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The equatorial anomaly in ionospheric total electron content and the equatorial electrojet current strength

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ABSTRACT

Faraday Rotation of 40 and 41 MHz signals from the satellite BE B (Explorer 22) recorded simultaneously at Ahmedabad (dip 34° N) and Kodaikanal (dip 3 4° N) during the years 1964–69 are used to derive the latitudinal profiles of Total Electron Content (TEC) over the Indian equatorial anomaly region From these profiles the diurnal development of the equatorial anomaly and its correlation with equatorial electrojet strength are studied The anomaly is found to maximise around 1400 L T *i e*, two–three hours after the electrojet attains its peak The anomaly parameters such as the dip latitude of the anomaly peak, ϕ, the normalised depth, *d*, of the anomaly and the strength of the anomaly defined as $S - \phi_{sd}$ are found to be well correlated with the electrojet strength

1 INTRODUCTION

AMONG the various techniques used to study the ionosphere, one of the most simple but elegant techniques is the Faraday rotation of a plane polarized wave emitted from a satellite. Low orbiting satellites at an altitude of about 1000 km with polar orbit thus offer a powerful tool to study, within a very short duration, the spatial variation of F-region ionisation From a single observing station about $\pm 10°$ in latitude can be studied using such satellites Latitudinal variation of Total Electron Content (TEC) has been studied by Basu and Das Gupta,[1] Titheridge and Smith [2] Mendonca *et al*,[3] Golton and Walker[4] and Rastogi *et al.*[5,6] in the equatorial and low latitude region using VHF signals from the satellites BE–B and BE–C These studies clearly indicated the existence of an equatorial anomaly in TEC, in its latitudinal variation, similar to the one in $f_0 F_2$.

Dunford[7] obtained a positive correlation between E-region current system near the magnetic equator and the equatorial anomaly using topside sounder data. Mac Dougall,[8] and Rastogi and Rajaram[9] using f_0F_2 values near the magnetic equator have given evidence that the equatorial anomaly shows high correlation with electrojet strength and poor correlation with Sq current system. Rush and Richmond[10] have obtained positive correlation between several parameters of the equatorial anomaly in f_0F_2 and electrojet strength. As for the equatorial anomaly in TEC is concerned, geomagnetic control of this anomaly has been studied by Das Gupta and Basu.[11] Influence of solar flux and electrojet on the diurnal development of equatorial anomaly in TEC has been investigated by Walker and Ma.[12] It must be borne in mind that the above two investigations are from a single station near the peak of the equatorial anomaly and hence a complete coverage of the anomaly region from dip equator to and beyond the peak is not obtained. Therefore we have, in the present investigation, studied the dependence of equatorial anomaly in TEC on the electrojet strength using the data of Faraday rotation recorded simultaneously at Kodaikanal (dip 3 4° N, geogr. long. 77° E) and Ahmedabad (dip 34° N, geogr. long. 73° E) thus covering the complete anomaly region from the dip equator to 30° N dip latitude.

2. DATA AND ANALYSIS

For the current investigation we have used the Faraday rotation data of 40 and 41 MHz signals recorded commonly at both Ahmedabad and Kodaikanal during the years 1964–69. Only the data from the satellite BE-B having an orbital inclination of 79 8° is used. This is to avoid any local time difference between the two extremeties of a pass common to both the stations. In order to show the region of coverage by observation from the two stations, in figure 1 two typical sub-satellite trajectories of the satellite BE–B, one north-bound and the other south-bound are shown. The north-bound pass was on 18 May 1967 and the south-bound pass on 27 May 1967. We can see that the local time difference between the two ends of the pass, *i.e.*, from 5° South to 35° North, is less than an hour and hence ideal for latitudinal study of TEC. The concentric circles centred on the observing stations are contours of satellite zenith angles (χ) as observed from the corresponding station. For example if the satellite is anywhere on the dashed circle labelled χ = 50° then the zenith angle of the satellite as seen from Kodaikanal would be 50°. There is a reasonable overlapping zone which can be studied from both the stations at zenith angles less than 60°, *i.e.*, with reasonable accuracy. This helps in matching the latitudinal profiles obtained from the two stations. The latitudinal coverage achieved is

