Available online at www.sciencedirect.com

SciVerse ScienceDirect

Advances in Space Research 50 (2012) 1352–1361

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Response of low latitude D-region ionosphere to the total solar eclipse of 22 July 2009 deduced from ELF/VLF analysis

Ashutosh K. Singh [a], Rajesh Singh [b], B. Veenadhari [c], A.K. Singh [a,*]

[a] Atmospheric Research Lab., Department of Physics, Banaras Hindu University, Varanasi, India
[b] KSK Geomagnetic Research Laboratory, IIG, Chamanganj, Allahabad, India
[c] Indian Institute of Geomagnetism, Navi Mumbai 410218, India

Received 3 March 2012; received in revised form 1 July 2012; accepted 3 July 2012
Available online 11 July 2012

Abstract

Response of the D-region of the ionosphere to the total solar eclipse of 22 July 2009 at low latitude, Varanasi (Geog. lat., 25.27° N; Geog. long., 82.98° E; Geomag. lat. = 14° 55' N) was investigated using ELF/VLF radio signal. Tweeks, a naturally occurring VLF signal and radio signals from various VLF navigational transmitters are first time used simultaneously to study the effect of total solar eclipse (TSE). Tweeks occurrence is a nighttime phenomena but the obscuration of solar disc during TSE in early morning leads to tweek occurrence. The changes in D-region ionospheric VLF reflection heights (h) and electron density (n_e: 22.6–24.6 cm^{-3}) during eclipse have been estimated from tweek analysis. The reflection height increased from ~89 km from the first occurrence of tweek to about ~93 km at the totality and then decreased to ~88 km at the end of the eclipse, suggesting significant increase in tweek reflection height of about 5.5 km during the eclipse. The reflection heights at the time of totality during TSE are found to be less by 2–3 km as compared to the usual nighttime tweek reflection heights. This is due to partial nighttime condition created by TSE. A significant increase of 3 dB in the strength of the amplitude of VLF signal of 22.2 kHz transmitted from JJI-Japan is observed around the time of the total solar eclipse (TSE) as compared to a normal day. The modeled electron density height profile of the lower ionosphere depicts linear variation in the electron density with respect to solar radiation as observed by tweek analysis also. These low latitude ionospheric perturbations on the eclipse day are discussed and compared with other normal days.

Keywords: Total solar eclipse; D-region of Ionosphere; ELF–VLF waves; Tweeks

1. Introduction

Eclipses, either solar or lunar, have been attracting the interest of people since the ancient years. In modern times solar eclipses have been still triggering the attention of scientists for testing the various physical hypotheses. The atmospheric effects of a solar eclipse have been subject of extensive research mainly on meteorological parameters (Anderson et al., 1972), boundary layer physics (Antonia et al., 1979), photochemistry (Srivastava et al., 1982; Zanis et al., 2007), total columnar ozone (Chakrabarty et al., 1997; Zerefos et al., 2000), gravity wave (Chimonas and Hines, 1970; Zerefos et al., 2007) and ionospheric parameters (Klobuchar and Whitney, 1965; Singh et al., 2011; Kumar and Singh, 2012). Solar eclipse is one of the important events for ionospheric research because it has direct influence on the Earth's ionosphere. During the period of solar eclipse, the amount of solar radiation reaching the Earth is reduced due to Moon's shadow resulting in the less production of the plasma while the loss processes remains unaffected (Sharma et al., 2010). Hence loss rate of plasma on the eclipse day dominates over the production rate, in

* Corresponding author. Address: Atmospheric Research Lab., Department of Physics, Banaras Hindu University, Varanasi 221005, India. Tel.: +91 9415303722; fax: +91 0542 2368390.

E-mail addresses: ashutoshksingh.bhu@gmail.com (A.K. Singh), rajeshsing03@gmail.com (R. Singh), bveena@iigs.iigm.res.in (B. Veenadhari), abhay_s@rediffmail.com (A.K. Singh).

0273-1177/$36.00
http://dx.doi.org/10.1016/j.asr.2012.07.005

comparison to normal quiet day. Thus electron density in the ionosphere decreases on the solar eclipse day (Chandra et al., 2007; Singh et al., 2011; Kumar and Singh, 2012). There are good numbers of ionospheric observations during solar eclipses mainly dedicated to E and F regions of the ionosphere through rocket, radar and ionosonde techniques (Klobuchar and Whitney, 1965; Farges et al., 2001; Chandra et al., 2007; Chen et al., 2010). Since the probing of D-region ionosphere is difficult as the altitude is too low for satellites and too high for balloon studies, it remains the least studied region of the Earth's atmosphere. Despite the large number of studies concerning eclipses, the event of a solar eclipse is always unique since it happens at different seasons, different time of the day, different locations and under different synoptic conditions.

ELF/VLF radio signals transmitted from the various transmitters across the world and those generated by lightning discharges propagate by multiple reflections through the Earth-ionosphere waveguide form the novel tools to study the D-region of the ionosphere (Kumar et al., 2008; Inan et al., 2010; Singh et al., 2011). Tweeks are formed when lightning generated ELF-VLF atmospherics propagate long distances, particularly in the night, in the Earth-ionosphere waveguide (EIWG) with a low attenuation (Yamashita, 1978; Singh and Singh, 1996). Burton and Boardman (1933) were first to report observation of tweeks during a total solar eclipse of 31 August 1932 at Conway, New Hampshire. Rycroft and Reeve (1970) observed about 60 tweeks during the total solar eclipse of 7 March 1970, in Newfoundland, Canada, and utilized these tweeks to determine the change in the ionospheric reflection heights during the eclipse. They estimated an increase of about ~7 km above the normal daytime reflection heights. Recently, Singh et al. (2011) reported observation of tweeks with higher harmonics ($n > 1$) at low latitude stations Allahabad and Nainital, in the Indian sector, during the total solar eclipse on 22 July 2009. The change in D-region ionosphere VLF reflection height and electron density (~22–23 cm^{-3}) during eclipse have been estimated from the first cut-off frequency of the tweeks. They estimated the increase of reflection height of about 5 km during eclipse.

