Study of O$^+$(2P-2D) 732.0 nm dayglow emission under geomagnetic storm conditions

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Received 29 July 2015; revised received and accepted 18 January 2016

The effect of geomagnetic storms on O$^+$(2P-2D) 732.0 nm dayglow emission is studied using recently updated photochemical model of Thirupathaiah et al. [An updated model of O$^+$(P) 7320 Å dayglow emission, Indian J Radio Space Phys, 44 (2015), 7]. Three geomagnetic storms, which occurred on 23-27 August 2005, 13-17 April 2006 and 1-5 February 2008 are chosen in the present study. A negative correlation is found between the volume emission rate (VER) and the Dst index for all the three geomagnetic storms. The present study shows that the relative variation of VER with respect to the initial value of VER (before the onset of a geomagnetic storm) during the main phase increases above 260 km. It is also found that the altitude of the peak emission rate does not show any appreciable variation with the activity of geomagnetic storm. A positive correlation is found between the zenith intensity and the atomic oxygen number density. The atomic oxygen number density obtained from NRLMSISE-00 model is compared with the measurements of Earle et al. [Low latitude thermospheric responses to magnetic storms, J Geophys Res (USA), 118 (2013), 3866] during a geomagnetic storm. This comparison shows that the atomic oxygen number density as provided by NRLMSISE-00 model is significantly lower than the measured value. Consequently, the atomic oxygen number density is treated as a variable parameter in the photochemical model and its effect on the VER of 732.0 nm dayglow emission is further studied. The zenith intensity is found to increase about 70% even in the case of weakest storm when the atomic oxygen number density is doubled. The latitudinal effect on the VER and zenith intensity of 732.0 nm is also studied. It is found that the VER decreases as the latitude increases. The decrease in VER from low to mid latitudes is due to the decrease in atomic oxygen number density with latitude. The zenith intensity at the maximum geomagnetic activity is about 12% higher than the zenith intensity before the start of the geomagnetic storm in equatorial region. However, no appreciable change in the zenith intensity is found at higher latitudes.

Keywords: Airglow emission, Atomic oxygen number density, Dayglow emission, Dst index, Geomagnetic storm, Volume emission rate (VER), Zenith intensity

PACS Nos: 92.60.hw; 94.20.Ac; 94.20.Vv; 96.60.Tf

1 Introduction
The variability of the thermosphere is greatly affected by solar and geomagnetic activity. The occurrence of solar flares and coronal mass ejections (CMEs) are indicative of a geomagnetic event. During a geomagnetic event, a large amount of energy gets deposited near the high latitude regions disrupting the Earth's magnetic field. These disturbances slowly drift towards the equator in duration of few hours. A geomagnetic storm lasts usually a few to several days in duration. However, sometimes the recovery phase of a geomagnetic storm lasts for one to two weeks or longer. A storm depending upon its Dst value is categorized as intense (great) (Dst ≤ -100 nT), moderate (-100 nT < Dst ≤ -50 nT) and weak (Dst > -50 nT) (Ref. 4). The another indicator to characterize the magnitude of geomagnetic storms is the Kp index. It quantifies the disturbance in the Earth's magnetic field on a 9 point scale. The thermospheric perturbations due to a geomagnetic activity result in heating and expansion of the thermosphere, which in turn change the temperature and densities of neutral and ion species with respect to both latitude and altitude. Earle et al. have reported the variations in neutral density, neutral velocity and temperature due to three moderate magnetic storms in 2011. They reported significant changes in the neutral densities during the onset of a geomagnetic storm. The geomagnetic storms alter the thermospheric densities, which in turn is likely to affect the thermospheric airglow emissions. Several researchers have reported strong correlation between the geomagnetic storms and airglow emissions. Culot et al. used the Transcar model to evaluate red line and green line emissions during magnetically active periods of 1992-1995 for low and middle latitude regions. Chung et al. have reported enhancement in OI 630.0 nm emission at mid latitude during an intense magnetic storm. The enhancement in
630.0 nm dayglow emission brightness was also reported by Pallamraju et al.\textsuperscript{14} during a geomagnetic storm at low latitudes.