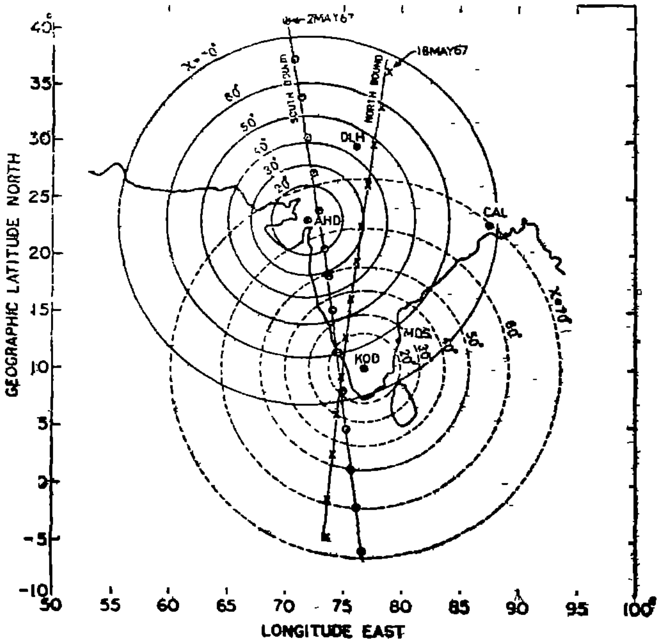

Figure 1. Contours of constant zenith angles for a satellite at 1000 km as observed from Ahmedabad (full lines) and Kodaikanal (dashed lines) Two typical sub-satellite tracks, one for 18 May 1967 (North-bound) and the other for 2 May 1967 (South-bound) are also shown to indicate the region of coverage when observed from both the stations.

from 5° South to 35° North geographic. It was found that in most of the passes, the TEC obtained from observations at the two stations, in the overlapping region, matched well

The receiving system at the two stations are identical and similar method of analysis is followed at both stations. The total rotation formula:

$$\Omega = \frac{k}{f^2} \bar{M} N_T$$

where Ω = Faraday rotation angle

$k = 2 \cdot 97 \times 10^{-3}$

f = frequency in Hz

$\bar{M}$ = Magnetic field factor at the mean field height and N_T = vertical total electron content

has been employed to derive TEC at every minute during a satellite pass. Only passes showing unambiguous QT transition are used in the present analysis. Near the QT region the above formula fails and hence a differential formula

$$\frac{d\Omega}{dM} = \frac{k}{f^2} N_T$$

It is known that about 80% of TEC is within one scale height above and below the height of $N_{max}\ F_2$. Hence to calculate N_T an effective mean field height $h = h_m + H$ where h_m is the height of peak F_2 ionization and H is the scale height at the F_2 peak is used.[13] This is a valid approximation as h now corresponds to the centroid of $N(h)$ distribution hence weighing M equally by the ionization above and below h. Thus h is chosen as 400 km for Kodaikanal and 350 km for Ahmedabad. TEC thus obtained from Kodaikanal and Ahmedabad were combined to obtain latitudinal profiles of TEC from 5° S to 35° N geogrpaphic latitude.

