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Nightglow observations of OI 630 nm emission during the beginning of solar cycle 24 over 25°N, India

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This paper presents the first nightglow observations of the thermospheric red line emission of atomic oxygen at 630 nm from Allahabad (25.4°N, 81.9°E), a low-latitude station in India, during October-November 2009 and 2010. These observations were made using a CCD based All-Sky Imaging system. Most of the observations presented here represent geomagnetically quiet nights. The variability of OI 630 nm emission as observed from this station has been presented and discussed.

Keywords: Nightglow emission, Thermospheric red line emission

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1 Introduction

The earth's ionosphere, magnetosphere and the solar wind constitutes a coupled system. The characteristics of the solar wind are strongly governed by the processes in the solar interior, and the solar radiation controls the behaviour of the ionosphere. When the sun is active, the ionosphere behaves differently than the times during which the sun is quiet. During geomagnetically disturbed times, the particle precipitation and Joule heating get enhanced; the ionospheric composition changes (e.g. the F-region electron density increases), and the prevalent electric fields/currents as well as the thermal structure are modified. Also, the manifestations of the geomagnetic disturbances vary with latitudes, i.e. some events are more pronounced at high and mid-latitudes, while the others are more prominent at low and equatorial latitudes[1].

Among other techniques (viz. incoherent/coherent scatter radars, ionosondes/ digisondes, radiowave scintillation techniques, *in situ* methods), the optical airglow technique has been successfully used to study the thermosphere around 250 km altitude region. Due to the presence of the ionized species and the associated photochemical processes, the red line emission of atomic oxygen at 630 nm is the characteristic feature of the spectrum of the terrestrial night sky (especially from the ionospheric F–region around 250 km). OI 630 nm emission is due to the forbidden transition between the ^1D and $^3P_2$ metastable states of atomic oxygen. During nighttimes, this emission is a consequence of charge exchange (involving O^+ ion and O_2) followed by dissociative recombination reaction (involving O_2^+ ion and electron) (Ref. 2) in the thermosphere region around 250 km. Hence, the 630 nm emission intensity strongly depends on the density of O^+ ion, O_2 molecule and electrons in the F-region. Also, the intensity decreases when the ionospheric layer moves up and vice versa.

Owing to this, the OI 630 nm emission is a sensitive indicator of the electrodynamical processes in the F-region, and hence, has been successfully used to study the ionospheric processes. These processes include ionization anomaly, plasma depletions/ blobs/bubbles, irregularities, travelling ionospheric disturbances, the phenomenon of midnight temperature maximum, and the geomagnetic storm induced changes in the ionosphere. The peak of this emission feature occurs around 250 km during nighttimes[3]. Rocket measurements of the OI 630 nm emission profiles during nighttimes by Sobral *et al.*[4] indicate the emission peak to be around 230 km. Zhang & Shepherd[5] investigated the emission rate profiles of O (^1D) 630 nm dayglow measured by Wind Imaging Interferometer (WINDII) instrument onboard Upper Atmospheric Research Satellite (UARS), and found the emission peak to lie between

190 km and 280 km (with the width of layer to vary from 42 to 54 km).

In the past, several investigators have investigated the relationship of OI 630 nm emission feature with the geomagnetic disturbances and the solar cycle. At 23°S, Sahai *et al.*[6] observed: (i) an intensity increase of the order of 7 times from the period of low to high solar activity, and (ii) large changes in the seasonal-nocturnal intensity variations between the years of low and high solar activity. Mukherjee *et al.*[7] found the seasonal variation of intensity to be dependent on the solar activity. Pallamraju *et al.*[8] observed an intensity increase of the order of 2 – 3 times of OI 630 nm emission during a geomagnetic disturbed night. Using WINDII instrument (onboard UARS) database, Zhang & Shepherd[5] investigated the solar dependence of this emission feature, and found the emission rate to be correlated with the solar F 10.7 cm radio flux over a solar cycle.

In recent years, the CCD based all-sky imaging of the F-region nightglow has emerged to be an excellent tool to investigate the ionospheric F-region around 250 km. Mukherjee *et al.*[9] noted the enhancement in the intensity of OI 630 nm emission and the occurrence of depletion in the F-region imaging observations during the geomagnetic storm. Pimenta *et al.*[10] reported the occurrence of plasma blobs in OI 630 nm imaging observations during a geomagnetic storm. Pimenta *et al.*[11] investigated the occurrence of dark band structures in OI 630 nm nightglow imaging over a solar cycle period, and found that (i) their occurrence was limited to the period of low solar activity and its ascending phase, and (ii) their lifetime was longer during the former than the latter one. Das *et al.*[12] reported the enhancement (~ 50%) in OI 630 nm dayglow emission connected to an X-class solar flare. Chakrabarty *et al.*[13] investigated the response of OI 630 nm emission over low-latitudes during substorm, and found enhancements in its intensity. The authors attributed the enhancement as a result of the supply of O_2^+ ions by the eastward electric field induced by the onset of substorm.