It is a well known fact that above 250 km the atomic oxygen is a dominant species and is solely responsible for the production of 732.0 nm dayglow emission. Consequently, any variation in the atomic oxygen number density would have the direct effect on the volume emission rate (VER) of 732.0 nm emission during a geomagnetic storm. There are only two production sources for the 732.0 nm dayglow emission, one is the direct photo ionization excitation of atomic oxygen by absorption of solar EUV photons with wavelength less than 66.6 nm and the other is photoelectron impact ionization of ground state atomic oxygen. Thus, any change in the atomic oxygen number density would directly affect the 732.0 nm dayglow emission. The 732.0 nm emission is observed only in dayglow because more than 18 eV energy (\(< 66.6 \text{ nm}\)) is needed for the excitation of atomic oxygen to the \(O^+(2\text{P})\) state and in night, such high energy due to photons and photoelectrons is unavailable.

There are a very few model studies reported in the literature on 732.0 nm dayglow emission. Singh & Tyagi\textsuperscript{15} have developed a model to study 732.0 nm dayglow emission. However, this model could not satisfactorily explain the measured WINDII profiles\textsuperscript{16}. In this model, Singh & Tyagi\textsuperscript{15} incorporated neutral number densities from MSIS-90 neutral model atmosphere\textsuperscript{17} and solar fluxes from Hinteregger et al.\textsuperscript{18} and Tobiska et al.\textsuperscript{19}. This model was updated by Sunil & Singh\textsuperscript{20} by incorporating solar fluxes from Solar Irradiance Platform (SIP v2.35)\textsuperscript{21} and neutral number densities from NRLMSISE-00\textsuperscript{22}. Recently, Dharwan et al.\textsuperscript{23} and Thirupathaiah et al.\textsuperscript{1} have further updated the model of Sunil & Singh\textsuperscript{20} by incorporating latest transition probabilities as given by Wiese et al.\textsuperscript{24} and reaction rate coefficients as given by Mclaughlin & Bell\textsuperscript{25}. The model of Thirupathaiah et al.\textsuperscript{1} is found to be in very good agreement with the measurements of AE-C satellites\textsuperscript{26}, DE-2 spacecraft\textsuperscript{27} and WINDII measurements\textsuperscript{28}. In the present study, the model of Thirupathaiah et al.\textsuperscript{1} is used to study 732.0 nm dayglow emission during geomagnetic storm conditions. Three geomagnetic storms, which occurred during 23-27 August 2005, 13-17 April 2006 and 1-5 February 2008 are chosen in the present study. A low latitude geomagnetic station Tirunelveli (8.7\(^\circ\)N,77.8\(^\circ\)E), which is very close to the geomagnetic equator is selected for the present study.

2 Methodology

The \(O^+(2\text{P} - 2\text{D})\) 732.0 nm emission is associated with two pairs of doublet. The transition of \(2\text{P}_1/2\) and \(2\text{P}_3/2\) to \(2\text{D}_3/2\) is associated with 733.0 lines and the transition of \(2\text{P}_1/2\) and \(2\text{P}_3/2\) to \(2\text{D}_5/2\) is associated with 732.0 lines. The two identified production sources of \(O^+(2\text{P})\) are:

- The direct photo ionization excitation of atomic oxygen by absorption of solar EUV photons with wavelengths less than 66.6 nm:\textsuperscript{21,34,35}
  \[ O + h\nu(\lambda < 666\text{Å}) \rightarrow O^+(2\text{P}) \]  

- The photoelectron impact ionization of ground state atomic oxygen:
  \[ O + e_{ph} \rightarrow O^+(2\text{P}) + 2e \]  

The \(O^+(2\text{P})\) produced is lost by radiative decay and quenched through collisional deactivation by \(N_2\), \(O\) and thermal electrons (\(e_{th}\)). The scheme for the loss mechanism of \(O^+(2\text{P})\) ions is:

\[ O^+(2\text{P}) \rightarrow A \rightarrow O^+(2\text{D}) + h\nu(7320\text{Å}) \]  
\[ O^+(2\text{P}) \rightarrow A \rightarrow O^+(2\text{D},4\text{S}) + h\nu(\text{total}) \]  
\[ O^+(2\text{P}) + N_2 \rightarrow O^+ + N_2^* \]  
\[ O^+(2\text{P}) + O \rightarrow O^+(2\text{D},4\text{S}) + O \]  
\[ O^+(2\text{P}) + e_{th} \rightarrow O^+(2\text{D},4\text{S}) + e_{th} \]