There is a significant variation in the received signal's amplitude and phase which arises due to changes in the lower ionosphere when the radio signals of fixed frequency transmitted from various VLF transmitters propagate inside the EIWG (Helliwell et al., 1973; Rodger et al., 1998). Phase and amplitude perturbations in ELF/VLF radio signals associated with total solar eclipses have been studied extensively (Lynn, 1981; Buckmaster and Hansen, 1998; Clilverd et al., 2001). Bracewell (1952) reported first time the eclipse effect at VLF transmitter signal on the GBR (Rugby, England) to Cambridge path during a partial eclipse in 1949. Typically increases in amplitude of 1 dB are observed and phase decrease of ~40° are seen (Lynn, 1981). Clilverd et al. (2001) reported the multi-receiver observation of VLF transmitter signals in the range 16–24 kHz located in the Europe during an eclipse of August 11, 1999. They reported that although there was significant variation in amplitude and phase from path to path, the typical changes were ~3 dB and ~50°. Recently, Zhang et al. (2011) analyzed the VLF signals observed at Nanjing, China during the total solar eclipse on 22nd July 2009 using the sudden ionospheric disturbance (SID) monitor provided by the Stanford University. They found that the intensity of the VLF signal varied anomalously during the total solar eclipse, exhibiting the effect similar to the sunrise and sunset. De et al. (2011) reported the results of the ionospheric response of solar eclipse of 22 July, 2009 from the measurements of VLF subionospheric transmitted signals at 19.8 kHz and 40 kHz recorded at Agartala, Tripura, India. They observed significant absorption in the amplitude of these signals during the eclipse period. Guha et al. (2010) also studied the changes in equatorial D-region electron density using subionospherically propagating VLF signal at 18.2 kHz over a distance of 2200 km over the total solar eclipse of 22 July 2009. But the study of the effect of this eclipse on the ionosphere simultaneously using both narrowband as well as broadband VLF signals is lacking. Since the solar eclipses are rare events, regular ionospheric effects of solar eclipses are still not completely understood. To complete this study, the present study have been initiated using analysis of both tweeks as well as VLF subionospheric transmitted signals simultaneously first time at low latitude Indian station, Varanasi during the total solar eclipse of 22 July, 2009.

The total solar eclipse of 22 July 2009 provided us a unique opportunity to study the response of low latitude D-region ionosphere to the sudden changes in the solar radiation by solar eclipse. In this study we have analyzed first time simultaneously both narrowband (amplitude and phase of transmitted signal) as well as broadband (entire VLF signal spectrum) VLF data to find any significant changes in amplitude and/or phase of the signals from subionospheric VLF signal of 22.2 kHz transmitted from JJI, Japan and any variation from the normal diurnal behavior of the D-region ionospheric parameters such as electron density and reflection height.

2. Experimental setup

The observations made on 22 July 2009 were done by using AWESOME ELF/VLF receiver developed by Solar Center of the Stanford University, USA (Cohen et al., 2009; Singh et al., 2010, 2011) installed at our low latitude station Varanasi. It consists of two orthogonal crossed loop antennas with 10 × 10 m base aligned in North–South (N–S) and East West (E–W) magnetic planes, matched pre-amplifier and line receiver. Pre-amplifier is kept as near as to the receiving antenna for the better amplification of received signals, then it is fed to the line receiver kept in the recording room, connected by a ~100 m long cable. GPS clock is connected with line receiver for time synchronization with improved accuracy of 100 ns. The frequency response of the ELF/VLF receiver is from 300 Hz to 47.5 kHz. Recorded VLF data are stored in a recording PC at 100 kHz, 16-bit sampling and 10 micro-seconds time resolution. These sampled data are analyzed by codes developed in MATLAB. We have two types of data recording: broadband data (300 Hz to 47.5 kHz) and narrowband data (amplitude and phase of the VLF transmitter frequencies transmitted from various navigational transmitter operating around the world). Normally broadband data is recorded in synoptic mode (one minute at every 15 min interval) but during the solar eclipse campaign period 19–25 July 2009, it was recorded in continuous mode.

3. Observations

All solar eclipses involve the Moon passing between the Earth and the Sun, and casting a shadow on the Earth. However, the type of eclipse which can be seen from a given location depends on whether the moon passes directly or only partly between the Earth and the Sun but also on where on Earth one stands to observe it and on a number of other factors. On 22nd July 2009, a total solar eclipse happened in the central part of India in the latitudes between 20° N and 30° N with totality duration of about 6 min and 39 s. This was unique in the sense that it occurred during night to day transition phase when the local ionosphere was in developing stage and also it was the longest solar eclipse of this century. The path of moon's umbral shadow started from western part of India and passed through Nepal, Bangladesh, Bhutan, Myanmar, China and then reached to the Pacific Ocean. With the AWESOME monitor provided by the Solar Center of the Stanford University, USA continuous VLF measurements were taken during the total solar eclipse at Varanasi (Geogr. lat., 25° 03′ N; Geogr. long., 82° 58’ E) where 100% totality was observed. The path of totality in India and in remaining part of Asia is shown in Fig. 1. Table 1 show local circumstances i.e. the variation of solar eclipse magnitude and duration observed at Varanasi during the eclipse (Source: http://www.eclipse.gsfc.nasa.gov/SEmono/TSE2009/TSE 2009.html). It started at 05:30:04.4 h IST (Indian Standard Time, IST = UT + 5:30 h) and lasted up to 07:27:34.4 h IST with totality from 6.25 IST to 6.27 IST in the morning hours at Varanasi. During this period lower ionosphere is in developing stage at our low latitude station. During eclipse period the temperature at Varanasi varied between 27.5 °C and 28.6 °C. The relative humidity (RH) generally varied between 86 and 92% and the atmospheric pressure varied between 988.5 and 989.2 hPa. The sky was partially cloudy in the morning of the day but it become clear and cloud free as soon as the eclipse period started and there was no rainfall on that day. One day before the eclipse and during the eclipse period, it was a magnetically quiet period but on the afternoon of the eclipse day a moderate magnetic storm occurred whose main phase onset occurred after the passage of the moon's umbral shadow with minimum *Dst* of −78 nT at 07:00 h UT. This disturbed condition continued on 23 July. The maximum value of Kp-index observed on July 22 was 6 with a value of only 3 during the eclipse period. The daily Ap-index (=25) was also low, confirming a local type moderate storm. However, moderate magnetic storm of such intensity has minimal effect on the D-region of the ionosphere (Singh et al., 2011).

Table 1
Local circumstances for total solar eclipse on July 22, 2009 at Varanasi.

Event	Time (UT)	Altitude (deg)	Azimuth (deg)
Start of partial eclipse	00:00:04.4	1.8	68.6
Start of total eclipse	00:54:14.7	12.8	73.4
Maximum eclipse	00:55:45.1	13.1	73.5
End of total eclipse	00:57:16.2	13.4	73.7
End of partial eclipse	01:57:34.7	27.0	79.0

Varanasi: Lat = 25.3°N, Long = 82.9°E, Eclipse magnitude = 1.065, Umbral Depth-0.424, Umbral Durat.-03m01.4s.

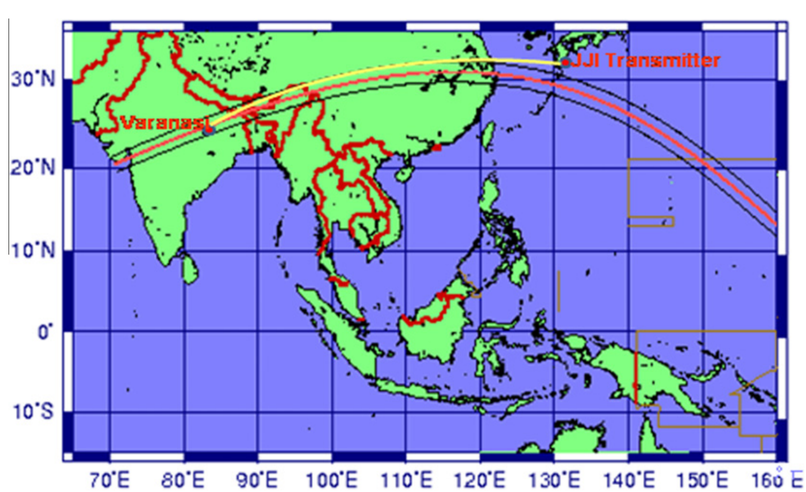

Fig. 1. Path of solar eclipse passing over India during 22 July 2009. Great circle path for VLF receiver at Varanasi and VLF transmitter, JJI Japan is also shown.

