Storm–associated Variations of [OI] 630.0 nm Emissions from Low Latitudes

G. K. Mukherjee[1]

ABSTRACT

The ground-based magnetic signature of particle precipitation from the ring current to low latitude regions during the recovery phase of a geomagnetic storm on 23 December, 1995, has been inferred by studying photometric 630.0 nm nightglow at a low latitude station, Kolhapur (7.5° N, 144.7° E; Geomagnetic, dip latitude 10.6° N) and magnetograms (H, D and Z) of nearby low latitude stations. The maximum optical emission occurred simultaneously with the maximum positive (north ward) excursions in the H trace of low latitude magnetograms associated with negative H excursions at high latitude observatories. Generally, an increase in Z component occurred at all low latitude stations. A large intensity increase of about seven times in 630.0 nm emission was observed at around 2:15 hrs I.S.T on 23 December, 1995. The 630.0 nm enhancement maximised at the time of high Dst or Kp index during the night. In addition, the ionosonde experiment conducted at Ahmedabad (13.8°N, 144.7°E; Geomagnetic) showed the enhancement of peak electron densities in the F-region and sudden lowering of the F layer in the ionosphere. A possible explanation of the effect is given in terms of emergence of energetic neutral atoms (Hydrogen or Oxygen) from high energy protons in a typical charge exchange process in the ring current depositing energy into the thermosphere-ionosphere system, also possibly due to changes in the composition of the thermosphere-ionosphere during magnetic storms that would enhance the 630.0 nm emissions.

(Key words: Ionosphere, Airglow, Precipitation)

1. INTRODUCTION

The deposition of energy from the ring current in the form of particle precipitation into the thermosphere-ionosphere system during a geomagnetic storm has been extensively studied, theoretically and experimentally, by a number of researchers during the past two decades (Moore and Weber, 1981; Mukherjee & Rajaram, 1989; Prolss, 1993; Rohrbaugh et al., 1983;

[1]Indian Institute of Geomagnetism, Colaba, Mumbai 400 005, India

Sahai et al., 1990; Tinsley & Burnside, 1981). These effects are very prominent in the high latitude and mid latitude regions, in contrast to their lesser low latitude manifestations. Particle precipitation induces rapid changes in the dynamics of the upper atmosphere during periods of large magnetic disturbance. Three types of precipitating particles at low and mid latitude regions have been suggested. Hot electrons and energetic ions precipitate directly along the magnetic field lines that connect the ring current and outer plasmasphere to mid latitude regions, while energetic neutral atoms precipitate at low and mid-latitude regions (Rassoul et al., 1992). Tinsley et al. (1986) reported a preliminary study of the local and global ground-based magnetic signatures associated with particle precipitation. They noted that enhancements of the observed optical emissions were associated with sharp variations in geomagnetic field components during the time interval when the IDstI index was large. Rassoul et al. (1992) further presented the results of the correlation of optical and magnetic data for a few events. They compared the airglow emission rate with the product of Dst and the amplitude of the short term excursion in horizontal components in the local magnetogram. In this report, we present a preliminary study of the ground-based magnetic signatures associated with the possible enhancements of particle precipitation, and their induced optical emissions during a magnetic storm, and discuss the correlation between optical 630.0 nm emission, ionospheric parameters and magnetic data for the event of 23 December, 1995. We also compute a new index P, defined as the product of Dst and local H variation and its rate of variation (dP/dt) to match the optical data. It is found that the rate of variation set by P fits the data better than have other indices used earlier.

2. EXPERIMENTAL SETUP AND PARAMETERS

In this section we examine several different simultaneous data sets including optical, ionospheric and geomagnetic data of 22-23 December, 1995. The night was moderately disturbed with the magnetic activity index value Ap equal to 20 and the Solar 10.7 cm flux 69 units.

2.1 Optical Data

Airglow observations were made from Kolhapur (7.5° N, 145.6° E; Geomagnetic, dip latitude 10.6 ° N) where tilting photometers were employed on the night of 22-23 December,1995, to monitor 630.0 nm emission intensities. The airglow intensity was not measured directly, but was obtained by taking measurements with the filter set in the normal position (background + airglow) and in a tilted position (background). The difference between the two consecutive records taken from the two positions gives the intensity of 630.0 nm emission. The specially designed photometers have a field of view (overall) of about 1° in diameter. The interference filter has a very narrow bandwidth of 0.3 nm centered at about 630.0 nm for normally incident light with 60 % transparency; it was supplied by Barr Associates, MA, U.S.A. The description of the experimental set-up has been given by Mukherjee and Dyson (1992). The photometers are portable and can be directed to any direction.

