Proc. Indian Acad. Sci., Vol. 85 A, No. 6, 1977, pp. 415-428.

Ionospheric total electron content and slab-thickness at low latitudes in Indian zone

R. G. RASTOGI, F.A.SC., K. N. IYER* AND R. P. SHARMA**

Physical Research Laboratory, Ahmedabad 380009

and

Indian Institute of Astrophysics, Kodaikanal 624103

MS received 24 December 1976

ABSTRACT

Observations of Faraday rotation of beacon signals from low orbiting satellite BE–B recorded at one station near the dip equator (Kodaikanal, dip 3·4° N) and at another station near the peak of the equatorial anomaly (Ahmedabad, dip 34° N) give a complete coverage of the equatorial anomaly belt in Indian zone. Contours of total electron content (TEC) are obtained on a grid of latitude *versus* local time for the different seasons of low (1964–66) and high (1967–69) solar activity epochs in the latitude belt 10° S to 26° N dip latitude. The development of the equatorial anomaly and its dependence on season and solar activity are discussed. Using similar contours of F_2 layer critical frequency, f_0F_2, contours of equivalent slab-thickness, τ are also constructed. The dependence of τ on season and solar activity and its implications on temperature are discussed.

1. INTRODUCTION

Low orbiting satellites at an altitude of about 1000 km offer a powerful tool to study, within a short duration, the spatial variation of F region ionization. Measurement of Faraday rotation of VHF signals from such satellites enables one to study the spatial distribution of total electron content (TEC). From a single observing station about 10° of latitude north and south of the station can be scanned using this technique with reasonably good accuracy. Latitudinal variation of TEC has been studied from a single observing station by Basu and Das Gupta[1] and Golton and Walker[2]

* Present address: Department of Physics, University of Kerala, Trivandrum 695581.

** Present address: Institute of Earth and Planetary Physics, University of Alberta, Edmonton, Alberta T6G 2E1, Canada.

for the northern hemisphere low latitudes using Faraday rotation of 40 and 41 MHz signals from low orbiting satellites. Similar studies for southern low latitudes have been carried out by Mendonca *et al.*,[3] and Titheridge and Smith.[4] The former authors also constructed contours of constant TEC for southern low latitudes indicating the latitudinal-diurnal variation of TEC. Results of joint observations at Singapore (dip 18° S), Bangkok (dip 13° N) and Hong Kong (dip 30·5° N), all in the same longitude zone have indicated a distinct trough of TEC near the dip equator and a peak at about 30° dip latitude.[5] Similar studies by Rastogi *et al.*,[6,7] using Faraday rotation of 40 and 41 MHz signals from BE–B and BE–C satellites recorded at Thumba (dip 0·6° S) Kodaikanal (dip 3·4° N) and Ahmedabad (dip 34° N) indicated clearly that the latitudinal anomaly in TEC is present while the diurnal anomaly of peak TEC in the forenoon and afternoon hours separated by a valley arond noon is absent. This implies a reconsideration of the relative importance of vertical drift and diffusion and other possible mechanisms responsible for the equatorial anomaly. It must be mentioned that with observations at a single station one gets only a sectional coverage of the equatorial anomaly belt and hence we have used in the present study of latitudinal variation of TEC, data recorded at Kodaikanal (dip 3·4° N) and Ahmedabad (dip 34° N). With such an arrangement we can have latitudinal coverage right from the dip equator to and beyond the anomaly peak. Furthermore, in the intervening region between the two stations an overlapping zone, where observations can be simultaneously had from both the stations, is available. In this zone the values of TEC from both the stations can be matched reasonably well. The range of latitudes of interest can be covered with a zenith angle of less than 60°. Such studies of latitudinal distribution of TEC from the above data by Iyer *et al.*[8] have shown the electroject control of the strength and depth of equatorial anomaly. In the present paper we present the latitudinal-diurnal variation of TEC, f_0F_2 and the equivalent slab-thickness for different seasons of low and high sunspot epochs. It must be noted that although there were two satellites, BE–B and BE–C with orbital inclinations of 79° and 41° respectively, the former is more suited for latitudinal variation studies as the local time changes within a satellite pass are quite small for this high inclination satellite.

2. DATA AND ANALYSIS

Faraday rotation of 20, 40 and 41 MHz signals from the satellite BE–B (Explorer 22) has been recorded at Ahmedabad since October 1964, *i.e.*, right from the launching of this satellite. The experimental set-up used has already been described by Rastogi and Sharma.[9] A similar recording system was operated at Kodaikanal also, giving continuous data from

November 1964. The measured Faraday rotation angle Ω is related to the electron content by the formula

$$\Omega = \frac{k}{f^2} \bar{M} \,(\text{TEC})$$

$$\bar{M} = B \cos \theta \sec \chi$$

$k = 0{\cdot}0297$ mks units, f is the frequency of the transmitted signal in Hz, B is the geomagnetic field in amp-turns/metre, θ the angle between the direction of propagation and the magnetic field vector and χ the zenith angle of the satellite. B, θ and χ are evaluated at the mean ionospheric height which is taken as 350 km for Ahmedabad and 400 km for Kodaikanal. This is a valid assumption and the errors involved are less than 10% if this height is chosen as one scale height above h_{max}, the height of maximum electron density in the F region. A fixed satellite height of 1000 km is chosen. Only passes having maximum elevation 30° are used. Faraday rotation is scaled off from the 40 or 41 MHz records at each minute interval during the pass showing clear Q.T. point and converted to TEC. Whenever the Q.T. transition is not clearly identifiable closely spaced frequency method using 40 and 41 MHz is used to analyse the records. Combining observations from Ahmedabad and Kodaikanal a latitudinal coverage from 10° S to 25° N dip latitude is obtained. A smooth curve is fitted for the observed plots of TEC *vs.* latitude for each pass. Such typical latitudinal profiles of TEC are shown in figure 1, in which noon TEC are plotted against

