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EXPERIMENTAL DETERMINATION OF THE D-REGION IONOSPHERE EFFECTIVE RECOMBINATION COEFFICIENTS FROM SOLAR ECLIPSE OBSERVATIONS

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Abstract. The photochemistry of processes in the D-region of the ionosphere is difficult and up to the end is not developed. Therefore introduction of the effective coefficients determining the total speed of several reactions was widely adopted when modeling the D-region. Experimental opportunities of obtaining of effective recombination coefficients are rather limited. One of the methods which gives an opportunity to determine effective recombination coefficients is based on the phenomenon of a solar eclipse. During several solar eclipses at the partial reflection facility of the observatory "Tumanny" (69.0N, 35.7E) observations of the lower ionosphere were made and profiles of the electron concentration at heights of the lower ionosphere were received. Using the data effective recombination coefficients at some heights of the D-region of the high-latitude ionosphere were defined. Transport processes in the atmosphere during the solar eclipses did not give the possibility to definite effective recombination coefficient values at many heights.

1. Introduction

The D-region of the ionosphere represents the most difficult area of the ionosphere for experimental study. The photochemistry of processes in the D-region is rather difficult and up to the end is not developed. Photochemical schemes demand specification, exist uncertainty in coefficients of separate reactions and concentration of small neutral components. Therefore introduction of the effective coefficients determining the total speed of several reactions was widely adopted when modeling the lower ionosphere, especially the D-region.

Possibilities of obtaining of the effective recombination coefficients (ERC) are limited therefore all experimental methods which can define them are of great importance. One of such methods is based on observations of changes of the electron concentration (EC) in the ionosphere during a solar eclipse [*Ratcliffe, Weekes*, 1963]. Intensity of solar ionizing radiation during a solar eclipse has short-term and known behavior that allows investigating photochemical processes at the known input parameters. The temporary delay between the eclipse maximum (the sunlight minimum) and the minimum of the EC during an eclipse allows calculating ERC at the considered ionosphere heights at the known values of the electron concentration.

This method with good approach can be used in the absence of transfer of electrons but the condition carried out not always. Appearance of acoustic-gravity waves at the region of observation, vertical movements etc. break an ideal picture of the EC behavior during "a short night". It considerably complicates obtaining ERC from the used data.

2. Determination of effective recombination coefficients during an eclipse

The EC values in the place of observation can be changed depending on the speed of ionization, transfer processes in the region of observation, and also as a result of disappearance of free electrons in the recombination processes or adhesion. The recombination represents a process, the opposite one to ionization, i.e. the process of neutralization. In view of complexity of recombination processes in each separate reaction of disappearance of electrons for the description of the recombination process enter an effective recombination coefficient α_{eff} which is defined as the total speed of disappearance of electrons in several reactions in unit of time and in unit of volume. In this way the effective speed (coefficient) of electron formation q is entered which is determined as the quantity of the electrons which have appeared in the unit of volume and in the unit of time. At the same time it is necessary to remember that ionization makes the main contribution to free electrons formation and therefore the speed (coefficient) of electron formation is actually the speed (coefficient) of ionization which depends, with other things being equal, first of all on the flux of solar ionizing radiation. But as in the D-region of the ionosphere electron formation is possible not only due to ionization, it will be more general to speak about the speed (coefficient) of electron formation. Therefore use of these two concepts in our case will mean almost same, except cases when their distinction has to be marked out especially.

In the D-region of the ionosphere the EC behavior at the fixed height in the absence of processes of electron transfer during changing of electron formation speed in time and disappearance of free electrons in recombination processes conform to the equation [*Ratcliffe, Weekes*, 1963]:

$$\frac{dn_e}{dt} = q - \alpha_{\text{эфф}} n_e^2 . \qquad (1)$$

Appleton has shown the analogy between the EC change in the ionosphere and behavior of a linear inductive chain [*Appleton*, 1953]. Having differentiated the equation (1) on time, he has received the equation:

$$\frac{d^2 n_e}{dt^2} + 2\alpha_{эфф} n_e \frac{dn_e}{dt} = \frac{dq}{dt} . \qquad (2)$$

