Journal of Atmospheric and Solar-Terrestrial Physics 138-139 (2016) 136–160

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Research Paper

Ionospheric F2 layer responses to total solar eclipses at low and mid-latitude

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ARTICLE INFO

Article history:
Received 17 August 2015
Received in revised form
8 January 2016
Accepted 11 January 2016
Available online 13 January 2016

Keywords:
NmF2 and hmF2
Equatorial/low-latitude
Mid-latitude
Solar ionizing radiation
Hemisphere

ABSTRACT

In this article, we presented ionospheric F2 responses to total solar eclipses on the basis of the data obtained from five (5) equatorial/low-latitude and twenty-seven (27) mid-latitude ionosonde stations, which are within the obscuration percentage of 50–100% of the path of the total solar eclipses progression. Statistically, the diurnal changes in the F2 layer peak height hmF2 and electron density NmF2, as well as the latitudinal and hemispheric dependence and the contribution of both magnetic and solar activities during the eclipse window were investigated. The estimation of the solar ionizing radiation that remains unmasked during the eclipse window was as well carried out. Plasma diffusion processes dominate the F2 region plasma, and determine the height at which the F2 peak formed at mid-latitude. The electron density decreased during the eclipse window, closely following the variation in the local solar radiation at the mid-latitude. However, at equatorial/low-latitude, the plasma distribution during total solar eclipse depends on combine effect of solar radiation and the background nighttime ionospheric irregularities mechanism. The uncertainty level of the estimated solar ionizing radiation was $< \pm 0.3$ at mid-latitude and greater ± 0.3 at equatorial/low-latitude. Their correlation ranges from (0.42–0.99). The ionospheric F2 layer eclipse effect is latitudinal and hemispheric dependent. The effect is largest at mid-latitude and relatively small at equatorial/low-latitudes. It is more pronounced at the equator, and decreases toward the equatorial ionospheric anomaly (EIA) region. The better correlation of 0.5840 and 0.6435 between geographic latitude and $E(t)$ and electron density justifies the latitudinal relationship. The increase in percentage deviation of electron density increases with latitude and delay time (ΔT) in the northern hemisphere of the mid-latitude. Conversely, in the southern hemisphere the percentage deviation decreases with an increase in ΔT and the latitude. The influence of the combined effect of solar activity and magnetic disturbances cannot the overlooked during total solar eclipse. At the eclipse shadow, the deviation increases with decreasing magnetic disturbances and solar activity. During magnetic quiet conditions the variation in maximum NmF2/hmF2 on the eclipse day are more decrease/increase than the control day and overturned during the magnetic disturbed condition.

1. Introduction

The occurrence of a solar eclipse provides an opportunity to investigate its effect on the terrestrial atmosphere. The short term duration nighttime conditions during an eclipse enable the scientific community to study the behavior and typical effects between different layers of the ionosphere using different measurements (Tsai and Liu, 1997; Chandra et al., 1980; Farges et al., 2001; Abidin et al., 2006; Adeniyi et al., 2007; Jakowski et al., 2008; Le et al., 2008a, 2008b; Le et al., 2009a, 2009b; Chernogor, 2010; An et al., 2010; Chen et al., 2011; Paul et al., 2011; Phanikumar et al., 2011; Kumar and Singh, 2012; Adekoya and Chukwuma, 2012; Chuo, 2013; Kumar et al., 2013; Lyashenko and Chernogor, 2013). A solar eclipse is similar to the onset of a short-time night; therefore, the accompanying effects in both cases are normally expected to be similar. However, dynamic process during a specific eclipse depend significantly on the time of occurrence in a day and geophysical and solar variations (Wang et al., 2010), so investigating solar eclipse effects on the ionosphere layer remains an important task.

Investigation of ionospheric effects during solar eclipse has contributed immensely to the understanding of the transient properties of ionizing radiation from the Sun as well as the chemical and transport processes in the ionosphere. In a number of papers, experimental and theoretical eclipse results have been compared to derive the rate of electron production and the loss of ionization (e.g. Davis et al., 2000; 2001; Chuo, 2013). The loss rate

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http://dx.doi.org/10.1016/j.jastp.2016.01.006
1364-6826/

of ionization at different altitudes depends on the composition of the ionosphere. The simultaneous decrement in the F1 region electron density with the increase is eclipse magnitude is seen on the eclipse day, without any time delay, due to higher loss rate of NO^+ and O_2^+ (e.g. Holt et al., 1984). However, the decrease in the electron density in the F2 region (in which O^+ is dominant) is found to show a time delay in the decrease due to the slower loss rate of O^+ (Rishbeth, 1988). The solar eclipse effect on the ionospheric F2 layer is thought very complex and puzzling when only the bottom side of the layer could be observed. Since is the only region of the ionosphere persistently remains at night; the electron density varies with latitude, local time, solar epoch and solar cycle, and could decrease, increase, or remain unchanged during the spectacular eclipse events. Phanikumar et al., (2011) reported that the negative/positive response of NmF2/hmF2 indicating that the electron density at F2-region peak region and the bottom side ionosphere during the eclipse period are quickly lost due to recombination.