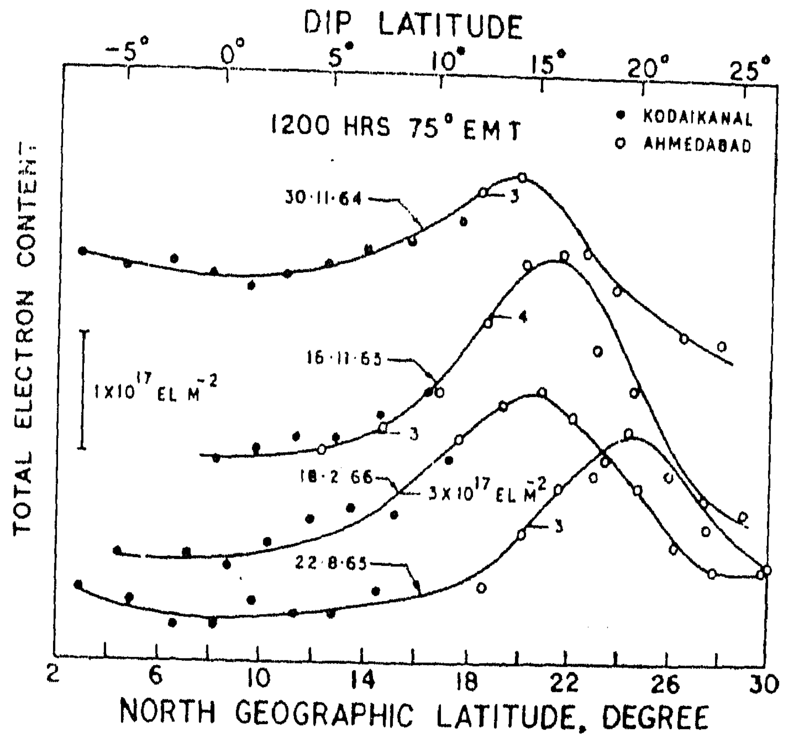

Figure 1. Typical examples of latitudinal variation of TEC, combining the observations at Kodaikanal (filled circles) and Ahmedabad (open circles) clearly showing the equatorial anomaly in TEC.

latitude for different typical days. In the diagram, the filled circles correspond to observations from Kodaikanal and the open circles to those from Ahmedabad. The continuity and good matching of observations from the two stations are also seen well. These plots indicate minimum values of TEC around dip equator and peak values at 15–20° N dip latitude, thus showing the well-known Appleton anomaly or equatorial anomaly.

The data is classified into low (1964–66) and high (1667–69 sunspot) epochs. Each epoch is again classified into winter (November, Decemper, January, February), summer (May, June, July, August) and equinoxes March, April, September, October) seasons. For each season, TEC values from passes around each full hr of LT (*e.g.*, passes between 0731 to 0830 LT being taken as belonging to 0800 hr group) are averaged out for every two degrees from 0° to 30° N geographic latitude. Any pass with abnormal variation of TEC was discarded from the analysis. No attempt is made to distinguish between quiet and disturbed days. Thus a mean latitudinal profile for each hour of each season of low and high sunspot activity periods is obtained. These TEC values at every two degrees of latitude are written down on a grid of local time *versus* latitude and contours of TEC constructed for each season of low and high solar activity.

3. RESULTS

3.1. LATITUDINAL VARIATION OF TEC

Contours of TEC for equinox, winter and summer seasons are shown in figures 2, 3 and 4 respectively. On the left-hand side the contours for

