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Solar eclipses at high latitudes: ionospheric effects in the lower ionosphere

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Abstract

The partial reflection facility of the Polar Geophysical Institute (the Tumanny observatory, 69.0N, 35.7E [https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/120560/] has observed the behaviour of the high-latitude lower ionosphere during the 20 March 2015 total solar eclipse. There were several effects during the eclipse. At heights of 60-70 km the ionosphere has shown the effects of a "short night", but at the higher altitudes the local enhanced electron concentration had a wave-like form. Data received by the riometer of the Tumanny observatory have also shown wave-like behavior. The behavior can be explained by influence of acoustic-gravity waves which originated after cooling of the atmosphere during the lunar shadow supersonic movement, and transport processes during the eclipse.

During the 21 August 2017 solar eclipse there was a substorm at the high latitudes. But after the end of the substorm in the region of the Tumanny observatory the observed amplitudes of the reflected waves had wave effects which could be connected with the coming waves from the region of the eclipse.

The wave features were also shown in the behavior of the total electron content (TEC) of the lower ionosphere. During several solar eclipses it was implemented observations of lower ionosphere behaviour by the partial reflection facility of the Tumanny observatory. The consideration of the lower ionosphere TEC has revealed common features in the TEC behaviour during the eclipses.

The photochemical theory of processes in the lower ionosphere is very complicated and up to now it is not completely developed. Therefore introduction of the effective coefficients determining the total speed of several important reactions has been widely adopted when modelling the D-region of the ionosphere. However, experimental opportunities for obtaining effective recombination coefficients are rather limited. One of the methods to estimate effective recombination coefficients uses the phenomenon of a solar eclipse. During some solar eclipses at the partial reflection facility of the Tumanny observatory observations were carried out. It gave possibility to obtain the behaviour of the electron concentration in time at the selected heights. Using the obtained experimental profiles, the effective recombination coefficients at the D-region heights of the ionosphere have been evaluated.

The 20 March 2015 total solar eclipse

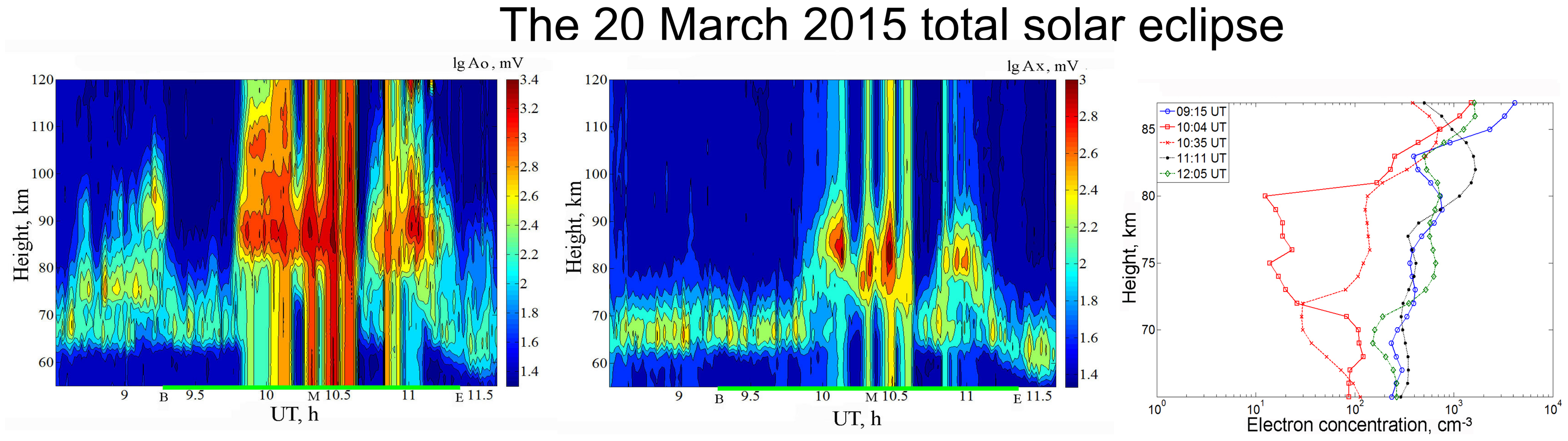

Fig.1. amplitude of ordinary (left) and extraordinary (middle) waves, and electron concentration (right) during the 20 March 2015 eclipse