Continuous monitoring of broadband VLF sferic/tweeks as well as narrowband subionospheric VLF radio signals transmitted from the various navigational transmitters operating around the world is being conducted at Varanasi. Here the main emphasis is given to the VLF signal transmitted at 22.2 kHz from the JJI transmitter in Japan because more than 60% of the Varanasi-JJI great circle path was laid in the totality region which is clearly visible in Fig. 1. In the one-week periods both before and after the total solar eclipse, the instrument worked normally and the external interference was small, but in the period of the total solar eclipse, the observed signals exhibited significant variations. Here we observe a significant increase in the strength of the amplitude of the signal around the time of the TSE as compared to a control day. This is attributed to the significant decrease in the electron density in the 'D' region of the ionosphere and the simultaneous increase in the width of the EIWG during the TSE. Typically, positive amplitude changes are observed throughout the whole eclipse period on path lengths ~4689 km (Varanasi, India to JJI, Japan) during the eclipse period.

Tweeks radio atmospherics are generated by lightning discharge mainly nighttime phenomenon because of low attenuation during nighttime (Singh and Singh, 1996; Kumar et al., 2008). Fig. 2 shows the examples of tweeks observed on 22 July 2009 during nighttime before the eclipse and during the eclipse period at Varanasi. We see some observable differences between them. Nighttime tweeks are brighter and have longer dispersion time compared to the eclipse period tweeks. The shorter duration of tweeks observed during the eclipse as compared to normal nighttime tweeks may be due to the short propagation distance of the tweeks. At Varanasi eclipse started at 00:00:04.4 UT (h) and lasted up to 01:57: 34.7 UT (h). A total of 18 tweeks were observed during the eclipse period with maximum occurrence during totality. Number of tweeks observed at our station is less as compared to tweeks observed at Allahabad (Singh et al., 2011).

4. Results

To see the effect of solar eclipse on D-region ionosphere we have analyzed the tweeks during the eclipse period (a partial nighttime condition generated due to solar eclipse) and compared the various parameters with the normal nighttime condition observed tweeks. The cut-off frequency (f_c) of each tweek has been measured with an accuracy of 26 Hz and time by 1 ms from the spectrogram. The ionospheric reflection height (h) from where tweeks/sferics are reflected back to the Earth are calculated by using the equation $h = c/2f_c$ (Yamashita, 1978), where c is the velocity of light in free space. The electron density (n_e) at the reflection height, h is determined by using $n_e\ (\text{cm}^{-3}) = 1.3651\text{x}10^{-2} f_c$ (Ohya et al., 2003). The average cut-off frequency of first harmonics of tweeks observed at Varanasi during 12:30–07:30 h (IST) is used to find the variation of reflection height (h) (upper panel) and electron density (n_e) (lower panel) respectively as shown in Fig. 3. One day before the eclipse it was a magnetically quiet day but on the eclipse day a moderate magnetic storm occurred with minimum Dst of −78 nT at 07:00 h UT (12:30 h IST). This disturbed condition continued on 23 July. However, moderate magnetic storm of such intensity has minimal effect on the D-region of the ionosphere. It is also obvious from the Fig. 3, that the h and n_e remains almost same on 21 to 23 July during 12:30–05:15 h (IST) indicating no effect of this storm on h and n_e, hence on D-region of the ionosphere. During the normal days it can be seen that h starts decreasing and n_e increasing after around ~ 04:30 h IST with no tweeks after 05:15 h IST. This is because of increased ionization and hence increased attenuation with sunrise (Kumar et al., 2008). On 22 July after sunrise when solar eclipse started, a partial nighttime condition was created and tweeks were again observed in the eclipse period. These tweeks has been utilized to estimate the reflection height, h and electron density, n_e at h with the variation in solar radiation during the eclipse.

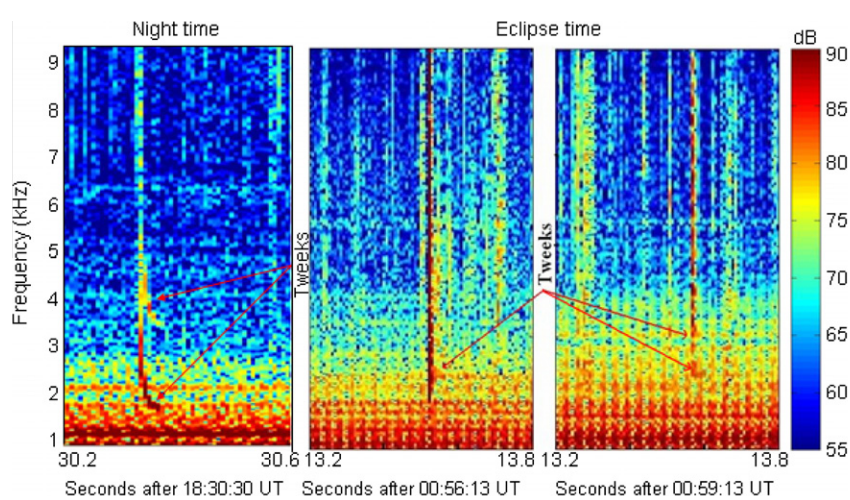

Fig. 2. Examples of the tweeks observed at Varanasi on 22 July 2009 before and during the total solar eclipse.

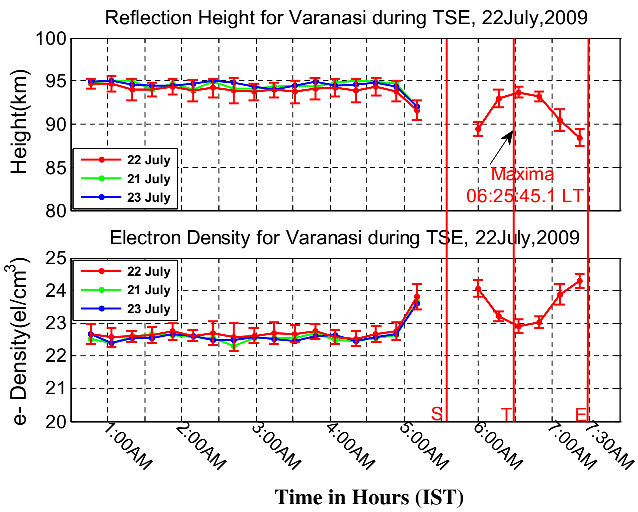

Fig. 3. The variation of reflection height and electron density at reflection heights observed at Varanasi on 21–23 July 2009 over 15 min intervals from 01:00–07:30 h IST.

