Ground-based optical measurements of daytime auroral emissions: A new means of investigating space-weather related processes

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The first optical signatures of plasmapause associated processes were gleaned from the daytime auroral emissions monitored from Maitri, the Indian station in Antarctica, using the newly built, ground-based, Multiwavelength Daytime Photometer (MWDPM). The plasmapause boundary inferred from these measurements conforms well with the known empirical relationship with the geomagnetic index K_P. The measurements made at 391.4, 486.1, 557.7 and 630.0 nm emissions revealed significant day-to-day variations in their spatial and temporal extents. These preliminary results are presented and discussed.

1. Introduction

Auroral emissions are the final outcome of complex interaction between the energetic charged particles and the constituents of the earth's upper atmosphere. These particles are primarily of solar wind origin and also of the magnetosphere from where they get accelerated by a variety of secondary processes. The interplanetary magnetic field (IMF) is carried from the sun by the magnetized plasma which gets deposited in the upper atmospheric regions of the earth at different latitudes depending on their energy. Because of their high energies, emissions covering a wide range of the electromagnetic spectrum, from EUV to IR wavelengths ensue from almost all simple atomic and molecular species. These optical emissions give us an indication of the sun-earth interaction and also of **space-weather** related processes. The physical processes that could be investigated would depend on the geographical location of the events and the consequent observations. The **cusp** on the magnetopause is located at ±80° mag. lat. and measurements from this region would represent the solar wind plasma, as this is the only region that maintains direct contact with it. The high energy solar wind plasma is known to be capable of penetrating impulsively, and eventually getting engulfed in the magnetosphere resulting in dips, or directional discontinuities observed in the densities (Lemair 1977). Such dynamical changes continuously occur in the magnetosphere, which has its boundary at $\sim 10 R_E$ on the dayside and at few tens of R_E on the nightside. As one moves away from the poles and reaches $\sim 60°$, the corresponding magnetic field lines would have crossed the magnetopause, magnetosphere, plasmapause and the plasmasphere. The plasmasphere, though embedded within the magnetosphere is defined as that region where the geomagnetic field lines corotate with the earth; while beyond the plasmapause they are governed by convective electric fields. The plasmapause is rather sharply defined, marked by a steep decrease in the plasma density between the plasmasphere (100–1000 el. cm^{-3}) and a tenuous (1–10 el. cm^{-3}) magnetosphere (Angerami and Carpenter 1966). OGO-5 satellite results have revealed the asymmetric nature of this boundary with a geocentric radius of $\sim 4 R_E$ at dawn and $\sim 6.5\ R_E$ in the dusk sector (Sharp and Johnson 1974). This plasmapause boundary, which is in some sort of a dynamic equilibrium, is affected by processes occurring between the sun and the earth. Recent results from *in situ* measurements revealed enhancements in electron densities and electric fields (Oya *et al* 1990; Okada

Keywords. Daytime-aurora; space-weather; auroral photometry; plasmapause related processes.

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **107**, No. 3, September 1998, pp. 203–211

et al 1993) and in Pc micropulsations (Popecki *et al* 1993) in the region beyond the plasmapause and within the magnetopause, indicating the highly active nature of this region. The results reported in the present paper are from the Indian Antarctic station Maitri (70° 45'S; 11° 38'E; 62.8° corrected geomagnetic latitude). The geomagnetic field lines when traced up to the equatorial plane cross the so-called plasmapause region during the daytime and hence the daytime optical measurements are considered to be representative of the energetic processes occurring therein.

So far, any systematic measurements were not available on the daytime auroral emissions, leave alone from a region which would get mapped to the plasmapause. Making use of the basic infrastructural facilities available in the Indian station Maitri, a new programme for monitoring the variability of daytime auroral emissions using ground-based optical technique was initiated during the XIIIth Indian expedition to Antarctica in the summer months of 1994. Observations were made from Maitri (L-value 4.8 R_E) during the XIIIth and XIVth expeditions. This was made possible by the development of a Multiwavelength Daytime Photometer (Sridharan *et al* 1993, 1998). It is well known that the daytime airglow/auroral intensity is rather faint when compared with that of the solar background continuum calling for innovative methods to retrieve the auroral signal buried in the strong solar background continuum. The latter has its own characteristic features, such as the Fraunhofer absorption lines, while the atmospheric constituents add telluric absorption lines. These absorption features, which are complicated due to the so-called **Ring effect** (Grainger and Ring 1962), are prominent when one is working in high resolution spectrophotometry. Pioneering contributions have been made by earlier workers (Roesler and Mack 1967; Barmore 1977; Cocks and Jacka 1979) in the development of multiple etalon high resolution spectrometers for line profile determination. For a photometer with a resolution of $\sim 10^4$ and a field of view of $\sim 4°$ (typical of the instrument under discussion), these absorption features in the vicinity of the emission lines of interest, are smoothed out and the solar spectrum resembles a continuum.

The first successful attempt to detect daytime auroral emissions was made by Noxon (1963) wherein the polarised nature of the background continuum and the unpolarised nature of the atmospheric emissions were used. Although the instrument enabled the detection of dayglow and daytime auroral emissions, its sensitivity was rather low. Hence a new approach was called for, details of which have been reported elsewhere in the literature (Narayanan *et al* 1989; Sridharan *et al* 1992a). Many observations were carried out from different latitudinal locations on the Indian sub-continent and new results pertaining to the geophysical processes of low-latitude ionosphere-thermosphere coupling were obtained (Sridharan *et al* 1991, 1992b, 1994; Pallam Raju *et al* 1996). The first systematic and continuous measurements of daytime auroral emissions were made from Maitri in the summer months of 1994, where a narrow zone of highly intense aurora was identified (Pallam Raju *et al* 1995). As mentioned earlier these results gain significance as they are obtained from a location from where the magnetic field lines get mapped to anywhere between the plasmapause and the magnetopause over the equatorial plane, thereby enabling one to investigate the so-called **space-weather** related processes.