2.2 Ionosonde Data:

The ionospheric parameters (critical frequency(foF2)) of the F2 layer and the virtual F-layer height (h'F) of the ionosphere were measured from a nearby station, Ahmedabad (13.8° N, 144.7° E; Geomagnetic), to know the ionospheric condition during the time of the airglow observation. The square of the parameter (foF2) is proportionate to electron density at the peak of the F2 layer (Moore and Weber, 1981).

2.3 Geomagnetic Field Data:

The geomagnetic field (H, D and Z) data discussed in this report were obtained from seven magnetic observatories in the Indian longitude sector . Table 1 shows the locations of these observatories with their geographic, geomagnetic coordinates and dip latitudes indicated. The magnetometers are of various types. Descriptions of the types of equipment and types of data display appear in the yearly magnetic data volumes published by the Indian Institute of Geomagnetism, Mumbai, India.

Geomagnetic field components: The geomagnetic force can be split into three cartesian components X, Y and Z. The X-component is in the direction of geographic meridian, reckoned positive if northward and negative if southward. The Y-component is in the direction transverse to the geographical meridian, reckoned positive if eastward, while the Z-component is in the vertical direction, reckoned positive if downward and negative if upward. The general manner of specification differs from this, and is related to X, Y and Z. X and Y together form the horizontal component (H) of the magnetic field and $H = (X^2+Y^2)^{1/2}$. H is positive at any point on the surface of the earth. We define declination D as the azimuth of the horizontal component H, reckoned positive (eastward) from the geographical north towards east. Each observatory usually measures the time variations of these geomagnetic components (H or X, Y or D and Z).

Table 1. The list of geomagnetic observatories with their geographic, geomagnetic coordinates and dip latitudes are shown in the table.

SHILLONG	SHI	25.92	91.88	15.49	164.16	20.0
UJJAIN	UJJ	23.18	75.78	13.97	48.84	18.1
NAGPUR	NAG	21.10	79.00	11.60	151.67	15.2
ALIBAG	ABG	18.63	72.87	9.74	145.57	13.2
VISAKHAPATNAM	VSK	17.67	83.32	7.82	155.47	11.6
PONDICHERRY	PND	11.92	79.92	2.37	151.69	4.5
TRIVANDRUM	TRV	8.48	76.95	-0.77(S)	148.45	0.2

3. COMPARISON OF OPTICAL DATA AND IONOSPHERIC PARAMETERS

In this section, we compare the simultaneous ground-based nighttime measurements of 630.0 nm emissions from Kolhapur and the ionosonde measurements available from the Ahmedabad station. These two data sets are used to investigate correlations between optical emissions and ionospheric parameters in the low-latitude ionospheric F-region to understand the dynamic processes occuring in the F-region during the time of precipitation. Figure 1 shows the time variations of the 630.0 nm emission and the variations of F-region parameters [$(foF2)^2$ and h'F] from Ahmedabad during the night of 22-23 December, 1995. The 630.0 nm intensity was weak during the night, to rise near the threshhold value of the detector. However, the observed intensities in 630.0 nm started to rise after midnight, at around 1:10 hrs I.S.T., and reached its maximum value at around 2:15. The intensity levels were much stronger than usual on quiet nights and were probably due to effects of the magnetic storm on the composition and dynamics of the F-region. It is interesting that comparison of the observations obtained during disturbed conditions reveals that the nocturnal intensity variations of the atomic oxygen (630.0 nm) emissions observed correlated well with the variations of the F-region parameters $(foF2)^2$ and h'F, showing the dominant role played by the enhanced F-region dynamic processes during disturbed periods, possibly induced by substorm-associated electric fields and disturbed neutral winds in the low latitude F-region. During magnetic disturbances, high latitude electric fields can penetrate into the low latitutde ionosphere (Kamide and Matsushita,1981). The direction of electric field is important. If the superposed electric field moves westward, it will push the F-layer downwards and, as there is more recombination in the low altitude region, the sharp airglow enhancement takes place (Fejer et al.,1990, Gonzales et al.,1979; Huang and Cheng, 1991; Hernandez and Roble, 1978). A clear case of electric field penetration into low and equatorial latitudes was observed during the great magnetic storm of March 13,1989, which showed the pronounced uplift of the F-layer simultaneously over Fortaleza and Cachoeira Paulista in Brazil (Batista et al., 1991). The equatorial F-region behavior is such that the layer height increases after sunset, due to intensification of the eastward electric field (F-region dynamo) before its reversal. Simultaneously, a high negative vertical drift velocity with lowering of height took place after the evening hours (Batista et al., 1991; Fejer et al., 1990; Gonzales et al., 1979; Huang and Cheng, 1991). Figure 1 indicates that $(foF2)^2$ values also increase two-fold during the enhancement of 630.0 nm emission. At the same time, h'F is lowered by several hundred kilometres.