In this paper, a case study of the variability of OI 630 nm emission during October-November of 2009 and 2010 (solar minimum epoch, solar cycle 24) has been done over a low latitude station Allahabad (25.4°N, 81.9°E), India. It was found that the intensity of OI 630 nm emission was relatively higher on the geomagnetically disturbed nights than that on quiet nights. A post-midnight increase in the emission intensity was also noted.

2 Experimental set up, Data processing and Observations

Nightglow observations of OI 630 nm emission were carried out at Allahabad (25.4°N, 81.9°E, dip angle ~+38.7°), India using a new installed CCD based All-Sky Imaging System (manufactured by Keo Scientific Ltd, Canada) during the new moon period of October-November in 2009 and 2010. The imaging system comprises a fast f/4 all-sky telecentric lens systems as the optical unit, and a back-illuminated 512 × 512 pixels CCD (Scientific Grade 1, 24 × 24 µm, and thermoelectrically cooled to –40ºC) as the photon detector. OI 630 nm emission was monitored using an optical filter having bandwidth of 2 nm and had transparency of 77%. The measurement of background emission at 530 nm was also carried out using an optical filter of 1.8 nm bandwidth and 66% transparency. The exposure time for each measurement was 90 s. The signal-to-noise ratio was better than 240 for the above mentioned settings of the imaging system. The image processing involved the flat-field correction (to approximately remove artefacts due to van Rhijn effect, atmospheric extinction and the non-uniform pixel-to-pixel sensitivity of the CCD detector), the east-west orientation, and scaling to 5-95% of the intensity range. On the beginning of each night, a flat-field image was acquired, and later on, the images captured were divided by the acquired flat-field images. The details of the All-Sky Imager as well as the image processing have been presented by Mukherjee *et al.*[14]. It is worthy to mention here that the field of view of imager was restricted to 140° in order to avoid contamination due to city lights, and following this, the spatial coverage of imager was a little over 2° at an altitude of 230 km. In present study, the averaged intensity of a square bin (16 × 16 pixel) of an individual image corresponding to a circular field of view of ~ 1° along zenith was investigated to depict the nocturnal variation of OI 630 nm intensity. A keogram analysis for each night was performed along the North South direction to identify the spatial features present in the imaging data.

In order to construct a keogram for a particular night, firstly a north-south aligned rectangular slice (centrally located in the image data and 3 pixel thick) of each image was selected, and then the obtained slices were appended side-by-side sequentially to yield keogram. Due to unavailability of a standard source of light, the nightglow intensities are not calibrated in Rayleigh, and hence, the intensities are presented in the arbitrary units. At present, the efforts are on to procure a secondary source (utilizing MgO coated screen illuminated by a standard tungsten ribbon lamp of known spectral output) for calibration. In future, the observed nightglow intensities will be presented on an absolute Rayleigh scale.

As mentioned earlier, the objective, here, was to study the behaviour of OI 630 nm during the beginning of solar cycle, it was decided to investigate this emission feature during the same season of two successive years to avoid any seasonal bias which may be present in the data. Over this location, the common nightglow database was available during October-November in 2009 and 2010. During observations, the lunar elevation from horizon was below 20°. Nightglow measurements during October-November were severely affected by the presence of cloud and foggy conditions, and the cloud/fog affected database was also not considered in this study. Keeping all this into account, the nightly database with the continuous observation of more than 6 hours was selected. Further, the database for quiet and most disturbed days were identified to study distinctly the solar influence. Herein, a case study of eight nights of airglow observations has been presented.

Table 1 summarizes the space weather conditions on the days of observations (data sources: http://www.ngdc.noaa.gov/geomag/data.shtml and http://spaceweather.com/), the averaged intensity during the night along with the standard deviation (in braces) and the duration of measurements on the particular night. Most of the nights fell in the category of quiet times except for 12 November 2010, which was a geomagnetically disturbed night. During quiet times, the dependence of the averaged nocturnal intensity on the geomagnetic activity index, Ap, and solar F 10.7 cm radio flux is not very forthcoming as expected and is apparent from the table. However, for a single event presented herein during November 2010, the averaged intensity was comparatively higher than the neighbouring quiet night (similar to those reported by Mukherjee *et al.*[7,9] and Pallamraju *et al.*[8]).