2. Instrumentation

The Multiwavelength Daytime Photometer (MWDPM) employs three narrow-band interference filters (bandwidth ~ 0.3 nm) for pre-filtering, followed by a low-resolution (order $\sim 10^4$) Fabry-Perot (FP)etalon as a spatial filter, an innovative set of masks that converts the spatial information of the FP fringes into temporal information, followed by a data acquisition system. This technique essentially exploits the spatial dispersion property of a Fabry-Perot interferometer and radial light selection property of the mask assembly to achieve the selection of wavelengths and also to estimate the contribution of the bright solar background continuum, which is then subtracted to retrieve the signal intensities alone. The details of the mask design have been presented by Sridharan *et al* (1993). By appropriately gating the photomultiplier tube electronically with respect to the mask assembly, the intensities corresponding to the fringes of the line emission and also those corresponding to the neighbouring regions (~ 0.06 nm away) are sequentially incremented within 10 ms in two separate photon counters. Different regions of the sky are selected by means of a stepped scanning mirror. All the operations of this instrument are achieved by a menu driven software controlled by a personal computer. The functioning of this unique instrument is described in detail elsewhere (Sridharan *et al* 1998).

3. Data presentation

Observations of daytime auroral emissions have been made on low-energy electron-induced emission at OI 557.7 nm, N_2^+ (1NG) high-energy electron-induced emissions at 391.4, 427.8 and 470.9 nm and proton induced H_β emission at 486.1 nm during the summer months (January and February) of 1994 and 1995. Data were also obtained on the OI 630.0 nm emission during 1995. During 1994, the MWDPM viewed different regions of the sky, only in the southward, i.e., poleward, direction from the observing station, Maitri, Antarctica. The first results have been discussed by Pallam Raju *et al* (1995). In all, 13 days of data in 1994 and 5 days of data during 1995 were collected as cloudy weather prevented data collection for an extended period during these years. Some of the interesting results obtained are presented below.

It is known that the OI 557.7 nm emission originates at $\sim$ 100–150 km, the N_2^+ 1NG band emission from $\sim$150 km and the OI 630.0 nm emission from $\sim$ 200 km. With this information, the different elevation angles for all these emissions were converted into their corresponding latitudes. Surface plots for the data have been obtained after correcting for the Van Rhijn advantage corresponding to various elevation angles. The figures presented in this paper show such plots obtained for different wavelengths. In these plots, the x-axis represents time, the y-axis represents corrected geomagnetic latitude, while the z-axis denotes the auroral emission intensity.

4. Results

The emission intensities at all wavelengths show a large day-to-day variability, both in the peak intensities as