VLF reflection height (h) is increased from 89 km at the beginning of solar eclipse to 93.5 km at the totality and then decreased to 88 km at the end of eclipse as shown in Fig. 3. The estimated n_e at h is found to vary between 22.6–24.6 cm^{-3}. Tweek propagation distance (D) in the Earth-ionosphere waveguide was calculated using the method used by Kumar et al. (2008), given as $D = \delta t (vgf_1 \times vgf_2)/(vgf_1 - vgf_2)$, where $\delta t = t_2 \sim t_1$ is the difference in arrival times of two frequencies f_1 and f_2 close to the cutoff frequency of the first harmonic of tweeks and vgf_1 and vgf_2 are the corresponding group velocities. Calculations shows that the propagation distance during the eclipse period varies between ~1000–4000 km as shown in Fig. 4, indicating source of lightning nearer (within 4000 km) to our observing station Varanasi. The world wide lightning location network (WWLLN) showed that most of the tweeks observed at Varanasi have their source in Asia-Oceania region lying in partial eclipse and totality regions (Singh et al., 2011).

Analysis of the subionospheric VLF radio signals transmitted mainly from the JJI transmitter in Japan is done to observe the effect of solar eclipse on VLF propagation henceforth D-region ionosphere. Fig. 5a shows the diurnal variation of VLF signal strength: two days before (20–21 July), on the day of eclipse (22 July) and one day after eclipse (23 July) during 00:00 UT (05:30 IST) to 05:00 UT (10:30 IST), transmitted from JJI-Japan and received at our observation site, Varanasi. Here we see a significant increase in the strength of the amplitude of VLF signal compared to normal days which is about 3 dB from the start of the eclipse (S) to the totality (T) and then attaining normal value at the end (E). This variation in the amplitude may be result of perturbation (decrease in ionization) in the EIWG due to eclipse. Fig. 5b shows the% change in the amplitude of the VLF signal compared to the mean of their ambient values for the same period during the adjacent 7 days. We observe here a maximum up to ~120% change in the strength of the VLF signal during the eclipse period. These low latitude ionospheric perturbations on the eclipse day are discussed and compared with other normal days.

To find the electron density variation of the D-region ionosphere during eclipse we have used exponential profile at a height of h km, Ne(h) described by Cummer et al. (1998) as:

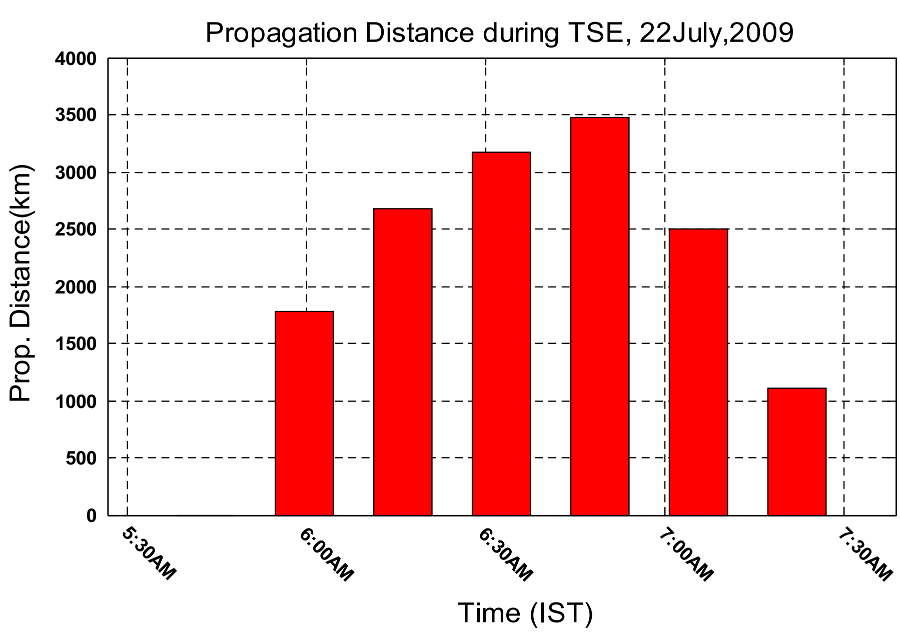

Fig. 4. Propagation distance traveled by tweeks observed during total solar eclipse of 22 July 2009 at Varanasi.

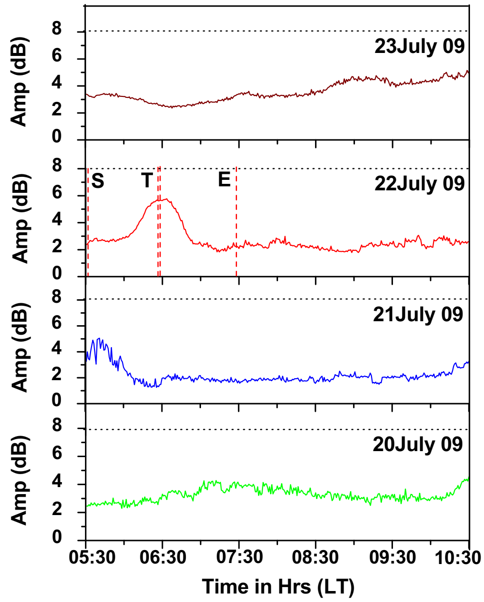

Fig. 5a. Variation of strength of the amplitude of VLF signal transmitted from JJI-Japan which is observed at Varanasi two days before eclipse (20–21 July), on the day of total solar eclipse (22 July) and one day after eclipse (23 July).

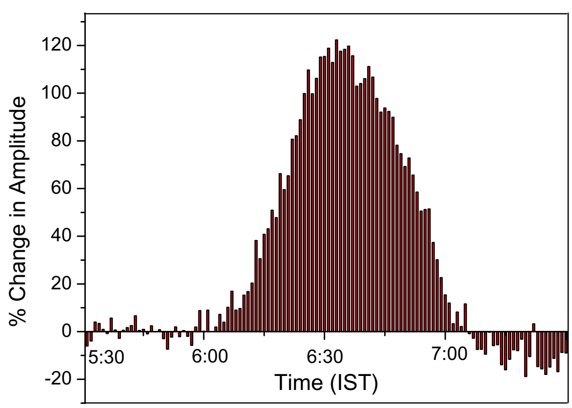

Fig. 5b. Percentage change in the amplitude of the signal during the solar eclipse period (05:39–07:30 h IST).

$$\mathrm{Ne}(h) = 1.43 \times 10^7 .exp(-0.15H').exp[(\beta - 0.15).(h - H')]\mathrm{cm}^{-3} \quad (1)$$

where H' is the D-region virtual reflection height in kilometers and β is Wait inverse scale height parameter in km^{-1}. We have taken $H' = 71$ km and $\beta = 0.43\ km^{-1}$ for unperturbed ionosphere (Thomson, 1993) for the modeling. Electron density profile derived from total solar eclipsed values of $H' = 74.3$ km and $\beta = 0.46\ km^{-1}$ (Clilverd et al., 2001) alongwith the unperturbed D-region profile is plotted in Fig. 6. It is observed that during totality the average electron density falls from 348 to 76 cm^{-3} at a height of 71 km which is about 78% less from normal condition. Corresponding% change in electron density with the height is shown in Fig. 7. The electron density decreases linearly with a rate of 0.67% km^{-1} from the height of 65–80 km.