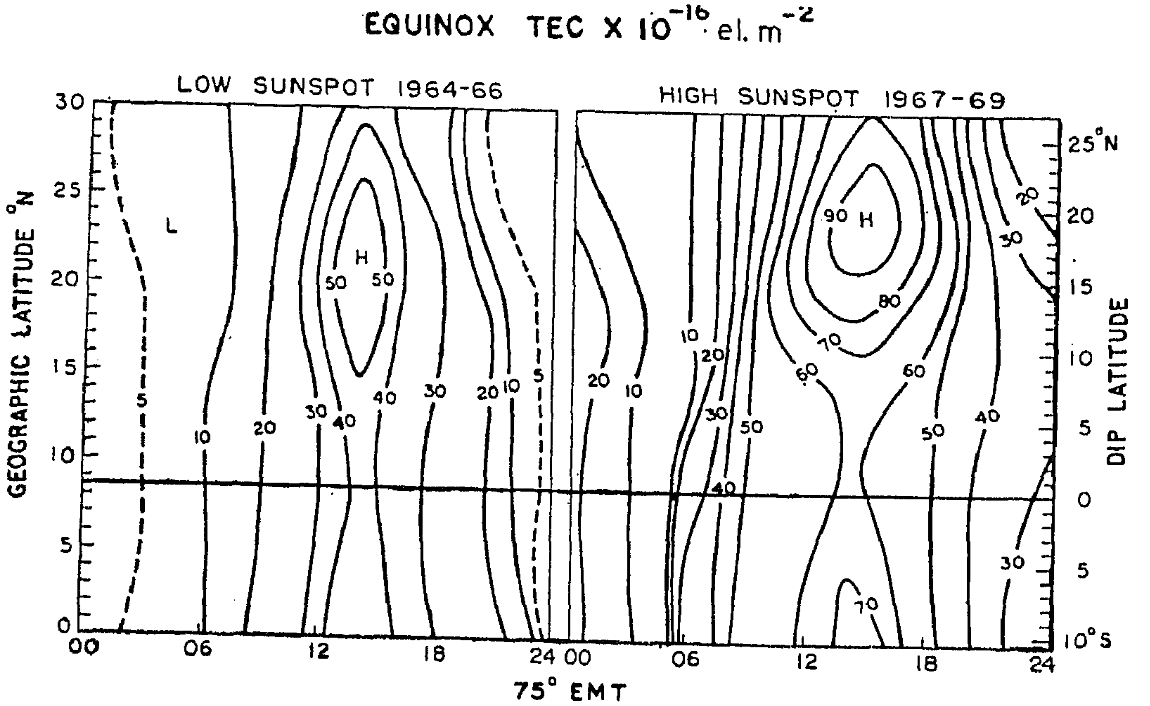

Figure 2. Contours of TEC on a grid of latitude *versus* time for low (left) and high (right) sunspot epochs for equinox season in Indian zone. On the left hand side the geographic latitude and on the right-hand side the corresponding dip latitude are marked.

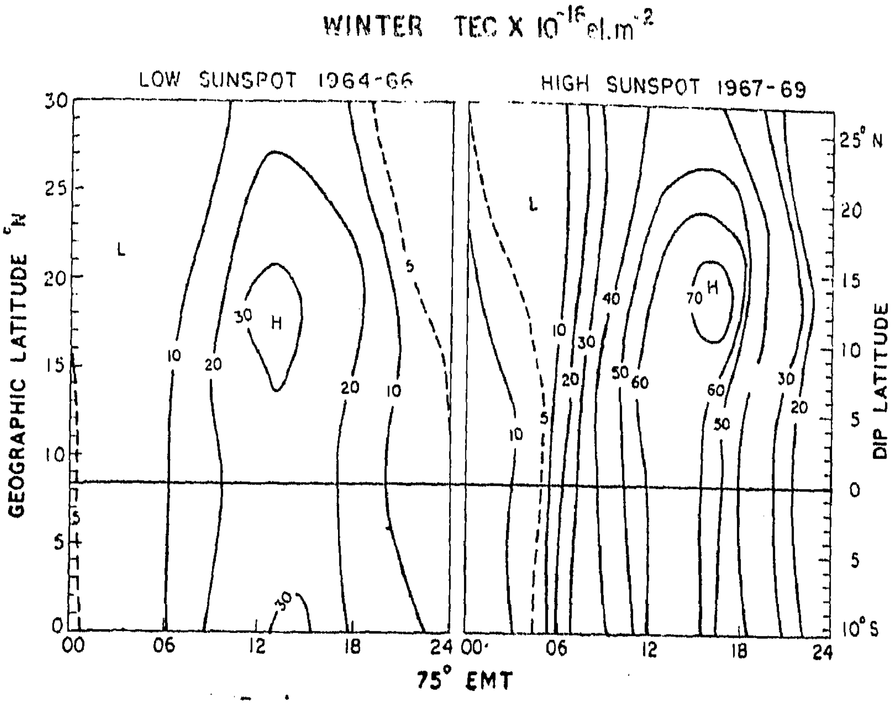

Figure 3. Contours of TEC on a grid of latitude *versus* time for low (left) and high (right) sunspot epochs for winter season in Indian zone. On the left-hand side the geographic latitude and on the right-hand side the corresponding dip latitude are marked.

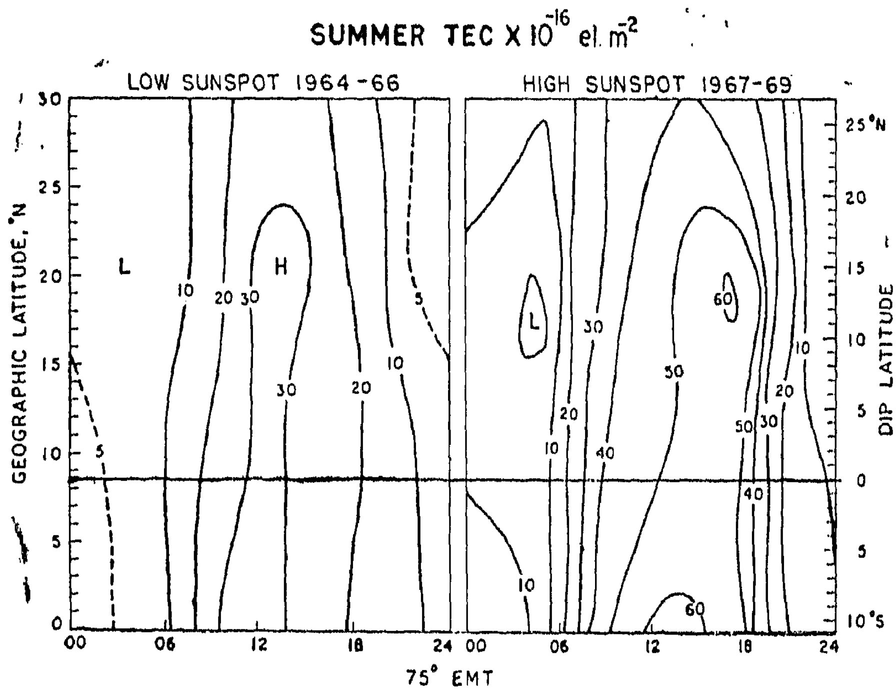

Figure 4. Contours of TEC on a grid of latitude *versus* time for low (left) and high (right) sunspot epochs for summer season in Indian zone. On the left-hand side the geographic latitude and on the right-hand side the corresponding dip latitude are marked.

low sunspot period and on the right-hand side those for high sunspot period are shown. Referring to figure 2 (equinoxes) the latitudinal peak of TEC during equinoxes is centred around 15° N dip latitude in low sunspot years while the peak is shifted to a higher latitude of about 20° N in high sunspot years. The magnitude of the peak TEC value in high sunspot years is 1·8 times that in low sunspot years. Diurnally, the peak is formed around 13–14 hr LT in both high and low solar activity epochs.

