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On the simultaneous existence of eastward and westward flowing equatorial electrojet currents

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ABSTRACT

The counter-electrojet currents are evidenced by the disappearance of the *q* type of *Es* layer (*Es*—*q*) or the appearance of the blanketing type of *Es* (*Es*–*b*) at Kodaikanal, associated with the depression of the geomagnetic *H* field and the reveısal of ionospberic drift at Thumba. The necessary condition for such an event is not the decrease of the *H* field below the night level but that the difference of the *H* field between an equatorial and a non-equatorial station should decrease below its night level.

The different kinds of association between the disappearance of *Es*–*q* and the depression in the *H* field are suggested due to superimposition over the *Sq* current system (at about 107 km) of a separate westward current system at a lower level (about 100 km).

The source of the reversed current over the dip equator during the daytime hours is sought in the current system generated by the lunar tides or in various magnetospheric processes generating the polar substorms.

Large day-to-day variations of the solar daily range of *H* at the equator independent of *Sq* variation at tropical latitudes are suggested to be due to superimposition at the equator of the two rather independent current systems.

INTRODUCTION

THE maximum frequency of radio waves reflected from the sporadic *E* layer (fE_s) during the daylight hours is known to have a narrow peak over the magnetic equator (Matsushita 1951; Knecht and McDuffie 1962). Matsushita (1957) noted that *Es* layer at Huancayo suddenly disappeared on certain occasions during the afternoon hours and showed the phenomenon to be related to the age of the moon. Bhargava and Subrahmanyan (1961) reported that *Es* layer at Kodaikanal sometimes disappeared during the main phase of the geomagnetic storms.

Cohen *et al* (1962) reported the disappearance of *Es* at Huancayo on a quiet day simultaneously with the decrease of the geomagnetic *H* field. Rastogi *et al.* (1971) showed the disappearance of equatorial *Es* layer and the decrease of the geomagnetic *H* field to be simultaneous with the reversal of ionospheric drift from westward to eastward direction. Rastogi (1972 *a*, *b*) has suggested that *Es–q* disappears precisely during the period when the *H* field is below its normal nighttime level. Fambitakoye *et al.* (1973) have shown that the criterion for *Es–q* disappearance is not necessarily ΔH becoming negative but the latitudinal profiles of ΔH and ΔZ reversing from its normal regular pattern.

In this paper, we examine the relationship between the disappearance of *Es–q* at Kodaikanal and the changes in the geomagnetic *H* field at the low-latitude stations in India, *viz.*, Trivandrum (dip 0·6° S), Kodaikanal (dip 3·4° N), Annamalainagar (dip 5·4° N), Hyderabad (dip 20·5° N), Alibag (dip 24·6° N) and Sabhawala (dip 45·4° N). The sudden disappearance of *Es–q* (SD*Es–q*) and the geomagnetic *H* field appears to be of three types as described below:

Disappearance of Es–q *simultaneous with the negative value of* ΔH *or* ΔSdI

In figure 1 are shown the variations on 6 August 1964 of the following parameters, daily variations of the *H* field (i) at Kodaikanal (KOD), (ii) at Alibag (ALB), (iii) the difference field between the two stations KOD–ALB, (iv) the index *SdI* defined by Kane (1973) as the index of electrojet currents, (v) the east–west component of the *F*-region drifts at Thumba and (vi) the latitudinal profiles of ΔH_t at a particular hour *t* which is taken as the difference of the field at *t* hr and at 00 hr. This day was geomagnetically very quiet, the magnetic character figure *C* was 0·3 and A_p was 7. The *Es–q* layer was first seen in the Kodaikanal ionograms at 0630 hr 75° EMT and the echoes were strong upto 0930 hr; at 0945 hr no *Es–q* was seen in the ionograms and this no-*Es* condition prevailed upto 1030 hr. Between 1045 and 1245 hr, some non-*q* type of *Es* reflections were seen and after 1300 hr no *Es* reflection was recorded on that day. The *H* field at Kodaikanal increased since sunrise upto 0900 hr after which its magnitude suddenly dropped and remained at even below the nighttime level. The *H* field at Alibag continued to increase since sunrise upto 1200 hr and its daily variation was very similar to the mean monthly behaviour. The value of *H* at Kodaikanal, the difference field between Kodaikanal and Alibag (KOD–ALB), as well as the index *SdI* became negative with regard to the respective nighttime value almost simultaneously with the disappearance of *Es–q*. The ionospheric *F*-region drift measured at Thumba, close to Trivandrum, was westward during the morning hours upto 0900 hr and was eastward from 1000 to 1600 hr. The latitudinal profiles of ΔH showed a maximum over

