The Effects of The Partial Solar Eclipse on January 4, 2011 in the Variety of Thermal Process Parameters in the Ionosphere

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Abstract. Modeling results of thermal process parameter variations in Geospace plasma during solar eclipse (SE) on January 4, 2011 are presented. It is shown that SE has essentially affected a thermal mode of an ionosphere. In the SE maximum phase reduction of the energy fed to the electrons was about 45—60% in the altitude range of 210—290 km. During the SE had been a decrease in the module heat flux density transported by electrons from the plasmasphere into the ionosphere by about 60—70% in the altitude range of 290—410 km. Comparative analysis results of the SE effects in variations of thermal process parameters in Geospace for the period 1999—2011, registered by means of the Kharkiv incoherent scatter radar are given.

Keyword: solar eclipse, ionosphere, thermal processes.

Introduction

Solar eclipses (SEs) are one of the unique phenomena in Geospace. During SEs are visible restructuring of near-Earth environment, similar to that which takes place during the dawn-dusk periods. SEs significantly affect the variation of the parameters of the atmosphere, ionosphere, magnetosphere and the current systems in Geospace plasma.

At present time fairly a large number of publications are devoted the study of the plasma Geospace response to the SEs. These studies are used as the experimental data obtained on the global network of ionosondes, incoherent scatter radars, magnetometer stations and satellite navigation systems (GPS, GLONASS) as well as theoretical studies and simulations (Afraimovich et al, 2002; Boitman et al., 1999; Chernogor et al., 2011a; Gokov et al., 2008; Le et al., 2008; Le et al., 2009a; Le et al., 2009b; Müller-Wodarg et al., 1998; Nayak et al., 2012; Paul et al., 2011; Stubbe, 1970; Tomás et al., 2009).

It should also be noted that the total SEs are a rather rare phenomenon and is not always possible to use the entire range of radio-physical means for to study the effects of the eclipse in the variety of parameters of the atmosphere, the ionosphere and geomagnetic field.

Earlier by incoherent scatter radar (ISR) several observations were carried out during the SEs over Kharkiv, Ukraine (50.0º N, 36.2º E) in the period from 1999 to 2011 (Akimov et al., 2002; Akimov et al., 2005; Chernogor et al., 2011a; Chernogor et al., 2011b; Chernogor et al., 2012; Domnin et al., 2012; Domnin et al., 2013; Grigorenko et al., 2008; Emelyanov et al., 2009; Lyashenko and Chernogor, 2008; Lyashenko and Chernogor, 2009). The effects of the SEs in the ionosphere well marked in the variations of the dynamic and thermal processes of Geospace plasma.

The aim of this paper is to present the results of simulation of the thermal process parameters in the Geospace plasma during the partial solar eclipse on January 4, 2011 over Kharkiv.

The solar eclipse general information

The SE on January 4, 2011 was partial. The eclipse was observed over Kharkiv from 07:29 to 10:28 UT. The maximum coverage of the solar disk was occurring at 08:58 UT. The coverage of the solar disk on the area was 0.71, on the diameter — 0.78. The illumination of the Earth's surface and near-Earth environment during the SE main phase is decreased by a factor of 4. The total duration of the partial SE over Kharkiv was 2 h 59 min.

The observation means

For modeling of the thermal process parameter variations were used the Kharkiv ISR (geographic coordinates: 49.6º N, 36.3º E; geomagnetic coordinates: 45.7º, 117.8º) data. At the present time the Kharkiv ISR is the only reliable and most informative data source of the Geospace plasma state in the mid-latitudes of Central Europe.

Radar allows measuring with high accuracy (usually error is 1—10%) and acceptable altitude resolution (10— 100 km) the following ionospheric parameters: electron density N, electron T_e and ion T_i temperatures, a vertical component of the plasma drift velocity V_z, and ion composition. The investigated altitude range is 100— 1500 km (Taran, 2001; Lysenko, 2001).

Space weather condition during the SE

Consider the temporal variations of the parameters describing the state of space weather during the SE on January 4, 2011 and reference day on January 5, 2011. For the analysis of geophysical conditions used the following data: the density of the solar wind (SW) particles n_{sw}, the SW temperature T, the SW radial velocity V_{sw} (ACE Satellite — Solar Wind Electron Proton Alpha Monitor data) and the SW dynamic pressure p_{sw} (calculation); the B_z, B_y components of interplanetary magnetic field (IMF) (ACE Satellite — Magnetometer data); the K_p-index values (Air Force Weather Agency) and D_{st}-index (from WDC-C2 for Geomagnetism Kyoto University).

The period of January 4—5, 2011 was characterized by quiet geophysical conditions. Geomagnetic activity index K_p did not exceed 3 units. The D_{st}-index ranged from 0 to —15 nT. The values of the IMF components B_z, B_y were varied in the range of 4 to —4 NT.