3 RESULTS

Typical latitudinal profiles on individual days are now studied in comparison with the diurnal variation of horizontal component of magnetic field, H at Kodaikanal. The diurnal amplitude of the H field is directly dependent on the ionospheric current strength flowing in the dynamo region of the ionosphere. Therefore a day showing large diurnal range of H field can be considered as one having a strong electrojet current and a small diurnal amplitude in H is indicative of weak electrojet current day. Therefore in figure 2 we have shown typical latitudinal profiles of TEC on a pair of strong and weak electrojet days as decided by the above criterion. The crosses and circles are observations from Kodaikanal and Ahmedabad respectively. The H magnetograms at Kodaikanal are also reproduced for comparison. For a typical quiet day 9 November 1965, the H field at Kodaikanal shows a normal diurnal variation with a maximum electroject strength just after 1100 LT. For this day, the latitudinal variation of TEC shows clearly the equatorial anomaly with maximum TEC around 23° N geogr. latitude and minimum around 8° N (which corresponds to the dip equator in Indian zone). On another quiet day, 29 October 1965, H field, though having a normal behaviour, the amplitude of the diurnal variation is very small indicating

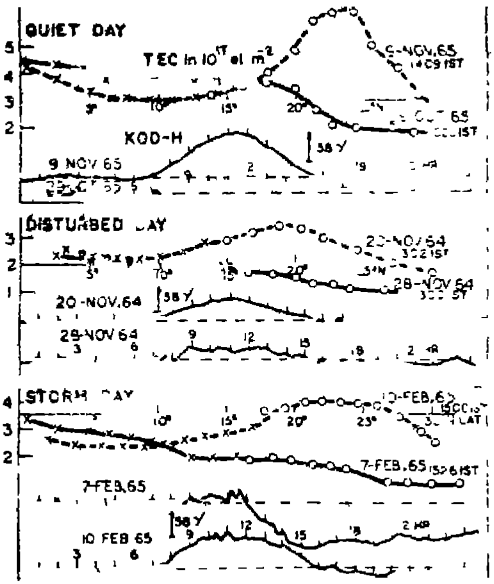

Figure 2 Latitudinal variation of TEC on typical pairs of strong electrojet and weak electrojet currents for Quiet, Disturbed and Stormy conditions. The diurnal variation of horizontal component of magnetic field on the corresponding days is also shown. X indicates observations from Kodaikanal and O that from Ahmedabad.

a weak electrojet current on that day. On this day, the latitudinal profile of TEC is completely changed with peak value near about 18° N and the peak is almost flat. The TEC near the latitude 25° N (peak on the strong jet day) is very small compared to that on the strong jet day. The same type of behaviour emerges on a pair of strong and weak electrojet days [illegible] seen from the pair of days 20 November 1964 and 28 November 1964. Similarly on a pair of storm days 10 February 1965 (strong electrojet) and 7 February 1965 (weak electrojet) also the latitudinal [illegible] variation of TEC is markedly [illegible] affected reducing the anomaly on the weak [illegible] jet days. It may be [illegible] the above examples are chosen [illegible] around 1400 hr LT. Thus the [illegible] latitudinal variation of TEC in the [illegible] anomaly belt [illegible] ed by the electrojet strength irrespective of the magnetic quietness or disturbance of the day.

Transport of equatorial ionization to low latitudes along the magnetic lines of force and its time history can be investigated best with latitudinal TEC profiles at different local times, since satellite passes cover the whole equatorial anomaly belt, with high spatial accuracy. With this purpose, the latitudinal profiles of TEC are classified into hourly groups, *viz.*, passes between 0930 LT and 1029 LT fall in the group for 1000 LT. From such hourly groups, the dip latitude of the anomaly was deduced at various local times. Figure 3 shows the result of this investigation. The peak of the anomaly is at 8° N dip latitude at 0900 LT and it moves to about 15° N dip latitude by 1300 LT after which it returns to about 12° N by 1700 LT. This shows that the diurnal development of the equatorial anomaly in TEC is similar to the one observed in f_0F_2.