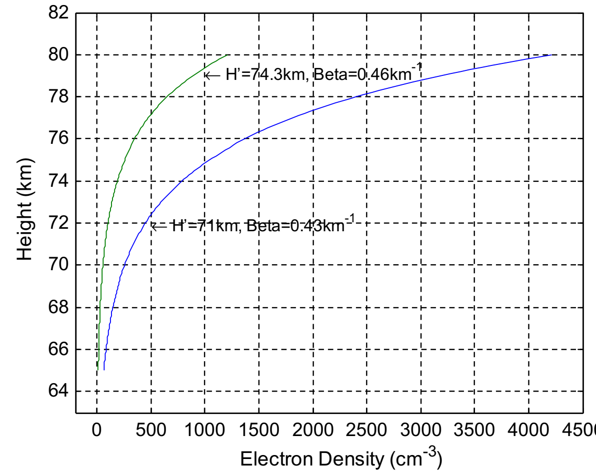

Fig. 6. Lower ionospheric electron density height profile under normal condition and during totality (100% obscuration) at virtual reflection height (H') and Wait inverse scale height parameter (β).

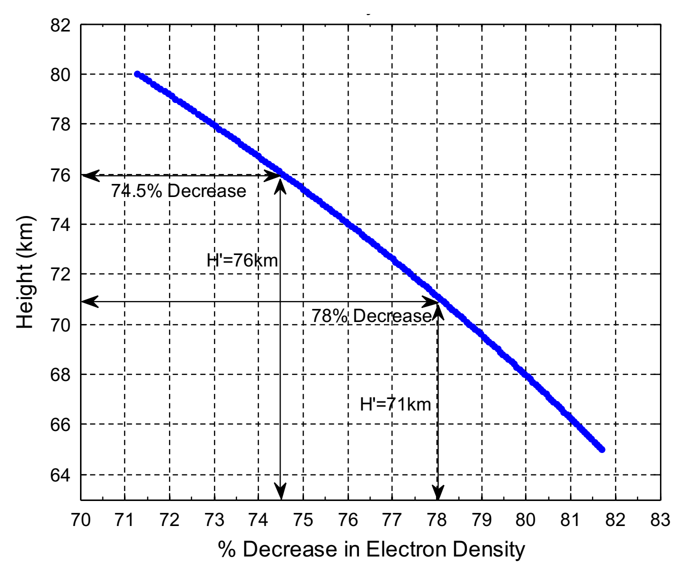

Fig. 7. Variation in percentage decrease in lower ionospheric electron density with height.

5. Discussions

A solar eclipse is a rare natural event and its effect on ionosphere is complicated by the involving many kind of processes, including ionization, chemical reactions, ambipolar diffusion, buoyancy forces, electro-dynamic drift, neutral wind effects etc., not to mention processes coupled into the ionosphere from magnetosphere, the mesosphere and lower atmosphere (Chen et al., 1999). It is generally regarded that the electron density in the D, E and F1 regions is dominated by a balance between photo-ionization and chemical recombination. During a solar eclipse, decrease in the solar flux causes direct reduction in the photo-ionization and destroys the previous photochemical equilibrium, resulting in the depletion in the electron density. The solar eclipse occurred on 22 July 2009 was unique as it occurred during dawn hours when local D-region ionosphere is in transition phase and was the longest TSE of the century.

In this study VLF observations from low latitude station Varanasi has been used to study D-region ionospheric response to the total solar eclipse. Here we have used first time both broadband as well as narrowband VLF analysis to study the eclipse effect. Tweek reflection height, electron density over these reflection heights, tweek propagation path along with the amplitude of the VLF transmitter signal has been used to determine the electron density and D-region ionospheiric height changes during the eclipse. Regular observations at our site shows that during the month of July tweek occurs during nighttime in between 19:00 h to 05:10 h $\pm$ 00:10 (IST) and then it disappears after sunrise. This is due to increased ionization hence higher attenuation (Kumar et al., 2008; Singh et al. 2010). On the day of eclipse (22 July), the tweeks were observed up to 05:15 h (IST) like normal days and they reappear at 06:00 h (IST) after the start of the eclipse with a gap of 45 min. A total of 18 tweeks were observed during eclipse period, less compared to tweeks observed at Allahabad (Singh et al., 2011). This might be due to much electrical noise in the vicinity of receiver at our observation site. A total of 12 tweeks observed only in 06:00–06:30 h (IST) i.e. from the first occurrence of the tweeks to the totality period. After the totality, tweeks occurrence rate decreases gradually showing a linear relation between occurrence rate of tweeks with the varying solar radiation during the eclipse. We observe that tweeks occurrence started only after 30–40% obscuration of solar disc which otherwise occur only in the nighttime (Singh et al., 2011). The propagation paths for most of the tweeks observed at Varanasi was in the partial eclipse region which causes more attenuation of the signal and lesser propagation distance. Due to higher attenuation and less propagation distances during solar eclipse as compare to normal nighttime conditions, the tweeks observed at Varanasi show less dispersed duration and are not very bright as compared to normal nighttime tweeks. Similar results have been reported by Singh et al. (2011) at a nearby station Allahabad.

The changes in D-region ionospheric VLF reflection heights and electron density during eclipse have been estimated from tweek analysis. The reflection height increased from ~89 km from the first occurrence of tweek to about 93.5 km at the totality and then decreased to ~88 km at the end of the eclipse showing an increase of about 5.5 km in tweek reflection height. The reflection heights are lower by 2 km as compared to the usual nighttime tweek reflection heights. Reeve and Rycroft (1972) from the analysis of the tweeks for the solar eclipse occurred on 07 March 1970 estimated an increase in the ionospheric reflection height of about 7 km over the normal daytime reflection heights while Singh et al. (2011) reported an increase of 5 km in ionospheric reflection height.

The electron density is found to vary from ~23–25 $\pm$ 0.5 cm^{-3} at the reflection heights. It is also observed that the electron density in the D-region ionosphere even during eclipse totality is higher than the usual nighttime electron density (Fig. 3). It is due to the partial nighttime conditions even at totality period. The primary ionizing radiation at the D-region altitude is Lyman-α which is blocked during the total solar eclipse but some of the solar soft X-ray and EUV radiations originating from the limb solar corona are not obscured during totality and produce some ionization (Davis et al., 2000; Curto et al., 2006) contributing to the reflection heights less than the normal nighttime conditions. Electron density shows almost a gradual increase up to totality time after start of the eclipse and then decreases. The variation in the ionization hence the electron density with the variation of solar flux seems to be linear. However a nonlinear relationship between electron density variation and solar flux in the lower ionosphere has been also reported (Patel et al., 1986; Guha et al., 2010).