Variations in the SW parameters are also close to the background. The SW velocity V_{sw} in the considered period does not exceed 410 km/s, and the SW temperature T varied within (0.5—0.75)· 10^5 K. The charged particle density n_{sw} did not exceed $2.5 \cdot 10^{-6}$ m^{-3}. Calculations showed that the SW dynamic pressure p_{sw} was varied in the range of 1—1.5 nPa.

Initial theoretical relations

Energy influx to the electron gas. In the ionospheric F region the collision frequency of electrons with neutrals is smaller than the ions. In this case the main mechanisms of electron gas cooling are heat loss in collisions of electrons and ions, excitation of the fine structure of the oxygen atoms and electron gas heat conductivity (Schunk and Nagy, 1978). There is also the photoelectrons transfer and the related this transfer non-local heating of the electron gas.

At altitudes $z \leq 350$ km heat conductivity of the electron gas can be neglected and the electron energy balance equation in the stationary case in the SI system has the form (Schunk and Nagy, 1978)

$$Q = L_{ei} + L_e ,$$

$$L_{ei} = 8 \cdot 10^{-32} N^2 (T_e - T_i) T_e^{-3/2} ,$$

$$L_e = 6.4 \cdot 10^{-37} N N(\mathrm{O}) (T_e - T_i) T_n^{-1} ,$$

where Q is the energy transferred to the thermal electrons at the Coulomb collisions with photoelectrons; L_{ei} — the energy lost in electron-ion collisions; L_e — the energy needed to excite the fine structure of the oxygen atoms; N — electron density (Kharkiv ISR data); N (O) — density of the oxygen atoms; T_e и T_i — electron and ion temperatures respectively (Kharkiv ISR data). The neutral temperature Tn and N (O) density were calculated with the assistance of the NRLMSISE-00 model (Picone et al., 2002).

Heat flux density. The heat balance of the electron gas depends on the heat flux carried by electrons from the plasmasphere into the ionosphere. The heat in the plasmasphere is accumulated by suprathermal electrons escaping from the place of its formation in the topside ionosphere. Some of the electrons lose their energy in Coulomb collisions with thermal electrons and ions. Another part of the electrons fall into the magnetic flux tube. In the magnetic tube trapped electrons thermalized in multiple reflections from the ends of the tube. Thus, in the plasmasphere an accumulation of heat, is fed back into the ionosphere by heat conductivity of the electron gas (Schunk and Nagy, 1978; Schunk and Nagy, 2000; Brunelly and Namgaladze, 1988).

Heat flux can be defined from the kinetic equation with the transport of suprathermal electrons. The expression to calculate the heat flux density from the plasmasphere in the vertical direction is given by (Schunk and Nagy, 1978; Schunk and Nagy, 2000):

$$\Pi_T = -\kappa_e \sin^2 I \frac{\partial T_e}{\partial z} , \qquad (1)$$

where I — inclination of the Earth's magnetic field (for Kharkiv I = 66.4^0); $\kappa_e = 2.08 \cdot k^2 N T_e / m\nu_{ei}$ — longitudinal component of the heat conductivity tensor of the electron gas, k — Boltzmann constant, m — the mass of the electron.

The collision frequency between electrons and O+ ions to calculate the longitudinal component of the conductivity tensor in (1) can be found by using the expression (Akimov et al., 2002; Akimov et al., 2005; Ginzburg, V.: 1971):

$$\nu_{ei} \approx 5.5 \cdot 10^{-6} N T_e^{-3/2} \ln(2.2 \cdot 10^4 T_e N^{-1/3}) .$$

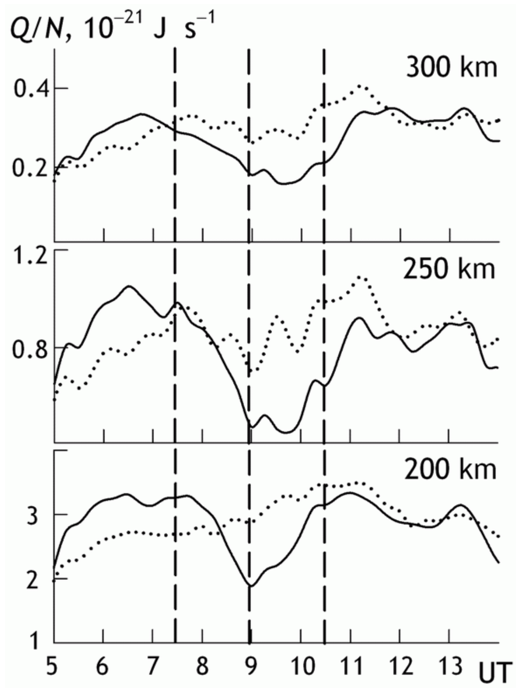

Figure 1: The temporal variations of the energy supplied to the electron gas Q/N during SE on January 4, 2011 (solid line) and reference day on January 5, 2011 (dots) at the fixed altitudes. The vertical lines correspond to moments of the beginning, the maximum phase and the end of the SE.

