NEW PHYSICAL MODEL DESCRIBING THE D IONOSPHERIC LAYER WITHIN THE VLF EXPERIMENT

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Abstract. The present models describing the ionosphere focus mostly on the E and F region, while the D region is marginalized. However, this area can easily be monitored by long-wave radio signals. The measurement has been conducted within so-called VLF experiment which is based on SID monitors, very simple inductive loops measuring the intensity level of radio signals transmitted on a characteristic frequency. Recently, partially in accordance with the experiment, a completely new research group Ionozor has been founded. The idea of the group is based on a creation of a cooperative network which is going to use the SID monitors, Doppler measurement and ionosondes together to get relevant knowledge about the ionosphere and its physical and chemical parameters. We present our recent work done in the field of SID monitors and the ionospheric physics. Our measurement provides us to model the ionospheric response induced by some high-energy phenomena in the Solar System or even in the deep space (e.g. some strong gamma ray bursts). Having described the ionospheric response, we are able to determine the basic attributes of the high-energy phenomena themselves. The basic idea of our model is given and discussed and some interesting results are shown, too. Special attention is now paid to the response caused to happen by meteoric impacts, solar eruptions and coronal mass ejections, Jupiter magnetic storms and radio outbursts in the deep space.

Keywords: astrophysics, radio astronomy, ionosphere, ionospheric response.

1. Introduction

Ionosphere is an atmospheric layer located approximately in the heights from 60 to 1000 kilometers. It's a characteristic region thanks to the low-temperature plasma which is located there. The ionosphere has an essential relevance in spreading the radio signals, for the radio waves are reflected in the layer. This feature is used to investigate the ionospheric plasma, because having determined the quantities of the measured radio signal, we are able to deduce what happens in the ionosphere. This proposition is discussed in the following sections.

The electron content, plasma temperature, the ionization degree and other physical properties of the ionospheric plasma are significantly dependent on the height. The amount of charge particles grows up with increasing height. It is known that the D region is the coldest and sparsest layer of the whole ionosphere because of its location in the lowest heights moving around from 60 to 85 kilometers.

Radicella and Zang [1] studied the electron density height profile and improved the DGR model to determine the total electron content profile, too. However, the model includes only the E and F region, even though the main idea is invariant to the behaviour of the D region. Better asumption was given by Pavelyev et al. [2] who investigated the wave structures in the D and E layer. The model suits well to the described problem, but only the vertical distribution was discussed. To model the ionospheric plasma distribution, both vertical and horizontal trend must be taken into account. The wave structure, moreover, does not need to be dependent only on the behaviour of charge particles, but it can also have a completely electromagnetic character. We modeled some basic kinematics of the system to get over this issue.

There was also a paper by Singh et al. [3], whose goal was to get the knowledge about the ionospheric response on several solar flares. The work done by the research group SID Monitoring Station A118 [4], however, shows that the electron plasma frequencies able to be computed from the results might not be so accurate. Very large scale of frequencies was monitored, but it can be expected that some of them would rather belong to the E layer. The ionosondes provide us to measure the exact height and electron density profile in the E and F layer. Such heights as computed from the results would have already exceeded the D layer.

Our model is based on the electron plasma frequency which can easily be compared with the frequency of the measured radio signal. Using this quantity, the electron density is able to be computed. Solving the appropriate differential equations, such quantites as the Debye radius and the plasma temperature can be determined, too. Within such a model, the ionospheric response caused to happen by some investigated high-energy phenomena was provided to be observed.

2. Model and measurement

In the model, we expect the electron density to be the function of measured radio signal intensity level. Such a quantity can be described as a relative amplitude of the signal and is transformed from the value of voltage induced on the SID monitor. Because of that, the SID monitor inductive coil has to consist of about hundred loops made of enamelled wire to have a good resolution. The coil is the main part of the whole measuring gadget, which is shown in figure 1. The measurement is able to be supplemented within using an amplifier, see figure 2.

Having done such a measurement, we are able to observe the periodical ionospheric variations which depend on the daytime and the ostensible motion of the Sun on the sky.