Nighttime reflection heights, electron density reported in Fig. 3 are consistent with the previous observations (Ohya et al., 2003; Kumar et al., 1994, 2008 Singh et al., 2010). The maximum difference observed in normal nighttime reflection height and the reflection height during eclipse period is ~2 km which is similar to that reported by Singh et al. (2011). This shows that electron density decreases during the eclipse but was not able to attain normal nighttime electron density. This is due to partial nighttime condition even at totality period. The primary ionizing radiation at the D-region altitude is Lyman-α which is blocked during the total solar eclipse but some of the solar soft X-ray and EUV radiations originating from the limb solar corona are not obscured during totality and produce some ionization (Davis et al., 2000; Curto et al., 2006) contributing to the reflection heights and electron density less than the normal nighttime conditions.

It is well known that during most solar eclipse the phase (Pierce, 1956) and amplitude (Pierce, 1961) of VLF signals propagating in the EIWG over long paths in the umbral shadow region of the Earth are changed. Previous studies using VLF transmitter signals during eclipse period showed both increase and decrease in amplitude (Lynn, 1981; De and Sarkar, 1997; Clilverd et al., 2001; Guha et al., 2010). This is attributed to the significant decrease in the electron density in the 'D' region of the ionosphere and the simultaneous increase in the width of the EIWG during the TSE. Typically, positive amplitude changes are observed throughout the whole eclipse period on path lengths ~4689 km (Varanasi, India to JJI, Japan) during the eclipse period. A significant increase of 3 dB in the strength of the amplitude of VLF signal transmitted from JJI transmitter in Japan is observed at Varanasi around the time of the total solar eclipse (TSE) as compared to a control day. Guha et al. (2010) also studied the changes in equatorial D-region electron density using subionospherically propagating VLF signal at 18.2 kHz over a distance of 2200 km over the same total solar eclipse of 22 July 2009 and observed an average decrease of 3.2 dB in signal strength compared to control days. Clilverd et al. (2001) reported positive amplitude changes throughout the whole eclipse period on path lengths <2000 km, while negative amplitude changes on paths >10,000 km. So it is highly necessary to continue studying already detected effects in more detail and to search for other manifestations of the solar eclipse in the atmosphere, especially at altitudes of the lower ionosphere.

We found two interesting results from our narrowband VLF data analysis during solar eclipse. First, the linear variation of the D-region electron density with the solar radiation as observed by broadband VLF (tweeks) data analysis. Second, the observation of 74.5% decrease in electron density at 76 km height during solar eclipse compared to normal condition which is almost 6% less than that derived by other workers (Smith, 1972; Clilverd et al., 2001) and only 2% less than that derived by Guha et al. (2010) at Indian low latitude region. We may expect 100% decrease in electron density during totality but observed only 78% decrease in our result of VLF analysis. This may be due to partial nighttime condition even at totality period. The primary ionizing radiation at the D-region altitude is Lyman-α which is blocked during the total solar eclipse but some of the solar soft X-ray and EUV radiations originating from the limb solar corona are not obscured during totality and produce some ionization (Davis et al., 2000; Curto et al., 2006) resulting in a electron density only up to 78%. The other reason for the difference in percentage obscuration and observed decrease could be error in the estimating the true electron density.

During the TSE, the decrease in solar flux due to moon's shadow causes sudden change in the D-region physical and chemical processes. During the totality due to blocking of Lyman-α 1215 Å (major D-region ionizing radiation) by moon's umbral shadow, the electron density decreases drastically towards the nighttime values (Smith, 1972). Since there is no production of ionization in the ionosphere and the ions and electrons in the lowest part of it recombined at a rapid rate resulting a depletion in the electron density in the 'D' region of the ionosphere and hence an increase in the effective width of the EIWG (Clilverd et al., 2001) hence increase in VLF reflection height. The upper surface is, of course, the lower ionosphere and for many purposes it can often be regarded as being a sharply-bounded, nearly perfect reflector which also changes the phase of the reflected wave by nearly 180°. An increase in the height of this reflecting surface causes the waveguide "cutoff" frequency to decrease with a resulting decrease in phase velocity and increase in phase delay. However, because of the 'decrease in "cutoff" frequency, the attenuation in the waveguide decreases, i.e. the amplitude of the signals increases, as observed in JJI VLF transmitter signal passing in the moon's umbral shadow.

As it is well known that at lower altitudes, most of the photo-electron heat is distributed locally; while at higher altitudes, the energetic electrons are able to propagate along the magnetic field lines to heat the gas in the conjugate hemisphere. That is, at higher altitudes, the photo-electron heat not only comes from local hemisphere but also from the conjugate hemisphere (Le et al., 2009). Some studies have shown that pre-sunrise plasma temperature enhancements were contributed by the photo-electron heating from the conjugate sunlit region (Evans, 1973; Peterson et al., 1977; Chao et al., 2003; Zhang et al., 2004). During a solar eclipse, photo-electrons in the eclipse region are reduced largely at totality, then in its conjugate region the inflow photo-electron flux from the eclipse region will decrease a lot, which results in a large decrease in electron temperature in this regions. Recent results show formation of counter electrojet, modification of electron density in E-region due to reduction in transport of ionization due to $\mathbf{E} \times \mathbf{B}$ upward diffusion during solar eclipse (Adeniyi et al., 2007; Tomas et al., 2008). After analyzing the VLF propagation delay time in the equatorial crest region, Cheng et al. (1992) showed that the time delay in VLF propagation is controlled by variation in average path obscuration. Based on the above discussions, we can say that there is some coupling between upper and lower ionosphere during eclipse periods which modifies the properties of the lower ionosphere, which needs further investigations.

6. Summary and conclusion

We have analyzed first time simultaneously both broadband ELF/VLF waves generated during lightning discharge and the narrowband VLF transmitter signal observed at a low latitude station Varanasi to study the response of low latitude D-region ionosphere during the total solar eclipse of 22 July, 2009. With the start of solar eclipse tweeks occurrence increases gradually and reaches maximum at the time of totality and then subsequently falls to zero at the end of TSE. Tweeks observed during TSE show different characteristic features than those observed during normal nighttime conditions. They have lesser propagation distance, lower VLF ionospheric reflection height varying 88–93.5 km from the eclipse start to the totality, thus showing an increase of about 5.5 km in reflection height during the eclipse. This increase in reflection height indicate reduction in D-region ionization during eclipse, which is confirmed by estimated electron density (23–25 cm^{-3}) compared to normal time electron density (22–23 cm^{-3}). Electron densities show a linear variation along with the solar flux during eclipse period. A significant increase of 3 dB in the strength of the amplitude of VLF signal transmitted from JJI transmitter in Japan is observed at Varanasi around the time of totality. Typically, positive amplitude changes are observed throughout the whole eclipse period on path lengths ~4689 km (Varanasi, India to JJI, Japan) during the eclipse period. An increase in the height of the reflecting surface causes the waveguide "cutoff" frequency to decrease. Because of this decrease in "cutoff" frequency, attenuation in the waveguide decreases, i.e. the amplitude of the signals increases. The model electron density height profile of the lower ionosphere depicted linear variation in the electron density with respect to solar radiation which supports the results of broadband (tweek) analysis. Lyman-α the main constituent responsible for D-region ionization is blocked during the eclipse, but some of the solar soft-X-ray and EUV radiation originating from the limb solar corona still arrive into the D-region and produce some ionization during eclipse, resulting in partial nighttime conditions and hence lower ionospheric height and higher electron density during eclipse compared to normal nighttime condition. The observed changes in the lower D-region ionosphere during sunrise transition phase in the eclipse period may be associated with the changes in the overall equatorial electrodynamics. Thus there is a need of further investigation to study the coupling between upper and lower ionosphere during solar eclipse.