The transition probabilities (\(A_i\)) and the reaction rate coefficients (\(k_i\)) in the updated photochemical model are taken from Wiese et al.\textsuperscript{24} and Mclaughlin & Bell\textsuperscript{25}, respectively. In the present study, the neutral number densities and temperature are adopted from the NRLMSISE-00 model\textsuperscript{22}. The electron densities and temperature are adopted from the IRI-07 model\textsuperscript{33}. The solar EUV fluxes are obtained from the Solar Irradiance Platform (SIP v2.36)\textsuperscript{21,34,35}. The above mentioned input parameters are incorporated in the photochemical model of Thirupathaiah et al.\textsuperscript{1} to obtain the volume emission rate of 732.0 nm dayglow emission. Further details of the model are provided in the paper of Thirupathaiah et al.\textsuperscript{1}. 

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3 Results and Discussion

In the present study, three geomagnetic storms have been identified and their effects on the 732.0 nm dayglow emission are studied.

3.1 Geomagnetic storm of 23-27 August 2005

This storm occurred during 23-27 August 2005 with maximum depletion in Dst index as -216 nT and maximum Kp index as 9 during the main phase of the storm indicating the storm to be an intense one (Fig. 1). It is noticed from Fig. 1(a) that the maximum variation in Dst index and Kp index in the main phase is close to 1100 hrs UT on 24 August 2005 at Tirunelveli (8.7ºN,77.8ºE) with solar zenith angle 61º. In the present study, therefore, 1100 hrs UT is chosen for each day during 23-27 August 2005. The Dst values for all the three geomagnetic storms chosen, in this paper, are taken from Space Physics Interactive Data Source (SPIDR) (http://spidr.ngdc.noaa.gov) and World Data Centre at IIG, Mumbai (http://wdciiig.res.in). The Kp values are taken from World Data Center for Geomagnetic Storm, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html). In Fig. 1(b), the variation of atomic oxygen number density at different altitudes is shown at 1100 hrs UT on each day during 23-27 August 2005. The atomic oxygen number density is obtained from NRLMSISE-00 model. It is noticed from this figure that the atomic oxygen number density increases as the value of Dst index decreases during the main phase of the storm, attaining the maximum value when Dst index goes minimum (-216 nT). On the other hand, it takes more than 72 hrs to recover the initial atomic oxygen number density in recovery phase. Figure 1(b) shows an increase of about 24% in the initial value of atomic oxygen number density in the main phase at 260 km, which further increases to about 29% at 320 km. These results show a negative correlation between the atomic oxygen number density and Dst index (and a positive correlation between the atomic oxygen number density and Kp index) from 260 km to 320 km. The variation of VER at different altitude at 1100 hrs UT on each day during 23-27 August 2005 is shown in Fig. 1(c). It is noticed from this figure that during the main phase of the storm, the VER starts to increase as the value of Dst index decreases and it attains a maximum value when the Dst index is minimum (-216 nT) and Kp index is maximum. In the recovery phase, the VER decreases slowly as the value of Dst index increases. Figure 1(c) shows that there is an increase of about 11% in the initial value of VER in the main phase at 260 km and it further increases to 26% at 320 km. These results show a negative correlation between the Dst index and the VER from 260 km to 320 km. Figure 1(d) shows the variation of zenith intensity computed at 1100 hrs UT on each day during 23-27 August 2005. One can notice from Fig. 1(d) that the zenith intensity increases as the value of Dst index decreases (and Kp index increases) during the main phase of the storm and it attains a maximum value when the Dst index is minimum (-216 nT) and Kp index is maximum. In the recovery phase, the zenith intensity decreases slowly as the value of Dst index increases (and Kp index decreases). There is an increase of about 13% in the initial value of zenith intensity in the main phase. These results show that there is a negative correlation between the Dst index and the zenith intensity (and positive correlation between Kp index and zenith intensity).

Figure 2 shows the variation of VER with altitude during the storm of 23-27 August 2005. It is noticed from this figure that the VERs do not show any appreciable dispersion below 220 km during all phases of the storm. However, VERs show dispersion above 220 km. It is, further, noticed that the VER is maximum during the main phase of the storm (24 August 2005) and it gradually decreases during the recovery phase of the storm. One can also notice from Fig. 2 that the altitude of peak emission rate...
(PER) does not show any appreciable change throughout the storm.