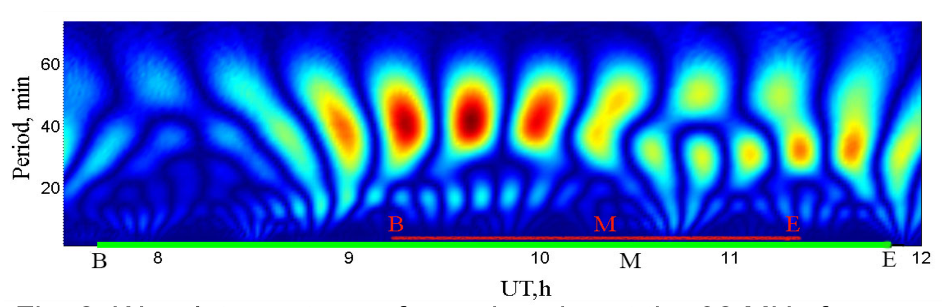

Fig. 2. Wavelet spectrum of cosmic noise at the 32 MHz frequency

Year	Month	Day	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24	Σ
1999	8	11	3-	2+	1-	1+	1+	1+	2+	2-	12+
2008	8	1	1-	1-	0+	0+	1+	1+	2-	1+	7
2011	6	1	3-	1+	3-	1+	2+	3+	2+	3-	18
2015	3	20	5-	3+	5-	3+	3-	2+	3+	4+	28
2017	8	21	2+	2+	3	3-	2-	1+	2	3-	18
2017	8	22	5-	4+	3	2-	3-	2+	2	3+	24

Table 1. Kp indexes for the days of the eclipses

Effective recombination coefficient calculation for solar eclipses

In the D-region of the ionosphere the behavior of electron concentration n_e at the fixed height in the absence of processes of transfer at change of rate of formation of electrons in time and disappearance of free electrons at a recombination process could be described by the equation

$$\frac{dn_e}{dt} = q - \alpha_{eff} n_e^2. \quad (1)$$

Appleton has drawn an analogy between change of electron concentration in the ionosphere and behavior of a linear inductive chain [Appleton, 1954]. Having differentiated the equation (1) on time, he has received the equation

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

Having compared it to the equation, describing behavior of current in an inductive chain,

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

where I – the electric current flowing on a chain with a resistance of R and inductance of L under the influence of the electromotive force ε it is possible to see analogy between coefficient $1/(2\alpha_{eff} n_e)$ in the equation (2) describing the ionosphere and a constant of time of an electric chain of L/R in the equation (3) describing an electric chain. Thus, it is possible to expect that the extremum of electron concentration of n_e will be reached through a period $\tau = 1/(2\alpha_{eff} n_e)$ after achievement of an extremum of rate of formation of electrons of q. By analogy with a constant of time of an electric chain of L/R Appleton called reaction of the ionosphere to ionization process lag effect of the ionosphere from a characteristic constant of time $\tau = 1/(2\alpha_{eff} n_e)$ which call "lag effect of the ionosphere" [Appleton, 1954], "relaxation time" [Appleton, 1954] or simply "ionosphere time constant".

The value of an ionosphere time constant can be found if we assume that the minimum of an electron formation rate q will be at the eclipse maximum, and electron concentration of n_e will reach its minimum later through some time of Δt.

We will receive expression for definition of Δt. For an electron formation rate q at the minimum of q_{min} the value dq/dt is equal 0 and the equation (2) it is possible to write down as the expression

$$\left(\frac{d^2 n_e}{dt^2}\right) = -2\alpha_{eff} n_{e q_{min}} \left(\frac{dn_e}{dt}\right)_{q_{min}}. \quad (4)$$

Using linear approach of the Taylor's theorem, it is possible to receive the value of change of electron concentration (dn_e/dt) through Δt period after achievement of q of its minimum:

$$\frac{dn_e}{dt} = \left(\frac{dn_e}{dt}\right)_{q_{min}} + \left(\frac{d^2 n_e}{dt^2}\right)_{q_{min}} \Delta t. \quad (5)$$

Let Δt be the period between a minimum of an electron formation rate q_{min} and a minimum of electron concentration n_e, i.e. relaxation time τ. In this case in a minimum of electron concentration of dn_e/dt = 0 and, using the equations (4) and (5), we will receive

$$\Delta t = \frac{\left(\frac{dn_e}{dt}\right)_{q_{min}}}{\left(\frac{d^2 n_e}{dt^2}\right)_{q_{min}}} = \frac{1}{2\alpha_{eff} n_{e q_{min}}}. \quad (6)$$

We will note that value $n_{e q_{min}}$ in the expression of a time delay (6) is equal to the value of electron concentration in the minimum of an electron formation rate, i.e. where $q = q_{min}$.