At night, the D layer does not exist and the only measurable plasma is constituded owing to the fragments of the D and also E regions located in similar heights. The plasma is mostly influenced by the cosmic radiation which does not let the area be completely recombined. Some strong meteoric impacts or gamma ray bursts can be measured in such a system, too.

Starting with the sunrise, the D layer is reconstituded thanks to the ionization potential coming from the solar radiation and also from the solar wind. After that, the intensity ascends until the local midday, when the highest amplitude is observed. In the afternoon, the signal intensity descends right to the sunset when the fast recomabination begins and the D and E regions are both fragmented again, which leads to the fluctuation of remaining charge particles between the former regions in the heights from about 80 to 90 kilometers.

The periodical dependence observed within a real mesurement is shown in figure 3. Radio signal intensity level is given in decibels.

However, we deduced that the periodical changes of the electron content were very small. It can be justified by the low energy of the whole D layer. If E labels the energy given to the system and W the acquired energy, we get the addiction

$$W = E + h(\omega + \mathrm{d}\omega_{,t}).$$

h is the Planck constant and ω is label for the electron plasma frequency. This quantity is described by a simple physical model. If the mass of electrons and heavy ions is compared, it can be deduced that the heavy ions would be almost motionless while the electrons would be oscillating aroound them. Such an oscillation is precisely described by the electron plasma frequency. Its value is dependent only on the current electron density, which can be described by the formula

$$\omega = \sqrt{\frac{n_e e^2}{m\epsilon_0}},$$

where n_e is the electron density and other parameters of the formula, elemental charge, vacuum permitivity and the quiscent mass of the electron are constants.

From the preceding, we are able to determine the relation between the radio signal intensity level and the physical parameters of the ionosphere. It is known that the radio wave is reflected in the height where its energy equals the plasma energy. In the other words, the reflection is dependent on the frequency. Investigating the reflection of a radio wave with the characteristic frequency ν, the relation with the electron plasma frequency is given by a simple equation

$$\nu + \mathrm{d}\nu_{,t} = \omega + \mathrm{d}\omega_{,t,H}.$$

New discovery done within our model is the descripiton of relation between the electron density and the measured radio signal intensity level. Having analysed the data, we were able to assemble a system of differential equations describing the relation within the electron plasma frequency. The resultant form of the equations gives the dependence by a partial differential gear of n_e using the polynomial aproximation within the radio signal intensity level L

$$\frac{\partial n_e}{\partial L} \approx -\frac{1}{4}L^{-4}.$$

The equation is able to be solved and its numerical solutions provides exact differentiation of the electron content including both periodial variations and ionospheric disturbances induced by a high-energy phenomenon. An example of the represented equation given by a real mesurement is shown in appendix, see figure 4.

2.1. Real physical parameters of the D layer

We drew a conclusion that the appropriate differential equations were invariant to the total momentum of the system which describes the discussed periodical and stochastic variations best. Owing to that, the mean electron plasma frequency and its stochastic changes can be computed. It, eventually, provides us to determine the current value of electron density compared in the time, see the appendix.

From the model, we are also able to compute the Debye radius and the both quadratic and cubic dimension of the Debye sphere. It could be said that the Debye radius converges to a constant value.

We were also interested in such quantities like the temperature, plasma parameter and the plasma energy and also in some basic kinematic attributes of electrons. The mean quadratic velocity and the fluctuation scope and the expected value of acceleration were modeled and are able to be determined within the measurement.

Even though that the D region consists of a sparsly-ionized gas, it was proven that the definition of plasma was definitely filled. It can be illustrated using a well-known condition $N_D \gg 1$ for the plasma parameter N_D in the ideal plasma. Measured near the area of the critical frequency of the D layer, the mean value of the plasma parameter approaches to 22.

The physical quantities used to describe the system were modeled by well-know equations ordinarily applied in the plasma physics. Some of the results are discussed more properly in the following sections, see 3. For astronomers, however, the distribution of the ionospheric plasma is interesting, too. To make such a model, both vertical and horizontal plasmatic flow need to be described.