Recent efforts in the last decade tried to unravel the eclipse effects on the ionosphere, using large number of experiments and modeling procedures (e.g., Müller-Wodarg et al., 1998; Davis et al., 2000, 2001; Grigorenko et al., 2008; Le et al., 2008a; Le et al., 2009a, 2009b; Wang et al., 2010; Guha et al., 2010; Chernogor, 2010; Domnin et al., 2013). The ionization process undergoes rapid, predictable changes during the solar eclipse, a rare event. Most studies on ionospheric eclipse had been focused on the mid-latitude ionosphere, though on different measurements and methodology. Amongst these are Müller-Wodarg et al. (1998), Afraimovich et al. (2002), Le et al. (2008a), Le et al. (2009a), Tomás et al. (2009), Wang et al. (2010), and Adekoya and Chukwuma (2012). Some of these studies discuss observations exclusively on the assumption that solar eclipse at mid-latitude is largely controlled by plasma diffusive transport process. Recently, Adekoya et al. (2015) have shown that at low-latitude region the plasma vertical drift was the principal ionospheric constituent that is responsible for the changes in the formation of the ionosphere during solar eclipse. However, the results were fewer and inconclusive.

In the current research, taking advantage of the dense network over geophysical observatories around the globe, the eclipse during different magnetic activity and solar epochs would be investigated using more data, which were not given much attention by previous workers. Also, the simultaneous investigation of latitudinal and hemispheric dependence of F2 layer during total solar eclipse events has been understudied. The quantitative relationship between the unmasked fraction of solar ionizing radiation to the total ionizing radiation and the electron density during total solar eclipse will be clearly shown in this work for ionospheric F2-layer using more data than ever recorded in literatures. The mechanisms responsible for ionospheric F2 formation during eclipse window are explained in details.

2. Ionospheric data source and total solar eclipse path

To analyze the ionospheric F2 layer response to solar eclipses, we selected ionosonde stations during nine total solar eclipse events when the path of the Moon shadow passed through equatorial/low- and mid-latitude. The path of totality across the earth with time of commencement and duration of eclipse are highlighted in Table 1. Total solar eclipses are rare event at any particular location because totality exists only along a narrow path on the Earth's surface traced by the Moon's umbra. Fig. 1 presents the geographic location of each equatorial/low-latitude station along the path of the eclipse used on the map. All the paths of totality were found from NASA National Aeronautics and Space Administration (NASA) service (http://eclipse.gsfc.nasa.gov).

The two sets of ionospheric data used in this study consists of 10- and 15-min regular values of ionospheric F2 parameters obtained from Space Physics Interactive Data Resource (SPIDR's) http://spidr.ngdc.noaa.gov) and the Global Ionospheric Radio Observatory (GIRO) networks of ionosonde stations located in the equatorial/low- and mid-latitude paths**,** as well as the eclipse progression time and percentage of maximum obscuration are presented in Table 2. The data from SPIDR which are normally automatically scaled were validated for accuracy by comparing the diurnal morphology of the derived NmF2 data from critical frequency (foF2) obtained from some of the stations under study against local time with the electron density profile at other stations (Chuo, 2013; Nayak et al., 2012; Adeniyi et al., 2007). The results agreed well with the known electron density profile. Furthermore, several works have been carried out using SPIDR data and their results are well documented and published (e.g. Adekoya et al., 2015; Adekoya and Adebesin, 2014; Adebesin et al., 2013; Adekoya et al., 2012; Oyeyemi et al., 2010; Akala et al., 2010). The direct scaled measurement data from GIRO network was manually validated. The digital Ionogram database (DIDBase) can be found at the web portal address http://ulcar.uml.edu/DIDBase/, with a minima latency allows for the assimilation of the Ionogram-derived data in real-time models such as the real-time extension planned for the International Reference Ionosphere (Reinisch and Galkin, 2011).

To ensure that the decrease in electron density because of eclipse was large in comparison with the background ionospheric

Table 1
Showing the date and the path of total solar eclipse, the time of eclipse commencement and visibility and the geographical region of visibility.

Total eclipse date yy/mm/dd	Time of commencement of eclipse hh/mm/ss (UT)	Time length at which eclipse can be seen	Geographical region of eclipse visibility	Path of totality at the geographical region
19880318	01:58:56	03m49s	east Asia, east Indies, Australia, Alaska	Malaysia, Indonesia, Philippines and Pacific
19970309	01:24:50	02m50s	Asia, Alaska	Mongolia, China, Siberia
19990811	11:04:09	02m23s	East of north America, north Africa, Europe, Asia	England, Europe, Middle East, Turkey, India
20010621	12:03:46	04m57s	east of South America, Africa	south Atlantic, south Africa, Madagascar
20021204	07:32:15	02m04s	South Africa, Antarctica, Indonesia, Australia	South Africa, South Indian, South Australia
20060329	10:12:22	04m07s	Africa, Europe, west Asia	central Africa, Turkey, Russia
20090722	02:36:25	06m39s	east Asia, Pacific Ocean, Hawaii	India, Nepal, China, Central Pacific
20121113	22:12:55	04m02s	Australia, N.Z., south Pacific, south S. America	north Australia, south Pacific
20150320	09:08:02	02m47s	Iceland, Europe, north Africa, north Asia	north Atlantic, Faeroe Island, Svalbard