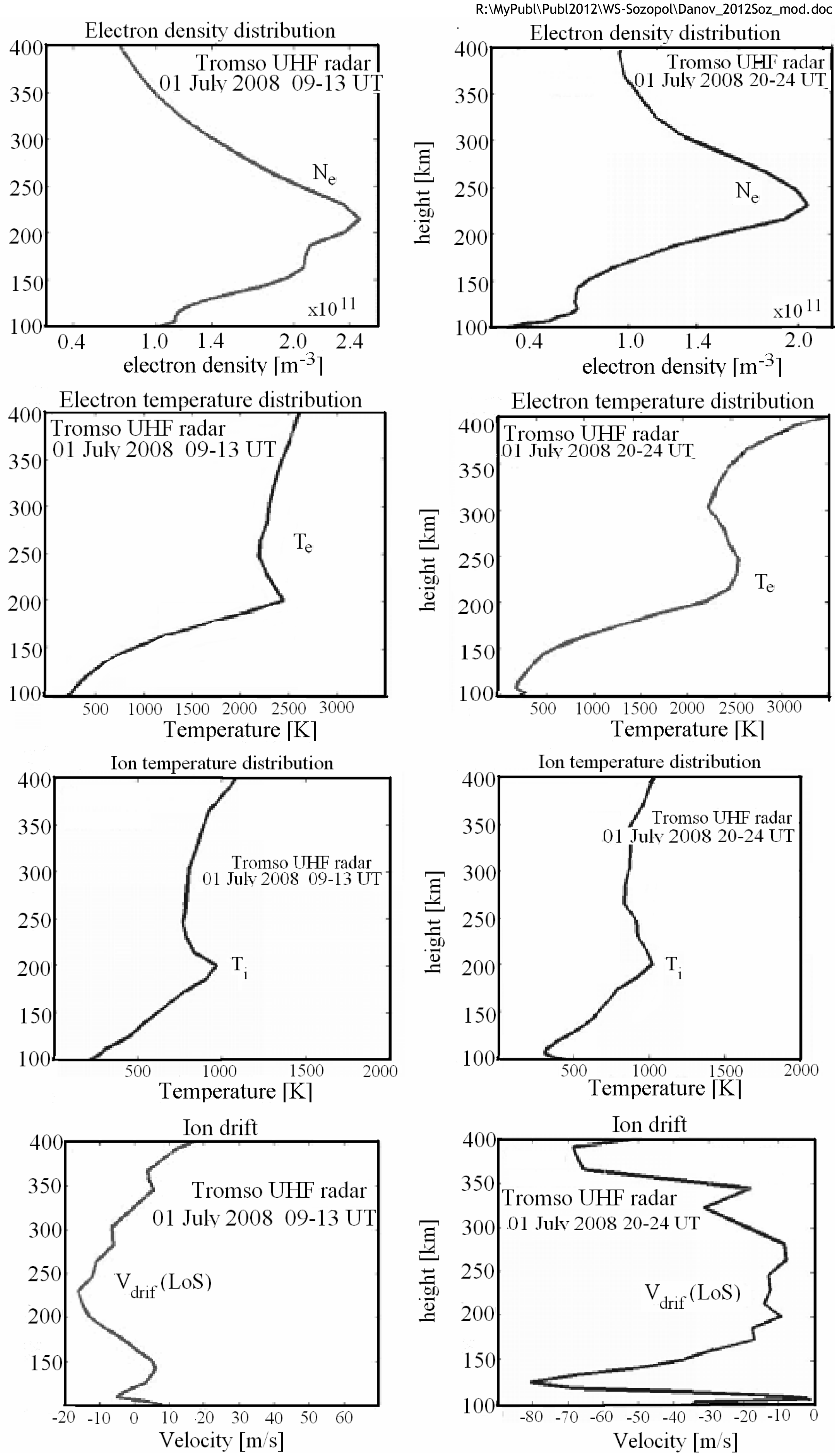

Electron density distribution
Tromso UHF radar
01 July 2008 09-13 UT
N_e
x10^11
electron density [m^-3]
Electron density distribution
Tromso UHF radar
01 July 2008 20-24 UT
height [km]
N_e
x10^11
electron density [m^-3]
Electron temperature distribution
Tromso UHF radar
01 July 2008 09-13 UT
T_e
Temperature [K]
Electron temperature distribution
Tromso UHF radar
01 July 2008 20-24 UT
height [km]
T_e
Temperature [K]
Ion temperature distribution
Tromso UHF radar
01 July 2008 09-13 UT
T_i
Temperature [K]
Ion temperature distribution
Tromso UHF radar
01 July 2008 20-24 UT
height [km]
T_i
Temperature [K]
Ion drift
Tromso UHF radar
01 July 2008 09-13 UT
V_drif (LoS)
Velocity [m/s]
Ion drift
Tromso UHF radar
01 July 2008 20-24 UT
height [km]
V_drif (LoS)
Velocity [m/s]

Figure 4. Ionospheric parameters distribution in height on 01.07.2008 for each of the mentioned four quantities is demonstrated. Only interval 100-400 km is depicted.