Simulation results

Energy influx to the electron gas

Figure 1 shows the temporal variation of the energy fed to the electrons Q/N during the solar eclipse and the reference day at the fixed altitudes. As seen in Figure 1, the effects of the eclipse in the variations of the Q/N appeared considerably. The solar eclipse led to a significant reduction in the amount of the energy in the altitude range 210—290 km. The values of Q/N before SE were $2.75 \cdot 10^{-21}$, $1.3 \cdot 10^{-21}$ and $0.5 \cdot 10^{-21}$ J·s^{-1} at the altitudes 210, 240 and 290 km respectively. During the SE the energy Q/N decreased to values $1.5 \cdot 10^{-21}$, $0.7 \cdot 10^{-21}$ and $0.2 \cdot 10^{-21}$ J·s^{-1} at the altitudes 210, 240 and 290 km respectively. Thus, in the SE maximum phase the energy reduction was about 45—60% in the considered altitude range.

Heat fluxes from the plasmasphere

In Figure 2 shows the variation of the heat flux density transferred from the plasmasphere into the ionosphere on the SE day January 4, 2011 and reference day January 5, 2011 at the fixed altitudes.

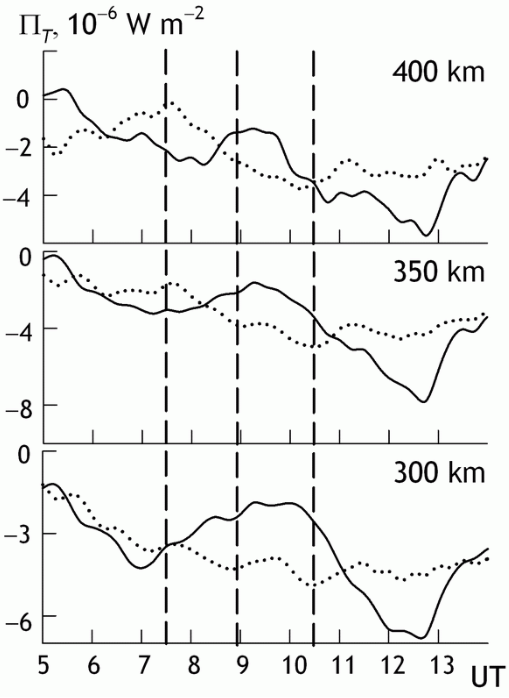

Figure 2: The temporal variations of the heat flux density Π_T during SE on January 4, 2011 (solid line) and reference day on January 5, 2011 (dots) at the fixed altitudes.

Figure 2 shows that during the SE had been a decrease in absolute values of the Π_T by about 60—70% in the altitude range of 290—410 km.

In general, the SE on January 4, 2011 led to a substantial restructuring of the thermal regime of the ionosphere.

Discussion

Energy influx to the electron gas. The solar eclipse on January 4, 2011 significantly affected on the heat processes parameters in geospace plasma. During the SE occurred transformation of the thermal regime of the ionosphere. Simulations showed that the eclipse has led to a decrease of energy supplied to the electrons. Reduction of Q/N at altitudes 210—290 km was 45—60%.

It should be noted that the variations of Q/N during the SE qualitatively reflect the variations in the electron temperature (Chernogor et al., 2011b). The decrease in the value of energy supplied to the electron gas can be explained by the fact that in the eclipse period there is a reduction of the specific energy transferred to electrons by photoelectrons at altitudes z<350 km (Schunk and Nagy, 2000; Brunelly and Namgaladze, 1988).

Heat fluxes

It is well known that the presence of a temperature difference in the medium of the layer with a layer of high temperature to a lower temperature heat flow is established. In the ionosphere usually is $\partial T_e/\partial z > 0$ and $\Pi_T < 0$. This means that the heat flux is directed down into the ionosphere. The electron temperature at the time of maximum coverage of the solar disk has decreased by about 130—370 K in the altitude range 190—410 km (Chernogor et al., 2011b). The decrease (by the modulus) of the heat flux values near the main phase of the eclipse were about 60—70% in the altitude range of 290—410 km. This is due mainly to the cooling of the electron gas ($\Pi_T \propto T_e^{5/2}\, \partial T_e/\partial z$).