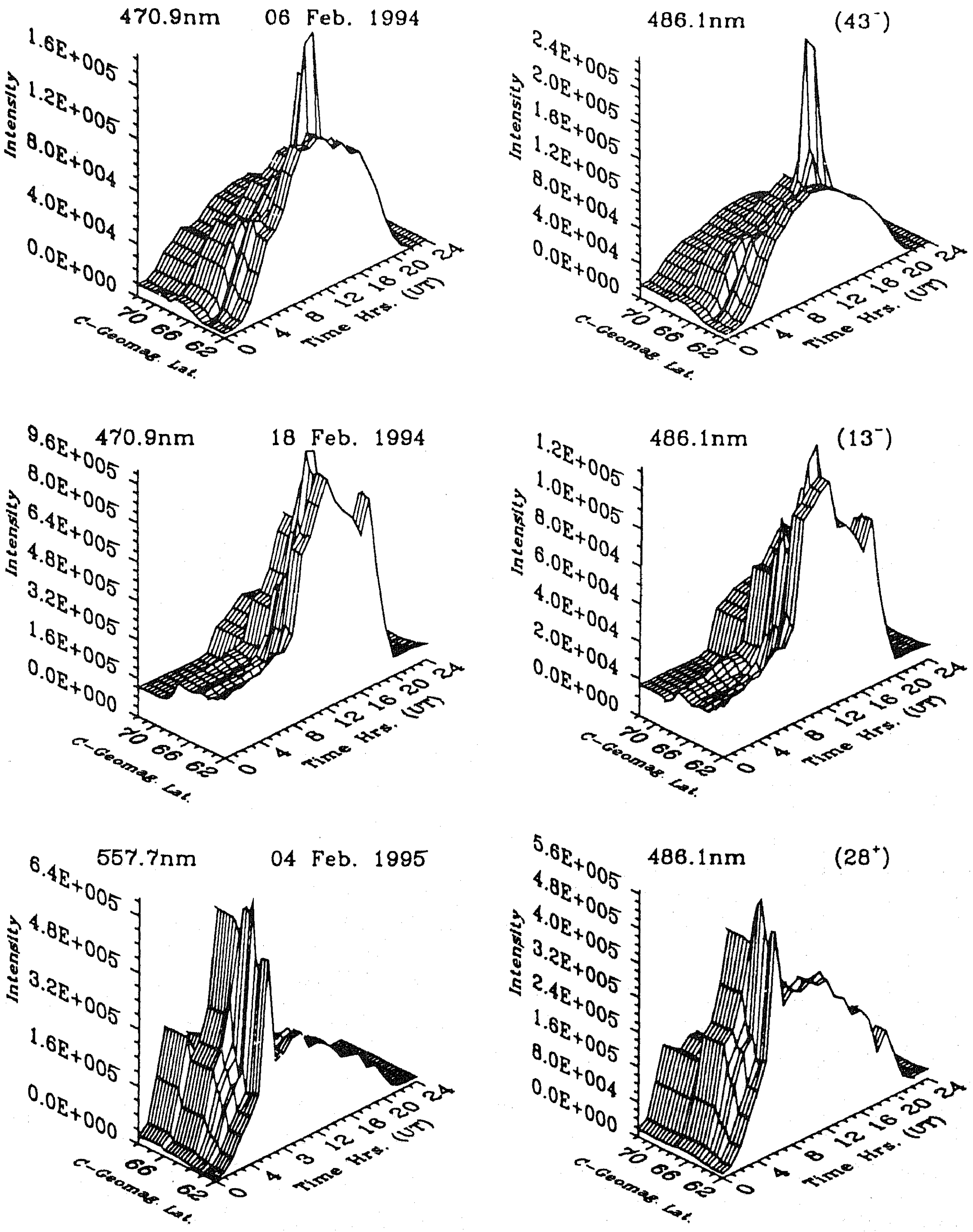

Figure 1. Similarities in the deposition and emission pattern between the high energy electron excited, low energy electron excited and proton excited emissions on a given day during 1994 and 1995.

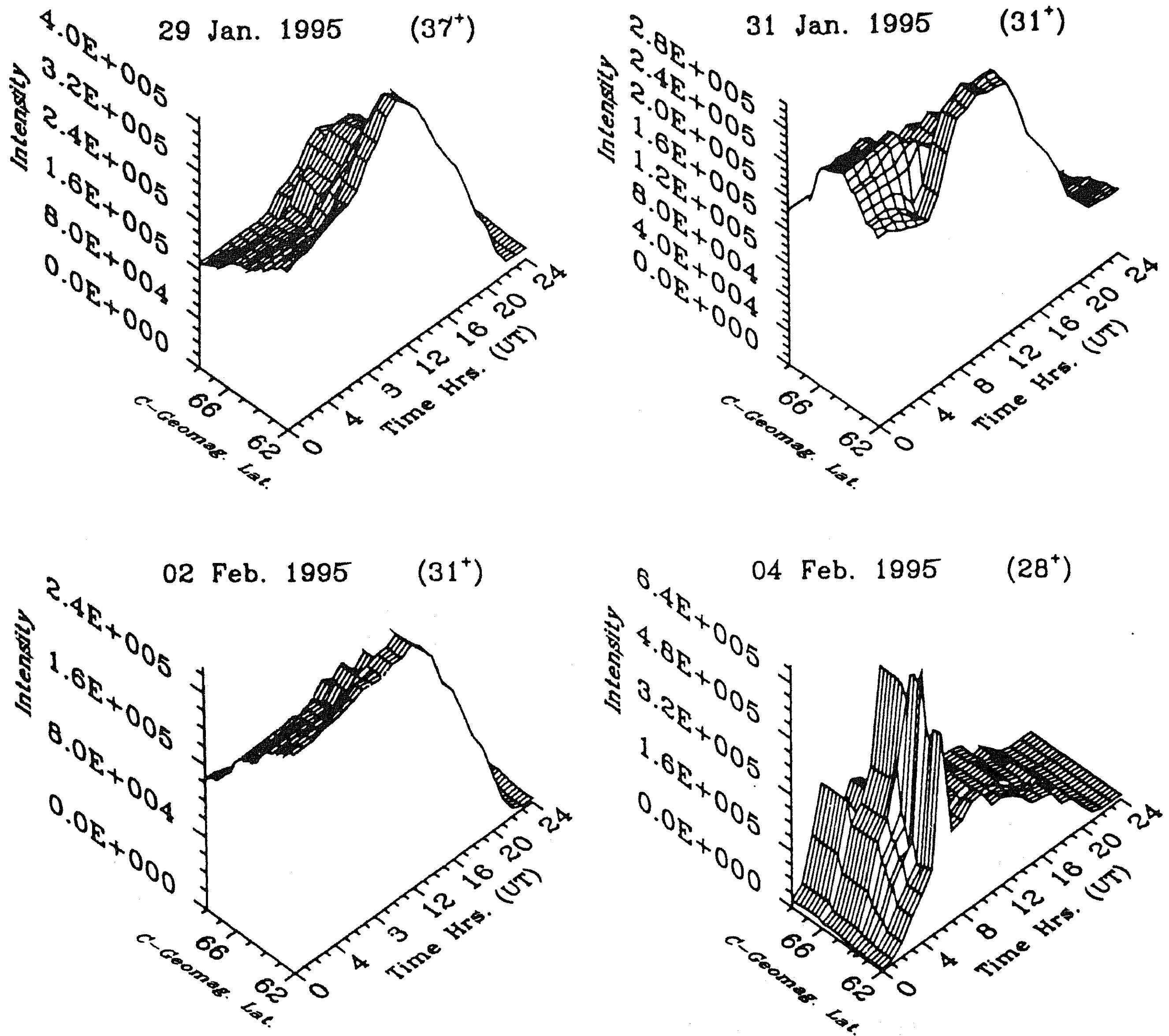

Figure 2. Surface plots of 557.7 nm emission intensities as observed from Maitri, Antarctica during January and February 1995. The X, Y and Z axis represent the universal time, I – corrected geomagnetic latitude and the relative intensities in photon counts respectively.