The current height of the D layer is probably the best property describing the horizontal flow. As mentioned, the improved DGR model [1] was used to determine that quantity. The authors recommend to read the cited paper, where other details are given and discussed. However, although the main ratio does not change, some parameters need to have been recounted for the D layer. The resultant equation has the shape

$$H = h_0 + \frac{B \ln\left(\frac{1}{2}\mathrm{d}n_{t,H}\frac{B}{NmD(1-mD)} - \sqrt{\left(\mathrm{d}n_{,H}\frac{B}{NmD(1-mD)}\right)^2 - 4}\right) + 2\pi}{1 - mD}.$$

NmD, mD and B parameters, used to compute the peak electron density, its momental height and to have a well-fitting polynomial ratio, can be computed from the appropriate differential equations, either. Within the outlined system of them, even the incipient height is able to be modeled and determined like

$$h_0 = \frac{\pi B}{2(1 + mD)}.$$

If the momental height is compared with the electron density or its peak values, we get a simple ionogram showing the real-time ionospheric response, which was mentioned to be one of the goals of our research, indeed. An example plot is given in figure 5, where some significant variations caused by a meteoric impacts can be seen.

The vertical drift had already been modeled by several authors, but there was no comparison to real data. To solve such a problem, the disipated energy and the angle between solar rays of light need to be known. It may seem that the model does not take note about other possible impacts except the solar ones, but it fits well to all of them. The solar rays of light are used, because the solar activity is the main source of ionization. However, the disipated energy is solved by a differential gear, so all of the stochastic changes caused to happen by anything are distinguished clearly.

The resultant form of the appropriate initial equation is

$$E_e = \frac{I_\odot}{R^2}\cos\alpha,$$

where $I_\odot \approx -26.74$ is the solar luminosity, R labels the astronomical unit as the mean distance between the Sun and the Earth, α is the angle of falling rays and E_e is the mark for the disipated energy able to be computed from the radio signal intensity level.

If that angle is known, the vertical dimension of the plasmatic drift is up to be approached by the appropriate trigonometric functions. Having done the computation, the whole plasmatic drift in the D layer can be modeled, see figure 6. The focusation and defocusation can both be seen clearly, even within the stron impacts.

The last model which we made to described the D region itself so far refers to the ionization energy level. Some simple molecules, such as nitrogen, oxygen, nitrogen oxides, nitrous acid and carbon dioxide were studied.

It is known that absorbing some energy quantum, the molecule transfers to an excitated state from which it is likely to be fragmented into free radicals. These particles, being excited again, release the energy and discharge readily.

Such a process leads to creation of electron-ion pairs, which can be detected by the SID monitors because radio signals are reflected just by them. Having known the concentration of the charge particles, which is easily computed from the electron density, and the current plasma temperature, we are able to use the Arrhenius equation to get the value of ionization energy. To include the excitation and breakdown into radical particles, the energies of Ly-α Lyman series are modeled simultaneously. As the result, the energy essential to hypothetic ionization the whole neutral gas in the D layer is reached. The results and possible use of this model are discussed in the following section and an illustrational plot is shown in the appendix.

Having look at the height-dependent plasma distribution, which is shown in figure 5, we can see that the current height is computed from the derivation of electron density. Retrospectively, after the height is determined, it is possible to compute such a differential gear more exactly using other partial dependences included to the original partial differential gear $n_{,t,H}$. This provides us to model the total electron flow in the ionosphere.

Such a phenomenon does not need to be caused only by the variations in the cold ionospheric plasma. High-energy phenomena, mostly some meteoric impacts or solar mass interactions, play a very important role. If the differential gear is solved, we get the electron density of the impact causing ionospheric variations to happen.

Within such a model, a precised time and quantitative differentiation is provided and other description of the impact is able to be done. Consequently, using the simple and low-cost VLF experiment, we are able to study the high-energy impacts which had reached the ionosphere. Special attention is now paid to meteoric impacts, but some diagnostics have already been implemented to study the solar activity as well.

Our recent results are more properly discussed in the following chapter.