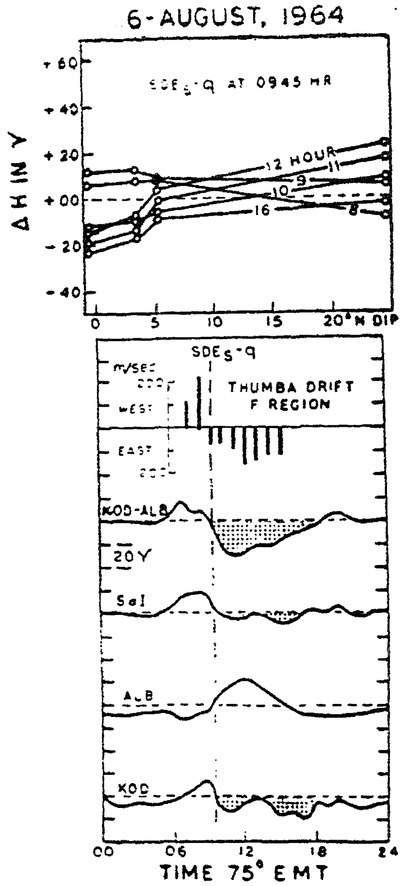

Figure 1. The daily variations of the geomagnetic H field at Kodaikanal (KOD) and Alibag (ALB), the difference of the field at two places (KOD$-$ALB), the electrojet index SdI and the ionospheric F-region drifts over Thumba on 6 August 1964. The upper diagram shows the latitudinal profiles of ΔH at a few fixed hours of the day. Note the simultaneous reversal of F-region drift and the latitudinal profiles of ΔH at the time of sudden disappearance of *Es–q*.

the magnetic equator at 0800 hr and 0900 hr but for period from 1000 to 1600 hr, there was a minimum of ΔH over the dip equator.

All these observations indicate a reversal of the ionospheric currents in the E-region of the ionosphere almost simultaneously with the disappearance of the *Es–q*.

Disappearance of Es-q *preceding the negative* ΔH or ΔSdI

Such an example is clearly shown in figure 2 for 31 October 1964, an exceptionally quiet day, C being 0·0 and A_p equal to 2. It can also be seen that K_p values for any of the three hourly periods under consideration did not rise above unity. The sporadic E reflections had disappeared at Kodaikanal at 1230 hr and did not appear again during the rest of the daytime. A depression was seen in the afternoon hours at the equatorial stations Trivandrum, Kodaikanal and Annamalainagar while the daily variation of H at Alibag was normal. The uncorrected ΔH at Trivandrum or at Kodaikanal decreased below the mean night level at 1330 hr but when corrections for *Dst* values were made this time modified to 1300 hr. The daily variation of SdI did show a plateau in the afternoon but its value during any time of the daylight hours was well above the nighttime level. The difference field between Kodaikanal and Alibag was below the nighttime level between

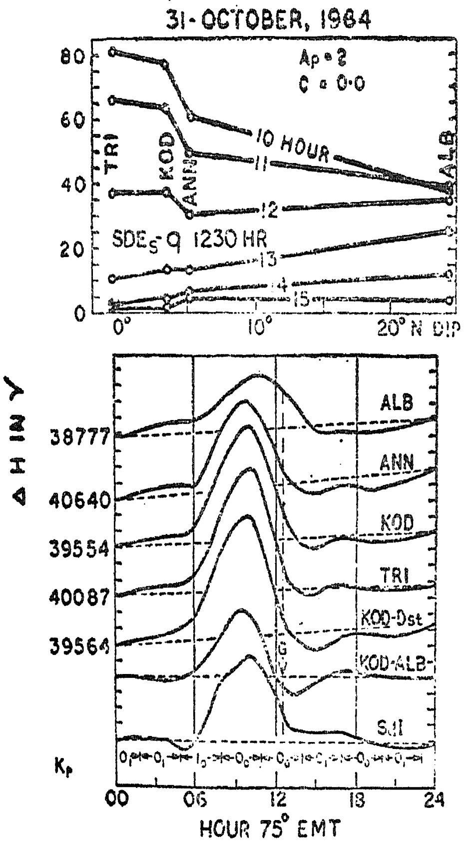

Figure 2. The daily variations of the H field at Indian stations and the latitudinal profiles of ΔH for fixed hours on 31 October 1964. Note *Es–q* disappeared when both ΔH at Kodaikanal and the ΔSdI index were positive but ΔH KOD–ALB) had just decreased below its mean nighttime value.