well as in the temporal variation on a given day. A major part of the data obtained during 1994 was reported by Pallam Raju *et al* 1995. The salient conclusions arrived at were:

- OI 557.7 nm intensities do not show any variation with magnetic activity;
- H_β 486.1 nm emissions showed an increase in intensity by at least a factor of two during moderately disturbed period indicating that the event under consideration was proton induced;
- On many occasions a narrow latitude ($\sim 2°$) region of peak intensities was obtained around 1200 UT in all the emissions;
- Significant wave activity was observed around this narrow region of energy deposition;
- There seemed to be a boundary at $\sim 68°$ corrected geomagnetic latitude beyond which the wave propagations abruptly cease and
- All the measured emission intensities showed an increasing trend towards the zenith, indicating the possibility of the existence of much larger intensities towards the North, i.e., the equatorward side of Maitri.

To investigate such an effect, an experiment was carried out in 1995, where measurements were made in the northern direction as well. We present here some striking revelations in the behaviour of various emissions on certain days.

Although various emissions originate at different altitudes, on some occasions the intensity patterns of

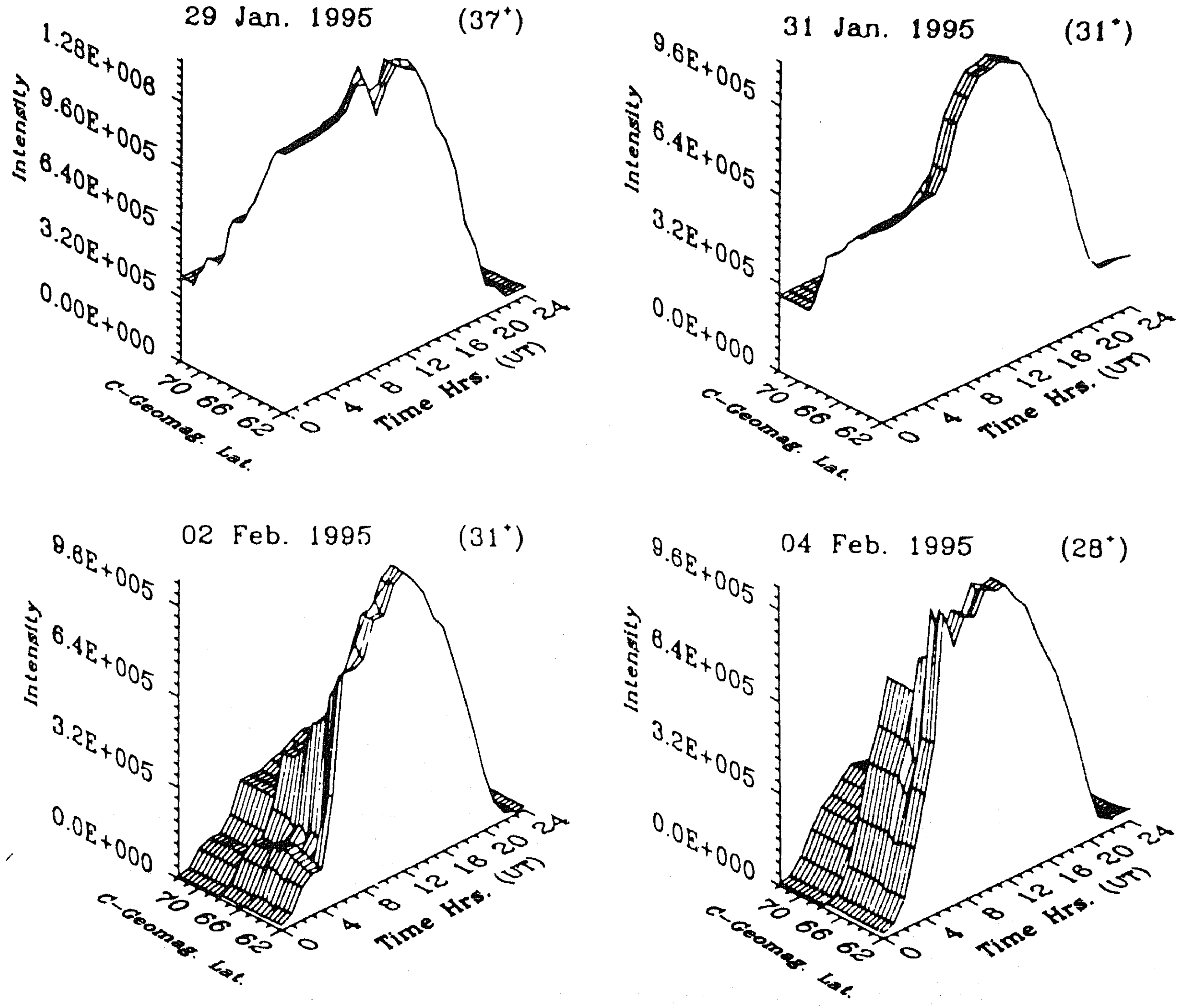

Figure 3. Surface plots for 391.4 nm emission depicting the large day-to-day variability during January and February 1995.

the emissions of different wavelengths show strikingly similar behaviour, samples of which are shown in figure 1. The figure also shows the ΣK_P values (in brackets) for the corresponding days. There is a remarkable similarity between the variations of the high-energy electron induced N_2^+ 1NG band emission (at 470.9 nm) and the proton-induced H_β (486.1 nm) emission on 6th and 18th February 1994. At the bottom, similarities in the low-energy electron induced OI (557.7 nm) emission and the H_β emission are shown. The intensities themselves however show distinct differences.