Figure 1 also shows that the enhancements observed in the [OI] 630.0 nm emission intensities on disturbed nights were associated with decreases in the bottomside of the F-layer, as evidenced from the h'F nocturnal variations. This behavior shows the importance of F-region dynamics on the [OI] 630.0 nm emission for both quiet and disturbed conditions, as a result of the dependence of this emission on the vertical motion of the F- layer bottom side where the volume emission rate maximises . The dynamic effects are more pronounced on disturbed nights with rapid changes in h'F layer heights. Variations in the electromagnetic plasma drifts and thermospheric neutral winds have a strong influence on the vertical motions of the F layer and on the shape of the electron density profile.

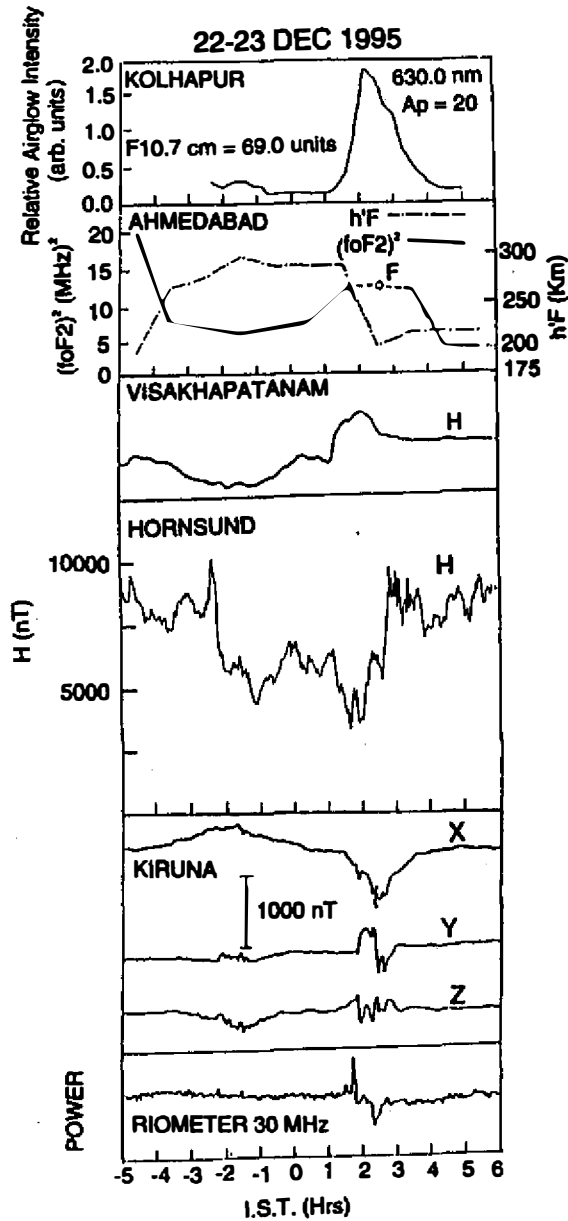As is well known, [OI] 630.0 nm emission due to dissociative recombination depends

Fig. 1. The variation of optical emission (630.0 nm) during the night of December 22-23, 1995, compared with the ionospheric parameters [(foF2)² (F-denotes measurement impossible due to spread echoes), h'F (km)] at Ahmedabad(13.8° N, 144.7°E; Geomagnetic), H variation at nearby low latitude station, Visakhapatnam (7.82°N, 155.47° E; Geomagnetic), high latitude station, Hornsund (73.86°N, 112.1° E; Geomagnetic) and X, Y, Z variation and Riometer absorption at 30 MHz at high latitude station, Kiruna (65.2° N, 116.0°E; Geomagnetic).