Comparing it with the equation describing an inductive chain

$$\frac{d^2 I}{dt^2} + \frac{R}{L}\frac{dI}{dt} = \frac{1}{L}\frac{d\varepsilon}{dt} , \qquad (3)$$

where I –the electric current flowing through the circuit with resistance of R and inductance of L under the influence of the electromotive force ε, one can see the analogy between $1/(2\alpha_{eff} n_e)$ in the equation (2), describing the ionosphere, and L/R which is the time constant in the equation (3), describing the electric chain. Thus, it is possible to expect that the extremum of the EC profile will be reached through the period $\tau = 1/(2\alpha_{eff} n_e)$ after reaching of the extremum by the electron formation speed q. By the analogy with the constant of time L/R of the electric chain Appleton called reaction of the ionosphere to an ionization process as the ionosphere sluggishness with the characteristic constant of time $\tau = 1/(2\alpha_{eff} n_e)$, which different researchers call as "sluggishness" [*Appleton*, 1953; *Ratcliffe*, *Weekes*, 1963], "relaxation time" [*Alpert*, 1972; *Appleton*, 1953] or simply "ionospheric time constant" [*Appleton*, 1953; *Ivanov et al.*, 2012].

This consideration can be applicable for the processes during a solar eclipse. At the eclipse maximum the electron formation speed q (ionization speed) becomes a minimum one, but at the same time the EC at the chosen height continues to decrease and it reaches the minimum only after some time. This temporary delay between the eclipse maximum (the ionization speed minimum) and the minimum of the EC profiles is defined as $\tau = 1 / (2\alpha_{eff} n_{eq})$. Thus, knowing the temporary delay between an eclipse maximum and a minimum of the EC profile at the chosen ionosphere height, it is possible to determine the ERC α_{eff} for this height by the formula:

$$\alpha_{эфф} = 1/\left(2\tau n_{eq}\right), \qquad (4)$$

where τ – a temporary delay between the maximum of an eclipse and a minimum of the EC profile; n_{eq} – the EC at the time of the minimum of an electron formation speed.

For the place of observations parameters of the maximum of a solar eclipse can be determined precisely using astronomical year-books of the Institute of Applied Astronomy RAS, see, for example, [*Astronomical Yearbook*, 2014]. The minimum of the EC is found from the experimental EC profile at the chosen height. If during an eclipse observations were made at several heights, then there was an opportunity to find values of ERC for each of these heights.

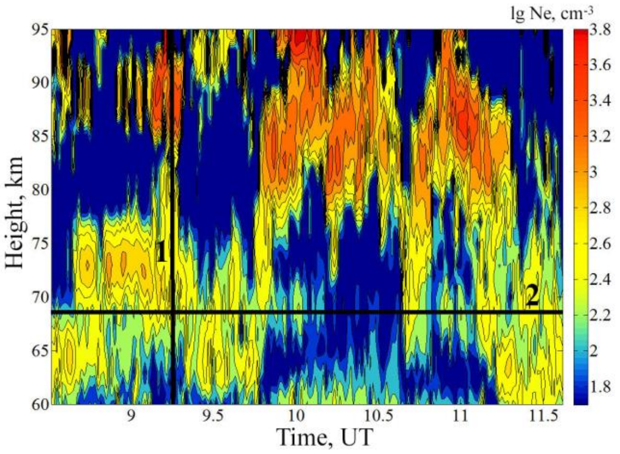

Figure 1. The two-dimensional picture of the electron concentration distribution on time and height in the day of the eclipse on 20 March 2015

3. Method and facility of partial reflections

The most effective research method of the D-region of the ionosphere is the method of partial reflections (MPR) offered in the early fifties by *Gardner* and *Pawsey* [1953]. This method has obtained further development [*Belrose*, *Burke*, 1964]. It represents radar sounding of the lower ionosphere in the band of decameter waves. The method is rather simple one in realization and allows receiving data on the EC and parameters of irregularities at the heights of the lower ionosphere. The cornerstone of the MPR is radiation of ordinary and extraordinary waves in the form of the alternating impulses or linearly polarized wave at frequencies in the range from 2 to 8 MHz and the separate receiving of radio waves dispersed by irregularities of the ionospheric plasma [*Rapoport*, 1972]. For determination of parameters of the environment, according to MPR, measurements of amplitudes or difference of absorption along trajectories of spreading of ordinary and extraordinary radio waves (the method of differential absorption) are widely used [*Belikovich et al.*, 2004].