Figures 2, 3 and 4 represent the intensities obtained during a few days in 1995 at OI (557.7 nm), N_2^+ 1NG (391.4 nm) and H_β (486.1 nm) respectively. The OI 557.7 nm emissions (figure 2) show great variability. Though there seems to be a broad agreement in the structure of the intensity pattern on 29th January and 2nd February the peak intensities are quite different. On 31st January there is a bite-out for at least four hours in the morning (0400–0800 UT) and up to $\sim 3°$ in latitude, while on 4th February there are enhancements in intensities by 0600 UT followed by a monotonous decrease.

The 391.4 nm intensities depicted in figure 3 also show a different behaviour on different days. A small bite-out in zenith intensities is seen on 29th January while the measurements on 31st January show a subdued level till noon then pick up and maximise around 1600 UT. There are overall similarities on 2nd and 4th February in the peak intensities. Figure 4 shows the variation in intensities of H_β 486.1 nm emissions on three days. The intensity variation on 31st January shows a similar behaviour as in the OI 557.7 nm emission depicted in figure 2. On 2nd and 4th February the peaks in intensities occur at different times. The intensity on 4th February shoots up to its maximum by 0700–0800 UT similar to the OI 557.7 nm emission intensities on the same day.

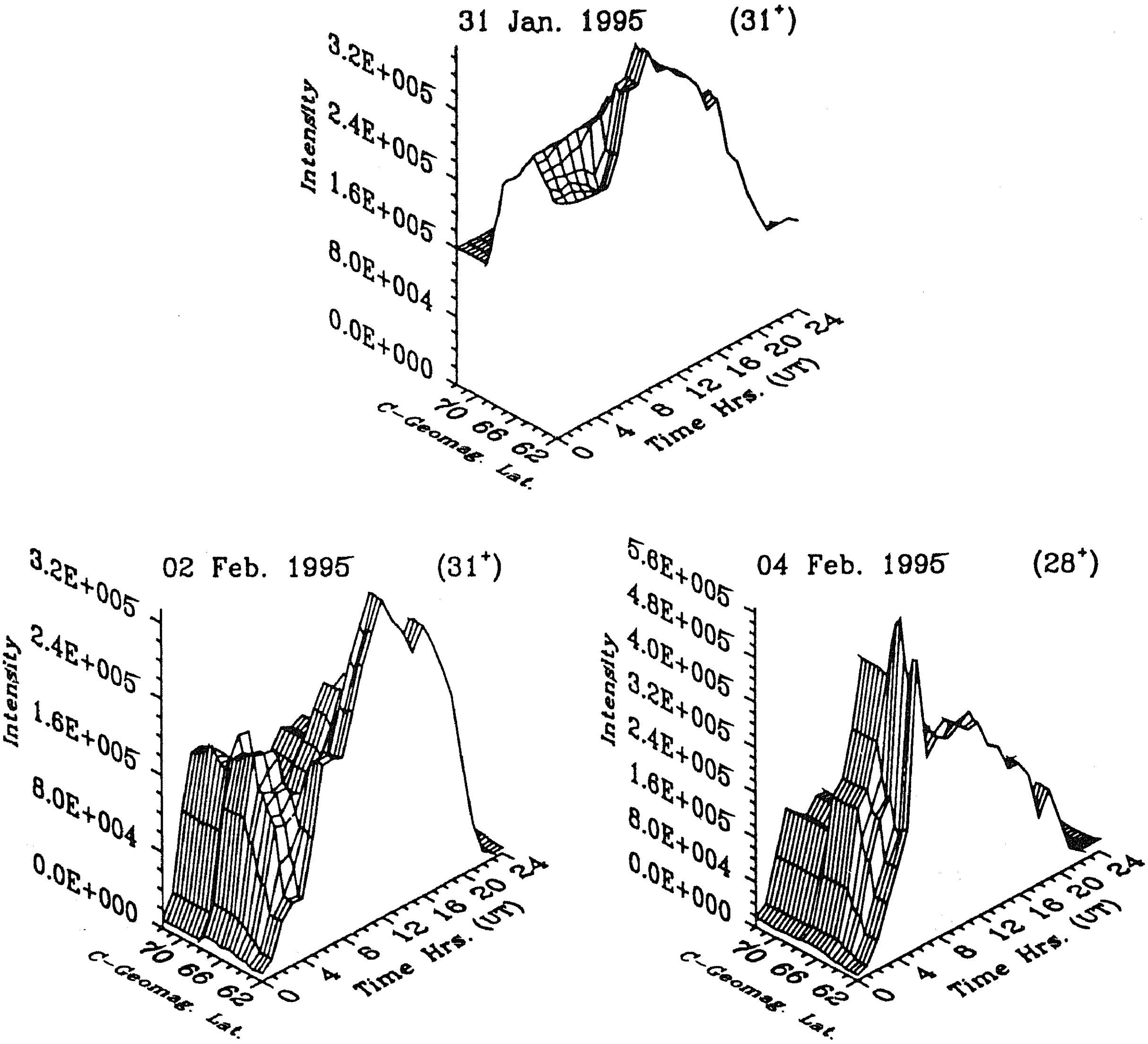

Figure 4. 486.1 nm intensity plots during 1995.