mainly on the vertical motions of the F-region and, more specifically, on the heights of the bottomside of the F-region. The correlation coefficients between airglow intensity variations and $(foF2)^2$ are positive and equals to 0.72 and that between 630 nm intensity variation and h'F(km) is negative and equals to -0.89. Generally, the correlation coefficients between the 630.0 nm intensity variation and F-region height variation on a disturbed night are larger as compared to their value on quiet nights (Sahai et al.,1990). Figure 1 also depicts the Riometer records of cosmic noise power at 30 MHz frequency at Kiruna (65.2° N,116.0°E, Geomagnetic). The zero power level is shown at the bottom of the panel. At the time of enhancement of 630.0 nm emission, the ionospheric absorption at the high latitude station also undergoes rapid fluctuations.

4. COMPARISON OF OPTICAL DATA AND MAGNETIC DATA LOW AND HIGH LATITUDES

We here compare the time variations of the 630.0 nm optical emissions from Kolhapur with magnetic variations measured from several Indian Stations during December 22, 1995 geomagnetic storm. The December 21-23 magnetic storm commenced at about 17:30 hrs I.S.T. on December 21; the maximum in Dst was reached at around 23:30 hours I.S.T. on December 22. The variation of Dst index on the night of 22-23 December is shown in Figure 3. The enhancement in airglow took place after 3-4 hours of maximum Dst during the recovery phase of the magnetic storm. Figure 2 shows the time variations of the magnetic perturbations (H, D and Z) measured from seven Indian observatories situated in the low latitude region during the geomagnetic storm. The magnetic perturbations of interest are those between 02:00 and 03:00
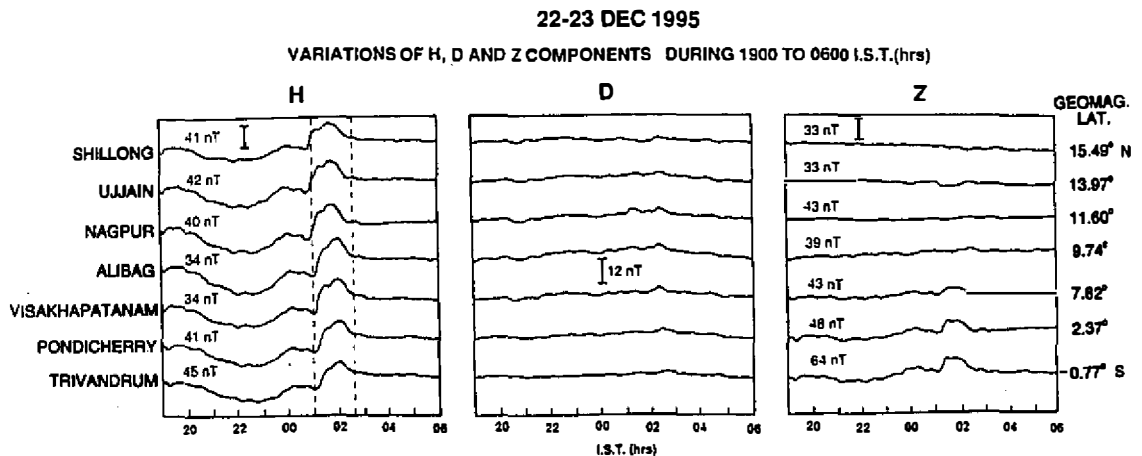

