FIRST ESTIMATION OF THE SUPRATHERMAL ELECTRON MOMENTUM IN THE UPPER IONOSPHERE

H. Marif[1] and J. Lilensten[2,3]

1 Laboratoire de Physique Théorique, Faculté de Physique, USTHB, Alger

2 Institut de Planétologie et d'Astrophysique de Grenoble, CNRS-UGA

3 Honoray Astronomer, ROB, Brussels

hanmarif@gmail.com

1. Introduction
2. Mathematical model
3. Suprathermal electron momentum
   - (0^{th} order momentum): the supra thermal electron density (in cm^{-3})
   - (1^{st} order momentum): the supra thermal electron velocity (in $cm.s^{-1}$)
   - (2^{d} order momentum): the supra thermal electron temperature (in K)
   - (3^{d} order momentum): the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)
4. Results
   - Low latitude Over Algiers
   - High latitude in the auroral oval

1 Introduction

2 Mathematical model

3 Suprathermal electron momentum

- (0^{th} order momentum): the supra thermal electron density (in cm^{-3})
- (1^{st} order momentum): the supra thermal electron velocity (in $cm.s^{-1}$)
- (2^{d} order momentum): the supra thermal electron temperature (in K)
- (3^{d} order momentum): the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)

4 Results

- Low latitude Over Algiers
- High latitude in the auroral oval

Ionospheric electrons

The ionospheric electron population is divided into two groups.

Ionospheric electrons

The ionospheric electron population is divided into two groups.
The ambient electrons are thermalized.

Ionospheric electrons

The ionospheric electron population is divided into two groups.
The ambient electrons are thermalized.

- Their energy is usually smaller than one electron volt.
- Their densities and temperatures are the usual ones measured by incoherent scatter radars, or modeled by international codes such as IRI.

Ionospheric electrons

The ionospheric electron population is divided into two groups.
The ambient electrons are thermalized.

- Their energy is usually smaller than one electron volt.
- Their densities and temperatures are the usual ones measured by incoherent scatter radars, or modeled by international codes such as IRI.

There is however a second population called *the suprathermal electrons.*

Ionospheric electrons

The ionospheric electron population is divided into two groups.
The ambient electrons are thermalized.

- Their energy is usually smaller than one electron volt.
- Their densities and temperatures are the usual ones measured by incoherent scatter radars, or modeled by international codes such as IRI.

There is however a second population called *the suprathermal electrons.*

- This one is either due to photoionization or to electron impact between the thermosphere and the precipitation in the high latitude zone.
- In the frame of space weather, it may be the source of scintillations, plasma bulks...

Suprathermal electrons

The suprathermal electron population cannot be measured and had never been modeled.

Suprathermal electrons

The suprathermal electron population cannot be measured and had never been modeled.
Its modeling requests the computation of the electrons stationary flux f by solving the Boltzmann transport equation.

Suprathermal electrons

The suprathermal electron population cannot be measured and had never been modeled.
Its modeling requests the computation of the electrons stationary flux f by solving the Boltzmann transport equation.
This flux is multiplied by various powers of the velocity and integrated to obtain the momentums.

Suprathermal electrons

The suprathermal electron population cannot be measured and had never been modeled.
Its modeling requests the computation of the electrons stationary flux f by solving the Boltzmann transport equation.
This flux is multiplied by various powers of the velocity and integrated to obtain the momentums.

- By integrating f over $v^0 f dv$, one deduces the suprathermal electron density (0^{th} order momentum).
- An integration of $v^1 f dv$ allows to compute their mean velocity (1^{st} order momentum).
- Higher momentums give access to their temperature (2^d order momentum) and finally to their heat flux (3^d order momentum).

We demonstrated for the first time the full and rigorous calculation of momentums up to 3, correcting errors that had been made in the literature (which prevented from computing them up to now).

We demonstrated for the first time the full and rigorous calculation of momentums up to 3, correcting errors that had been made in the literature (which prevented from computing them up to now).
As two case studies, we focused on high latitude in the auroral oval and low magnetic latitude over Algiers.