During an eclipse maximum the electron formation rate (ionization speed) becomes minimum, but at this time electron concentration at the chosen height continues to decrease and it reaches the minimum after some time τ. This period between the eclipse maximum (an ionization speed minimum) and the electron concentration minimum by Appleton's method is determined as the ionosphere relaxation time. Thus, knowing the relaxation time at the chosen ionosphere height, it is possible to determine an effective recombination coefficient α_{eff} for this height by the formula

$$\alpha_{eff} = 1/(2\tau n_{e q_{min}}), \quad (7)$$

where τ – relaxation time; $n_{e q_{min}}$ – electron concentration in the minimum of electron formation rate.

The 21 August 2017 total solar eclipse

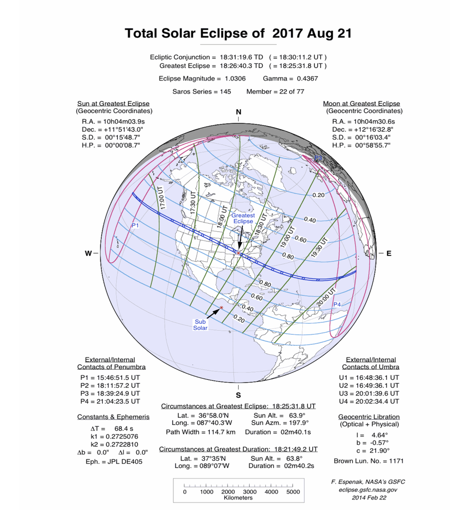

Fig. 3. Map and parameters of the 21 August 2017 total solar eclipse

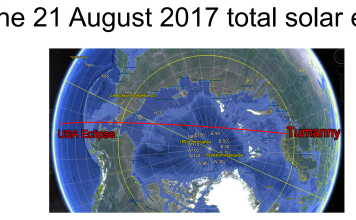

Fig 4. Position of the beginning of the total solar eclipse and the observatory Tumanny