The facility of partial reflections of the Polar Geophysical Institute for research of the lower ionosphere consists of the transmitter, the receiver, the transduced phased array and the automated system of data sampling. It is located at the observatory "Tumanny" (69.0N, 35.7E). Key parameters and the technique of processing of signals are specified in the work [*Tereshchenko et al.*, 2003]. Technical characteristics of the radar: working frequencies – 2.60-2.72 MHz; transmitter power in an impulse – about 60 kW; impulse duration – 15 microsec; sounding frequency – 2 Hz. The antenna array consists of 38 couples of crossed dipoles, occupies the space of 10^5 m^2 and has directional pattern width on the level of half power about 20°. Alternatively two circular polarization are received which are amplified by the receiver of direct amplification with the band of 40 kHz. Registration of signal amplitudes can be carried out in the range of heights from 30 to 240 km. A step of record of data along height from $h = 0.5 \cdot n$ km, where n = 1, 2, 3, … .

4. Profiles of electron concentration

Amplitudes of ordinary and extraordinary waves received during observations are used for calculation of the electron concentration. The two-dimensional picture of the EC distribution on time and height received in the day of the eclipse on 20 March 2015 is given in Fig. 1. The two-dimensional picture allows receiving EC profiles on height for the chosen time (for example, the line 1 on Fig. 1, see also Fig. 2, a) and EC profiles on time for the chosen height (for example, the line 2 on Fig. 1, see also Fig. 2, b). The EC profiles on time for various heights (Fig. 2, b) are used for finding of the delay of the EC minimum relatively the ionization speed minimum.

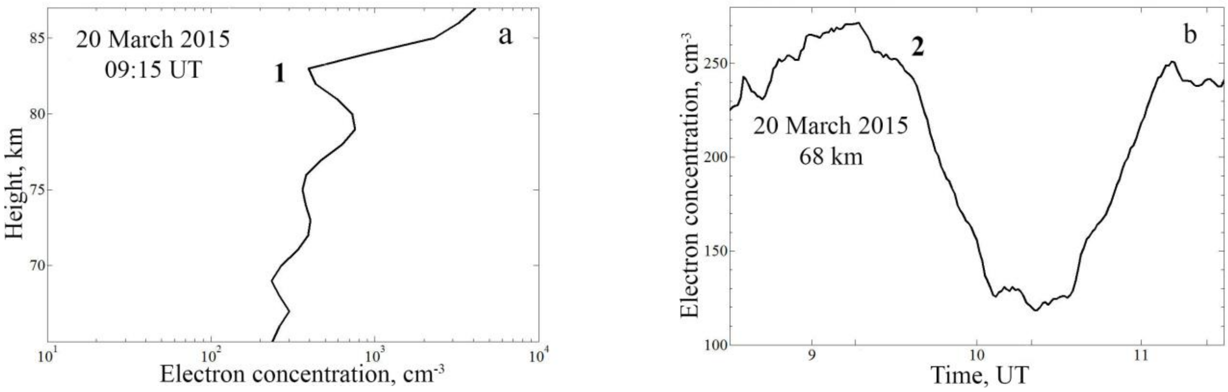

Figure 2. The electron concentration profile on height for the chosen time (**a**) and the electron concentration profile on time for the chosen height (**b**)

In the early seventies *Chimonas* and *Hines* [1970] have assumed that during a solar eclipse the atmospheric gravity waves caused by a supersonic passing of a lunar shadow across the Earth's surface and cooling of the atmosphere because of reduction of sunlight in the field of the shadow have to be observed. In the next years researchers have received confirmation of existence of the effect [*Hanuise et al*., 1982; *Šauli et al*., 2007]. In addition, during a solar eclipse other processes of transfer in the ionosphere influence on the EC profiles. Therefore the “classical” behavior of the EC profiles usually could not be seen. It hampers to determine the EC profile minimum and consequently relaxation time for chosen heights.

