Observations of plasma depletions in 557.7-nm images over Kavalur

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[1] An all sky imaging system was operated at Kavalur (12.56°N, 78.83°E, 4.6°N, geomagnetic), India, during February-April 2002. We observed plasma depletions in the 557.7- and 630.0-nm images in several nights and found that in most of the nights, the 557.7-nm depletions appeared around midnight and became very pronounced in the postmidnight hours. A simulation is carried out to understand the important physical parameters that influence the emissions of the 557.7 nm in various local times and solar activities, and that result in the appearance of depletions in the integrated images.


1. Introduction

[2] The characteristics of large-scale ionospheric plasma depletions have been studied extensively using all sky imagers for more than two decades. Many experiments were carried out using the 630.0-nm emission [Makela et al., 2004, and references therein]. In contrast, there are rather limited reports using 557.7 nm [Mendillo et al., 1997; Sinha et al., 2001; Takahashi et al., 2001; Kelley et al., 2002; Mukherjee, 2003]. The 557.7-nm emission has two main source regions: one in the thermosphere, located at about 250-km altitude, and the other one in the upper mesosphere, at about 97-km altitude. The thermospheric component is virtually nonexistent except at equatorial latitudes [Shepherd et al., 1997], and, in presence of strong mesospheric emission, it is difficult to observe the F region structures in the 557.7-nm all sky images [Mendillo et al., 1997; Takahashi et al., 2001].

[3] All sky imaging experiments were conducted at Kavalur (12.6°N, 78.8°E, 4.6°N, geomagnetic), India, during February-April 2002. The observations revealed the occurrence of field-aligned structures in 557.7 nm, which showed eastward drifts and were very similar to those observed simultaneously in 630.0 nm in several nights. In this paper, we examine the appearance of plasma depletions in 557.7-nm images and simulate the emissions to evaluate the masking of the thermospheric component of 557.7-nm emission by its mesospheric counterpart and find the essential causative factors.

2. Observations

[4] The all sky imaging system was operated for 33 nights at Kavalur, during February-April 2002. The low Kp values (0+ to 4−) indicated that there was no significant geomagnetic activity during the observation period. The imaging system uses a high gain image intensifier and a sensitive 12-bit charge-coupled device camera. The images reported here were taken with narrow band (1-nm bandwidth) interference filters of central wavelengths 630.0 and 557.7 nm, and with exposure times of 60 and 30 s, respectively. Very intense depletions of the 630.0-nm images were seen in 27 nights out of the 33-day observation period. These include two consecutive 11-night depletions during 4–14 March and 5–15 April 2002. About 70% (19/27) of the nights with depletions in 630.0 nm are accompanied by remarkable depletions in 557.7-nm images (Table 1). Note that this is the longest period and the most pronounced depletions in 557.7 nm ever observed at Kavalur.

[5] Figure 1 illustrates some examples selected from a series of 557.7-nm images taken from the evening of 12 March 2002 to the morning of 13 March 2002. Depletions appear in the image at 2201 LT, become pronounced around 0200–0230 LT, and gradually disappear after 0300 LT. We find the depletions generally with 70- to 85-km width in the east-west direction, drifting eastward at about 55–65 m/s. The calculations were made assuming a mean altitude of 250 km for the airglow layer. Similar depletion features were also observed in several other nights (12 and 15 February; 5, 9–14, and 17 March; 5–8 and 10–13 April). To understand the behavior of the emissions and depletions in 557.7 nm, the relative intensities of 557.7 and 630.0 nm, as well as the associated depletions, are compared in Figure 2. The relative intensities plotted in Figure 2a are the average intensities in a rectangular area of 10 × 10 pixels near the center of each image. A region in the image aligned along the magnetic north-south and drifting eastward, with a maximum intensity reduction of about 10% or more with respect to the background, is identified as a depletion. Figure 2b displays the nights of the 557.7- and 630.0-nm depletions during the observation period. The amplitude of intensity reduction for a given depletion could vary from a few percentages to few tens of percentage during the course of its development.