1215 and 1530 hr. The latitudinal profile of ΔH at 1000 and 1100 hr shows a distinct peak over the magnetic equator. This peak had weakened at 1100 hr and a distinct minimum had appeared at 1300, 1400 and 1500 hr. It is to be noted that at any of these hours ΔH was positive at any of these stations. This indicates the current had reversed sometime between 1200 and 1300 hr. The ΔH (KOD-ALB) indicates the reversal around 1215 hr and the disappearance of *Es–q* occurred between 1215 and 1230 hr. Thus, the reversal of current from the variation of ΔH at a single station does indicate a delay in the reversal of the current and the disappearance of the *Es–q* near the magnetic equator.

Another example of the disappearance of *Es–q* when ΔH at Kodaikanal was positive is shown in figure 3 for 14 January 1964. This day was a quiet day, A_p being 1 and C being 0·0. The *Es–q* at Kodaikanal had disappeared around 1130 hr when ΔH was about $+30\gamma$ and ΔSdI was $+20\gamma$, but the difference field between Kodaikanal and Alibag was -5γ. Thus the disappearance of *Es* corresponds with the time of reversal of ΔH (KOD–ALB) and not with ΔH (KOD). The latitudinal profile of ΔH also shows reversal between 1100 and 1200 hr, suggesting the existence of counter-electrojet currents in spite of positive ΔH (KOD).

Disappearance of Es–q *when* ΔH *does not decrease below the nighttime level*

Such an example was very clearly seen at Indian stations on 6 March 1967 ($A_p = 8$, $C_p = 0{\cdot}4$). In figure 4, the daily variations of the H and Z

fields on 6 March 1967 are compared with the corresponding monthly mean Sq variations for all the geomagnetic stations in India. The shaded portion in the diagram indicates the period of no Es–q condition at Thumba. On 6 March 1967, a prominent dip in the H field was seen around 1400 hr at Trivandrum, Kodaikanal and Annamalainagar, but it is interesting to note that the minimum of the field was very much above the mean nighttime level. Further the ΔH in the forenoon hours at these stations was significantly smaller than the corresponding mean $Sq(H)$ value. The daily variation of the H field at non-equatorial stations Hyderabad, Alibag and Sabhawala did not show any significant difference from the average monthly curve. The daily variation of the Z field on a normal day showed a prominent minimum around 1200 hr at any of these stations except Trivandrum. This is as expected of the stations situated north of the dip equator. The daily range of Z was seen to be largest at Annamalainagar, station close to the edge of the electroject region.

On 6 March 1967, the Z field at Kodaikanal was almost at a constant level during the whole day and no midday minimum was seen. At Annamalainagar, a distinct maximum of ΔZ was seen around 1300 hr. At Hyderabad, a weaker maximum of ΔZ was seen around 1300 hr. At Alibag and Sabhawala, the daily variation of Z on 6 March 1967 was very similar to that on normal days except that the daily range was comparatively smaller. The dip in H at all the equatorial stations coupled with the maximum of ΔZ around 1300 hr at Annamalainagar indicated the effects of westward

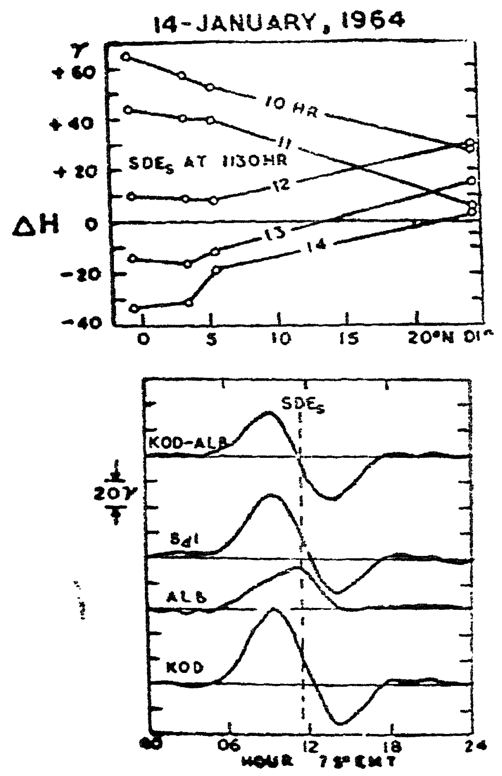

Figure 3. Daily variations of the H field and the latitudinal profiles of ΔH on 14 January 1964. Note the Es–q disappeared when H at Kodaikanal was positive but ΔH (KOD–ALB) had just become negative.