2.1 Behaviour of OI 630 nm Intensity on quiet nights

The variations of the intensity of OI 630 nm emission during the quiet nights on 13 October 2009, 17 November 2009, 04 October 2010 and 05 October 2010 are presented in Fig. 1 (temporal evolution presented in hrs UT and IST = UT + 0530 hrs). The keograms for these nights are presented in Figs 2 and 3. In the keograms, the contrast adjustment has been made so as to enhance the spatial features present in them. A common feature that can clearly be noticed on most of the nights is the intensity decreases from dusk to midnight hours, a general feature of OI 630 nm emission globally. It has been explained on the basis of diminishing ionizing action of the solar radiation. As the sun moves below horizon, the ionizing action of the solar radiation decreases, and hence, the electron density decreases after dusk hours, thereby resulting in the decrease of the intensity of OI 630 nm emission.

Often, over the latitudes located between the geomagnetic equator and the anomaly crest, the movement of equatorial ionization anomaly manifests itself as a peak in the intensity variations during the pre-midnight hours. The variation observed on the night of 13 October 2009 represents a manifestation of this process. The geomagnetic coordinates of Allahabad are 16.20°N, 155.72°E and inclination is 38.65°. The growth/decay of equatorial ionization anomaly depends on the strength of eastward electric field (a parameter dependent upon the zonal component of the thermospheric wind), and the

Table 1—Nights of observation and space weather conditions, duration of measurements, and averaged intensity during night (standard deviation in brackets)

Day	Geomagnetic activity index (Ap)	Solar F 10.7 cm radio flux, 10^{-22} W m^{-2} Hz^{-1}	Nightly averaged intensity, arb. units (Standard deviation)	Duration of measurements, h
13.10.2009	3	62.5	941 (207)	6.5
15.10.2009	5	63.0	893 (057)	7.0
17.11.2009	1	67.9	673 (116)	9.0
20.11.2009	2	66.9	1048 (85)	9.0
04.10.2010	2	68.5	634 (121)	9.0
05.10.2010	5	67.8	588 (140)	10.0
10.11.2010	4	75.5	711 (034)	11.0
12.11.2010*	16	75.3	757 (112)	11.0

*Geomagnetically disturbed night

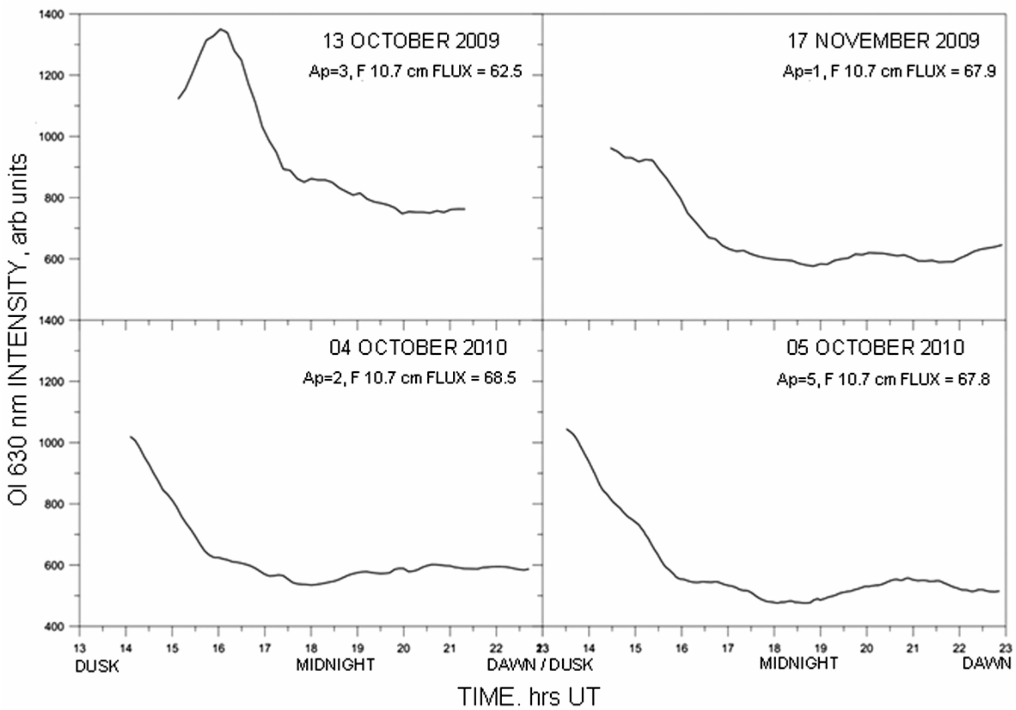

Fig. 1—Nocturnal variations of the intensity of OI 630 nm emission on few quiet nights