The winter contours shown in figure 3 indicate that peak TEC is almost at the same latitude of 12° N in low and high sunspot years. However the diurnal development of the anomaly is different in winter than in the equinox in the sense that the peak is attained earlier in low sunspot years at about 13 hr LT and it is delayed to 15–16 hr LT in high sunspot years. High sunspot winter TEC values are more than double that of low sunspot years.

The contours of TEC for summer are shown in figure 4. The latitudinal peak of TEC is broadened in low sunspot years compared to that in high sunspot years. The peak is formed around 12–13° N dip latitude in both epochs. The diurnal peak develops earlier in low sunspot years (13 hr LT) while it is delayed to 16–17 hr LT in high sunspot years. The peak value of TEC in high sunspot summer is double that in low sunspot years.

In order to bring out the latitudinal variation of daily maximum electron content more clearly, TEC at the time of diurnal peak is plotted against latitude in figure 5 for low and high solar activity periods separately. It is found that the anomaly develops into a broad peak around 14° N dip latitude in low sunspot in all seasons. In high sunspot years, the picture is however different. The peaks are far thest in equinox (19° N dip latitude) and closest to the equator (12° dip latitude) in summer.

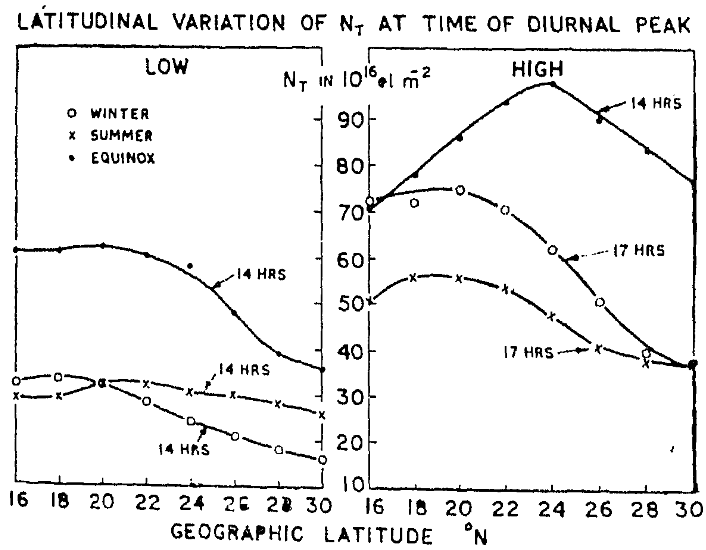

Figure 5. Latitudinal variation of TEC at the time of diurnal peak for low (left-hand side) and high (right-hand side) sunspot epochs for different seasons.

In figure 6 the diurnal variation of TEC at the latitudinal peak is shown. In low sunspot years, the winter and summer values of TEC are almost the same indicating a semi-annual variation of TEC with equinoxial peaks and of amplitude of 2:1. In high sunspot years the winter values of daily maximum TEC are $1\frac{1}{2}$ times larger than the summer values indicating the presence of a winter anomaly in high sunspot TEC similar to the one in f_0F_2. Studies by Walker[10] for another northern low latitude station at Hong Kong also indicate that the winter anomaly becomes apparent only in high sunspot years. Whereas in low sunspot years the diurnal maximum is reached around 13–14 hr LT in all seasons, in high sunspot years the peak is delayed to 16–17 hr LT in summer and winter while it is remained at 13 hr LT equinoxes for all solar activity levels.

3.2. Comparison of latitudinal variation of TEC and f_0F_2

Studies of latitudinal variation of the critical frequency of the F layer are comparatively few mainly because of the lack of a chain of ionospheric sounding stations at closely spaced intervals of latitude. However, the chain of IGY ionospheric sounding stations have provided a means to overcome this difficulty. Thus contours of f_0F_2 over a grid of magnetic dip *versus* local time were derived by Sanatani[11] for different solar activity conditions and seasons. These contours scaled down for appropriate solar activity levels as the mean low and high solar activity levels to which our TEC contours refer to, have been shown in figures 7, 8 and 9.

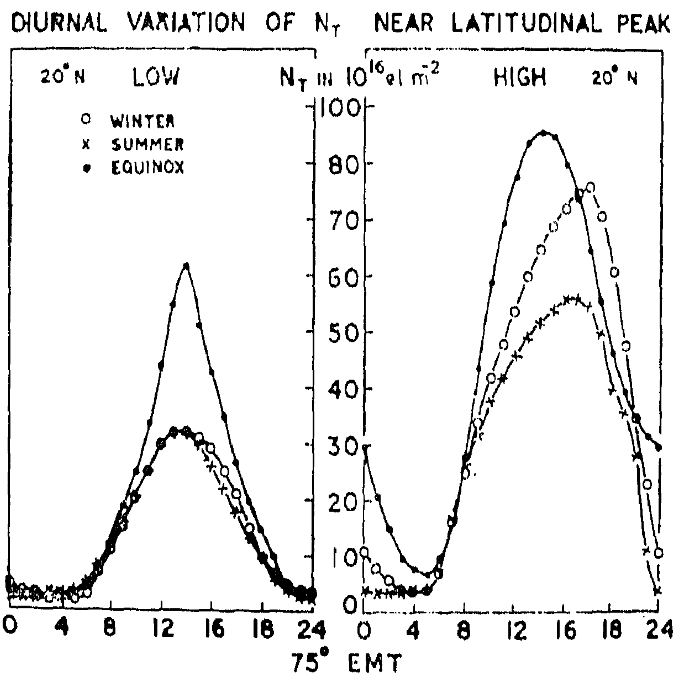

Figure 6. Diurnal variation of TEC near the latitudinal peak for low (left-hand side) and high (right-hand side) sunspot epochs for different seasons.