3. Results

Within the VLF experiment and our model, the ionosphere can be measured and modeled using several VLF frequencies. However, it was observed that the frequencies between 10 kHz and 15 kHz were not very useful for a properly analysis. The ionospheric plasma, if it is even located at such a small energy level, is actually so sparse that the amount of charge particles is insignificant.

Better results were reached while observing frequencis converging to the scale from 20 kHz to 30 kHz. Recently, the frequency of 23.4 kHz, which is sent by the VLF transmitter DHO 38 located in North Germany, has been analysed completely. We modeled the height of energy state invariant to such a frequency and it was proven that the mean value approached 80 kilometers. Possibly, it can also approach the critical frequency of the whole D layer.

Such a frequency is also well-fitting to the observation of ionospheric response induced by meteoric impacts. The results provide us to model the meteoric or fireball plasmatic impact itself. In this area, special attention has been paid to the investigation of meteoric events.

The problem was simplified by determining the total electron density from the equation

$$N \approx \int_{H_0}^{H} \sum n_{,H} \, \mathrm{d}H,$$

where $\sum n$ is the total electron content in the ionosphere dependent on the momental electron density and the high-energy plasmatic impact, H is the current height where the impact was detected and N is the electron density of the impact itself. As seen in the relation, it can be approximated having determined the height-dependent distribution.

Moreover, the real physical parameters of the ionosphere are able to be used to determine other properties of the plasmatic impact. Its temperature can be computed within the known electron density and having determined the parameters of ionospheric response, first of all the Debye radius and plasma parameter.

The temperature and electron density of some strong meteoric or fireball impacts detected stands up the comparsion with the quantification given by laboratory measured ablation spectra.

It is even possible to compose the time-differed spectra where the wavelength is compared with the peak intensity. The relative intensity can be described having known the electron density and the plasma temperature of investigated event. The wavelength on which the biggest quantum of energy is currently emitted, is approached by the Wien's Displacement Law written like

$$\lambda = \frac{b}{T_{eff}}.$$

T_{eff} labels the radiation effective temperature and $b \simeq 2.898 \cdot 10^{-3}$ m$\cdot$ K is the Wien constant. It can be seen that the approximation for the radiation of absolutely black solid was used. The mistake which might be caused by ununitary emissivity has not been taken into account yet, but by the time enough data is measured and compared, this issue will have been examined.

A plot showing the time-resolved meteoric spectra mesured during the maximum of Perseid meteoric shower in 2015 is enclosed, see figure 7.

Having described the electron density, plasma temperature and the emission spectra, it is possible to draw out the model of the meteoric plasma solid. Necessarily, it needs to be constructed within the system of differential equations having the initial parameter $\mathrm{d}N_{,i}$ where the total electron content of the event is significantly dependent on a quantity i.

We decided to model the temperature-dependent plasma distribution, so the appropriate differential gear is given by the expression $\frac{\partial N}{\partial T}$ for the impact temperature T.

Interesting results were reached within the investigation of a strong fireball event detected on March 7, 2016 at about 21:36 UT. Later, the fireball was labeled as EN060316 and was investigated by the Czech Fireball Network [5].

However, our measurement gave the ability to model the fireball solid and analyse its spectra, too. The temperature-dependent plasma distribution is shown in figure 8. The electron density and the plasma temperature in appropriate ratio were computed and also figured within the model.

In the spectra, the significant peaks of calcium, chromium, magnesium, potassium and lithium and even some peaks belonging to titanium or vanadium occured. From the contour distribution plot, it can be seen that the primary and secondary discharge were both lighted up during the fireball event. The secondary discharge might have been caused to happen by the physical-chemical interaction in the ionosphere, because the mean temperature was boldly lower then the value connected with the primary one.

While the heavy metallic elements were detected in the primary discharge, the alkali metals and magnesium are expected to have been present in the secondary discharge.

Such work is now being conducted to observe the meteoric showers in radio spectrum within the ionospheric response and also to look for some interesting spectral-analysed meteoric events in the main season showers. Some interesting meteorites like carbonaceous chondrites have already been observed.