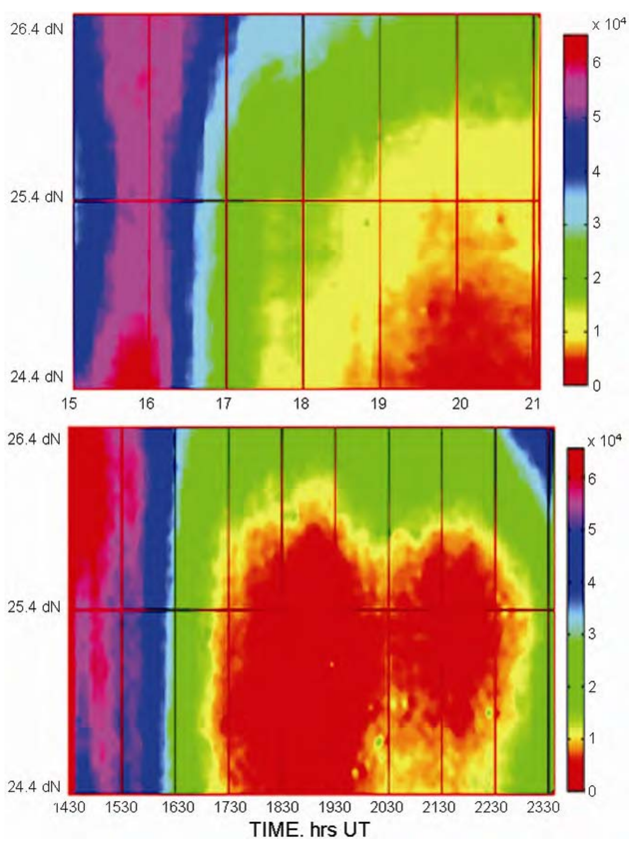

Fig. 2—OI 630 nm emission intensity keograms along North-South on 13 October 2009 (top row) and 17 November 2009 (bottom row)

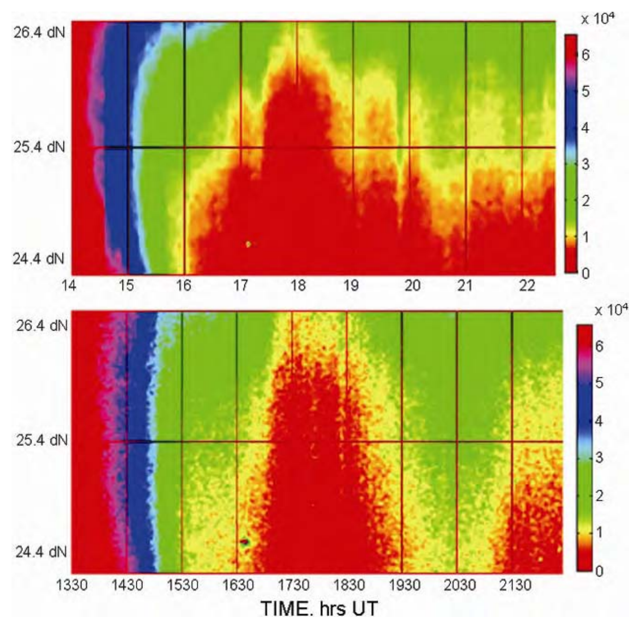

Fig. 3—OI 630 nm emission intensity keograms along North-South on 04 October 2010 (top row) and 05 October 2010 (bottom row)

strength of equatorial electrojet (EEJ) is a proxy of this electric field. Studies indicate that the strength of equatorial ionization anomaly (EIA) is positively correlated with EEJ strength[15].