3.2 Geomagnetic storm of 13-17 April 2006

The second storm chosen in the present study is a moderate one, which occurred during 13-17 April 2006 with maximum depletion in Dst index as -111 nT and maximum Kp index as 7 during the main phase (Fig. 3). It is noticed from Fig. 3(a) that the maximum depletion in the Dst index is found to be close to 0900 hrs UT on 14 April 2006, which lies in the daytime at Tirunelveli (8.7°N, 77.8°E) with solar zenith angle 32°. The VER and zenith intensity for this storm are calculated corresponding to 0900 hrs UT on each day during 13-17 April 2005. The variation of atomic oxygen number density, which is obtained from NRLMSISE-00 model, at 0900 hrs UT for different altitudes on each day during 13-17 April 2006 is shown in Fig. 3(b). One can notice from this panel that the atomic oxygen number density increases as the value of Dst index decreases during the main phase of the storm and it attains a maximum value when the Dst index is minimum (-111 nT). In the recovery phase, the atomic oxygen number density starts decreasing slowly as the value of Dst index increases. It is noticed from Fig. 3(b) that there is an increase of about 24% in the initial value of atomic oxygen number density in the main phase at 260 km and it, further, increases to 28% at 320 km. These results show a negative correlation between the atomic oxygen number density and the Dst index from 260 km to 320 km. Figure 3(c) shows the variation of VER at 0900 hrs UT on each day during 13-17 April 2005 at different altitudes. One can notice from this figure that VER starts increasing during the main phase of the storm and attains a maximum value when the Dst index is minimum (-111 nT) (and Kp index is maximum). In the recovery phase, the VER decreases slowly as the value of Dst index increases. It is noticed from Fig. 3(c) that VER increases to about 10% of its initial value in the main phase at 260 km and it, further, increases to 24% at 320 km. These results show a negative correlation between the VER and the Dst index from 260 km to 320 km. The variation in zenith intensity is computed at 0900 hrs UT on each day during 13-17 April 2006 and is depicted in Fig. 3(d), which shows that the zenith intensity increases with decrease in Dst index during the main phase of the storm and attains a maximum value when the Dst index is minimum (-111 nT) (and Kp index is maximum). In the recovery phase, the zenith intensity decreases slowly as the value of Dst index increases (and Kp index decreases). One can notice an increase of about 12% in the initial value of zenith intensity in the main phase. These results show that there is a negative correlation between the Dst index and the zenith intensity (and a positive correlation between Kp index and zenith intensity).
The variation of VER with altitude during the storm of 13-17 April 2006 is shown in Fig. 4. One can notice from this figure that the VERs do not show any appreciable dispersion below 220 km during all phases of the storm. It is, further, noticed that the VER is maximum during the main phase of the storm (14 April 2006) and gradually decreases during the recovery phase of the storm. One can also notice from Fig. 4 that the altitude of PER does not show any appreciable change throughout the storm.

3.3 Geomagnetic storm of 1-5 February 2008

This storm occurred during 1-5 February 2008 when the Dst index was as low as -49 nT and the Kp index was as high as 5 during the main phase (Fig. 5). This may be considered as a weak geomagnetic storm. Figures 5(a-d) show the variation of Dst and Kp index, atomic oxygen number density, VER and the zenith intensity during this storm, respectively with time. Figure 5(b) shows that there is an increase of about 19% in the initial value of atomic oxygen number density in the main phase at 260 km and it, further, increases to 22% at 320 km. Figure 5(c) shows that there is an increase of about 10% in the initial value of VER in the main phase at 260 km and it, further, increases to 20% at 320 km. One can notice from Fig. 5(d) that there is an increase of about 8% in the initial value of zenith intensity in the main phase.

Figure 6 shows the variation of VER with altitude during the storm of 1-5 February 2005. It is noticed from this figure that the VERs do not show any appreciable dispersion below 220 km during all phases of the storm. However, VERs show dispersion above 220 km. It is, further, noticed that the VER is maximum during the main phase of the storm (2 February 2008) and it
gradually decreases during the recovery phase of the storm. One can also notice from Fig. 6 that the altitude of PER does not show any appreciable change throughout the storm.