Fig. 2. The magnetograms (H, D and Z) from seven Indian observatories on 22-23 December, 1995, showing the period (1:30 - 2:30 hrs I.S.T.) of particle precipitation. Geomagnetic co-ordinates have been provided for each observation site.
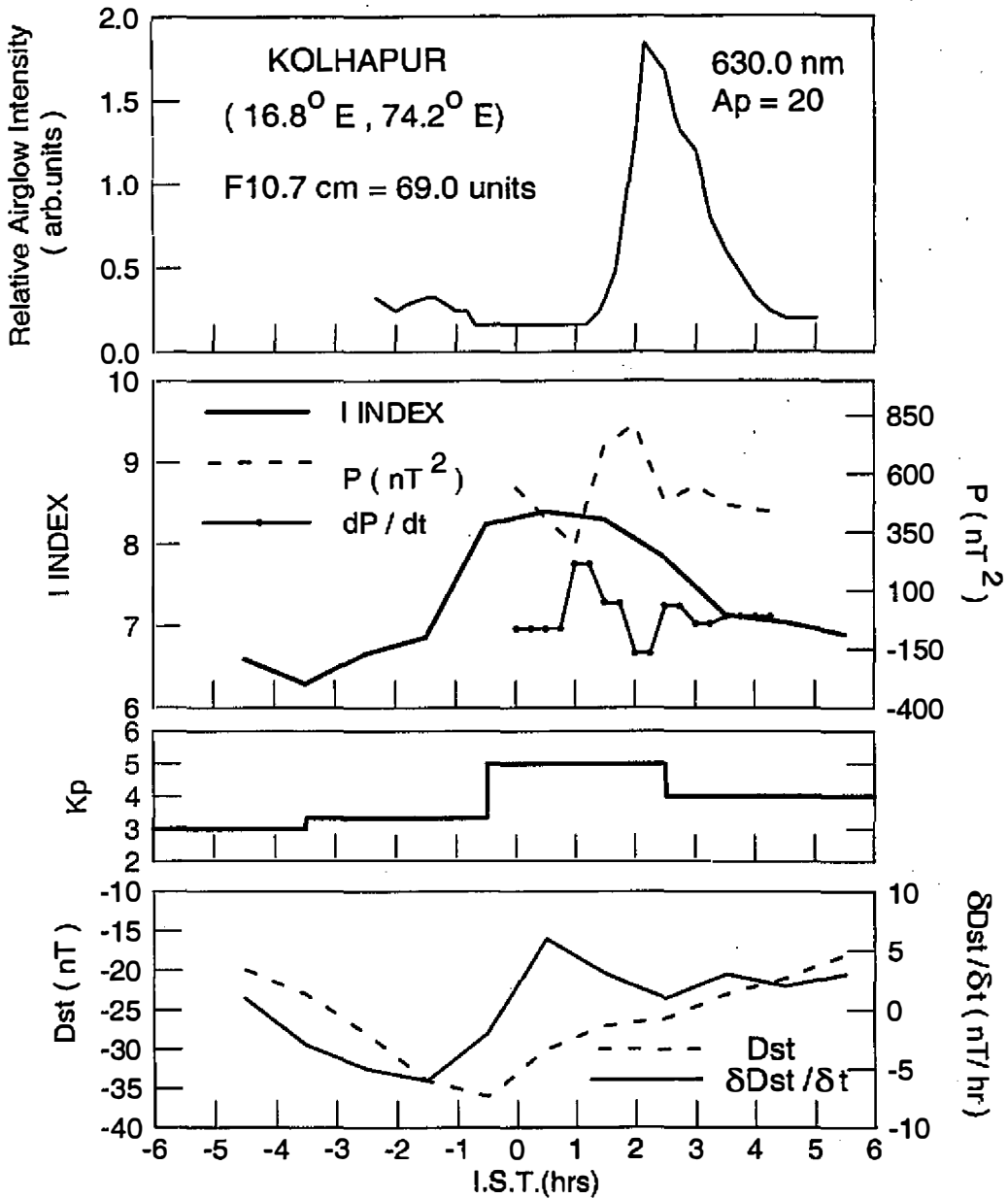
22-23 DEC 1995

Fig. 3. This portrays the comparison of time variation of 630.0 nm emission with I and a new parameter, P, dP/dt along with the variation of Dst, rate of it's variation (dDst/dt) and Kp during the night of 22-23 December, 1995. Note the similarity between the variation of 630.0 nm enhancement and the variation of the parameter dP/dt.