The spectral analysis model was also implemented to study high-energy solar events such as solar eruptions and coronal mass ejections. Interesting outcome has recently been given within the measurement of strong heliospheric flux which was followed by cracks in the Earth's magnetosphere. During the event, significantly higher energy state in the solar spectra was detected and kept appearing in accordance to other variations of the heliosphere or solar wind.

We managed to measured the electron density of a stronger heliospheric event. Some heterogenities caused by the interaction between the heliosphere and magnetosphere of the Earth were measured well, see figure 12.

Some efforts in the area of gamma ray bursts or the outbursts following young stars in the deep space are also in progress. So far, a radio outburst caused to happen by an infant star HH34 detected also by the Hubble Space Telescope [6] in Orion has been measured. The effective temperature of the star during the event was modeled and the emission spectra were composed. The results are represented by figures 9, 10 and 11.

We are now working on the model which would describe the ionospheric response on the gamma ray bursts. Having compared a well-known databases, there were some strong peaks in radio spectra by the time some longer GRBs were detected. The discussion and more detailed analysis of such results has begun.

4. Conclusions

We introduced a new physical model which had been made to describe the D ionospheric layer and the phenomenon of ionopsheric response in this region. Within our results, we are able to monitor the meteoric events and solar energy variations routinely. The improvement of gamma ray bursts detection is in progress and a strong radio outburst induced by a young star has already been detected and analysed properly.

The measurement of such phenomena and the spectral analysis of high-energy events was discussed with the czech academy of sciences and new research programmes are in progress.

The results were presented at the international conference IBWS, which took place in Karlovy Vary at the end of March 2016.

This work is a good motivation to keep studying ionosphere, because a lot of essential informations about phenomena which are now being investigated by several astronomers can be determined having analysed the behaviour of such an interesting cosmic plasma laboratory.

Our measurement is being conduced within the low-cost VLF experiment including the SID monitors, which are very easy to build and use nearly for everyone.

The Ionozor Measuring Network is now open for new collaborates who would like to take part at this new astrophysical research.

Acknowledgements

We would like to acknowledge the greeting to our wholesouled consultants Martin Ferus and Zbysek Mosna for the every willing help in the scholarly issues which has always given us the chance to follow the right direction.

We would also like to thank Michal Zejdl for very appreciated technical support, Jakub Kubecka for the help with creating the matematical model and Vojtech Stransky for the sympathetic help in the area of formal aspects of our work and its presentation.

For the all support, our thanks belong to to the whole Ionozor research group, first of all our colleague Jakub Kakona for his appreciated remarks to our work.

Definitely not at last, we would like to thank our home institution, Frantisek Krejci Observatory Karlovy Vary, for the possibility to conduct our research itself.

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5. Appendix

Figure 1: SID monitor measuring at the Frantisek Krejci Observatory.

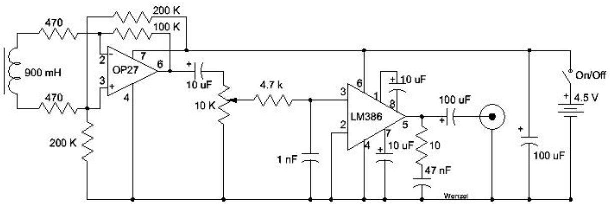

Figure 2: Possible scheme of the amplifier.

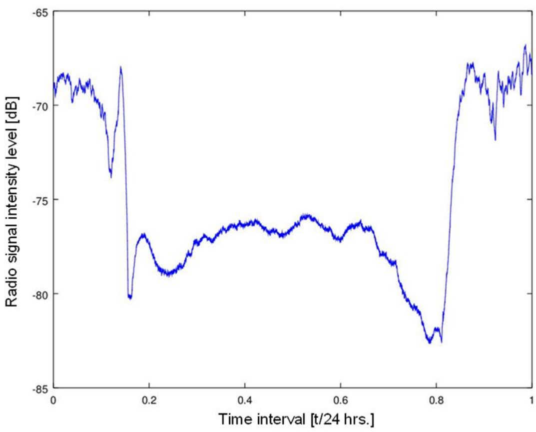

Figure 3: Periodical dependence of the radio signal intensity level. June 4, 2015