Acknowledgments

The work is partially supported by ISRO, Bangalore under CAWSES-India program and partially by DST, New Delhi. We are thankful to the reviewer for his valuable comments and suggestions to improve the quality of the paper. Author is also thankful to Mr. Prashant Singh of Deptt. of Physics, Banaras Hindu University, Varanasi for his valuable help in computation. Ashutosh K. Singh is thankful to the University Grant Commission, New Delhi for providing UGC-Research Fellowship in Science for Meritorious Students (UGC-RFSMS).

References

Adeniyi, J.O., Radicella, S.M., Adimula, I.A., Willoughby, A.A., Oladipo, O.A., Olawepo, O. Signature of the 29 March 2006 eclipse on the ionosphere over an equatorial station. J. Geophys. Res. 112, A06314, http://dx.doi.org/10.1029/2006JA012197, 2007.

Anderson, R.C., Keefer, D.R., Myers, O.E. Atmospheric pressure and temperature changes during the 7 March 1970 solar eclipse. J. Atmos. Sci. 29, 583–587, 1972.

Antonia, R.A., Chambers, A.J., Phong-Anant, D., Rajagopalan, S., Sreenivasan, K.R. Response of atmospheric surface layer turbulence to a partial solar eclipse. J. Geophys. Res. 4, 1689–1692, 1979.

Bracewell, R.N. Theory of formation of an ionospheric layer below E layer based on eclipse and solar flare effects at 16 kc/sec. J. Atmos. Terr. Phys. 2, 226–235, 1952.

Buckmaster, H.A., Hansen, C.H. 26 February 1996 total solar eclipse induced LF (60 kHz) phase retardation. J. Atmos. Terr. Phys. 48, 393–397, 1998.

Burton, E.T., Boardman, E.M. Effects of solar eclipse on audio frequency atmospherics. Nature 131, 81–82, 1933.

Chakrabarty, D.K., Shah, N.C., Pandya, K.V. Fluctuation in ozone column over Ahmadabad during the solar eclipse of 24 October 1995. Geophys. Res. Lett. 24 (23), 3001–3003, 1997.

Chandra, H., Sharma, S., Lele, P.D., Rajaram, G., Hanchinal, A. Ionospheric measurements during the total solar eclipse of 11 August 1999. Earth Planets Space 59, 59–64, 2007.

Chao, C.K., Su, S.-Y., Yeh, H.C. Presunrise ion temperature enhancement observed at 600 km low and mid-latitude ionosphere. Geophys. Res. Lett. 30 (4), 1187, http://dx.doi.org/10.1029/2002GL016268, 2003.

Chen, A.-H., Yu, S.-B., Xu, J.-S. Ionospheric response to a total solar eclipse deduced by the GPS Beacon observations. Wuhan Univ. J. Natural Sci. 4, 439–444, 1999.

Chen, G., Zhou, Z., Yang, G., Zhang, Y. Solar eclipse effects of 22 July, 2009 on sporadic E. Ann. Geophysicae 28, 353–357, 2010.

Cheng, K., Huang, Y.-N., Chen, S.-W. Ionospheric effects of the solar eclipse of September 23, 1987, around the equatorial anomaly crest region. J. Geophys. Res. 97 (A1), 103–111, 1992.

Chimonas, G., Hines, C.O. Internal gravity-wave motions induced in the Earth's atmosphere by a solar eclipse. J. Geophys. Res. 75, 5545–5551, 1970.

Clilverd, M.A., Rodger, C.J., Thomsone, N.R., Lichtenberger, J., Steinbach, P., Cannon, P., Angling, M.A. Total solar eclipse effects on VLF signals: observations and modeling. Radio Sci. 36 (4), 773–788, 2001.

Cohen, M.B., Inan, U.S., Paschal, E.W. Sensitive broadband ELF/VLF radio reception with the AWESOME instrument. IEEE Trans. Geosci. Remote Sens. 47, 3–17, http://dx.doi.org/10.1109/TGRS.2009.2028334, 2009.

Curto, J.J., Heiig, B., Pinol, M. Modeling the geomagnetic effects caused by solar eclipse of 11 August 1999. J. Geophys. Res. 111, A07312, http://dx.doi.org/10.1029/2005JA011499, 2006.

Cummer, S.A., Inan, U.S., Bell, T.F. Ionospheric D region remote sensing using VLF radio atmospherics. Radio Sci. 33, 1781–1792, 1998.

Davis, C.J., Lockwood, M., Bell, S.A., Smith, J.A., Clarke, E.M. Ionospheric measurements of relative coronal brightness during the total solar eclipses of 11 August, 1999 and 9 July, 1945. Ann. Geophysicae 18, 182–190, 2000.

De, B.K., Sarkar, S.K. Anomalous behavior of 22. 3 kHz NWC signal during total solar eclipse. Kodaikanal Obs. Bull. 13, 205–208, 1997.

De, B.K., De, S.S., Bandyopadhyay, B., Pal, P., Ali, R. Paul, S., Goswami, P.K. Effects of a solar eclipse on the propagation of VLF-LF signals: observations and results. Terr. Atmos. Ocean Sci. 22, http://dx.doi.org/10.3319/TAO.2011.01.17.01. AA, 2011.

Evans, J.V. Seasonal and sunspot cycle variation of F region electron temperatures and protonospheric heat flux. J. Geophys. Res. 78, 2344–2349, 1973.

Farges, T., Jodogne, J.C., Bamford, R., Le Roux, Y., Gauthier, F., Vila, P.M., Altadill, D., Solef, J.G., Miro, G. Disturbances of the western European ionosphere during the total solar eclipse of 11 August 1999 measured by a wide ionosonde and radar network. J. Atmos. Solar-Terr. Phys. 63, 915–924, 2001.

Guha, A., De, B.K., Roy, R., Choudhury, A. Response of the equatorial lower ionosphere to the total solar eclipse of 22 July 2009 during sunrise transition period studied using VLF signal. J. Geophys. Res. 115, A11302, http://dx.doi.org/10.1029/2009JA015101, 2010.

Helliwell, R.A., Katsufrakis, J.P., Trimpi, M.L. Whistler induced perturbation in VLF propagation. J. Geophys. Res. 78, 4679–4688, 1973.

Inan, U.S., Cummer, S.A., Marshall, R.A. A survey of ELF and VLF research on lightning-ionosphere interactions and causative discharges, J. Geophys. Res. 115, A00E36, http://dx.doi.org/10.1029/2009JA014775, 2010.