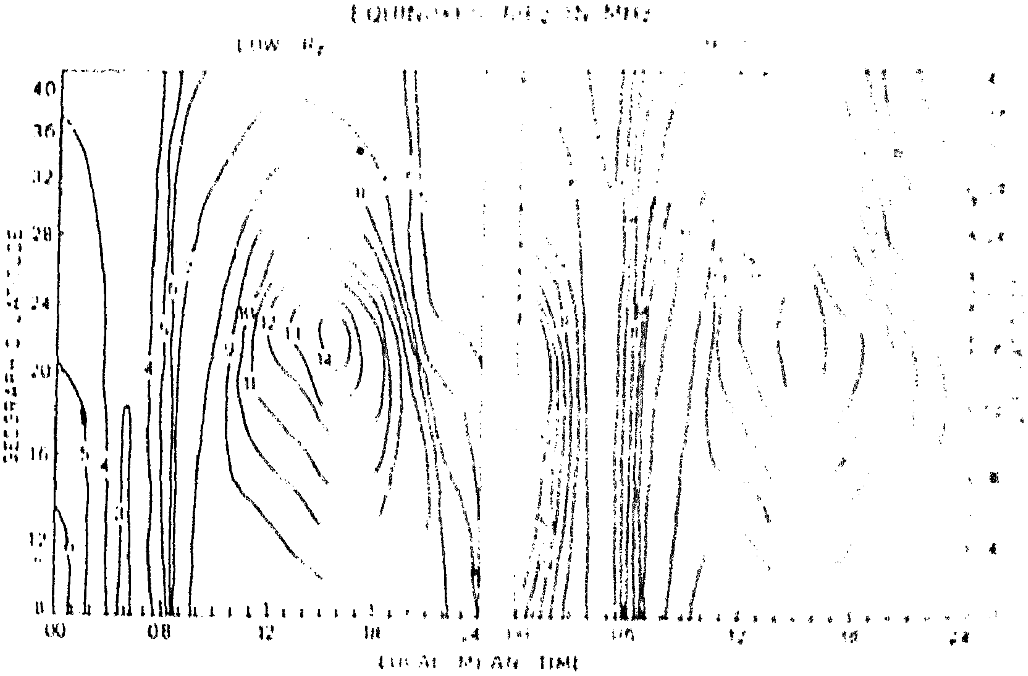

Figure 7. Contours of f_0F_2 over a grid map of latitude *versus* time for low (left-hand side) and high (right hand side) sunspot epochs for equinox season. On the left-hand side the geographic latitude and on the right-hand side the corresponding dip latitude are indicated.

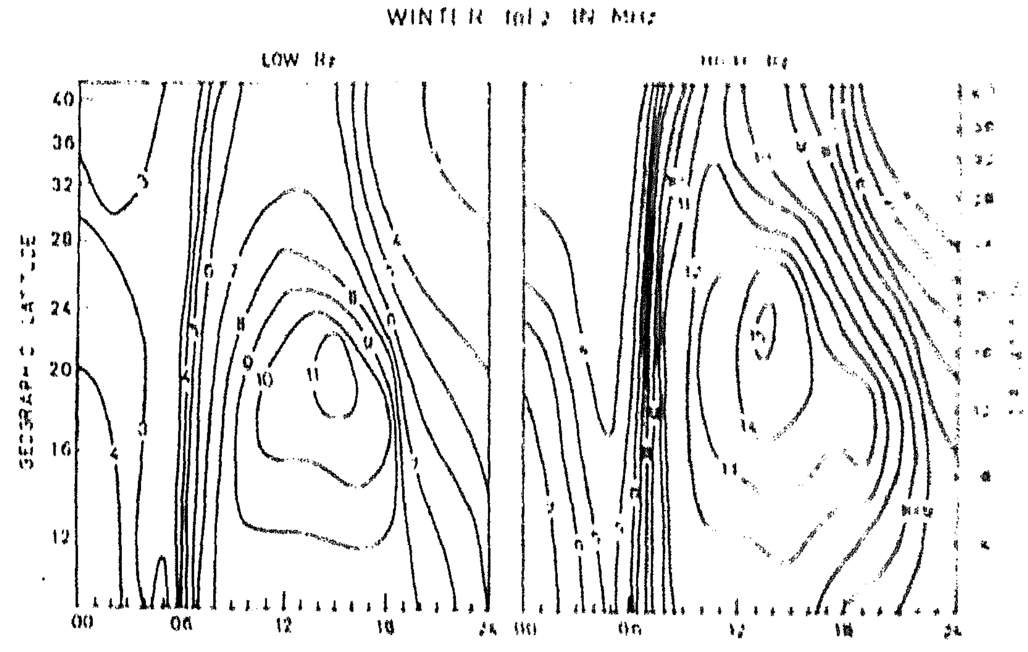

Figure 8. Contours of f_0F_2 over a grid map of latitude *versus* time for low (left hand side) and high (right hand side) sunspot epochs for winter season. On the left hand side the geographic latitude and on the right hand side the corresponding dip latitude are indicated.

