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Research paper

Impact of the 15 January 2010 annular solar eclipse on the equatorial and low latitude ionosphere over the Indian region

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ABSTRACT

The annular solar eclipse of 15 January 2010 over southern India was studied with a multi-instrument network consisting of magnetometer, ionosonde and GPS receivers. The presence of a counter electrojet (weakened or westward zonal electric field) during the eclipse and adjacent days suggests the strong gravitational tidal effect associated with the exceptional Sun–Moon–Earth alignment around the eclipse day. With a strong backup of magnetometer recordings on the day of eclipse, its adjacent days and the normal electrojet day, it is argued that the regular eastward electric field for the whole day at the equator was not just weakened, but actually was flipped for several hours by the influence of enhanced lunar tides. The effect of flipping the electric field was clearly seen in the equatorial ionosonde data and through the large array of GPS receivers that produced the total electron content (TEC) data. The main impact of flipping the electric field was poor feeding of equatorial ionization anomaly (EIA) due to the severely weakened fountain effect on the eclipse day, with the regular anomaly crest shifting towards the equator. The equatorial ionosonde profile was also showing an enhanced F2 region peak in spite of a reduced vertical TEC. While the plasma density depletion at the lower F region altitude over the equator was due to the temporary lack of photo-ionization, the reductions in high altitude plasma density beyond the equator were caused by the electrodynamics taking place around the eclipse. The important finding of this analysis is that the electrodynamical consequences on the low latitude ionosphere were mainly due to the combination of eclipse and lunar tides which were far more significant and influenced the EIA density rather than eclipse alone. Based on these findings, it is argued that the prevailing lunar tidal impact also needs to be taken into account while seeking to understand the electrodynamical impact of the solar eclipse on the low latitude ionosphere.

1. Introduction

A solar eclipse is of paramount importance for researchers as it provides a unique opportunity to investigate the atmospheric and ionospheric effects caused by the rapidly moving shadow of the Moon over the Earth. The effects associated with solar eclipses can alter the whole electrodynamics of the low latitude ionosphere specially when the eclipse occurs near the dip equator. Nowadays, the availability of simultaneous observations from different ground and space based instruments gives a good opportunity for understanding the changes in the regular electrodynamics during solar eclipse and its consequences at the equatorial and higher latitudes. Although studies have been performed over various parts of the globe to realize the temporal and spatial ionospheric variations with the passage of solar eclipses, their effects over the equatorial and low latitude ionosphere are of unique interest. In view of this, we tried to investigate the response of the equatorial and low latitude ionosphere using multi-instrument network consisting of magnetometer, ionosonde and GPS receivers to the annular solar eclipse of 15 January 2010 as observed over southern India.

The regular electrodynamics of ionosphere near the dip equator is greatly influenced by the enhanced Cowling conductivity. Manifestation of this is seen as an intense current, flowing eastward in the ionospheric E-layer during the daytime, within a narrow belt of $\pm 3°$ latitude over the magnetic dip equator, this current is referred to as the equatorial electrojet (EEJ) (Chapman, 1951). In the vicinity of the dip equator, the EEJ is seen as a daytime enhancement in the horizontal component (H) of the

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geomagnetic field. However, it is also observed that on certain geomagnetic quiet days the EEJ current direction reverses to westward generally during the morning and evening hours, giving rise to a negative depression in magnetometer *H* data. The resulting current is termed as counter electrojet (CEJ) (Gouin and Mayaud, 1967). Any equatorial phenomenon causing disturbance in the net zonal electric field eventually affects the E and F-region and hence the distribution of plasma in the low latitude ionosphere. The total electron content (TEC) measured from the GPS observables is a powerful tool to study the static as well as dynamic characteristics of the F-region plasma and its photochemistry, as the main contribution to the TEC comes from the F-region. The vertical drift of the F region plasma gives rise to the equatorial ionization anomaly (EIA) in the low latitudes. The EIA is characterized by a trough in the ionization density at the geomagnetic equator and crests on either side of the equator within $\pm 15^{\circ}$ magnetic latitudes (Appleton, 1946). The EIA development is affected by various transient processes like geomagnetic storms, prompt penetration electric fields, solar eclipses, etc. The underlying physical processes during the eclipses can be probed by studying the variations in EEJ, TEC, and related ionospheric parameters.

The effects associated with a solar eclipse are always unique, since the solar eclipses may occur at various geographic locations during different phases of the solar activity, geomagnetic conditions, seasons, as well as local times of the day. Moreover, a particular eclipse does not repeat in any recognizable pattern due to the diverse Sun–Moon–Earth alignment geometries and different lunar orbital characteristics (Espenak and Meeus, 2006); hence the study of individual eclipses becomes necessary. Also, induced ionospheric effects have significant impact on satellite-based trans-ionospheric radio-telecommunication and navigation systems (Vyas and Sunda, 2012). The obscuration of solar radiation during partial, annular or total solar eclipse, leads to spatial and temporal ionospheric and thermospheric variations through the reduced production of electrons and accelerated recombinations (Rishbeth and Garriott, 1969). Ionospheric responses to the earlier solar eclipses have been broadly studied by many researchers across the globe with different techniques, such as incoherent scatter radar (Evans, 1965; Salah et al., 1986), Faraday rotation measurement (Klobuchar and Whitney, 1965), ionosonde (Adeniyi et al., 2007), ground and space based GPS observations (Tsai and Liu, 1999; Tomás et al., 2008), satellite (Cohen, 1984), rocket-borne measurements (Manju et al., 2012, 2014), and magnetometers (Sridharan et al., 2002; Tomás et al., 2008). Model calculations of the eclipse effects have also been carried out by Le et al. (2010) and Lin et al. (2012).