We demonstrated for the first time the full and rigorous calculation of momentums up to 3, correcting errors that had been made in the literature (which prevented from computing them up to now).
As two case studies, we focused on high latitude in the auroral oval and low magnetic latitude over Algiers.
In this presentation, I will

- show briefly the process for the computation of momentums,
- demonstrate the results
- compare them to the thermal electron parameters (density, temperature).

1. Introduction
2. **Mathematical model**
3. Suprathermal electron momentum
   - (0^{th} order momentum): the supra thermal electron density (in cm^{-3})
   - (1^{st} order momentum): the supra thermal electron velocity (in $cm.s^{-1}$)
   - (2^{d} order momentum): the supra thermal electron temperature (in K)
   - (3^{d} order momentum): the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)
4. Results
   - Low latitude Over Algiers
   - High latitude in the auroral oval

Mathematical model

In the ionosphere, primary photoelectrons or precipitating electrons move along the magnetic field.

Mathematical model

In the ionosphere, primary photoelectrons or precipitating electrons move along the magnetic field.
produce heat and provoke processes such as excitation and ionisation.

Mathematical model

In the ionosphere, primary photoelectrons or precipitating electrons move along the magnetic field.
produce heat and provoke processes such as excitation and ionisation.
During these processes, the electrons lose gradually their energy until thermalization with ambient electrons.

Mathematical model

In the ionosphere, primary photoelectrons or precipitating electrons move along the magnetic field.
produce heat and provoke processes such as excitation and ionisation.
During these processes, the electrons lose gradually their energy until thermalization with ambient electrons.
We present the first calculation of the macroscopic parameters of this suprathermal electron population based on the the suprathermal velocity distribution f derived from the stationary flux calculated by the electron kinetic transport model.

Boltzmann distribution function and stationary flux

The Boltzmann equation describes the evolution of these precipitated electrons during collisions with other particles through the stationary electron flux ϕ depending on the altitude z, the electron energy E and pitch angle θ relative to the magnetic field.

Boltzmann distribution function and stationary flux

The Boltzmann equation describes the evolution of these precipitated electrons during collisions with other particles through the stationary electron flux ϕ depending on the altitude z, the electron energy E and pitch angle θ relative to the magnetic field. Classically, the Boltzmann distribution function (in $cm^{-6}s^{3}$) is $f(t, \overrightarrow{r}, \overrightarrow{v})$.

Boltzmann distribution function and stationary flux

The Boltzmann equation describes the evolution of these precipitated electrons during collisions with other particles through the stationary electron flux ϕ depending on the altitude z, the electron energy E and pitch angle θ relative to the magnetic field. Classically, the Boltzmann distribution function (in $cm^{-6}s^{3}$) is $f(t, \overrightarrow{r}, \overrightarrow{v})$.

Which is splitted in velocities parallel and perpendicular to the magnetic field line:

$$\overrightarrow{v} = v_{//}\overrightarrow{i_{//}} + v_{\perp}\overrightarrow{i_{\perp}}$$

Taking into account the following hypothesis:

Boltzmann distribution function and stationary flux

The Boltzmann equation describes the evolution of these precipitated electrons during collisions with other particles through the stationary electron flux ϕ depending on the altitude z, the electron energy E and pitch angle θ relative to the magnetic field. Classically, the Boltzmann distribution function (in $cm^{-6}s^{3}$) is $f(t, \overrightarrow{r}, \overrightarrow{v})$.
Which is splitted in velocities parallel and perpendicular to the magnetic field line:

$$\overrightarrow{v} = v_{//}\overrightarrow{i_{//}} + v_{\perp}\overrightarrow{i_{\perp}}$$

Taking into account the following hypothesis:

- Stationary plasma ($\frac{\partial \varphi}{\partial t} = 0$)
- A plane-parallel atmosphere structure
- No macroscopic electric field in perpendicular direction (oz)
- We are interested in the vertical transport of suprathermal electrons (along the axis (oz) which is the direction of $\vec{B}$.)