Referring to the contours in equinoxes (figure 7) we find that peak values of f_0F_2 are seen around 16° N dip latitude in low and high sunspot periods. Diurnally, the peaks are formed around 15 16 hr LT in both epochs. Thus there is a time lag of about 2 hr in the diurnal maximisation of the equatorial latitudinal anomaly in f_0F_2 relative to that in TEC. However, in high sunspot years they maximise almost at the same time.

Contours of f_0F_2 for winter are shown in figure 8. The latitudinal peak occurs at about 14° and 18° dip latitude respectively in low and high solar activity periods. Peak f_0F_2 develops earlier in high sunspot years (13–14 hr LT) as compared to low sunspot years (15–16 hr LT).

Figure 9 shows contours of f_0F_2 for summer. In both low as well as high sunspot years, the peak f_0F_2 occurs around 16° dip latitude in low as well as high sunspot periods. The diurnal peak is around 14–15 hr LT in low and 15–16 hr LT in high solar activity periods.

Thus the general features of latitudinal variation of TEC and f_0F_2 are similar, though they differ in details. The obvious differences are (i) the shifting of the latitudinal peak of TEC to higher latitudes in high sunspot years which is missing in f_0F_2 contours for the same season and (ii) the earlier maximisation of TEC by 1–2 hr in low sunspot years as compared to f_0F_2.

3.3. Latitudinal variation of equivalent slab-thickness (τ)

The ratio of the vertical columnar electron content to that of the maximum electron density in the F region is known generally as the equivalent slab-thickness (τ). From the above discussed contours of TEC and f_0F_2 values of τ have been derived at grid intervals of latitūde and local time and contours of τ constructed. Such contours of τ for equinox, winter

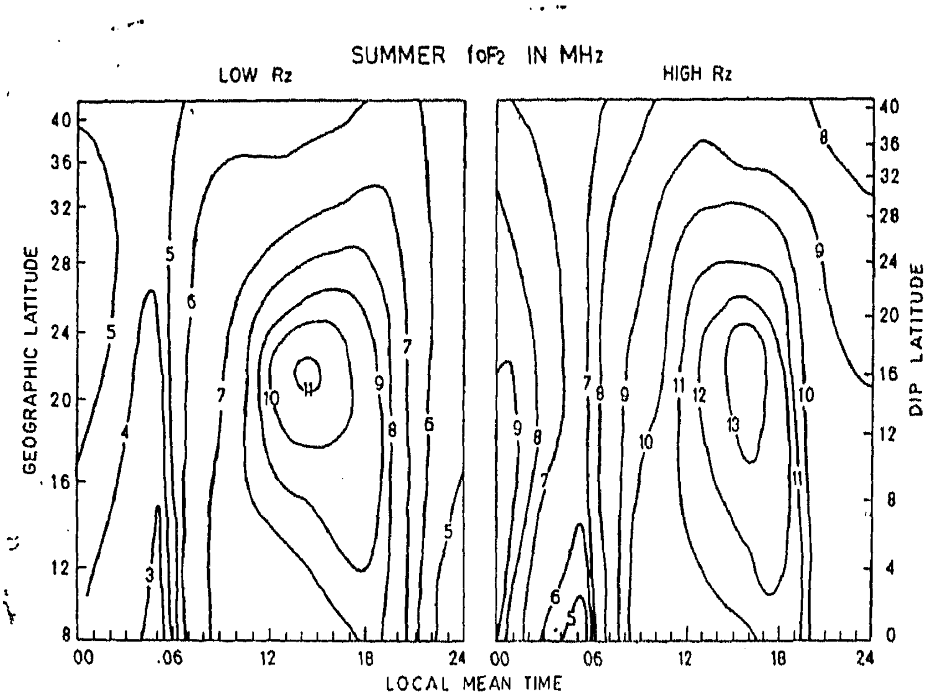

Figure 9. Contours of f_0F_2 over a grid map of latitude *versus* time for low (left-hard side and high (right-hand side) sunspot epochs for summer season. On the left-hand side the geographic latitude and on the right-hand side the corresponding dip latitude are indicated.