I.S.T on December 23, 1995, associated with the enhancement in the optical emissions, as shown in Figure 1. Examination of the stacked magnetograms shows that, at the time associated with enhancement in the optical emissions, predominantly positive excursions in H at the low latitude and large negative H excursions in high latitude observatories occur (Figure 1) . The correlation coefficient between 630.0 nm intensity fluctuations and low latitude H field variations at Visakhapatnam during the period of enhancement is positive and equals to 0.60. The increase in H, Z and D components is also evident at all the low latitude stations during the time of enhancement of airglow, though the fluctuations in D are smaller than in H and Z, and note the decrease in Z at Ujjain. Figure 1 also shows the variation of X, Y and Z components at a high latitude station, Kiruna($65.2°N$, $116.0°E$, Geomagnetic). Note also that positive excursions in H at low latitude stations are accompanied by rapid negative excursions in H at high latitude stations, Hornsund ($73.86°N$, $112.1°E$, Geomagnetic). A good correlation between the optical and magnetic variations (H and Z) can be noted at the time of enhancement of 630.0 nm nightglow. The precipitation is associated with positive (northward) excursions in the H trace and positive (eastward) excursion in D component. The increase in Z component is noted at all low latitude stations in the magnetograms except at Ujjain. Such signatures in low and midlatitude magnetograms of particle precipitation were also reported by Tinsley et al. (1986). The 630.0 nm intensity enhancement took place during the time interval when the value of the three hourly Kp index (≈ 5) during the night was maximum.

In sum, the magnitude of fluxes of precipitating particles originating from the ring current correlated, not only with the Kp index, but with local north-south magnetic perturbations observed near the emission regions. The precipitation of hot electrons is easily recognized by an enhancement in the intensity of 630.0 nm emission, and exceeded that usually expected from ionospheric dissociative recombination processes.

5. CORRELATIONS WITH DST, KP AND OTHER PARAMETERS (I , P AND dP/dt)

The Dst parameter is proportional to the total energy content of trapped particles constituting the ring current. Its values are obtained from the longitudinal average of H variations measured at low latitude observatories, and it represents a global measure of the strength of the ring current energy. The indices generally tend to reduce the local effects. Noted from the Figure 3 that the maximum optical emission takes place around 2:15 hrs and maximum Dst value occurs around 23:30 hrs on the 22nd. The time of maximum optical emission also coincides with the highest Kp interval (Kp = 5) during the night.

The activity index I was plotted by Voss and Smith (1979) to characterise the particle precipitation measured by satellite and rocket borne detectors using the three hourly Kp and hourly Dst indices defined as follows:

$$I = Kp + \ln I \, Dst \, I$$

Another index J tried by Rassoul et al. (1992) was found to better represent the time variation of particle precipitation. However, we tried an activity index P similar to J which we found to

represent better time variation of particle precipitation.

The new index P is defined as:

$$P = I \, Dst \, I \times \Delta H$$

where H is the magnitude of positive excursion from its base line taken as minimum in H value during the night. Since both Dst and H values are positive quantities, P is also positive. The new parameter was computed to match the optical intensity variation. In Figure 3, we plot the time variation of Dst, rate of variation of Dst (dDst/dt), Kp, and activity indices I and P on 22-23 December, 1995. There is agreement between the time variation of airglow enhancement associated with particle precipitation and the index P with a small shift in phase. We also compute the variation of the parameter dP/dt as a function of local time during the period of observation. It is found that the rate of variation of the parameter P matches well with the enhancement of 630 nm emission Three hourly values of the Kp index are also listed in the figure.

Cummings and Dessler (1967) derived a formula for ionosphere power dissipation which when converted to CGS units becomes

$$dQ/dt = -4 \times 10^{20} \, d(B)/dt \text{ erg sec}^{-1}$$

with d(B)/dt given in gammas per second. The dashed curve in Fig. 3 is a plot of dDst/dt with respect to time. The curve representing dDst/dt shows a prominent peak at 00:30 hrs that indicates abrupt energy inputs to high latitudes which cause further heating of the thermosphere. This occurs one and a half-hours prior to the occurrence of the maximum in 630.0 nm emission observed at low latitude regions. The energy dissipation of the asymmetrical ring current also occurs in the nighttime high latitude thermosphere and it is linearly related to dDst/dt (Hernandez and Roble, 1978).

6. DISCUSSION

The thermal, ionospheric and dynamic effects of energy input into low latitudes during magnetic disturbances have been observed for several decades (Prolss, 1973; Rohrbaugh et al., 1983). The observed enhancement in the intensity of 630.0 nm emission occurs as a sum of contributions of two independent sources, viz.,

i) Dissociative recombination produces a higher yield of excited atoms leading to the enhanced 630.0 nm emission. The higher yield could be due to the lowering of h'F and a consequent increase in foF2.

ii) Particle precipitation from the ring current during geomagnetic storms.