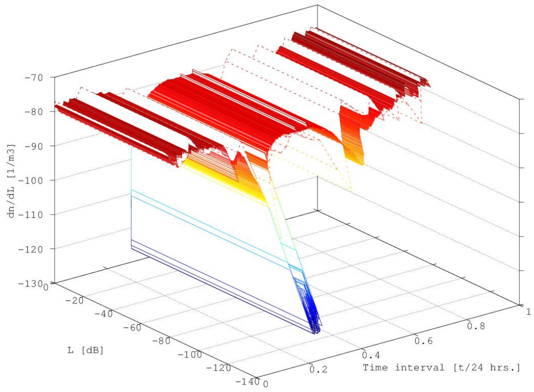

Figure 4: The partial derivation for the electron density is represented. Some stronges variations caused by ionospheric disturbances can be recognised. March 6, 2016

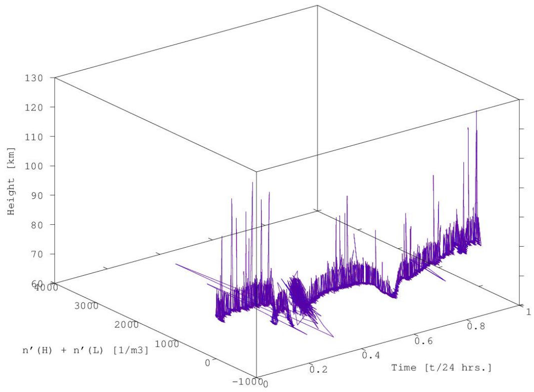

Figure 5: The ionogram of D region is shown. Some strong peaks can be recognised having compared the height and the TEC differential gear. March 6, 2016

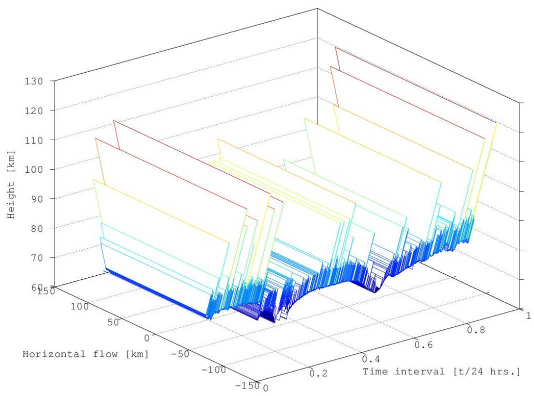

Figure 6: The ionospheric drift is described in this plot. March 6, 2016

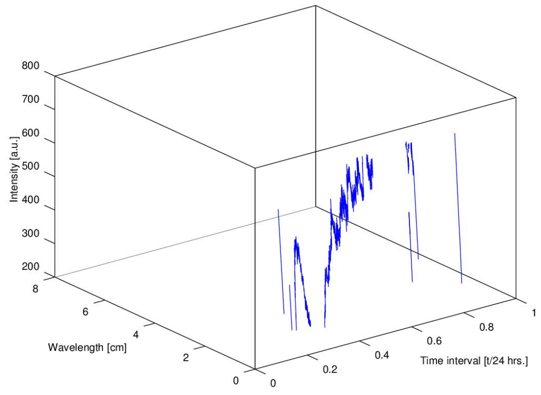

Figure 7: Time-resolved emission spectra of expected meteoric events during the Perseid shower are given. August 13, 2015

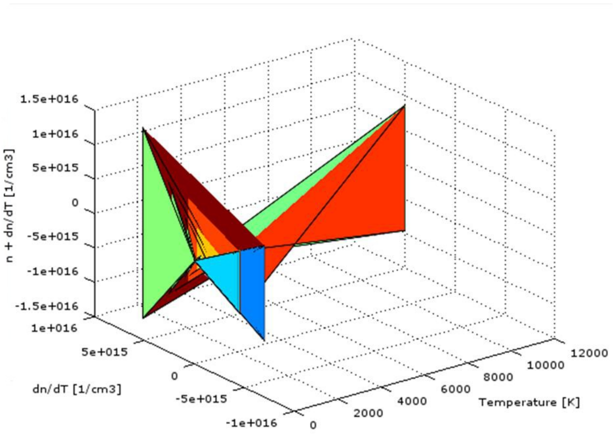

Figure 8: The temperature-dependent plasma distribution in a fireball solid is modeled in this figure. The primary and secondary discharge are both distinguished clearly. March 6, 2015