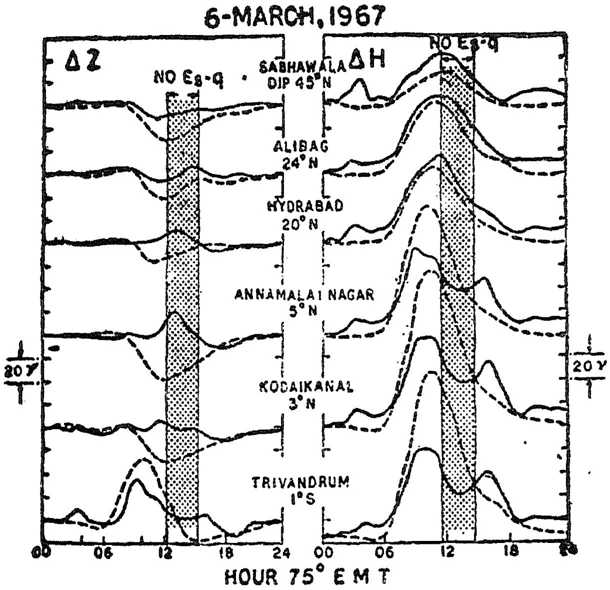

Figure 4. Daily variations of ΔH and ΔZ fields at geomagnetic stations in the Indian zone on 6 March 1967, compared with the corresponding mean monthly variations. Dotted portion of time interval indicates when no *Es* was seen in ionograms at Thumba. Note the decrease of *H* field at low latitudes is associated with an increase of *Z* field at Annamalainagar.

flowing electrojet currents on 6 March 1967 in the Indian zone throughout the whole day being significantly between 1300 and 1600 hr.

Let us examine the effects of this event on the ionospheric regions at Kodaikanal and Thumba. In figure 5 are shown the daily variations on 6 March 1967 of the following parameters, (i) difference of *H* field between TRV–ALB and KOD–ALB, (ii) E–W component of the *F*-region drifts at Thumba, (iii) fading rate of *F*-region echo at Thumba, (iv) f_0Es Thumba and Kodaikanal, and (v) height of the peak ionisation in the F_2 region at Thumba and Kodaikanal. The ΔH(TRV–ALB) or ΔH(KOD–ALB) decreased below the night level between 1130 and 1500 hr. The E–W drift in the *F*-region was westward up to 1130 hr but at 1230 hr and 1430 hr the drift was definitely eastward. The fading of the *F*-region echo was about 40 fades per minute at 1130 hr, about 10 fades per minute at 1230 hr and became as low as 2 fades per minute between 1330 and 1430 hr indicating the absence of irregularities causing the fading of radio waves. The *Es* reflection at Thumba or Kodaikanal showed *q* type of *Es* up to 1200 hr; between 1215 and 1500 hr no *Es–q* was seen at Thumba while at Kodaikanal the blanketing type of *Es* had appeared. The ionogram of Kodaikanal at 1445 hr showed *Es* echoes at different constant levels. The height of the peak ionization in the *F*-region (hpF_2) at Thumba as well as at Kodaikanal showed a distinct dip between 1215 and 1500 hr when *Es–q* echoes were absent at Thumba.