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Similar patterns in the nocturnal variations of the 557.7- and 630.0-nm intensities in Figure 2a yield less intensities in the period 1900–2200 LT, but suddenly increase after 2200 LT. However, the occurrences of the depletions observed in these emissions (Figure 2b) are very different that the depletions in 630.0 nm become pronounced during 2000–0000 LT while the maximum in 557.7 nm lies between 0200 and 0300 LT. In 630.0 nm, depletions can be observed even when the emission is weak, with the maximum occurrence in the premidnight period. By contrast, the depletions in 557.7 nm start appearing with the sudden increase in intensity around 2200 LT, and the occurrence of depletions reaches its peak in the postmidnight hours. Note that the thermospheric component of 557.7-nm intensity is usually very weak [Shepherd et al., 1997] and could be masked by the strong mesospheric component making the intensity variations caused by the F region plasma depletions difficult to detect from ground [Mendillo et al., 1997; Takahashi et al., 2001]. Figure 2b shows that the masking effect is not present throughout the night, or at least in the postmidnight period of some nights during February-April in 2002.

3. Simulation

To further understand the appearance of depletions in 557.7 nm observed in 2002, the mesospheric and the thermospheric components are simulated and the ratio of their intensities is calculated. The volume emission rate for the mesospheric component of 557.7-nm emission ($V_M$) arises through Barth mechanism [McDade et al., 1986] given by,

$$V_M = \frac{A_S k_1 [O]}{(A_0 + k_5 [O_2]) (C^{O_2}/C[O_2] + C^{e}/C[O])] (1)$$

where $A_S$ is the 557.7-nm line (O$^1$D-O$^1$S) transition probability, $k_1$ is the rate coefficient for the three body recombination of atomic oxygen, $A_0$ is the inverse radiative life time of O$^1$S state, and $k_5$ is the quenching coefficient of O$^1$S state by O$_2$. $C^{O_2}$ and $C^{e}$ are the empirical parameters provided by McDade et al. [1986].

The thermospheric 557.7-nm emission arises through the dissociative recombination of O$_2$ [Peterson et al., 1966], which is produced through the charge exchange reaction between O$^+$ and neutrals, mainly O$_2$. The volume emission rate of the thermospheric 557.7 nm is given as

$$V_T = \left(1 + \frac{A_{2S}}{A_{1S}}\right)^{-1} \mu_S g [O_2][e] (2)$$

where $A_{1S}$ and $A_{2S}$ are the transition probabilities corresponding to the 557.7- and 297.2-nm emissions, $\gamma$ is the rate of the charge exchange process, $\mu_S$ is the quantum yield of the O$^1$S state responsible for the 557.7-nm emission, and [O$_2$] and [e] stand for the oxygen and electron densities, respectively. The laboratory experiments have shown O$^1$S quantum yields of 3–4% for electron temperatures ($T_e$) in the range of 600–1100 K [Peverall et al., 2000], but are much less than the values inferred from rocket measurements [Sobral et al., 1992]. In view of this large discrepancy, a quantum yield of 8% [Sobral et al., 1992]...
is used in the simulations for both solar maximum and solar minimum, which is justified considering the complexity involved in the laboratory experiments. The charge exchange rate is given by St.-Maurice and Torr [1978], and the transition probabilities are taken from the work of Baluja and Zeippen [1988] (for details, see papers listed in the study by Singh et al. [1995] and Vlasov et al. [2005]). It can be seen from equation (1) that the mesospheric intensity is sensitive to the atomic oxygen density. Equation (2) reveals that the dissociative recombination depends on electron density as well as the neutral density. The integrated intensities for the mesospheric (80- to 120-km altitude) and the thermospheric (200- to 600-km altitude) components under quiet geomagnetic conditions during the equinox of 2002 (near solar maximum) and 1996 (solar minimum) are simulated. The O$_2$ density and neutral temperature are computed using the Mass Spectrometer Incoherent Scatter (MSISE-90) model, while the electron density and electron temperature are derived from the International Reference Ionosphere (IRI-01) model.