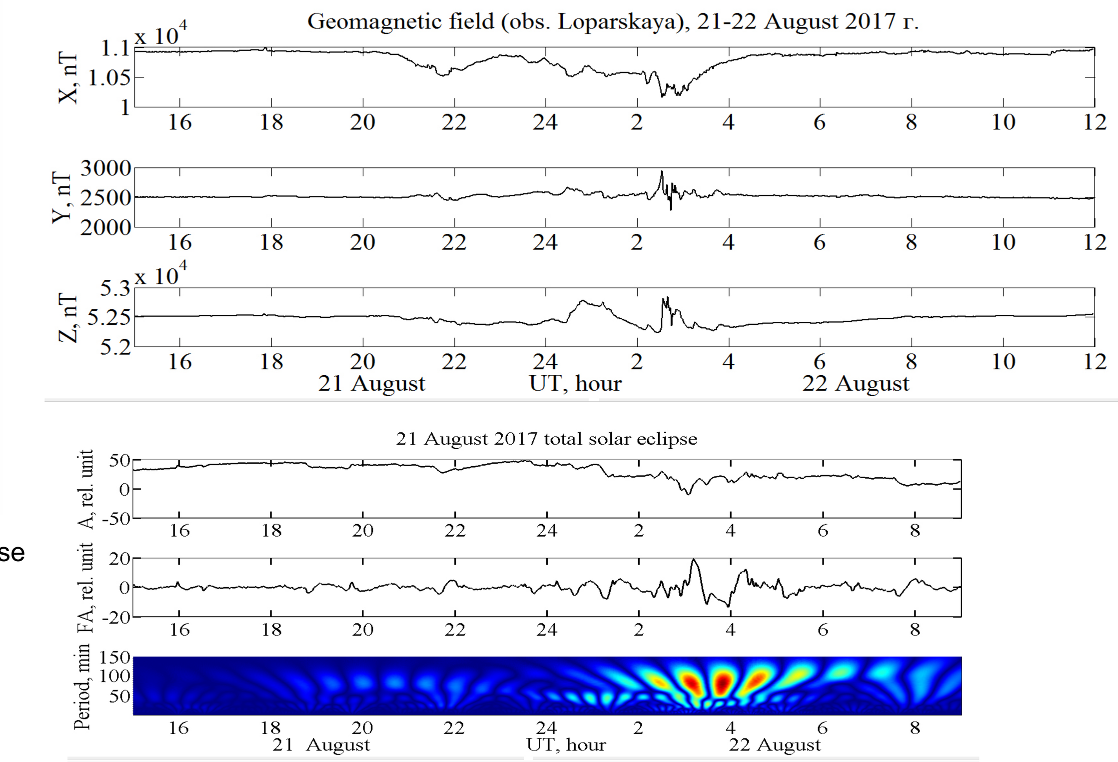

Fig. 5. Behaviour of the geomagnetic field (upper) and cosmic noise (lower) at the place of observation

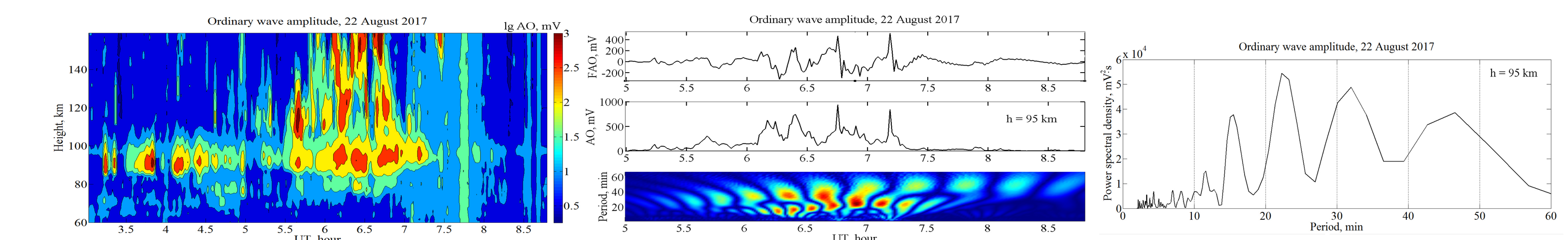

Fig. 6. Two-dimension picture of the ordinary partial reflected wave (left), wavelet spectrum and behaviour of the wave (middle) and the spectrum of the amplitude at the height of 95 km (right)