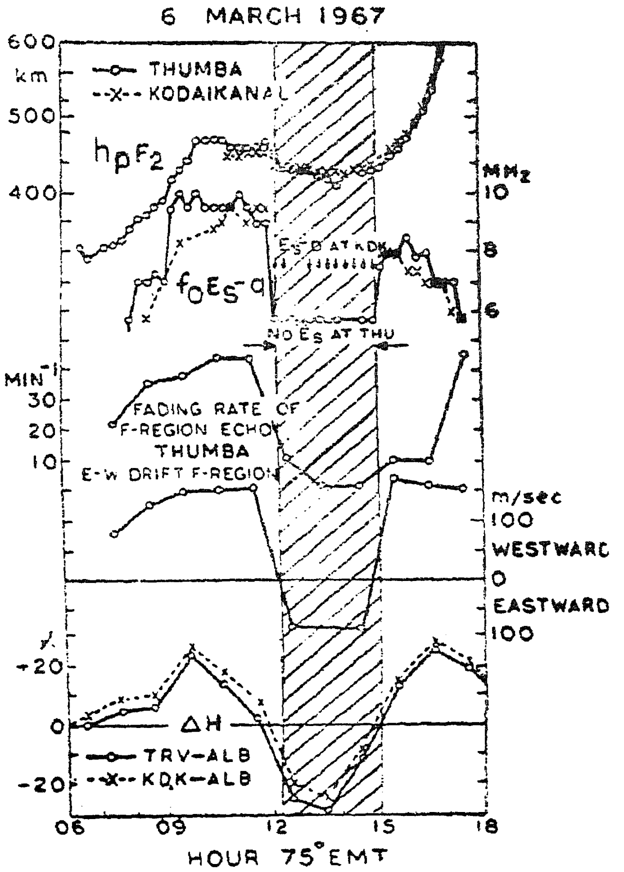

Figure 5. Daily variations on 6 March 1967 of the following parameters: (i) the difference of the H field between Trivandrum and Alibag (TRV–ALB) and between Kodaikanal and Alibag (KOD-ALB), (ii) E–W component of the F-region drifts at Thumba, (iii) fading rate of F-region echo at Thumba, (iv) f_0 Es–q at Thumba and Kodaikanal, and (v) the height of peak ionisation in F_2 region, hpF_2 at Thumba and Kodaikanal. Note the partial counter-electrojet is associated with the reversal of ionospheric drift, disappearance of Es–q and the lowering of hpF_2.

Thus, although the depression in H field at Trivandrum or at Kodaikanal was well above the nighttime level, the various features of the E- and F- region echoes showed characteristic of a counter-electrojet current. The partial counter-electrojet is indicated by the negative value of ΔH (KOD–ALB) rather than that of ΔH (KOD).

Some further examples of the disappearance of Es–q at Kodaikanal during the partial counter-electrojet are shown in figure 6. The disappearance of Es–q is indicated by the letter 'G' in the diagram. It is seen that in everyone of the three cases shown here, the minimum value at the afternoon depression of H at Kodaikanal is definitely above the nighttime value, but the difference field ΔH (KOD–ALB) is below the nighttime value for the time almost corresponding to the period of no-Es–q condition.

In figure 7 are shown two cases of partial counter-electrojet indicated by a minor depression of the H field at Trivandrum with no perceptible change at Alibag. The difference field showed values below the nighttime level. The F-region drift at Thumba showed temporary reversal during the period of negative ΔH (TRV–ALB).

Thus it is seen that in certain occasions when ΔH at Kodaikanal shows a minor decrease or even no decrease, but H (Kodaikanal *minus* Alibag) decreases below the night level, the ionospheric drifts at equator are eastward and no *Es–q* layer is seen in the ionograms. These features are taken to indicate a reversal of equatorial electrojet at the base of the *E*-region when the *Es–q* is formed.

Discussion

The discovery by Matsushita (1961) of the similarities in the diurnal variations of the top frequency reflected from the *Es* region of the ionosphere and the daily range of the geomagnetic *H* field at low-latitudes had clearly indicated the close association between the equatorial *Es* layer and the

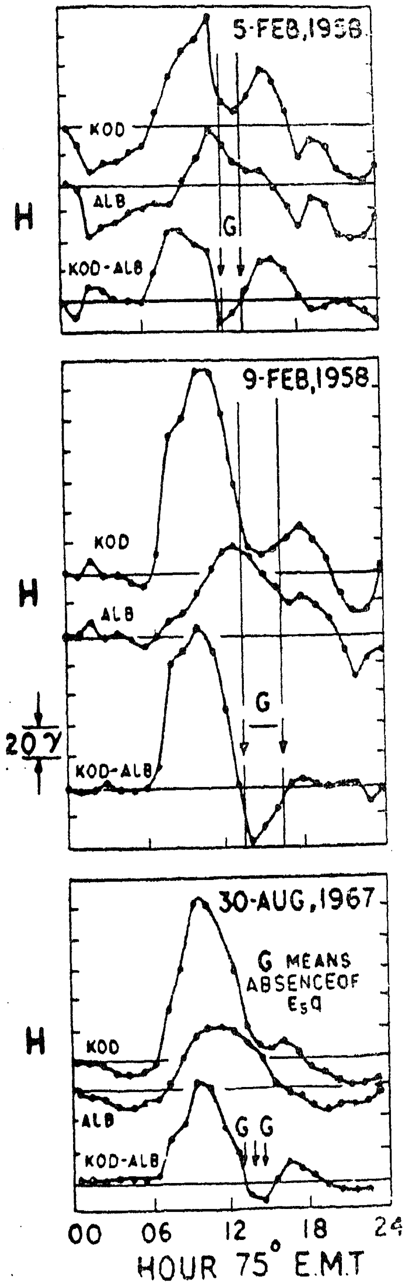

Figure 6. Some examples of partial counter-electrojet effects in the daily variations of the *H* field at Kodaikanal causing the disappearance of *Es–q* at Kodaikanal.