The simulation results are illustrated in Figure 3. The total 557.7-nm intensity exhibits lower values in the 1900–2200 LT, increasing thereafter, and attains peak value in the postmidnight period around 0100 LT (Figure 3a). This nocturnal variation agrees with that of the observed intensity in Figure 2a. The mesospheric 557.7-nm intensity at

Figure 2. (a) Nocturnal variation of the total 557.7-nm (asterisks) and 630.0-nm (open circles) intensities (in relative units of 8-bit scale), measured near the center of the image. (b) A summary plot showing the number of nights with depletions in 557.7- and 630.0-nm images at different local times. The nights are binned into groups of every hour from 1800 to 0600 LT, and if at least one depletion is present in a given hour interval, that period is counted in the graph. (c) Amplitude of depletions for 557.7 and 630.0 nm. The solid and dashed lines represent the amplitudes of 557.7 and 630.0 nm, respectively, in the night of 12 March 2002.

Figure 3. Simulations of the 557.7-nm emission using the IRI-01 and MSIS-90 models under equinoctial conditions. (a) Dashed, dotted, and solid lines stand for the 557.7-nm emission from the thermosphere and from the mesosphere, and the ratio of the thermospheric to the mesospheric components, respectively. The heavy and thin curves denote the years of solar maximum in 2002 and solar minimum in 1996. The asterisks represent the 557.7-nm intensity extracted from the WINDII measurements for the latitude corresponding to that of Kavalur, made in the equinox period in 1992. The thick, light curve gives the total 557.7-nm intensity for the year 2002. (b) hmF2 as well as the electron density, O$_2$ density, and their product at the altitude of the emission peak in the nights of 2002. The quantities to the right of [e$^-$/C0] and [O$_2$] are the scaling factors used to fit the values within the range of the y axis used, and apply to the product [e$^-$] × [O$_2$] as well. The concentration is in the cgs unit.
Figure 4. Ratio of thermospheric to the mesospheric 557.7-nm intensities as well as the electron density, O$_2$ density, and their product in the equinox period from 1995 to 2004. The quantities to the right of $[e^{-}]$ and $[O_2]$ are the scaling factors used to fit the values within the range of the $y$ axis used, and apply to the product $[e^{-}] \times [O_2]$ as well. The concentration is in the cgs unit.

solar maximum is greater than that in the solar minimum by a factor of about 2. By contrast, the thermospheric intensity at solar minimum is very small, but is much greater during solar maximum and drastically enhances after 2300 LT. Note that in the solar minimum, the thermospheric component of 557.7-nm emission is much weaker than the mesospheric component throughout the night. Therefore it is unlikely to observe the thermospheric emissions during solar minimum. Moreover, during the premidnight period 2000–2300 LT, the mesospheric intensity is constantly stronger than thermospheric intensity either in solar maximum or solar minimum, and therefore it is also difficult to observe the thermospheric emission. In contrast, the thermospheric component becomes stronger in the postmidnight hours in the solar maximum, and the ratio of the thermospheric to mesospheric intensities reaches a maximum at 0200 LT. The mesospheric region is very dynamic and photochemically active, but least explored, and hence the atomic oxygen density derived from the models may have limitations. In order to verify how well the simulation reproduces the mesospheric emission, the simulated results are compared to the intensities extracted from the WINDII measurements in the same latitude region for the equinox period of 1992 [Zhang and Shepherd, 1999; Zhang et al., 2001]. Figure 3a confirms that the simulated results are consistent with the WINDII measurements.