Earlier studies demonstrate the reductions in the ionization during the eclipses, based on the comparison of the solar eclipse day with one or more control days, mainly the previous and succeeding days of the eclipse (Evans, 1965; Adeniyi et al., 2007; Chandra et al., 2007; Manju et al., 2012; Madhav Haridas and Manju, 2012; Kumar et al., 2013). Some studies also have considered mean variations of first five international geomagnetically quietest days (Q-Days) or monthly averages excluding the disturbed days (Sharma et al., 2010; Choudhary et al., 2011; Kumar and Singh, 2012). Sridharan et al. (2002), St.-Maurice et al. (2011), and Choudhary et al. (2011) demonstrated the effects of the eclipse-induced terminators, by using observations and models which are really thought-provoking. Most of the studies ascribe the reduced TEC to the obvious temporary interruptions of the solar radiation due to the obscuration. However, the equatorial dynamics during the eclipse and control days has to be taken into account for a reliable and better physical picture. One has to be careful in selecting control days as studies reveal that the frequency of CEJ occurrence increases during geomagnetically quiet days through changes in the zonal electric field, which are more prevalent during solar minimum solstice months (Mayaud, 1977). This could result in ambiguity when the eclipse observations are compared with the control or quiet days, without verifying the disturbances in the zonal electric field of these days. Note that the disturbances in the zonal electric field are reflected in the magnetometer EEJ data. Therefore, some information of the equatorial ionosphere can be derived based on the EEJ strength. Hence, the present study is based on due consideration of the EEJ strengths during the eclipse as well as during the control days.

The eclipse of 15 January 2010 gave a unique opportunity to understand the changes in the electrodynamics of the ionosphere during the passage of the Moon's shadow across the Indian region. The eclipse took place during the solar minimum, in the ascending phase of the 24th solar cycle. The geomagnetic condition was very quiet. It happened to be the longest annular eclipse of the 3rd Millennium with the maximum duration of annularity 11 min 08 s (its duration will not be exceeded until the year 3043). It was visible over a 333 km wide track covering almost half of the Earth (Espenak and Meeus, 2006). The annularity was clearly visible from South Kerala and South Tamil Nadu in India, while other parts of the Indian region witnessed only a partial eclipse. The major attraction of the present solar eclipse is that it occurred during the early afternoon hours, i.e., peak ionization time over the Indian EIA region. Also, the path of the annularity crossed the dip equator over the peninsular part of India.

Though there are numerous studies on the occurrence of CEJ during quiet days, very few investigations have tried to understand the physical mechanism of CEJs occurring during solar eclipses (Tomás et al., 2008; Bhaskar et al., 2011). Therefore, it is still a controversial issue, whether the CEJ is induced/modulated by the effects associated with reduced radiation during the eclipse or it is due to the enhanced lunar tidal forces. Also, it could be a superposition of both effects. We believe that adopting different criteria for the selection of control days gives rise to variations in the inferences drawn from the studies. What was unique about this particular solar eclipse is that it crossed the dip equator during the peak hours of the day, when the EIA development was supposed to be in its progressive state. Therefore, in the present work, we set our main objectives of the eclipse study, as (1) to probe the underlying mechanism of the CEJ that occurred during the eclipse, (2) investigate the influence of prevailing electrodynamics on the behavior of ionospheric electron densities, and (3) examine latitudinal variations of TEC to assess the possible impact of anomalous electrodynamics on the fountain effect and hence the EIA. The availability of global geomagnetic and interplanetary parameters, local magnetometer, ionosonde, and the large array of GPS receivers gave us an opportunity to investigate these objectives with a modern multi-instrument study. The comprehensive presentations of Rastogi (1989), Choudhary et al. (2011), St.-Maurice et al. (2011), Madhav Haridas and Manju (2012), and Manju et al. (2012, 2014) motivated to investigate the peculiar ionospheric aspects of the exceptional eclipse configuration during the period.

2. Data used and methods of treatment

The locations of magnetometer (blue square), ionosonde (black square), and GPS (red dot) observation stations used in this study are marked on a map showing the path of the solar eclipse in Fig. 1 (modified from Espenak and Anderson, 2008). The corresponding geographic and geomagnetic coordinates, as well as the dip angle of the locations, are listed in Table 1. The onset time of the eclipse, time of centrality, and the end time of the eclipse, along with the obscuration magnitudes at the observation stations are shown in Table 2. Note that annularity was observed at Trivandrum and