5. Discussion

On all the days mentioned above irrespective of the emission wavelength, in general there are larger intensities in the zenith as compared with other locations. These results can be understood in the light of the gross behaviour of the plasmapause under varying geophysical and solar input conditions as this seems to be the main cause which gives rise to noontime airglow enhancements via some possible acceleration mechanisms.

Both *in situ* measurements (Sharp and Johnson *et al* 1974) and whistler observations (Serbu and Maier 1970) show that the plasmapause is an asymmetric boundary with a minimum on the dawnside $\sim 3R_E$ and a bulge on the duskside $\sim 6R_E$. The location of this boundary is mainly affected by the magnetic activity. *In situ* measurements of H^+ density profiles observed by a light ion mass spectrometer onboard OGO-5 (Chappell *et al* 1970) showed that for smaller K_P values the plasmapause can be at $\sim 6R_E$ while for large K_P values it would be compressed to anywhere between 3–4 R_E. The results obtained during different solar epochs from independent measurements compiled by Serbu and Maier (1970) show conclusively that the location of plasmapause varies with the variation in the magnetic activity. Based on a large number of data sets an empirical relationship between the plasmapause location L_{PP} (in earth radii) and the instantaneous K_P index was shown by Rycroft and Thomas (1970) to be:

$$L_{PP} = 5.64 - (0.78 \pm 0.12)\sqrt{K_P}.$$

For most of the days of our observations the ΣK_P was > 30. Hence for an average value of 3.7 for three hours duration, one can see by using the above relation that the plasmapause would be located $\sim 4.8R_E$ which is the L value of our observational location Maitri. This implies that the magnetic field lines passing through Maitri when mapped to the equatorial plane lie in the

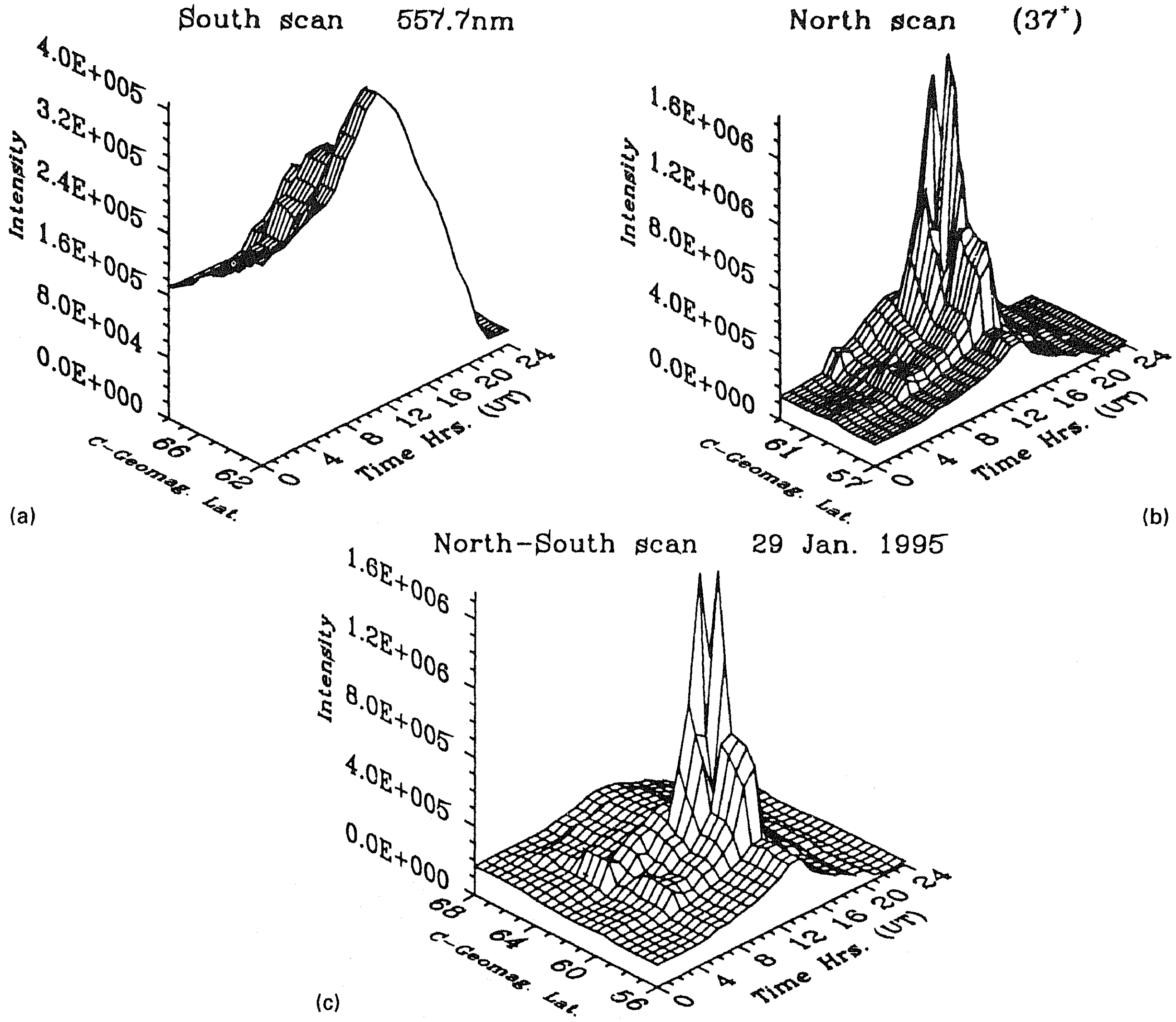

Figure 5. (**a**): South pointing scan of 557.7 nm similar to the earlier figures but for 29th January 1995; (**b**): North pointing scan; (**c**): Combined representation.