Klobuchar, J.A., Whitney, H.E. Ionsopheric electron content measurement during solar eclipse. J. Geophys. Res. 70, 1254, 1965.

Kumar, S., Dixit, S.K., Gwal, A.K. Propagation of tweek atmospherics in the Earth-ionosphere waveguide. Nuovo Cimento 17C, 275–281, 1994.

Kumar, S., Kumar, A., Ramachandran, V. Higher harmonic tweek sferics observed at low latitude: estimation of VLF reflection heights and tweek propagation distance. Ann. Geophysicae 26, 1451–1459, 2008.

Kumar, S., Singh, A.K. Changes in total electron content (TEC) during the annular solar eclipse of 15 January 2010. Adv. Space Res. 49, 75–82, 2012.

Le, H., Liu, L., Yue, X., Wan, W. The ionospheric behavior in conjugate hemispheres during the 3 October 2005 solar eclipse. Ann. Geophysicae 27, 179–184, http://dx.doi.org/10.5194/angeo-27-179-2009, 2009.

Lynn, K.J.W. The total solar eclipse of 23 October 1976 observed at VLF. J. Atmos. Terr. Phys. 43, 1309–1316, http://dx.doi.org/10.1016/0021-9169(81)90156-2, 1981.

Ohya, H., Nishino, M., Murayama, Y., Igarashi, K. Equivalent electron density at reflection heights of tweek atmospherics in the low-middle latitude D-region ionosphere. Earth Planets Space 55, 627–635, 2003.

Patel, D.B., Kotadia, K.M., Lele, P.D., Jani, K.G. Absorption of radio waves during a solar eclipse. Proc. Indian Acad. Sci. Earth Planet. Sci. 95, 193–200, 1986.

Peterson, W.K., Doering, J.P., Potemra, T.A., McEntire, R.W., Bostrom, C.O. Conjugate photoelectron fluxes observed on Atmosphere Explorer C. Geophy. Res. Letter 4 (3), 109–112, 1977.

Pierce, E.T. Attenuation coefficients for propagation at VLF during a sudden ionospheric disturbance. Radio Propagat. 65D, 543–546, 1961.

Pierce, J.A. "VLF phase" shifts associated with the disturbance of February. J. Geophys. Res. 61, 475–483, 1956.

Reeve, C.D., Rycroft, M.J. The eclipsed lower ionosphere as investigated by natural very low frequency radio signals. J. Atmos. Terr. Phys. 34, 667–672, http://dx.doi.org/10.1016/0021-9169(72)90154-7, 1972.

Rodger, C.J., Molchanov, O.A., Thomson, N.R. Relaxation of transient ionization in the lower ionosphere. J. Geophys. Res. 103, 6969–6975, 1998.

Rycroft, M.J., Reeve, C.D. VLF radio signal observed in Newfoundland during the Solar eclipse of March 7. Nature 226, 1126–1127, http://dx.doi.org/10.1038/2261126a0, 1970, 1970.

Sharma, S., Dashora, N., Galav, P., Pandey, R. Total solar eclipse of July 22, 2009: its impact on the total electron content and ionospheric electron density in the Indian zone. J. Atmos. Solar-Terr. Phys. 72, 1387–1392, 2010.

Singh, A.K., Singh, R.P. Propagation features of higher harmonic tweeks at low latitude. Earth Moon Planet 73, 277–290, http://dx.doi.org/10.1107/BF00115886, 1996.

Singh, R., Veenadhari, B., Cohen, M.B., Pant, P., Singh, A.K., Maurya, A.K., Vohat, P., Inan, U.S. Initial results from AWESOME VLF receivers: Setup in low latitude Indian region under IHY2007/UNBSSI program. Current Science 98 (3), 398–405, 2010.

Singh, R., Veenadhari, B., Maurya, A., Cohen, M.B, Kumar, S., Selvakumaran, R., Pant, P., Singh, A.K., Inan, U.S. D-region ionosphere response to the Total Solar Eclipse of 22 July 2009 deduced from ELF-VLF tweek observations in the Indian sector. J. Geophys. Res., 116, http://dx.doi.org/10.1029/2011JA016641, 2011.

Smith, L.G. Rocket observations of solar UV radiation during the eclipse of 7 March 1970. J. Atmos. Terr. Phys. 3 (1), 601–611, 1972.

Srivastava, G.P., Pakkir, M.P.M., Balwalli, R.R. Ozone concentration measurements near the ground at Raichur during the solar eclipse of 1980. Proc. Indian Natl. Sci. Acad. A48 (3), 138–142, 1982.

Thomson, N.R. Experimental daytime VLF ionospheric parameters. J. Atmos. Terr. Phys. 55, 173–184, 1993.

Tomas, A.T., Lühr, H., Rother, M., Manoj, C., Olsen, N., Watari, S. What are the influences of solar eclipses on the equatorial electrojet? J. Atmos. Solar Terr. Phys. 70, 1497–1511, 2008.

Yamashita, M. Propagation of tweek atmospherics. J. Atmos. Terr. Phys. 40, 151–156, 1978.

Zanis, P., Katragkou, E., Kanakidou, M., Psiloglou, B.E., Karathanasis, S., Vrekoussis, M., Gerasopoulos, E., Lysaridis, I, Markakis, K., Poupkou, A., Amiridis, V., Melas, D., Mihalopoulos, N., Zerefos, C. Effects on surface atmospheric photooxidants over Greece during the total solar eclipse event of 29 March 2006. Atmos. Chem. Phys. 7, 6061–6073, 2007.

Zerefos, C. S, Balis, D.S., Meleti, C., Bais, A.F., Tourpali, K., Vanicek, K., Cappelani, F., Kaminski, U., Tiziano, C., Stubi, R., Formenti, P., Andreae, A. Changes in environmental parameters during the solar eclipse of 11 August 1999, over Europe. Effects on surface UV 20 solar irradiance and total ozone. J. Geophys. Res. 105 (D21), 26463–26473, 2000.

Zerefos, C.S., Gerasopoulos, E., Tsagouri, I., Psiloglou, B.E., Belehaki, A., Herekakis, T., Bais, A., Kazadzis, S., Eleftheratos, C., Kalivitis, N., Mihalopoulos, N. Evidence of gravity waves into the atmosphere during the March 2006 total solar eclipse. Atmos. Chem. Phys. 7, 4943–4951, 2007.

Zhang, S.-R., Holt, J.M., Zalucha, A.M., Amory-Mazaudier, C. Midlatitude ionospheric plasma temperature climatology and empirical model based on Saint Santin incoherent scatter radar data from 1966 to 1987. J. Geophys. Res. 109, A11311, http://dx.doi.org/10.1029/2004JA010709, 2004.

Zhang, X.-F., Du, R.-Y., Gu, S.-M., Wu, T., Wang, Y.-N. Anomalous variation of VLF signals in the total solar eclipse of 22nd July 2009. Chinese astron. Astrophys. 35, 54–61, 2011.