The study of above three geomagnetic storms shows that there exists a negative correlation between VER of 732.0 nm dayglow emission and the Dst index. Further, the zenith intensity and the Dst index also show a negative correlation. The qualitative analysis of these results shows that the VER and the zenith intensity have a similar type of variation for all the three storms. However, there are quantitative differences in the variation of VERs and zenith intensities of 732.0 nm dayglow emission amongst the above three geomagnetic storms. The main phases of these storms occurred at different times and solar zenith angles. This may be the reason for the quantitative differences in the results of these three geomagnetic storms.

3.4 Atomic oxygen number density variation during geomagnetic storms

It is already discussed that there are two identified sources for the production of 732.0 nm dayglow emission. The production rates due to these two sources (as can be seen from Eqs (1 and 2)) depend upon the atomic oxygen number density, which in the present study is used from NRLMSISE-00 neutral model atmosphere. It is quite likely that the atomic oxygen number density provided by NRLMSISE-00 model may not account properly the effects of geomagnetic storm. This fact has been discussed by Dharwan et al. in their study of 844.6 nm dayglow emission under geomagnetic storm conditions. They have compared the atomic oxygen number density obtained from NRLMSISE-00 model with the measurements of Earle et al. for a geomagnetic storm of 24-27 October 2011 at 400 km near equator. Dharwan et al. found that the fluctuations in the atomic oxygen number density as given by NRLMSISE-00 model are significantly smaller than the measured values of Earle et al. as shown in Fig. 7. Consequently, atomic oxygen number density is used as a variable parameter in the photochemical model to study its effect on VER of 732.0 nm dayglow emission during a geomagnetic storm. The atomic oxygen number density is varied by using the formula:

\[
[O] = \beta \times [O]_{\text{NRLMSISE}}
\]  \quad \text{(8)}

where, \([O]\), is the new calculated value of atomic oxygen number density; \([O]_{\text{NRLMSISE}}\), the value obtained from NRLMSISE-00 neutral model atmosphere; and \(\beta\), the multiplication factor, which is varied from 1.2 to 1.8 (in an increment of 0.2). Figure 8 shows the fluctuations in the zenith intensity \((I_{\beta}-I_1)/I_1\), where, \(I_\beta\), is the intensity at a particular value of multiplication factor; and \(I_1\), is the intensity when the multiplication factor is 1 (before the onset of geomagnetic storm). It is noticed from Fig. 8 that the fluctuation in the zenith intensity increases as the value of \(\beta\) increases. It is, further, noticed from Fig. 8 that the increase in zenith intensity may be as large as 70% even in the case of weakest storm.

![Fig. 7 — Comparison of atomic oxygen number density fluctuations as given by NRLMSISE-00 model with the measurements of Earle et al. at equator during a geomagnetic storm (24-27 October 2011) at 400 km [Source: Dharwan & Singh, Adv Space Res (UK), 55 (2015) 2526]](image)

![Fig. 8 — Fluctuations in the zenith intensity \((I_{\beta}-I_1)/I_1\) with respect to factor \(\beta\) \([I_\beta\) is zenith intensity at particular \(\beta\); and \(I_1\) is zenith intensity before the onset of geomagnetic storm]](image)
3.5 Latitudinal study of 732.0 nm dayglow emission

The results presented for the 732.0 nm dayglow emission in the above sections are at a fixed latitude and longitude (8.7ºN, 77.8ºE). This latitude is very close to the equator. However, it would be quite interesting to extend this study to other latitudes. Subsequently, three more latitudes (30ºN, 50ºN, and 60ºN) are chosen and the longitude is kept fixed (77.8ºE). It has been discussed above that the qualitative variation of VER is more or less of similar type for all the three geomagnetic storms chosen in the present study. Therefore, the geomagnetic storm of 23-27 August is only chosen for the latitudinal study of 732.0 nm dayglow emission. The altitude variation of VER of 732.0 nm dayglow emission at different latitudes (8.7ºN, 30ºN, 50ºN, and 60ºN) is shown in Fig. 9. Figure 9(a) shows the variation of VER with altitude before the start of the storm (quiet day, i.e. on 23 August 2005) at 1100 hrs UT and the Fig. 9(b) shows the variation of VER with altitude at 1100 hrs UT when the geomagnetic activity is maximum (disturbed day, i.e. on 24 August 2005). It is noticed from these figures that VER decreases as the value of latitude increases. This decrease in VER can be explained on the basis of the variation in atomic oxygen number density with latitude. The altitude variation of atomic oxygen number density, which is obtained from NRLMSISE-00 model at different latitudes (8.7ºN, 30ºN, 50ºN and 60ºN) at 1100 hrs UT is shown in Fig. 10. Figure 10(a) shows the atomic oxygen number density variation for quiet day, i.e before the start of the geomagnetic storm (23 August 2005) and Fig. 10(b) shows the atomic oxygen number density variation for the magnetically disturbed day, i.e. at the time of maximum geomagnetic activity (24 August 2005). These figures show that the atomic oxygen number density decreases as the latitude increases. Consequently, VER in Fig. 9 shows a positive correlation with the atomic oxygen number density. It would be worthwhile to mention here that the study of Pallamraju et al. also supports the present findings that the enhancement in the airglow emission intensity may be due to the enhancement in neutral number density over equatorial region during the geomagnetic storm. Further, the possible cause of the higher density of atomic oxygen in equatorial region may be due to intense Joule heating which takes place over high latitudes during geomagnetic storm. This Joule heating may modify the horizontal and vertical components of winds at higher latitudes, which may transport more atomic oxygen towards equatorial