inner magnetosphere in the morning hours. With the rotation of the earth the field lines over Maitri come closest to the plasmapause at noon only to move away by dusk time. Hence one would expect the northward meridional scans of the optical emissions to give a better clue to the plasmapause associated processes. Such an experiment was done on 29th January 1995 when the sky was completely clear in all directions by monitoring OI 557.7 nm and 630.0 nm emissions. These data depicted in figures 5 and 6 show the measured intensities obtained from both southward and northward meridional scans along with the combined data (north-south scan). It can be clearly seen from these figures that the high intensities in the zenith in the earlier measurements show an increasing trend in the northward direction reaching approximately an order of magnitude higher intensities in both emissions. The latitude of this peak occurs at 63° and 61° corrected geomagnetic latitude for 557.7 nm and 630.0 nm respectively. The field lines through 62° corrected geomagnetic latitude pass close to $\sim 4.5R_E$ which agrees well with the empirical relationship for the prevailing level of geomagnetic activity.

These results are therefore interpreted as the first signature of the plasmapause boundary during daytime as seen in ground-based optical measurements. The peak intensities obtained sometimes in the southward directions represent emissions in the region outside the boundary of the plasmapause. Similar enhancements in electron densities and electric fields are also known to exist in these regions as was shown both experimentally and theoretically by many workers (Oya *et al* 1990; Okada *et al* 1993; Popecki *et al* 1993). The variations discussed are manifestations of auroral phenomena during daytime. Systematic measurements of such auroral emissions during daytime

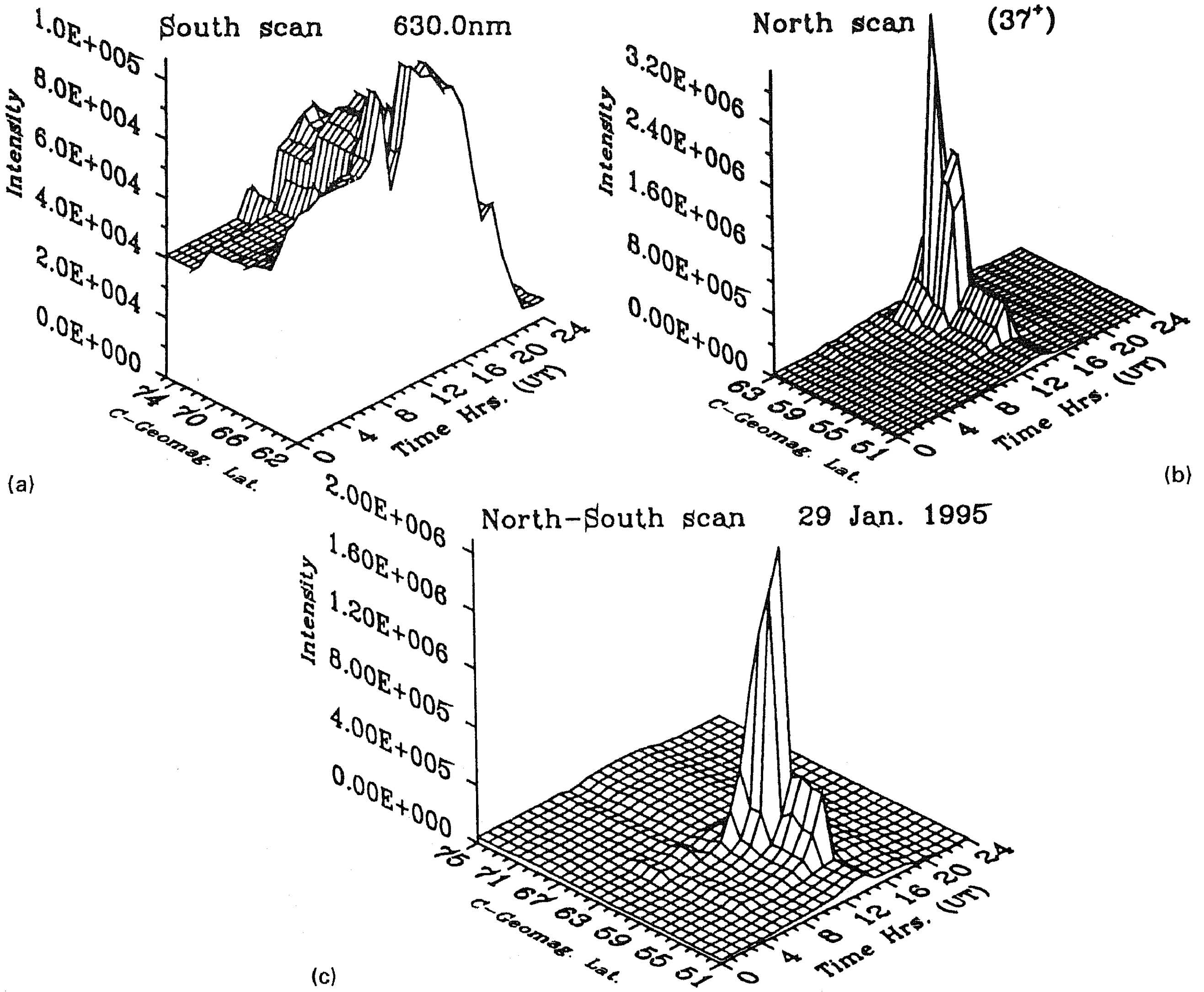

Figure 6. (**a**): South pointing scan of 630.0 nm for 29th January 1995; (**b**): North pointing scan; (**c**): Combined representation.

made at different elevation angles or a mapping of these emission features can be used to detect regions of excess energy deposition associated with solar wind magnetosphere interactions and also decipher characteristics of natural plasma waves in the frequency range of 20 KHz–5 MHz which originates both at the plasmapause boundary (Oya *et al* 1990; Okada *et al* 1993) and around the regions of excess energy deposition mentioned above. It is envisaged that a concerted multi-technique approach both using ground-based and space-borne methods would be required to understand such space-weather processes. Ground-based daytime photometers hold certain distinct advantages in this regard.