In Figure 3b, the nocturnal variation of the electron $[e^{-}]$ and oxygen $[O_2]$ densities corresponding to the altitude of peak thermospheric 557.7-nm emission for the solar maximum of the year 2002, their product, as well as the ratio of the electron density (hmF2) are displayed. The electron density has higher values in the period 2200–0200 LT, and the nocturnal variation of the product $[e^{-}] \times [O_2]$ is identical to that of the thermospheric component of 557.7-nm emission (Figure 3a). The hmF2 shows a gradual decrease with time, with a reduction of about 100 km from the sunset to 0100 LT.

To understand the solar activity variation, we further calculated the ratio at 0200 LT in the equinox period from 1995 to 2004. Figure 4 illustrates that the ratio is less than 1 in the solar minimum and rapidly increases near the solar maximum years, reaching values of about 2. Similarly, the electron and oxygen densities at the peak altitude of the thermospheric emission at 0200 LT vary accordingly with the solar activity.

4. Discussion and Conclusions

The results show that the observed occurrence of depletions in 557.7 nm and the ratio of the simulated thermospheric to mesospheric emissions concurrently reach their maximum at about 0200 LT. The higher value of the ratio implies the masking of the thermospheric component to be insignificant in the postmidnight period of 2002. Figure 4 further demonstrates that during postmidnight period, the masking is efficient in the solar minimum years, but not in the solar maximum. The simulations during solar maximum reveal that the integrated 557.7-nm emission is dominated by the mesospheric component in the premidnight hours, whereas the thermospheric component becomes significant in the postmidnight period. It can be seen that the thermospheric intensity is weaker than the mesospheric intensity in the evening hours (2000–2330 LT). Bittencourt and Sahai [1979] found that the higher F layer altitude slows down the dissociative recombination and results in less thermospheric emission. Figure 3b illustrates that the F2 peak height (hmF2) descends by about 100 km from 2000 LT to 0100 LT in the equinoctial period of 2002. The F2 layer at a higher altitude results in the weak thermospheric 557.7-nm intensity between 2000 LT and 2330 LT. However, the F2 layer descent increases the O$_2$ density and, in turn, enhances the thermospheric emission, which becomes stronger than the mesospheric emission after 2330 LT. Meanwhile, it can be seen that the electron density also increases toward midnight, which adds to the greater thermospheric emission in the postmidnight period and reaches the peak emission around 0100 LT. Moreover, the auroral intensity increases after midnight could be also caused by equatorward movement of the electron density crest associated with the equatorial anomaly by westward electric fields. The mesospheric intensity becomes very weak around midnight because of diurnal tide [Shepherd et al., 1997], causing the ratio to be much higher.

Similar tendencies in solar activity variations of the electron, oxygen densities, and their product as well as the ratio of the thermospheric to the mesospheric intensities of the 557.7 nm suggest that the plasma depletions in 557.7-nm emission most likely occur in the postmidnight period in the solar maximum (Figure 4). While the mesospheric contamination can mask out the depletions in the thermospheric 557.7 nm, there is no such secondary source for the 630.0-nm emission. Thus in 630.0 nm, one would expect to observe the depletions even if the intensity is low. This is evident from the higher occurrence during 2000–0000 LT (Figure 2b), although the emission is less intense during 2100–2200 LT (Figure 2a), and also explains the difference in the observed occurrence of depletions in 557.7 and 630.0 nm (Figure 2b).
Note that the masking effect significantly affects the chances of observing the 557.7-nm depletions. Meanwhile, the much stronger 630.0-nm emission intensity might result in the associated depletion having a better chance to be observed. The two facts might be the reason for the depletions of 630.0 nm appearing more frequent than those of the 557.7 nm during the observation period.

[14] In conclusion, because of enhancement of the thermospheric component of the 557.7-nm emission and/or the less efficient masking effect, the occurrence of depletions becomes pronounced in the postmidnight period of the solar maximum. By contrast, the significant mask results in the 557.7-nm depletions of the thermosphere being unlikely observed during years of the solar minimum. The simulation further shows that the recombination process related to the ionospheric height as well as the electron and oxygen densities plays important roles.

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