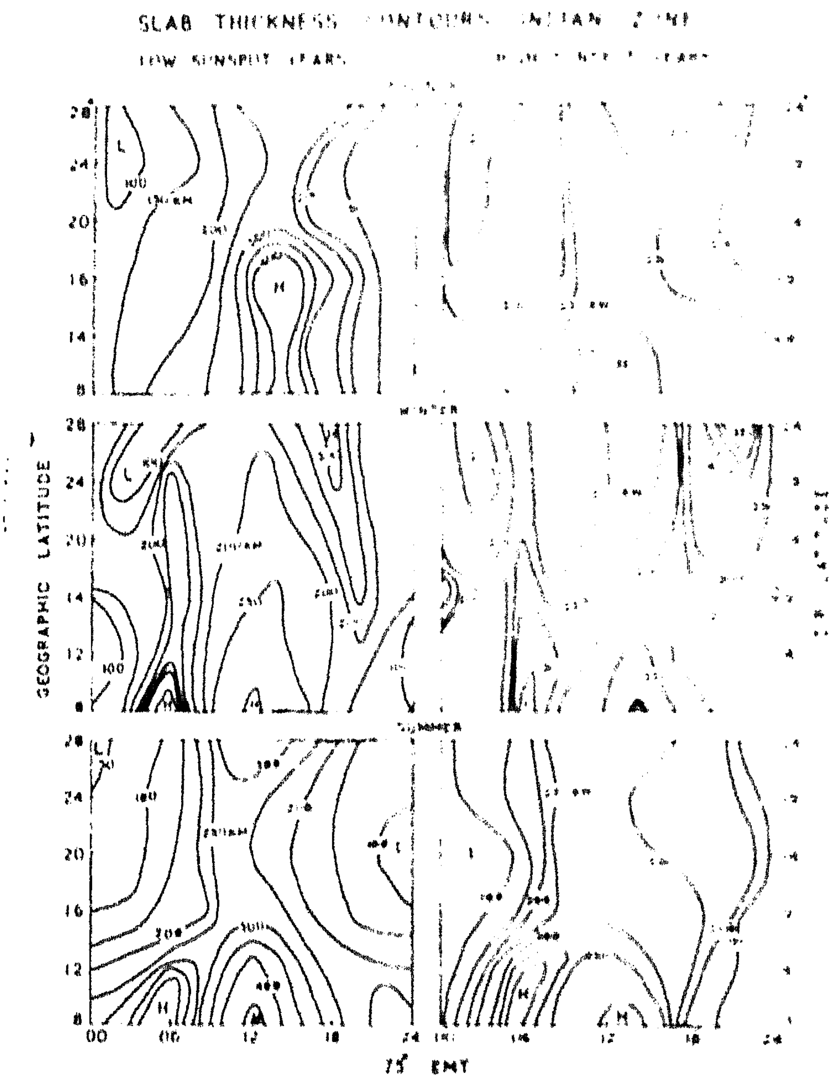

Figure 10. Iso-slab-thickness contours in Indian zone over a grid of latitude *versus* time for equinox (top), winter (middle) and summer seasons. The left hand side contours are for low sunspot conditions and right hand side contours for high sunspot conditions. Both geographic and the corresponding dip latitude are indicated in the diagram.

and summer seasons of low as well as high solar activity conditions are presented in figure 10. τ attains larger values around noon and smaller values at night. τ is larger near the dip equator and again near 20° dip latitude. The midday values of τ are around 250–300 km in winter, 350 km in summer and 400 km in equinoxes. There is a tendency for τ to increase with solar activity. Equivalent slab-thickness is an important physical parameter as it depends on the temperature. Implications of this on temperature will be discussed in the following section.

4. Discussion

The present work brings out the existence of the equatorial anomaly in the latitudinal variation of TEC similar to the one in f_0F_2. Titheridge and

Smith[4] using the observations of TEC from Rarotonga (21·2° S, 200° E) had studied the latitudinal variation of TEC in the southern hemisphere. They found that there is a sharp transition at 21° S in winter and at 23° S in summer from approximately constant TEC at medium latitudes to rapidly decreasing content near the dip equator. Mendonca *et al*,[3] have presented contours of TEC for the different seasons of the year 1966 for the southern hemisphere, again evidencing the equatorial anomaly. Hunter *et al.*[12] using the data of BE–B satellite recorded at Nairobi (African zone) has shown that the expected latitudinal anomaly in TEC is most apparent only in equinoxes. Golton and Walker[2] using the data of Hong Kong have studied the latitude variation of TEC for the northern hemisphere. It must be emphasised here that for the first time contours of TEC have been presented for the northern hemisphere, in this work, combining observations from two stations.

There are quantitative differences between the northern and southern hemisphere. In southern hemisphere the anomaly peak is around 10° dip latitude moving southward in summer and northward in winter by about 5° dip angle. On the other hand the northern peak is around 15° dip latitude in summer and winter while it is around 20° in equinoxes. This indicates a north-south asymmetry in the sense that the northern peak is farther away from the dip equator than the southern one. Golton and Walker[2] have also discussed the diurnal development of the anomaly. It first starts at a dip angle of 10° at 10 hr LT and attains its maximum extent around 14–15 hr LT and disppears by midnight. The general diurnal behaviour in the northern hemisphere is similar to that in southern hemisphere but the anomaly seems to disappear early and the time of maximum development of the anomaly is seasonally dependent.

Das Gupta and Basu[13] have studied the development of the anomaly in TEC on quiet and disturbed days separately. They found a decrease of the anomaly on disturbed days. This was atrributed to weak electrodynamic drift on disturbed days at the equator. Walker and Ma[14] have investigated the influence of solar flux on the latitude variation of TEC. They found that TEC maximises one hour after h_{max} (height of peak F_2 ionization) maximises. Latitude of the crest and h_{max} are positively correlated with solar flux.

The continuation of equatorial anomaly in TEC after 17 hr LT and subsidiary enhancement at least in summer after 21 hr LT near Nairobi (African sector) have been found by Hunter and Webster,[15] Legg *et al.*[16]

and Jayendran and O'Brien.[17] Ruffenach *et al.*[5] Basu and Das Gupta[1] and Tyagi and Mitra[18] find an early disappearance of total electron content anomaly in Asian zone. There seems to be thus a definite longitudinal effect which merits further study. The asymmetry between the northern and southern hemisphere disappears in equinoxes indicating that the longitudinal differences are connected with the relative positions of dip and geographic equators.