Comparison of the solar eclipse effects. Earlier, in the works (Akimov et al., 2002; Akimov et al., 2005; Chernogor et al., 2011a; Chernogor et al., 2011b; Chernogor et al., 2012; Domnin et al., 2013; Grigorenko et al., 2008; Emelyanov et al., 2009; Lyashenko and Chernogor, 2008; Lyashenko and Chernogor, 2009) the ISR observation results of the effects in the near-Earth environment during the partial SEs on August 11, 1999, May 31, 2003, October 3, 2005, March 29, 2006, August 1, 2008 and January 4, 2011 over Kharkiv were presented.

Table 1: General information about SEs and helio-geophysical condition in period from 1999 to 2011.

Date	T_1, UT	T_{max}, UT	T_2, UT	A	D/D_0	$\bar{F}_{10.7}$	A_p
11.08.99	09:57:32	11:15:40	12:29:27	0.75	0.79	158	6
31.05.03	02:16:08	03:14:34	04:17:27	0.66	0.74	125	49
03.10.05	08:41:40	09:41:57	10:42:34	0.15	0.26	79	7
29.03.06	10:02:47	11:12:59	12:21:59	0.72	0.77	78	6
01.08.08	09:11:28	10:15:41	11:17:47	0.33	0.44	66	3
04.01.11	07:29:36	08:58:30	10:28:36	0.71	0.78	83	4

Table 1 shows the main characteristics of the partial SE over Kharkiv in 1999—2011 (the start time of the SE T1, the time of the SE main phase Tmax and the end time of the SE T2, the values of the solar disk coverage area (A) and diameter (D/D0)). The table also provides information about solar and geomagnetic activity for the considered dates.

Table 2 shows the relative variations in the parameters of thermal processes ($\Delta(Q/N)$ and $\Delta\Pi_T$) for each of the eclipses in the relevant range of altitudes.

Table 2: Variations of the thermal process parameters.

Date	z, km	$\Delta(Q/N)$, %	$\Delta\Pi_T$, %
11.08.99	308	30	50
31.05.03	270	30	48
03.10.05	290 – 340	20 – 40	13 – 17
29.03.06	290 – 340	20 – 25	17 – 37
01.08.08	210 – 340	12	9 – 16
04.01.11	210 – 410	45 – 60	60 – 70

The Table 1 shows that the most suitable for comparison are the SE on August 11, 1999 and March 29, 2006. For these SEs the value of the solar disk covering and the time of the maximum phase are almost the same. Geomagnetic conditions during these SEs were quiet. It should also be noted that the eclipse on August 11, 1999 took place in the period of maximum solar activity (SA), and the eclipse on March 29, 2006 — during the SA minimum.

The effects of the SEs distinctly observed in variations of the value of the energy supplied to the electron gas. Modeling has shown that during the eclipse on August 11, 1999 and March 29, 2006 the Q/N values decreased by 20—30% in the altitude range 290—340 km. During the eclipse on October 3, 2005 (maximum phase does not exceed 15%) the decrease of the energy Q/N was about 20—40% in this altitude range. During the eclipse on January 4, 2011, the phase of which was similar in magnitude phases of SEs on August 11, 1999 and March 29, 2006, but the eclipse occurred near local noon, reduced Q/N was 45—60% in the altitude range 210—410 km.

Variations in the density of the heat flux were qualitatively similar for all SEs. In all cases, a decrease of the heat flux modulus observed at the moment of maximum coverage of the solar disk. During the eclipse on August 11, 1999 reduction in the heat flux density (in modulus) was about 50% at the altitude of 310 km (see Table 2). During the eclipse on March 29, 2006 the heat flux density decreased by about 17—37% in the altitude range of 290— 340 km. During the SE on October 3, 2005 the Π_T reduction was no more than 17% in this range of altitudes. The simulations show that at the time of the SE on January 4, 2011 there has been a decrease of the Π_T by about 60—70% in the altitude range of 210—410 km.

Comparative analysis showed that for each of the eclipses observed qualitative similarity of effects in thermal process parameter variations in geospace. Quantitative differences in the variations of ionospheric parameters and dynamic processes to a greater extent are explained by different levels of solar and geomagnetic activity, as well as the value of the SE phase.

Conclusion

The solar eclipse on January 4, 2011 effects confidently were observed in variations of the thermal process parameters in geospace plasma. The simulation results showed the following.

1) The solar eclipse on January 4, 2011 has reduced the value of the energy supplied to the electron gas by about 45—60% in the altitude range 210—290 km.

During the eclipse had been a decrease of the module heat flux density transported by electrons from the plasmasphere into the ionosphere by about 60—70% in the altitude range of 290—410 km.

Effects of the SE on January 4, 2011 in the variations of heat flux density and energy influx to the electron gas were qualitatively similar variations of Π_T and Q/N during the SEs observed by the ISR over Kharkiv in 1999—2008.

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