Some features of the 1 August 2008 and 20 March 2015 solar eclipses

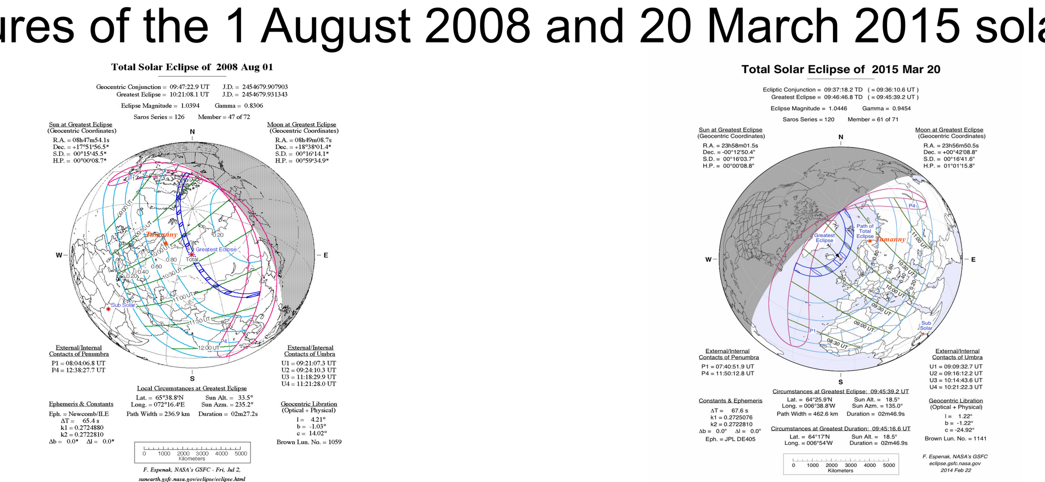

Fig 7. Maps and parameters of the 1 August 2008 and 20 March 2015 solar eclipses

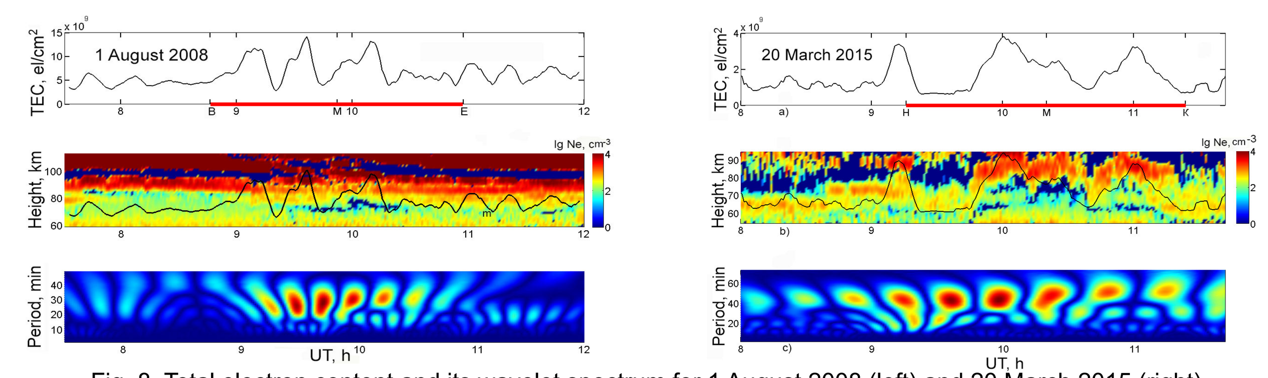

Fig. 8. Total electron content and its wavelet spectrum for 1 August 2008 (left) and 20 March 2015 (right)

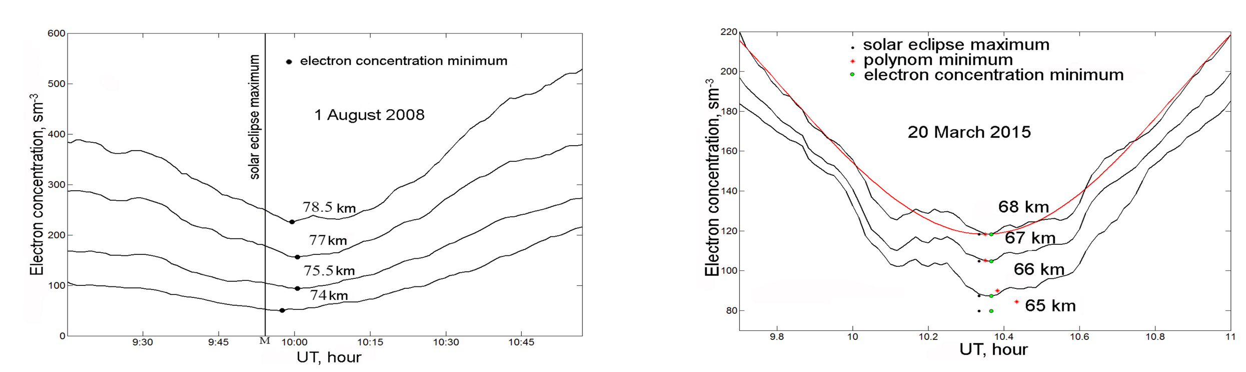

Fig. 9. Profiles of electron concentration at different heights for 1 August 2008 (left) and 20 March 2015 (right)

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

Table 2. Effective recombination coefficients 1 August 2008 solar eclipse

Height, km	Effective recombination coefficient, $sm^3 \cdot s^{-1}$
68	$3.71 \cdot 10^{-5}$
67	$4.18 \cdot 10^{-5}$
66	$5.02 \cdot 10^{-5}$
65	$5.48 \cdot 10^{-5}$

Table 3. Effective recombination coefficients 20 March 2015 solar eclipse

Introduction

Experimental and theoretical studies of dynamic processes in the near-earth space during periods of unique events are important and urgent tasks in the study of the geospace environment. Such unique events are total and partial solar eclipses. The solar eclipses allow researchers to observe the change in the earth space during a controlled experiment. Astronomical parameters of eclipses known with sufficient accuracy, and it allows us to describe the changing conditions of the eclipse and to see the reaction of the atmosphere on the eclipse. In general, a solar eclipse is like the transition from day to night and then from night to day, and therefore the associated effects in both cases are partly similar. However, every eclipse takes place at its conditions, and dynamic processes during an eclipse depend on heliogeophysical situation, time of day and year, etc. Solar eclipses cause in the atmosphere different processes: a decrease of the temperature and electron concentration in the ionosphere, the generation of atmospheric waves, etc. Researches of the response of the ionosphere to solar eclipses in the lower ionosphere are the least studied and therefore are of greatest interest. In this work several samples of different effects in the D-region of the high-latitude ionosphere for the solar eclipses of 1 August 2008, 20 March 2015 and 21 August 2017 are presented. Description of the experimental facilities are given in the work [Cherniakov, 2016].