Boltzmann distribution function and stationary flux

the Boltzmann distribution function $f(t, \overrightarrow{r}, \overrightarrow{v})$ (in $cm^{-6}s^{3}$) can be simply expressed as $f(z, v_{\perp}, v_{//})$.

Boltzmann distribution function and stationary flux

the Boltzmann distribution function $f(t, \overrightarrow{r}, \overrightarrow{v})$ (in $cm^{-6}s^{3}$) can be simply expressed as $f(z, v_{\perp}, v_{//})$.
It can be also expressed as a function of the suprathermal electrons stationary flux $\phi(z, E, \mu)$ $(cm^{-2}eV^{-1}s^{-1})$ solution of the Boltzmann transport equation:

$$f(z, v_{\perp}, v_{//}) = \frac{m^2}{2E}\phi(z, E, \mu) \quad and \quad 2\pi v_{\perp} dv_{\perp} dv_{//} = 2\pi\sqrt{\frac{2E}{m^3}} d\mu dE$$

Boltzmann distribution function and stationary flux

the Boltzmann distribution function $f(t, \vec{r}, \vec{v})$ (in $cm^{-6}s^{3}$) can be simply expressed as $f(z, v_{\perp}, v_{//})$.
It can be also expressed as a function of the suprathermal electrons stationary flux $\phi(z, E, \mu)$ ($cm^{-2}eV^{-1}s^{-1}$) solution of the Boltzmann transport equation:

$$f(z, v_{\perp}, v_{//}) = \frac{m^2}{2E}\phi(z, E, \mu) \quad and \quad 2\pi v_{\perp} dv_{\perp} dv_{//} = 2\pi\sqrt{\frac{2E}{m^3}} d\mu dE$$

$\mu = \cos(\theta)$ and θ is the angle between the magnetic field line and the electron trajectory (usually also called "pitch angle").

Boltzmann distribution function and stationary flux

the Boltzmann distribution function $f(t, \overrightarrow{r}, \overrightarrow{v})$ (in $cm^{-6}s^{3}$) can be simply expressed as $f(z, v_{\perp}, v_{//})$.
It can be also expressed as a function of the suprathermal electrons stationary flux $\phi(z, E, \mu)$ $(cm^{-2}eV^{-1}s^{-1})$ solution of the Boltzmann transport equation:

$$f(z, v_{\perp}, v_{//}) = \frac{m^2}{2E}\phi(z, E, \mu) \quad and \quad 2\pi v_{\perp} dv_{\perp} dv_{//} = 2\pi\sqrt{\frac{2E}{m^3}}d\mu dE$$

$\mu = \cos(\theta)$ and θ is the angle between the magnetic field line and the electron trajectory (usually also called "pitch angle").
$E = \frac{1}{2}mv^2$ is the non-relativistic electrons kinetic energy and the velocity of the particle is $\overrightarrow{v}$ which is splitted in velocities parallel and perpendicular to the magnetic field line $\overrightarrow{v} = v_{//}\overrightarrow{i_{//}} + v_{\perp}\overrightarrow{i_{\perp}}$.

3 Suprathermal electron momentum

- (0^{th} order momentum): the supra thermal electron density (in cm^{-3})
- (1^{st} order momentum): the supra thermal electron velocity (in $cm.s^{-1}$)
- (2^{d} order momentum): the supra thermal electron temperature (in K)
- (3^{d} order momentum): the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)

(0^{th} order momentum): the supra thermal electron density (in cm^{-3})

In Boltzmann's formalism, the density n(z) (in cm^{-3}) is:

(0th order momentum): the supra thermal electron density (in cm^{-3})

In Boltzmann's formalism, the density n(z) (in cm^{-3}) is:

$$n(z) = \int f(z,v)dv = \int f(z,v_{\perp},v_{//})2\pi v_{\perp}dv_{\perp}dv_{//}$$
$$= 2\pi \iint \sqrt{\frac{m}{2E}}\phi(z,E,\mu)d\mu dE$$

(0^{th} order momentum): the supra thermal electron density (in cm^{-3})

In Boltzmann's formalism, the density n(z) (in cm^{-3}) is:

$$n(z) = \int f(z,v)dv = \int f(z, v_\perp, v_{//}) 2\pi v_\perp dv_\perp dv_{//}$$
$$= 2\pi \iint \sqrt{\frac{m}{2E}} \phi(z, E, \mu) d\mu dE$$

We can now compute the average $< X >$ of any random variable X as :

$$< X > = \frac{1}{n(z)} \int X f(z, v_\perp, v_{//}) 2\pi v_\perp dv_\perp dv_{//}$$

and transform it in the (μ, E) frame using exactly the same method.