By inference, the primary source of the particles is the ring current. The observed emis-

sions at low latitude sites may be due to energetic neutral atom precipitation at several kilometres altitude from the main ring current population on L value of about 3. These energetic neutrals, which are unaffected by the geomagnetic field , move along straight lines, either to escape from the earth's atmosphere or to deposit energy into the atmosphere. During intense geomagnetic storms and substorms, the convection of magnetospheric plasma into low latitudes is enhanced in the nightside of the magnetosphere. The high latitude convection electric field can penetrate into the low latitude ionosphere, driving the magnetospheric plasma into the ring current region. The energetic neutral trajectories that intersect the earth are few in number but they are sufficient to cause observed airglow emissions. Due to solar wind flow, energetic ions and hot electrons may precipitate directly along the geomagnetic field lines; that leads to the ring current and the energetic neutral atom precipitation produced by charge exchange between energetic ring current ions and the geocoronal Hydrogen or Oxygen. The latitude variation of energy deposition rate shows a strong increase from low latitude to midlatitudes. The strongest emission occurs in the evening to midnight hours during the main phase of a storm. Lower limits for the energy deposition rates for the strongest emissions at 40-45° N dip latitude are 1-2 mWm^{-2} and for the strongest emissions at 12° S dip latitude, 0.05 mWm^{-2} (Rohrbaugh et al., 1983). The excursion in H is due to the compression of the magnetosphere, ring currents normally flowing round the earth at 7 R_E during quiet periods from east to west. The direction of the current is such that its magnetic field acts to oppose the geomagnetic field. During strong magnetic storms the ring current can come even closer to earth, within about 2 R_E. Evidence of high energy particle (protons with energy > 500 MeV) precipitation at balloon altitudes near the equator in India during a magnetic storm has been provided by Elliot and Hynds(1970). Tinsley (1979) shows that the particles may have been energetic H, He or O atoms before entering the denser medium.

The signatures of particle precipitation are more pronounced at mid latitude and high latitude regions than in their low latitude manifestation. This is due to the penetration of high latitude electric fields into mid latitude regions associated with strong currents, while the low latitude region is shielded from it. The time variations of the observed optical emissions correlate well with variations in P index, which connects the ring current and local magnetospheric substorm current system.

7. CONCLUSION

Particle precipitation from the ring current region into the low latitude thermosphere has been inferred by studying night glow (630 nm) data at Kolhapur on the night of 22-23 December, 1995. Also, ionosonde data (foF2)^2 shows enhancement of electron density and sudden lowering of virtual height h'F of the F-layer of the ionosphere at the time of enhancement of 630.0 nm emission. Comparison of optical data and ionospheric parameters from a low latitude station taken during disturbed conditions, shows that the nocturnal variations observed in atomic oxygen airglow emissions correlate well with the dynamical variations seen in the F-region ionospheric parameters. The event analysed is the first of its kind reported for the Indian longitude zone.

In addition, time variations among the 630.0 nm optical emissions from Kolhapur are compared with magnetic variations measured from several Indian observatories. The observations of the geomagnetic storm December 22, 1995, reveal a good correlation between the optical and magnetic variations. Geomagnetic records at low latitude stations show simultaneous enhancements in H, D and Z components. Examination of the stacked magnetograms shows that the positive excursions in H at low latitude observatories at times of maximum optical emissions are associated with negative H excursions at high latitude observatories. The enhancement of 630.0 nm emission correlates well with the Kp index. A number of parameters I and J are applied as was done by Voss and Smith (1980) and Rassoul et al. (1992) to interpret the data. A new index (P) similar to J but equal to Dst x DH has been used to better fit the data. This index gives a better time resolution of the enhancement of 630.0 nm intensity variation during the night. The event analyzed here also confirms similar findings reported earlier by Rassoul et al. (1992) from another longitude zone. More such events are being looked into using the simultaneous data sets of various nightglow emissions (630.0 nm, 557.7 nm, 777.4 nm, OH emissions) and thermospheric temperature data from Fabry-Perot Interferometer, to be compared with low latitude magnetograms taken during strong magnetic disturbances.

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