Results

On the Fig. 1 amplitudes of ordinary (left) and extraordinary (middle) waves, and electron concentration (right) during the 20 March 2015 eclipse are shown. It can be seen that during the eclipse electron concentration at the heights 72-80 km has decreasing of its value almost by ten times. Wave variations in the amplitudes as well as in the riometer data (Fig. 2) are very clear seen. Red line shows beginning and end of the eclipse at the place of observation, green line shows beginning and end of the eclipse on the whole Earth. Wavelet spectra of amplitudes and electron concentration show that the ones also have wave features at different heights.

The 21 August 2017 total solar eclipse was far from the observatory Tumanny (about 8000 km) (Fig. 3, 4). The place of observation had no direct influence of the solar eclipse. Chimonas and Hines [1970] suggested that during solar eclipses atmospheric gravity waves can be generated by supersonic moving of the Moon's shadow through the Earth's atmosphere and ground facilities would be able to register their manifestation. A big number of researches were implemented to confer the suggestion [Šauli, 2007]. So we considered wave behaviour of the lower ionosphere after the 21 August 2017 solar eclipses in the region of the radio physical observatory «Tumanny» (69.0N, 35.7E). Fig 5 shows variations of the geomagnetic field and cosmic noise at the 32 MHz frequency. There was a substorm at the high latitudes. It can be seen that after 5 UT at the place of observation the geomagnetic situation was rather quite. So after it we can consider that wave effects could be from the solar eclipse. On the Fig. 6 it can be seen that after 5:30 UT ordinary amplitude (left) shows appearance of wavelike structure at the heights 95, 120 and 150 km. If we consider that spreading of acoustic disturbances began at 16:50 UT (U2 contact, Fig.3) and the distance to the observatory Tumanny from the point of U2 contact is about 8000 km, then we receive the velocity of spreading of the wave disturbances about 175 m/s. The velocity corresponds to the velocities of internal gravity waves. Wavelet spectrum of ordinary amplitude variations at the height of 95 km (Fig.6, middle) shows presence of different waves with the periods of 15, 22, 31 and 45 min (Fig. 6, right). So we could suggest that we have recorded the coming internal gravity waves from the 21 August 2017 total solar eclipse.

The another feature during eclipses is presence of changes in the total electron content (TEC) of the lower ionosphere which have wavelike structures (Fig. 8). For consideration of wave effects in TEC we used the Cauer's filter and wavelet analysis of the programming language MATLAB. In all cases TEC shows presence of wave structures with period about 20-60 min. The time of appearance of waves does not coincide fully with the time of eclipses at the place of observation. During eclipses of August 2008 and 20 March 2015 three obviously expressed maxima can be seen. The periods coincide to periods of acoustic-gravity waves and could be result in supersonic moving of the Moon's shadow through the Earth's atmosphere.

In the "Effective recombination coefficient calculation for solar eclipses" it is shown how an effective recombination coefficient could be calculated in the case of a solar eclipse. On the Fig. 9 electron concentration profiles are shown for some heights in the D-region of the ionosphere. Using the obtained experimental profiles, the effective recombination coefficients at the D-region heights of the ionosphere have been evaluated and their values are shown in the Tables 2 and 3. However, experimental opportunities for obtaining effective recombination coefficients are rather limited because of presence of processes of transfer in the ionosphere during eclipses.

References

Cherniakov S. Wave effects in the total electron content of the high-latitude lower ionosphere during solar eclipses. AGU Fall Meeting, 12-16 December 2016, San-Francisco, USA. Poster. SA33A-2412, https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/120560.

Chimonas G., Hines C.O., 1970. Atmospheric gravity waves induced by a solar eclipse. J. Geophys. Res., V. 75, N 4, P. 875 (doi:10.1029/JA075i004p00875).

Šauli P., Roux S. G., Abry P., Boška J. Acoustic-gravity waves during solar eclipses: detection, characterization and modeling using wavelet transforms. J. Atmos. Sol.-Terr. Phys. 2007. V. 69, N 17-18. P. 2465-2484.

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Eclipse map/figure/table/predictions courtesy of Fred Espenak, NASA/Goddard Space Flight Center, from eclipse.gsfc.nasa.gov.

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