5. Results of observations

During the solar eclipses on 11 August 1999, on 1 August 2008, on 1 June 2011 and on 20 March 2015 on the facility of partial reflections at the observatory Tumanny [*Cherniakov et al*., 2016; *Tereshchenko et al*., 2001, 2009, 2012] observations of reaction of the lower ionosphere to solar eclipses have been made. On the basis of the obtained data experimental profiles of the electron concentration at heights of D-region of the ionosphere were received. Calculation of temporary delays between the maximum of an eclipse and the minimum of an electron concentration profile has allowed defining values of effective recombination coefficients at heights of D-region of the ionosphere.

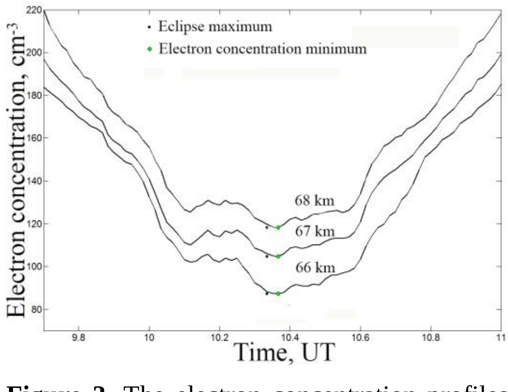

Figure 3. The electron concentration profiles, the solar eclipse on 20 March 2015

5.1. Eclipse on 20 March 2015

The 20 March 2015 solar eclipse was the total one. In the place of observation, the solar eclipse was a partial one: the beginning - at 09:15:8 UT, the maximum - at 10:20:06 UT, the end - at 11:23:58 UT; value of the greatest phase of the eclipse was equal to 0.877; Sun height over the horizon at the time of the greatest phase of the eclipse was 20.5°. The geomagnetic situation in the period of the eclipse was weakly disturbed.

The two-dimensional picture of the EC distribution for the period of the eclipse is shown in Fig. 1. In Fig. 3 the EC profiles at various heights used for calculation of ERC are shown. The left points in the figure have designated eclipse maximum time, circles – the minimum of the electron concentration profiles. During the analysis of observation data similar figures were drawn for all heights, but because of influence of various factors, including transfer processes, it was not succeeded to receive ERC for the majority of heights.

ERC values calculated from the EC profiles received during observations. For this purpose the EC values at the time of the minimum of the electron formation speed function (in Fig.3 the minimum is designated by a point) were found. Then from the times of the EC minima of the profiles (circles in Fig. 3) the temporary delays were received. Finally on the formula (4) ERC were calculated. Heights and values of effective recombination coefficients are specified in tabl. 1. For the solar eclipses on 11 August 1999, on 1 June 2011 and on 1 August 2008 the technique of receiving of ERC was similar.

Table 1. Effective recombination coefficients, the solar eclipse on 20 March 2015

Height, km	Effective recombination coefficients, $cm^3 \cdot s^{-1}$
68	$3.7 \cdot 10^{-5}$
67	$4.2 \cdot 10^{-5}$
66	$5.0 \cdot 10^{-5}$
65	$5.5 \cdot 10^{-5}$

5.2. Eclipse on 1 June 2011

The 1 June solar eclipse was partial one. Parameters of the partial eclipse at the place of observation: the beginning - at 8:33:49 UT, the maximum - at 9:23:17 UT, the end - at 10:12:37 UT; the value of the greatest phase of the eclipse was 0.598; the height of the Sun over the horizon at the time of the greatest phase of the eclipse was 1.1°. The geomagnetic situation was weakly disturbed.

The two-dimensional picture of the EC distribution in the period of the eclipse is given in Fig. 4. Letters B, M and E mean the beginning, the maximum and the end of the eclipse, respectively. During the eclipse the polar night was, the Sun at the time of observation was practically on the horizon. Consideration of EC profiles on ionospheric heights have not revealed profiles, using which it would be possible to calculate effective recombination coefficients.