It appears that the electric field was strong enough to drive plasma to latitudes as high as of Allahabad. However, due to unavailability of any EEJ data, this can only be conjectured. Zhao *et al.*[16] investigated the behaviour of equatorial ionization anomaly over a solar cycle in the Asian-Australian longitudinal sector using the ionospheric total electron content derived from the trans-ionospheric GPS signal and found the ionization crest to be located between 20–25° geographic latitudes in the northern hemisphere. An analysis of the intensity variations along the off-zenith directions indicates that the movement of the peak was towards South-North direction with the speed of 215 m s^{-1}. A careful look on the keogram for this day i.e. 13 October revealed that the peak was more pronounced at 24.4°N near 1600 hrs UT (2130 hrs IST) at par with the observation of EIA by Zhao *et al.*[16]. Another possibility is that an intense lowering of the height of the F-region took place, and hence, more recombinations occurred to produce enhancement in the OI 630 nm emission. Earlier, Mukherjee *et al.*[7] have reported similar observations of such peaks in OI 630 nm intensity variations from Kolhapur (17°N), India. However, such peaks were more frequently observed over Kolhapur (it is worthy to mention here that Kolhapur is located between the dip equator and crest of anomaly).

On rest of the nights shown in Fig. 1, the OI 630 nm emission intensity was found to enhance after 1900 hrs UT (0030 hrs IST), i.e. during the post-midnight hours. This feature can also be noted in the corresponding keograms of those nights. Further, an enhancement of intensity in the post-midnight hours was seen on most of the nights while another enhancement also occurred between 1900 and 2200 hrs UT. On most of the occasions, the intensity was found to increase beyond 2200 hrs UT on almost all the nights of observations. Rao & Sastri[17] have attributed this post-midnight enhancement as a consequence of the midnight temperature maximum (MTM) phenomenon, an anomalous behaviour of the F-region neutral temperature during night. Simulation studies by Fesen[18] suggest MTM to be a consequence of interaction between the upward propagating tides and those produced *in situ* in the thermosphere. MTM influences the dynamics of the F-region and triggers a downward decent of plasma, i.e. a decrease in the height of the F-region. Mukherjee *et al.*[19] presented a comprehensive report of this MTM phenomena in OI 630 nm nightglow measurements over Kolhapur. They observed OI 630 nm intensity to enhance between 2015 and 2215 hrs UT. However, the enhancements reported in their studies were more pronounced than those observed herein. An extensive analysis of this phenomenon is going on and a detailed report with comparative study will be presented in future. On the whole, the nocturnal behaviour on quiet nights was marked by a decrease of intensity from dusk to mid-night. In the post-midnight sector, an enhancement of intensity associated, perhaps, with the MTM phenomena was observed and a gentle peak of intensity appeared between 1900 and 2200 hrs UT. This was followed by a gradual increase of intensity during the dawn hours.

2.2 Behaviour of OI 630 nm intensity on 12 November 2010, a geomagnetically disturbed night

The top panel of Fig. 4 presents the variation of OI 630 nm intensity on this night. Also, shown in the figure are the Dst index (middle panel) and Kp index (bottom panel). On this night, the behaviour of intensity is similar to other quiet nights till 2100 hrs UT. Around 2100 hrs UT, a sudden change in both Dst index and Kp index is observed, and an hour onwards (near dawn), a secondary peak in OI 630 nm intensity (encircled by dashed line in the topmost plot of Fig. 4) is observed. This can also be noticed in