(1^{st} order momentums): the supra thermal electron velocity (in $cm.s^{-1}$)

We note that around a full rotation, the average of the perpendicular velocity is null, so that $< v >=< v_{//} >$.

(1^{st} order momentums): the supra thermal electron velocity (in $cm.s^{-1}$)

We note that around a full rotation, the average of the perpendicular velocity is null, so that $< v >=< v_{//} >$.

$$< v >=< v_{//} >= \frac{1}{n(z)} \int v_{//} f(z, v_{\perp}, v_{//}) 2\pi v_{\perp} dv_{\perp} dv_{//}$$
$$= 2\pi \frac{1}{n(z)} \iint \phi(z, E, \mu) \mu d\mu dE$$

2^d order momentum: the supra thermal electron temperature (in K)

The instantaneous velocity of the electrons may be divided in the mean velocity along $\vec{B}$, in relation to the overall or drift motion of the electrons, computed in the previous equation and specific velocity depending on each electron agitating energy: $\overrightarrow{c} = \overrightarrow{v} - \overrightarrow{<v>}$. So

2^d order momentum: the supra thermal electron temperature (in K)

The instantaneous velocity of the electrons may be divided in the mean velocity along $\vec{B}$, in relation to the overall or drift motion of the electrons, computed in the previous equation and specific velocity depending on each electron agitating energy: $\overrightarrow{c} = \overrightarrow{v} - \overrightarrow{<v>}$. So

$$
\begin{aligned}
T &= \frac{m<v^2>}{3k} - \frac{m<v_{//}>^2}{3k}\frac{2\pi}{3k}\frac{1}{n(z)} \\
&= \iint \sqrt{2mE}\phi(z,E,\mu)d\mu dE - \frac{m<v_{//}>^2}{3k}
\end{aligned}
$$

(3^d order momentum: the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)

$$\overrightarrow{q}(z) = \frac{1}{2} n(z) m c^2 \overrightarrow{c}$$

(3^d order momentum: the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)

$$\overrightarrow{q}(z) = \frac{1}{2} n(z) m c^2 \overrightarrow{c}$$

Of the same, since we are going to make a mean by integrating on the Boltzmann function its value is then:
$\chi(z) = < q_{//}(z) > = \chi_1(z) + \chi_2(z) + \chi_3(z) + \chi_4(z) + \chi_5(z)$ where:

(3^d order momentum: the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)

$$\overrightarrow{q}(z) = \frac{1}{2} n(z) m c^2 \overrightarrow{c}$$

Of the same, since we are going to make a mean by integrating on the Boltzmann function its value is then:
$\chi(z) =< q_{//}(z) >= \chi_1(z) + \chi_2(z) + \chi_3(z) + \chi_4(z) + \chi_5(z)$ where:

$$\begin{cases} \chi_1(z) & = \int E\phi_1(z,E)dE \\ \chi_2(z) & = - < v > \int \phi_0(z,E)\sqrt{\frac{m_e}{2E}}dE \\ \chi_3(z) & = \frac{3}{2}m \int \phi_1(z,E)dE \\ \chi_4(z) & = - < v >^3 \frac{m^3}{8} \int \phi_0(z,E)\frac{1}{\sqrt{(E)}}dE \\ \chi_5(z) & = - < v > \int \phi_2(z,E)\sqrt{2m_e E}dE \end{cases}$$

(3^d order momentum: the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)

$$\overrightarrow{q}(z) = \frac{1}{2} n(z) m c^2 \overrightarrow{c}$$

Of the same, since we are going to make a mean by integrating on the Boltzmann function its value is then:

$\chi(z) =< q_{//}(z) >= \chi_1(z) + \chi_2(z) + \chi_3(z) + \chi_4(z) + \chi_5(z)$ where:

$$\begin{cases} \chi_1(z) & = \int E\phi_1(z,E)dE \\ \chi_2(z) & = - < v > \int \phi_0(z,E)\sqrt{\frac{m_e}{2E}}dE \\ \chi_3(z) & = \frac{3}{2} m \int \phi_1(z,E)dE \\ \chi_4(z) & = - < v >^3 \frac{m^3}{8} \int \phi_0(z,E)\frac{1}{\sqrt{(E)}}dE \\ \chi_5(z) & = - < v > \int \phi_2(z,E)\sqrt{2m_e E}dE \end{cases}$$

and $\phi_j(z,E) = \int \mu^j \phi(z,E,\mu)d\mu$

1. Introduction
2. Mathematical model
3. Suprathermal electron momentum
   - (0^{th} order momentum): the supra thermal electron density (in cm^{-3})
   - (1^{st} order momentum): the supra thermal electron velocity (in $cm.s^{-1}$)
   - (2^{d} order momentum): the supra thermal electron temperature (in K)
   - (3^{d} order momentum): the supra thermal electron heat flow (in $eV.cm^{-2}s^{-1}$)
4. **Results**
   - Low latitude Over Algiers
   - High latitude in the auroral oval

Low latitude over Algiers

The solar activity (through F10.7) influences the suprathermal electrons through the neutral atmosphere, through the characteristics of the electron precipitation spectrum and through the initial electromagnetic solar flux.

Low latitude over Algiers

The solar activity (through F10.7) influences the suprathermal electrons through the neutral atmosphere, through the characteristics of the electron precipitation spectrum and through the initial electromagnetic solar flux.
We aim at showing the effect of the solar activity on the suprathermal electron macroscopic parameters.

Low latitude over Algiers

The solar activity (through F10.7) influences the suprathermal electrons through the neutral atmosphere, through the characteristics of the electron precipitation spectrum and through the initial electromagnetic solar flux.

We aim at showing the effect of the solar activity on the suprathermal electron macroscopic parameters.

We present the calculated suprathermal velocity momentums up to the third order, as function of the suprathemal electrons stationary flux calculated by the electron transport code along the Earth magnetic field.

Low latitude over Algiers

The solar activity (through F10.7) influences the suprathermal electrons through the neutral atmosphere, through the characteristics of the electron precipitation spectrum and through the initial electromagnetic solar flux.
We aim at showing the effect of the solar activity on the suprathermal electron macroscopic parameters.
We present the calculated suprathermal velocity momentums up to the third order, as function of the suprathemal electrons stationary flux calculated by the electron transport code along the Earth magnetic field.
The ionospheric parameters used as input to the code have been computed by the IRI 90 and NRLMSISE models.

Low latitude over Algiers

We change the F10.7 index and leave all the other parameters constant. Three values of the solar activity parameter $F10.7 = 80,\ 120\ and\ 300$ are considered.

Low latitude over Algiers

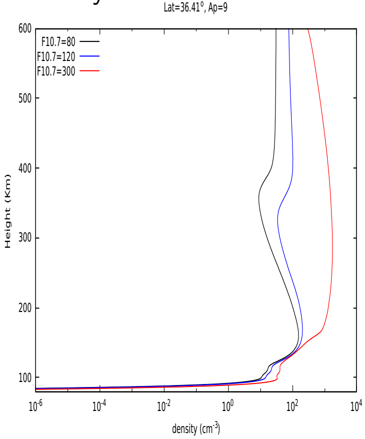
We change the F10.7 index and leave all the other parameters constant.Three values of the solar activity parameter $F10.7 = 80,\ 120\ \textit{and}\ 300$ are considered.
The figures below show suprathermal densities obtained over Algiers (36.41^o of latitude), at 12:00 LT assuming an Ap index of 9 for the three values of F10.7. Thermal densities are also represented for sames geophysical parameters.