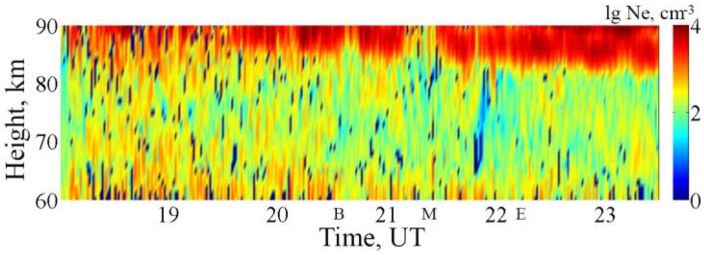

Figure 4. Electron concentration distribution, the solar eclipse on 1 June 2011

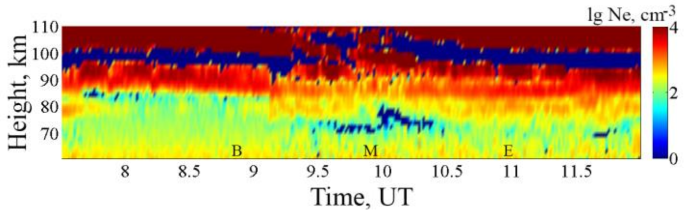

Figure 5. Electron concentration distribution, the solar eclipse on the 1 August 2008

5.3. Eclipse of the 1 August 2008

In Tumanny the 1 August 2008 total solar eclipse was partial one: the beginning - at 8:48:10 UT, the maximum - at 9:54:08 UT, the end - at 10:59:28 UT; value of the greatest phase of the eclipse was 0.827; the height of the Sun over the horizon at the time of the greatest phase of the eclipse was 38.8°. The 1 August 2008 the geomagnetic situation was quiet.

The two-dimensional picture of the electron concentration distribution in the period of the eclipse is given in Fig. 5. Letters B, M and E mean the beginning, the maximum and the end of the eclipse, respectively.

All the possible electron concentration profiles were considered for calculation of effective recombination coefficients but only for several heights the ERC were received. The heights and values of the ERC are specified in tabl. 2.

5.4. Eclipse on the 1 August 1999

The beginning of the eclipse in Tumanny was at T1 = 9:57:43 UT. The greatest phase of the eclipse was 0.44 at Tm = 10:54:26 UT, the height of the Sun over the horizon at the time of the greatest phase of the eclipse h was 35.1°. The end of the eclipse was at T4 = 11:50:17 UT. The geomagnetic situation in the period of the eclipse was quiet.

Table 2. Effective recombination coefficients, the solar eclipse on the 1 August 2008

Height, km	Effective recombination coefficients, $cm^3 \cdot s^{-1}$
78.5	$6.6 \cdot 10^{-6}$
77	$8.1 \cdot 10^{-6}$
75.5	$1.3 \cdot 10^{-5}$
74	$4.7 \cdot 10^{-5}$

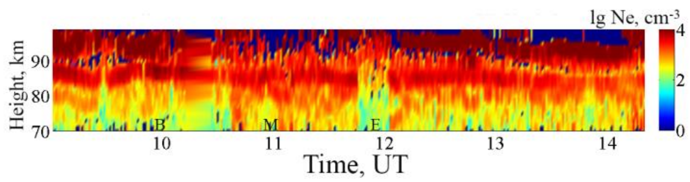

Figure 6. Electron concentration distribution, the solar eclipse on the 11 August 1999

The two-dimensional electron concentration distribution is given in Fig. 6. Consideration of electron the concentration profiles on heights have not revealed profiles which could be used for calculating effective recombination coefficients.

6. Conclusion

Observation of the ionosphere during solar eclipses on 1 August 1999, on 1 August 2008, on 1 June 2011 and on 20 March 2015 on the radar of partial reflections of the observatory "Tumanny" have allowed calculating of the values of effective recombination coefficients for the heights of D-region of the high-altitude ionosphere. The received values have agreement with experimental and model data. Processes of transfer during the solar eclipses significantly influence on the electron concentration profiles at the heights of the D-region of the ionosphere in high latitudes that complicates determination of effective recombination coefficients. Nevertheless observations of electron concentration behavior during a solar eclipse allow receiving values of effective recombination coefficients under favorable conditions.

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