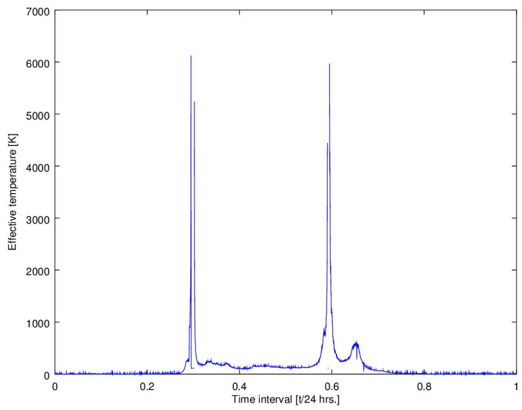

Figure 9: The effective temperature of HH34 during its detected radio outburst is shown. December 21, 2015

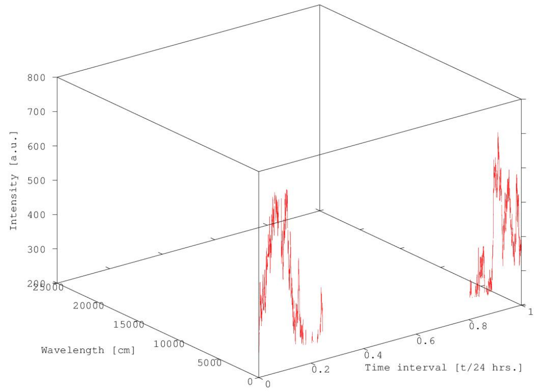

Figure 10: The time-resolved spectrum of HH34 radio outburst. December 21, 2015

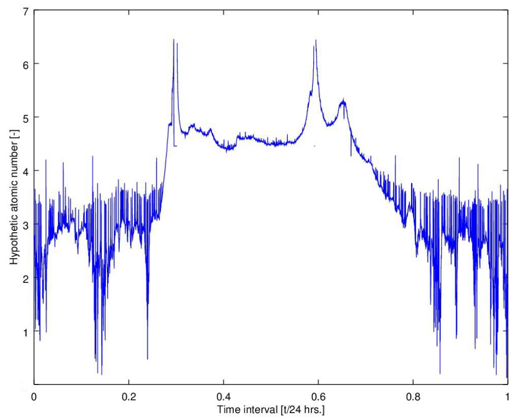

Figure 11: The atomic numbers of elements expected to emitted by HH34 on December 21, 2015 which were computed within the spectral analysis.

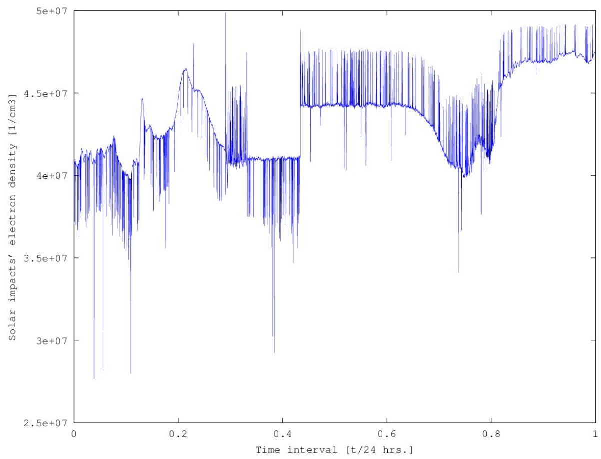

Figure 12: The result of time-resolved detection of solar electron density flow during the increased heliospheric activity is given. April 30, 2016