Now, from each latitudinal profile the following indices of the equatorial anomaly are scaled. The dip latitude of the anomaly peak (ϕ), the normalized depth of the anomaly (d) defined as

$$d\,(\%) = \frac{N_T\,(\text{peak}) - N_T\,(\text{dip equator})}{N_T\,(\text{dip equator})} \times 100$$

and the strength of the anomaly $S = \phi \times d$

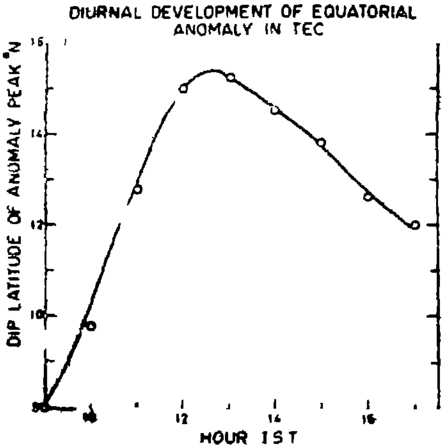

Figure 3. Diurnal development of the equatorial anomaly in TEC depicted by the movement of the dip latitude of the peak of the anomaly

The following scheme has been used to determine an index (Sd_t) of the electrojet strength, suggested by Kane[14] Sd_t is obtained by subtracting hourly H field at a low latitude station outside the electrojet belt from the hourly H field at the dip equatorial station In this procedure, the normal S_q field at the dip equator is also subtracted out thereby undermining the electrojet strength To correct for this, the monthly mean $S_q(H)$ field at the low latitude station for the particular is added In the present case the low latitude station is taken as Alibag and the dip equatorial station as Kodaikanal Therefore,

$$Sd_t = H(\text{KOD}) - H(\text{ALB}) - \bar{H}(\text{ALB})$$

The above index has the advantage that any non-ionospheric contribution to the H field is removed in the subtraction process Moreover, on a storm day there is no other way of estimating the electrojet strength as the diurnal variation may be completely masked by storm effects Thus this index is particularly advantageous for storm days [15] Now Sd_t at t hour LT is defined as $Sd_t(t) - Sd_t$ meaned over 00–04 hrs LT. $Sd_t(t)$ for each hour of the days (t varying from 06–18 hr ST) having a latitudinal profile of TEC has been calculated.

The correlation between the dip latitude of the anomaly peak at t hour and the electrojet strength at ($t - \triangle t$) hours is next computed, where the time shift $\triangle t$ is varied from 0, 1, 2 and 3 hrs. This is to investigate the time lag between the maximisation of the anomaly and the electrojet strength The correlation coefficient thus obtained is plotted against time shift in figure 4. It is found that maximum correlation of about 0 7 exists for a time shift of 2–3 hrs, thereafter the correlation falls off rapidly. This indicates that TEC anomaly lags by 2–3 hrs with respect to the electrojet.

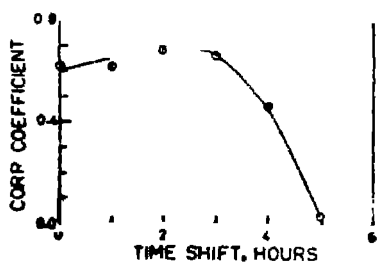

Figure 4. Correlation coefficient between anomaly parameter and electrojet strength plotted against different time shifts. Note the correlation falling rapidly after about a time shift of 3 hours

Having established the time lag between anomaly and electrojet our next intention is to investigate the dependence of the anomaly parameters, *viz* the quantities ϕ, d and s defined earlier, at t hours on the electrojet parameters at $(t-2)$ hours. For this, the anomaly parameters between 1100 and 1700 hrs are used. The anomaly parameters in this interval are plotted against electrojet index Sd_r allowing for a lag of 2 hrs. These results are shown in figure 5. The best fitted least square regression lines are also shown in the figure. It is found that a good correlation of 0.68 between ϕ and $Sd_r(t-2)$, 0.63 between d and $Sd_r(t-2)$ and 0.48 between s and $Sd_r(t-2)$ exist. These results indicate that the equatorial anomaly parameters are strongly controlled by electrojet currents.