Acknowledgements

The measurements from Antarctica were made possible by the active interest of the Department of Ocean Development (DOD) Government of India which is the agency that provides all the logistic support for the Indian Antarctic Programme. This work is supported by the Department of Space, Government of India.

References

Angerami J J and Carpenter D L 1966 Whistler studies of plasmapause in the magnetosphere. 2. electron density and total tube electron content near the knee in magnetospheric ionization; *J. Geophys. Res.* **71** 711–725

Barmore F E 1977 High resolution observations of the OI 6300 A° oxygen line in the day airglow; *Planet. Space Sci.* **25** 185–191

Chappell C R, Harris K K and Sharp G W 1970 A study of influence of magnetic activity on the location of plasmapause as measured by OGO-5; *J. Geophys. Res.* **75** 50–56

Cocks T D and Jacka F 1979 Daytime thermospheric temperatures wind velocities and emission intensities derived from groundbased observations of the OI 630.0 nm airglow line profile; *J. Atmos. Terr. Phys.* **41** 409–415

Grainger J F and Ring J 1962 Anomalous Fraunhofer line profiles; *Nature (London)* **193** 762

Lemaire J 1977 Impulsive penetration of filamentary plasma elements into the magnetospheres of the Earth and Jupiter; *Planet Space Sci.* **25** 887–890

Narayanan R, Desai J N, Modi N K, Raghavarao R and Sridharan R 1989 Dayglow Photometry: a new approach; *Appl. Opt.* **28** 2138–2142

Noxon J F 1963 Observations of daytime aurora; *J. Atmos. Terr. Phys.* **25** 645–673

Okada T, Hayakawa H, Tsuruda K, Nishida A and Matsuoka A 1993 EXOS-D observations of enhanced electric fields during the giant magnetic storm in March 1989; *J. Geophys. Res.* **98** 15417–15424

Oya H, Morioka A, Kobayashi KIijima M, Ono T, Miyoka H, Okada T and Obara T 1990 Plasma wave observations and sounder experiments (PWS) using the Akebono (EXOS-D) satellite instrumentation and initial results including discovery of the high altitude equatorial plasma turbulence; *J. Geomag. Geoelectr.* **14**, **42** 411–442

Pallam Raju D, Sridharan R, Narayanan R, Modi N K, Raghavarao R and Subbaraya B H 1995 Ground-based optical observations of daytime auroral emissions from Antarctica; *J. Atmos. Terr. Phys.* **57** 1591–1596

Pallam Raju D, Sridharan R, Gurubaran S and Raghavarao R 1996 First results from ground-based daytime optical investigations of the development of Equatorial Ionization Anomaly; *Ann. Geophysicae* **14** 238–245

Popecki M, Arnoldy R, Engebretson M J and Cahill Jr L J 1993 High-latitude ground observations of PC 1/2 micropulsations; *J. Geophys. Res.* **98** 21481–21491

Roesler F L and Mack J E 1967 PEPSIOS – purely interferometric high resolution scanning spectrometer; *J. Phys.* **28** Suppl C-2 313–320

Rycroft M J and Thomas J O 1970 The magnetospheric plasmapause and the electron density trough at the Alouette I orbit; *Planet. Space Sci.* **18** 65–80

Serbu G P and Maier E J R 1970 Observations from OGO5 of the thermal ion density and temperature within the magnetosphere; *J. Geophys. Res.* **75** 6102–6113

Sharp R D and Johnson R G 1974 Low energy auroral particle measurements from polar satellites; *The radiating atmosphere* (ed.) B M McCormac (Dordrecht, Netherlands: D Riedel) pp. 239–254

Sridharan R, Gurubaran S and Suhasini R 1991 Coordinated thermospheric and F-region measurements from low latitudes; *J. Atmos. Terr. Phys.* **53** 515–519

Sridharan R, Narayanan R and Modi N K 1992a An improved chopper mask design for the dayglow photometer; *Appl. Opt.* **31** 425–426

Sridharan R, Haider S A, Gurubaran S, Sekar R and Narayanan R 1992b OI 630.0 nm dayglow in the region of equatorial ionization anomaly: Temporal variability and its causative mechanism; *J. Geophys. Res.* **97** 13715–13721

Sridharan R, Narayanan R, Modi N K and Pallam Raju D 1993 Novel mask design for Multiwavelength dayglow photometry; *Appl. Opt.* **32** 4178–4180

Sridharan R, Pallam Raju D, Raghavarao R and Ramarao P V S 1994 Precursor to Equatorial Spread-F in OI 630.0 nm dayglow; *Geophys. Res. Lett.* **21** 2797–2800

Sridharan R, Modi N K, Pallam Raju D, Narayanan R, Tarun K Pant, Alok Taori and Chakrabarty D 1998 Multiwavelength daytime photometer – A new tool for the investigation of atmospheric process; *Measurement Sci. and Technology* **9** 585–591

MS received 24 June 1998; revised 28 July 1998