Slab-thickness has been used by a number of workers as an index of temperature[19,20]. Yeh and Flaherty[21] have derived empirical relation between the electron to ion temperature ratio (T_e/T_i) and slab-thickness for a hybrid model with Chapman type bottomside and diffusion transport topside. Titheridge[22] holds that slab-thickness depends on the scale height of ionizable constituent and the scale height of loss processes both of which are dependent on neutral temperature. Therefore slab-thickness should indicate neutral temperature. Furman and Prasad[23] hold the view that slab-thickness is neither a measure of neutral temperature, nor of T_e/T_i ratio. According to Chapman's isothermal ionosphere theory, slab-thickness was shown to be equal to $4 \cdot 15\ H$, H being the neutral scale height at the peak.[24] The departure of τ from the value of $4 \cdot 15\ H$ is indicative of the deviation from diffusive equilibrium in the topside as measured by $D/H^2 - \beta$, where D is the diffusion coefficient, H, the neutral scale height and β the photochemical loss coefficient.

As the f_0F_2 contours are difficult to derive in the absence of large network of ionospheric sounding stations, contours of τ have not been presented before. Contours of τ presented in this study follow the diurnal temperature curve with large values around noon. There is a tendency for presunrise peaks in τ in low solar activity period. τ is larger in equinoxes than in solstices. τ increases with solar activity. However, the detailed association between τ, neutral temperature and T_e/T_i ratio needs further investigation and theoretical modelling.

5. CONCLUSIONS

Combining the observations of Faraday rotation of 40 and 41 MHz signals from the satellite BE–B (Explorer 22) recorded at Kodaikanal (dip 3·4° N) and Ahmedabad (dip 34° N), contours of total electron content on a grid of local time *versus* latitude have been constructed for different seasons of low and high solar activity conditions. These studies bring out the latitudinal, diurnal, seasonal and solar activity changes of TEC over the Indian continent.

Equatorial anomaly in the latitudinal variation of TEC is clearly seen. In equinox the anomaly peak is around 13–14 hr LT in both low and high solar activity periods. Latitudinal peak is formed at 15 and 20° respectively in high and low solar activity conditions.

In winter, latitudinal peak is around 12° dip latitude in both low and high solar activity periods. The diurnal peak is around 13 hr LT in low and 15–16 hr LT in high solar activity periods.

In summer the peak is very broad around 13° N dip latitude in low and high solar activity. It is formed around 13 hr LT in low and 16–17 hr LT in high solar activity periods.

In high sunspot years only winter anomaly becomes apparent with winter values 1·5 times summer values. In low sunspot years semiannual variation of TEC with equinoxial peaks is evident.

Equivalent slab-thickness follows the diurnal temperature curve with a tendency to increase with solar activity.

ACKNOWLEDGEMENTS

The authors are pleased to express their gratefulness to Drs. M. K. V. Bappu and J. C. Bhattacharyya of the Indian Institute of Astrophysics, Kodaikanal, for the hospitality and facilities provided to the authors for the study of the excellent series of data collected at their observatory in Kodaikanal. The research program in PRL is financed by the Department of Space, Government of India.

REFERENCES

1. Basu, S. and Das Gupta, A., *J. Geophys. Res.* 73 5599 (1968).
2. Golton, E. and Walker, G. O., *J. Atmos. Terr. Phys.* 33 1 (1971).
3. Mendonca, F. de., Cantor, I. J. and Clemesha, B. R., *Radio Sci.* 4 823 (1969).
4. Titheridge, J. E. and Smith, W. D., *Planet. Space Sci.* 17 1667 (1969).
5. Ruffenach, C. L., Nimit, V. T. and Leo, R. E., *J. Geophys. Res.* 73 2459 (1968).
6. Rastogi, R. G., Sharma, R. P. and Shodhan, V., *Planet. Space Sci.* 21 713 (1973).
7. Rastogi, R. G., Iyer, K. N. and Bhattacharyya, J. C., *Curr. Sci.* 44 531 (1975).
8. Iyer, K. N., Deshpande, M. R. and Rastogi, R. G., *Proc. Indian Acad. Sci.* A84 129 (1976).
9. Rastogi, R. G. and Sharma, R. P., *Planet. Space Sci.* 19 505 (1971).
10. Walker, G. O., *J. Atmos. Terr. Phys.* 33 1041 (1971).
11. Sanatani, S., *Ph.D. Thesis*, Gujarat University (1966).

12. Hunter, A. N., Hibberd, F. and Mulkowa, W., *Radio Sci.* 4 817 (1969).

13. Das Gupta, A. and Basu, S., *Indian J. Pure Appl. Phys.* **9** 509 (1971).

14. Walker, G. O. and Ma, J. H. K., *J. Atmos. Terr. Phys.* **34** 1419 (1972).

15. Hunter, A. N. and Webster, A. R., *Proc. Second Int. Symp. Equat. Aeron.* 152, Sao Jose dos Campos, Sao Polo, Brazil (1965).

16. Legg, A. J., King, J. W. and Precce, D. M., *J. Atmos. Terr. Phys.* **29** 1397 (1967).

17. Jayendran, R. and O'Brien, *J. Atmos. Terr. Phys.* **31** 555 (1969).

18. Tyagi, T. R. and Mitra, A. P., *J. Atmos. Terr. Phys.* **32** 1807 (1970).

19. Bhonsle, R. V., da Rosa, A. V. and Garriott, O. K., *Radio Sci.* **69D** 929 (1965).

20. Hibberd, F. H. and Ross, W. J., *J. Geophys. Res.* **71** 2243 (1966).

21. Yeh, K. C. and Flaherty, B. J., *J. Geophys. Res.* 71 4557 (1966),

22. Titheridge, J. E., *Planet. Space Sci.* **21** 1775 (1973).

23. Furman, D. R. and Prasad, S. S., *J. Geophys. Res.* 78 5837 (1973).

24. Wright, J. W., *J. Geophys. Res.* **65** 185 (1960).