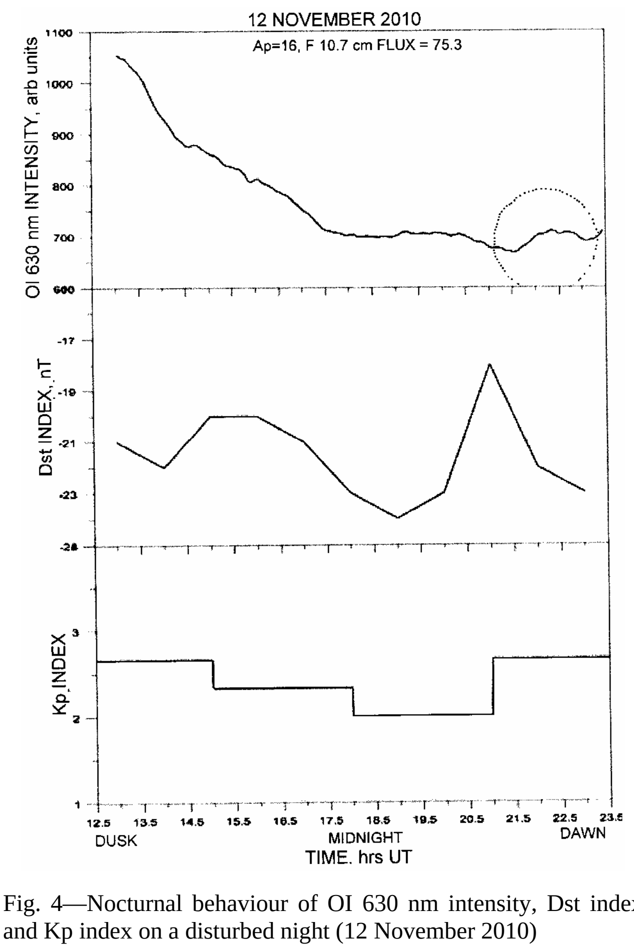

Fig. 4—Nocturnal behaviour of OI 630 nm intensity, Dst index and Kp index on a disturbed night (12 November 2010)

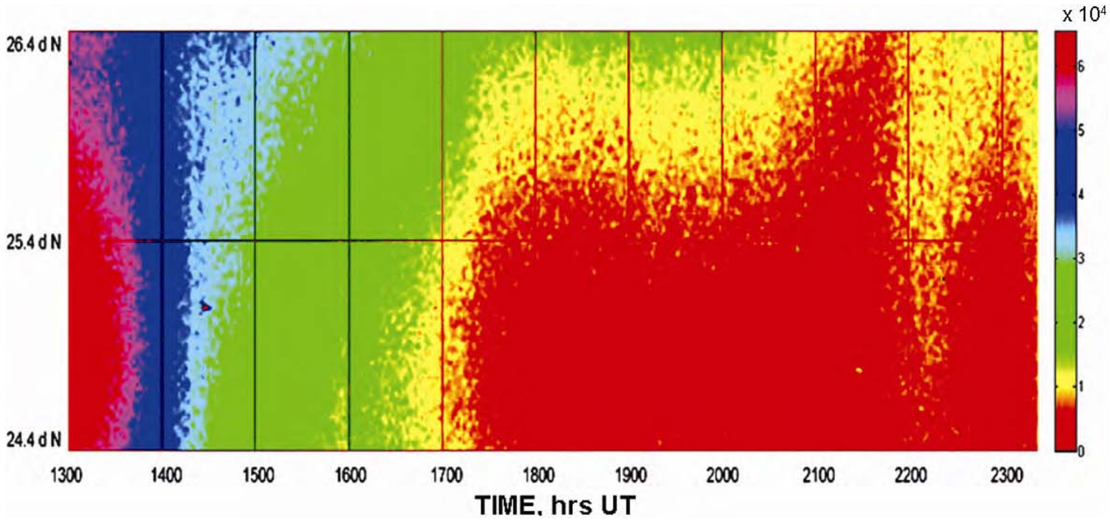

Fig. 5—North-South keogram of OI 630 nm emission intensity on a disturbed night on 12 November 2010

the keogram for this date (Fig. 5). The appearance of the secondary peak around dawn hours is something different from what was observed on the quiet nights (viz. the gradual increase of intensity during dawn hours as seen in Figs 1, 2 and 3). Mukherjee[20] investigated the variation of OI 630 nm during the geomagnetic storm of 23 December 1995 at 17°N and have reported a similar behaviour of OI 630 nm emission vis-a-vis changes in the Dst index. A large intensity increase was found nearly 2 hours after the peak in Dst index. This has been explained on the basis of the precipitation of energetic neutrals (produced by the charge exchange between the energetic ring current ionized species and the geocoronal hydrogen or oxygen) at low latitudes during geomagnetically disturbed times, and due to associated favourable changes in the ionospheric composition, there is enhancement in the intensity of OI 630 nm emission. Also, the averaged OI 630 nm intensity on this night was comparatively higher than the neighbouring quiet night.

3 Conclusions

Nightglow measurements of the atomic oxygen red line at 630 nm have been made, for the first time, at Allahabad (25.4°N, 81.9°E, dip angle ~ +38.7°), India. The variability of the emission intensity during October-November in 2009 and 2010, solar minimum epoch and solar cycle 24, have been presented and discussed. On geomagnetically quiet nights, the intensity variation is marked first by a decreasing trend in the pre-midnight sector, followed by an enhancement in post-midnight hours. This is succeeded by a gradual increase of intensity during the dawn. The post-midnight enhancement of intensity appeared to be a permanent feature of the F-region above Allahabad, and is attributed to the phenomena of midnight temperature maximum (MTM). The behaviour of OI 630 nm emission was distinctly different on the disturbed night.

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