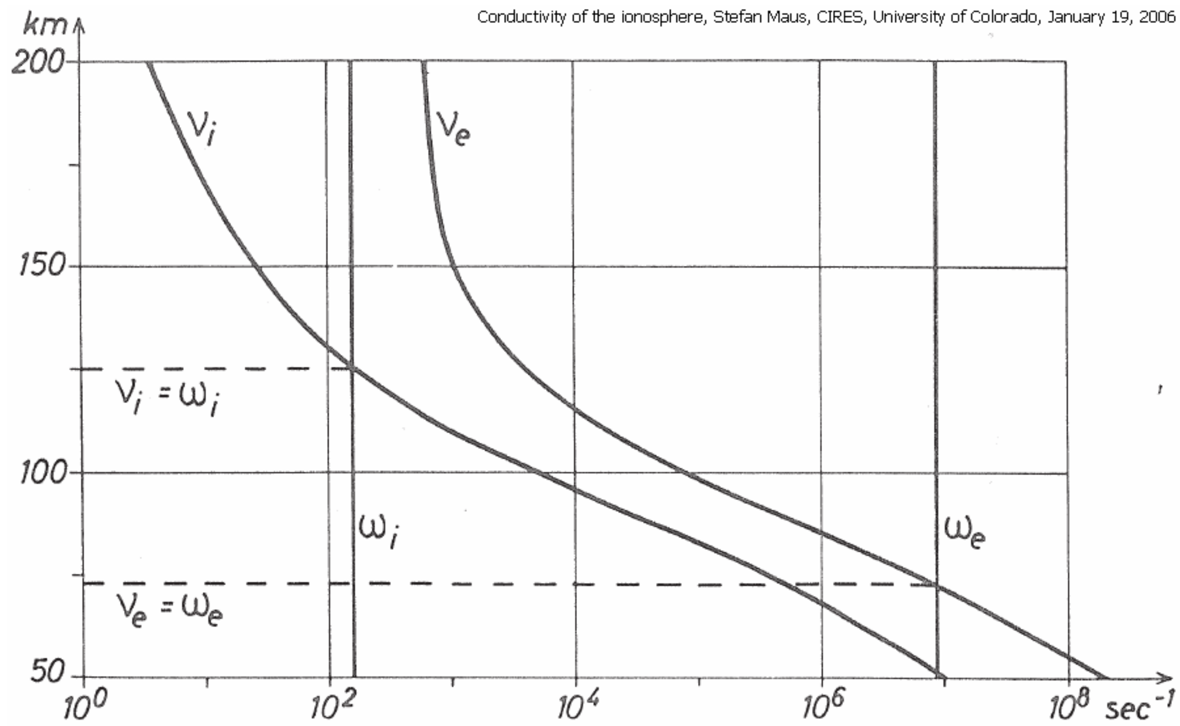


Figure 5. Day side vertical profile of collision frequencies of ions v_i and electrons v_e in comparison to their gyro-frequencies ω_i ω_e

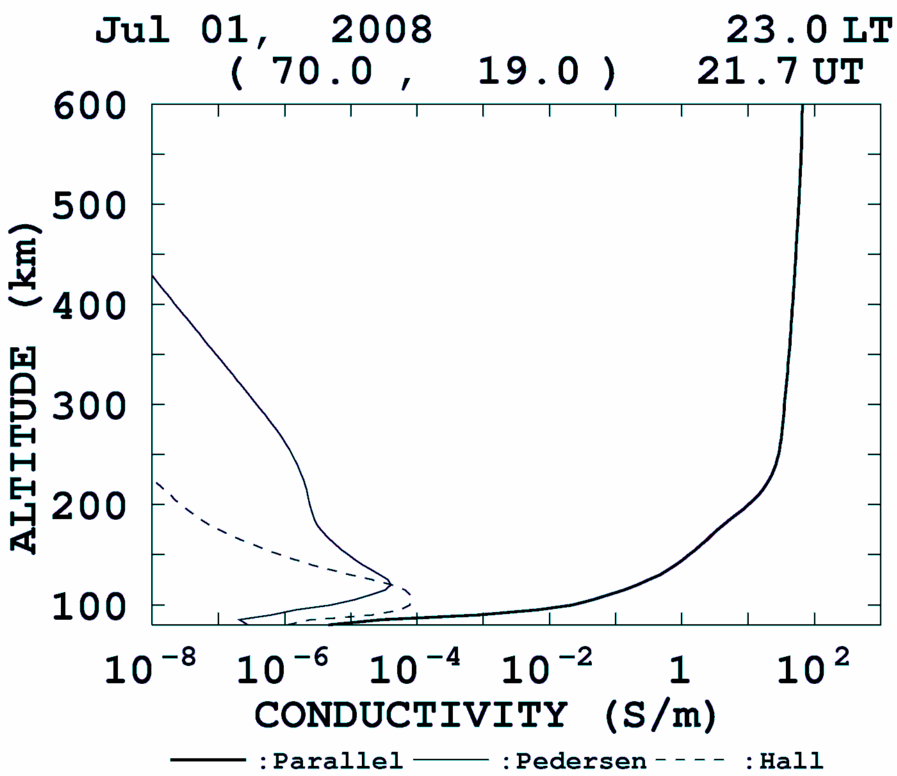


Figure 6 Vertical profiles of Ionospheric conductivity over Tromso at night