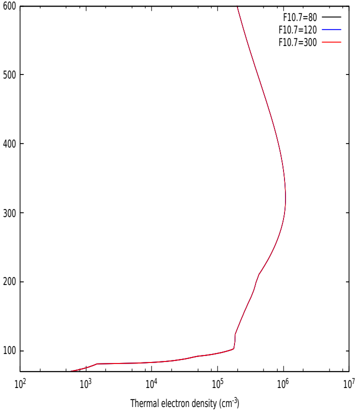
Low latitude over Algiers

- Suprathermal density profiles are almost the same as those of the suprathermal electron productions. They present picks whose values and altitudes increase with increasing solar activity.

Low latitude over Algiers

- Suprathermal density profiles are almost the same as those of the suprathermal electron productions. They present picks whose values and altitudes increase with increasing solar activity.





Low latitude over Algiers

- The sensitivity of the densities to the variation of F10.7 is minimal below the altitude of the picks given the reduction in incident solar flux as one moves deeper into the atmosphere.

Low latitude over Algiers

- The sensitivity of the densities to the variation of F10.7 is minimal below the altitude of the picks given the reduction in incident solar flux as one moves deeper into the atmosphere.
- Any change in solar flux due to the varying solar activity will be minimal in these lower altitude regions thus the photoelectron production will not change much.

Low latitude over Algiers

- The sensitivity of the densities to the variation of F10.7 is minimal below the altitude of the picks given the reduction in incident solar flux as one moves deeper into the atmosphere.
- Any change in solar flux due to the varying solar activity will be minimal in these lower altitude regions thus the photoelectron production will not change much.
- Since secondary production will remain linked to localized primary production this will not change much either.

Low latitude over Algiers

- The sensitivity of the densities to the variation of F10.7 is minimal below the altitude of the picks given the reduction in incident solar flux as one moves deeper into the atmosphere.
- Any change in solar flux due to the varying solar activity will be minimal in these lower altitude regions thus the photoelectron production will not change much.
- Since secondary production will remain linked to localized primary production this will not change much either.
- Hence, at lower altitude regions, the suprathermal electron density changes only slightly as the solar activity advances.

Low latitude over Algiers

- The sensitivity of the densities to the variation of F10.7 is minimal below the altitude of the picks given the reduction in incident solar flux as one moves deeper into the atmosphere.
- Any change in solar flux due to the varying solar activity will be minimal in these lower altitude regions thus the photoelectron production will not change much.
- Since secondary production will remain linked to localized primary production this will not change much either.
- Hence, at lower altitude regions, the suprathermal electron density changes only slightly as the solar activity advances.
- The density profile above the peak will increase as the enhanced solar flux takes effect.

Low latitude over Algiers

- The sensitivity of the densities to the variation of F10.7 is minimal below the altitude of the picks given the reduction in incident solar flux as one moves deeper into the atmosphere.
- Any change in solar flux due to the varying solar activity will be minimal in these lower altitude regions thus the photoelectron production will not change much.
- Since secondary production will remain linked to localized primary production this will not change much either.
- Hence, at lower altitude regions, the suprathermal electron density changes only slightly as the solar activity advances.
- The density profile above the peak will increase as the enhanced solar flux takes effect.
- We would suggest that the effect of enhanced photoelectron transport from the upper altitude regions will produce additional secondary production and the increase in the suprathermal electron density.

Low latitude over Algiers

- The density of the suprathermal electrons is 10^5 ($F10.7 = 80$) to 10^3 ($F10.7 = 300$) times smaller than that of the thermal electrons.

Low latitude over Algiers

- The density of the suprathermal electrons is 10^5 ($F10.7 = 80$) to 10^3 ($F10.7 = 300$) times smaller than that of the thermal electrons.