4. Discussion

Two unique features of magnetic equatorial latitudes are the equatorial electrojet current in the E-region and equatorial anomaly in the F-region. Both are controlled by the electric fields set up in the dynamo region of the ionosphere. So it is natural that the two phenomena are well correlated. The electrojet strength should depend on the conductivity of the equatorial ionospheric E-region and the electric fields driving the current. The present results show that the anomaly maximises around 1400 LT and the anomaly therefore lags by about 2 hours behind the electrojet which is known to maximise between 1100 and 1200 LT.

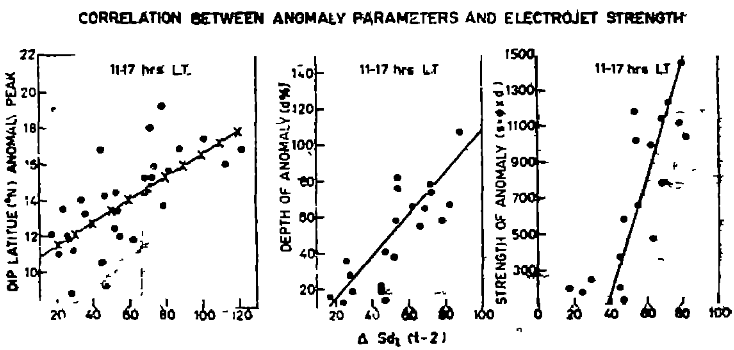

Figure 5. Variation of the dip latitude, ϕ, of the anomaly peak (left), the normalized depth, d (middle), and the strength, $S = \phi \times d$ (right) of the anomaly with equatorial electrojet strength two hours prior to the anomaly.

The equatorial anomaly is well explained as due to the vertical drift of the F-region ionization under the $E \times B$ drift over the equator and its subsequent downward diffusion along the magnetic lines of force. The time of maximisation of the anomaly will therefore depend on the time of maximum of electric fields, the time taken for vertical drift and the diffusion time of the electrons from equator to around 15° dip latitudes. The time taken by F-region plasma for vertical drift with drift velocities of 20–30 m/sec and the subsequent diffusion time are discussed in literature. Baxter and Kendall[16] have theoretically computed this time constant to be 2½ hours. The calculations of Sterling et al[17] distinguish between an early $E \times B$ drift, *i.e.*, the drift maximising around noon and late drift, *i.e.*, drift maximising afternoon. In both cases they find the anomaly peak to be formed around 14° dip latitude. But the late drift case does not reproduce the observed noon bite-out in the diurnal variation of $N_m F_2$, the maximum electron density in F-region. This leads to the conclusion that what is actually existing is the early drift, *viz.*, drift maximising around noon. They also observe that the controlling factor in the position of the latitudinal peak is the electrodynamic drift while the time of maximum development of the anomaly is controlled by the diffusion velocities. The present analysis shows that in high sunspot years the peak is delayed by ½ to 1 hour as compared to low sunspot years which is due to the solar activity changes of neutral densities. The anomaly is found to maximise around 1500 hr LT on average. This indicates an average time lag by about 3 hours between the electrojet anomaly maximisation. This agrees well with our observations of 2 to 3 hours time lag

It is also expected that increasing electrojet strength will lead to increased vertical drifts which in turn will create anomaly peaks further away from the dip equator. Thus the correlation between dip latitude (ϕ) of anomaly peak and electrojet strength can be interpreted as due to increased vertical drifts. The parameter d will also be larger for higher electrojet strengths since lifting to a higher altitude leads to increased gradients and hence increased diffusion. This in turn increases the depth of the anomaly

5. CONCLUSIONS

Equatorial anomaly in the latitudinal variation of TEC maximises around 1400 hr LT, thus having a time lag of about 2 hrs between electrojet strength and anomaly. This time lag agrees well with the theoretically estimated diffusion time. The anomaly strength is well correlated with equatorial electrojet strength. These results tend to conclude that the equatorial anomaly in TEC is mainly the manifestation of vertical electrodynamic drift and ambipolar diffusion of ionization, although the role played by neutral density anomaly[18] cannot be ignored.

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