![Fig. 9 — Variation of VER with altitude for different latitudes during: (a) magnetically quiet day; and (b) disturbed day](image1)

![Fig. 10 — Variation of atomic oxygen number density with altitude for different latitudes during: (a) magnetically quiet day; and (b) disturbed day](image2)
latitudes. The latitudinal variation of zenith intensity is shown in Fig. 11(a). The zenith intensity of 732.0 nm dayglow emission is obtained by integrating the VER over the vertical column of altitude. $I_{\text{quiet}}$ is the zenith intensity before the start of the storm and $I_{\text{disturbed}}$ is the zenith intensity at the time of maximum geomagnetic activity. It is noticed from Fig. 11(a) that the zenith intensity decreases as the value of latitude increases for both the cases. The reason for this decrease in zenith intensity is due to the fact that the atomic oxygen number density decreases as the latitude increases (Fig. 10). It is also noticed from Fig. 11 that the zenith intensity at the maximum geomagnetic activity is about 12% higher than the zenith intensity before the start of the geomagnetic storm near equatorial latitudes. However, relative variation in zenith intensity ($I_{\text{disturbed}} - I_{\text{quiet}} / I_{\text{quiet}}$) reduces to about 2% at 60°N latitude. The variation in zenith intensity as shown in Fig. 11 is quite consistent with the results of VER as shown in Fig. 9. It would be worthwhile to mention here that the latitudinal variation of emission rate is studied using the atomic oxygen number density from NRLMSISE-00 model. If the atomic oxygen number density in NRLMSISE-00 model is varied using Eq. (8), then similar type of variations as shown in Fig. 8 are expected in zenith intensity.

4 Conclusion

The effect of geomagnetic storm on the 732.0 nm dayglow emission is studied in the dayglow using an updated photochemical model. A negative correlation is found between atomic oxygen number density and the Dst index. The VER of 732.0 nm dayglow emission shows a negative correlation with the Dst index. It is found that the variation in the VER of 732.0 nm dayglow emission during the main phase increases as the altitude increases above 260 km. The present study also shows that the altitude of the peak emission rate remains unaffected by the activity of geomagnetic storm. The variation in the zenith intensity of 732.0 nm dayglow emission during the main phase increases as the altitude increases above 260 km. The present study also shows that the altitude of the peak emission rate remains unaffected by the activity of geomagnetic storm. The variation in the zenith intensity of 732.0 nm dayglow emission is about 12% higher than the zenith intensity before the start of the geomagnetic storm near equatorial latitudes. However, relative variation in zenith intensity ($I_{\text{disturbed}} - I_{\text{quiet}} / I_{\text{quiet}}$) reduces to about 2% at 60°N latitude. The variation in zenith intensity as shown in Fig. 11 is quite consistent with the results of VER as shown in Fig. 9. It would be worthwhile to mention here that the latitudinal variation of emission rate is studied using the atomic oxygen number density from NRLMSISE-00 model. If the atomic oxygen number density in NRLMSISE-00 model is varied using Eq. (8), then similar type of variations as shown in Fig. 8 are expected in zenith intensity.

Acknowledgement

One of the authors (MD) is thankful to the Ministry of Human Resource Development, Government of India for providing the financial support.
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