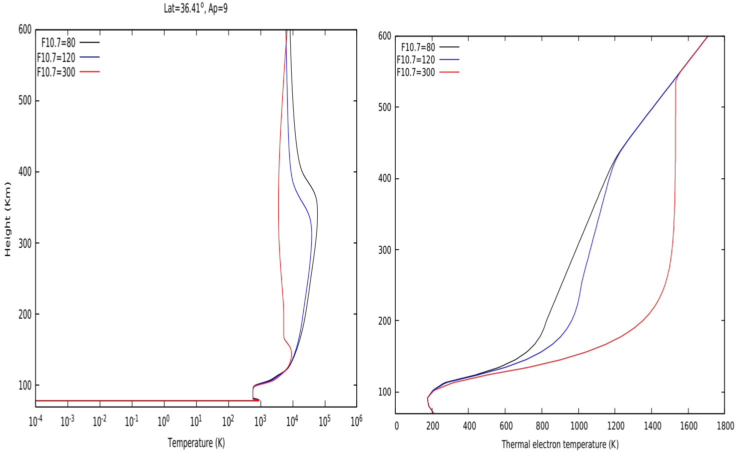
The figures below represent the suprathermal electron temperature, velocity and heat flux for sames geophysical parameters.

Low latitude over Algiers

- Enhancement in the solar activity results in a decrease of the suprathermal electron temperature and velocity above the pick which is in agreement with the density curves.

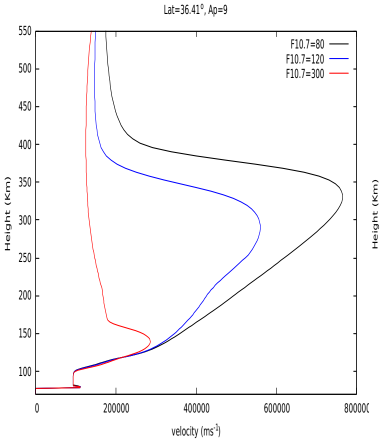
Low latitude over Algiers

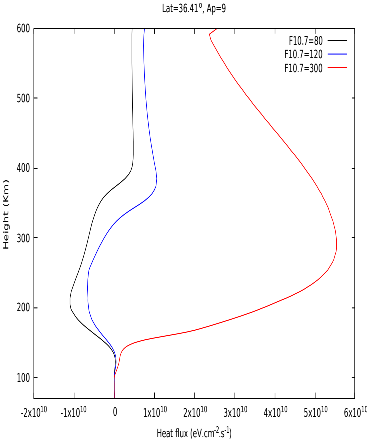
- Enhancement in the solar activity results in a decrease of the suprathermal electron temperature and velocity above the pick which is in agreement with the density curves.



Low latitude over Algiers

- Enhancement in the solar activity results in a decrease of the suprathermal electron temperature and velocity above the pick which is in agreement with the density curves.





High latitude in the auroral oval

For high latitudes, in the presence of electron precipitation, we have varied separately the F10.7 index, the geomagnetic index Ap through the neutral density and temperature, the total energy of the precipitated electrons E_{tot} and the mean energy E_0 of these electrons as well.

High latitude in the auroral oval

For high latitudes, in the presence of electron precipitation, we have varied separately the F10.7 index, the geomagnetic index Ap through the neutral density and temperature, the total energy of the precipitated electrons E_{tot} and the mean energy E_0 of these electrons as well.

Our results show clearly that:

- Macroscopic parameters of the supathermal electrons(density,velocity, temperature and heat flow) are insensitive to the variation of the geomagnetic parameter Ap.
- Suprathermal momentums are very affected by the variation of the solar flux through the F10.7 index, the total and the mean energies of the precipitated electrons.

High latitude in the auroral oval

For high latitudes, in the presence of electron precipitation, we have varied separately the F10.7 index, the geomagnetic index Ap through the neutral density and temperature, the total energy of the precipitated electrons E_{tot} and the mean energy E_0 of these electrons as well.

Our results show clearly that:

- Macroscopic parameters of the supathermal electrons(density,velocity, temperature and heat flow) are insensitive to the variation of the geomagnetic parameter Ap.
- Suprathermal momentums are very affected by the variation of the solar flux through the F10.7 index, the total and the mean energies of the precipitated electrons.
- Suprathermal electron momentums are a good indicator of the variation of solar activity.