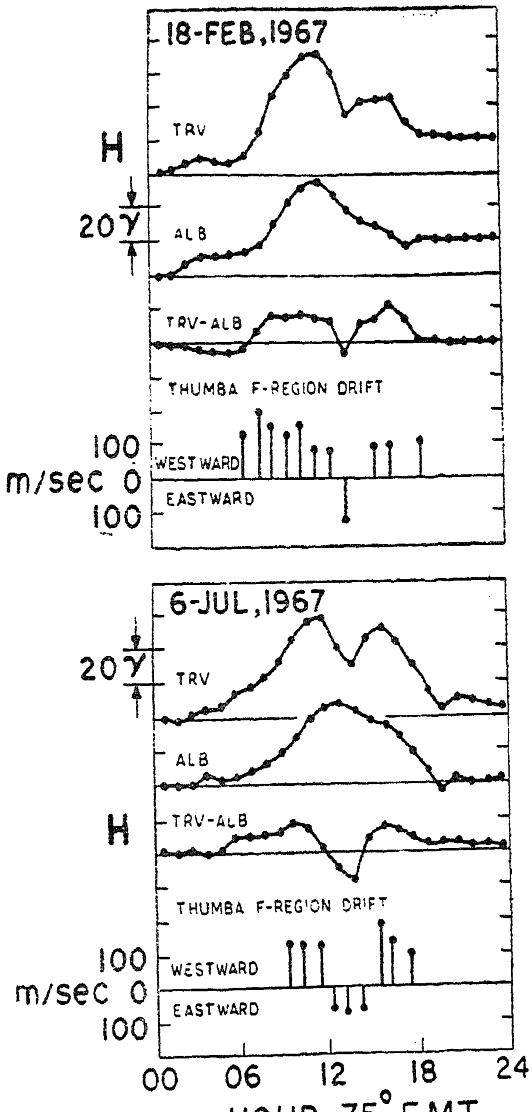

Figure 7. Examples of partial counter-electrojet effects at Trivandrum and the associated reversal of *F*-region drifts at Thumba.

equatorial electrojet currents. Examining the ionograms obtained at Kodaikanal, Rangarajan (1954) found that the equatorial *Es* may be classified broadly into two main types, (i) the patchy type with a well-marked diurnal variation now denoted as *Es–q*, and (ii) multiple or blanketing type occurring mostly during afternoons denoted as *Es–b*. Knecht and Schlitt (1961) showed that *Es–q* in the American zone occurs within a belt between magnetic dip of $\pm 10°$ (width about 700 km) while the occurrence of *Es–b* decreases from a value of 90% at 6° dip down to zero at about 2° dip, and thus the occurrences of *Es–q* and *Es–b* are complimentary to each other. A detailed study of equatorial *Es–b* was first described by Bhargava and Subrahmanyan (1964) and they concluded that almost all the ionospheric and geomagnetic features observed under the influence of electrojet are suppressed during the blanketing *Es* events and that an electric current probably westward is introduced during its occurrence. Rastogi (1974 *a*) has shown that the effect of the counter-electrojet currents is either the disappearance of the *q* type of *Es* layer or the appearance of the blanketing type of *Es*.

Rastogi (1972 *c*) has shown that the *Es–q* occurs at the base of the *E* layer where both the Hall polarization field as well as the plasma density gradient are maximum. He suggested *Es–q* due to the cross-field instabilities created in the *E*-region by the interaction of the northward *H* field on the vertically upward plasma gradient and upward Hall field. In cases of counter-electrojet the horizontal electrostatic field is reversed and so the vertical Hall field is downward and the conditions for the generation of the cross-field instabilities are not fulfilled causing the disappearance of the *Es–q* reflections.

During the events when the blanketing *Es* are seen associated with the counter-electrojet, it has been found that besides the reversal of the ionospheric drift, a significant component of the equatorialward drift was present (Chandra and Rastogi 1974). The *Es–b* was interpreted as the accumulation of metallic ions from the tropical to the equatorial latitudes by the equatorward wind.

These arguments are perfectly consistent with the first type of counter-electrojet and *Es* association. The second type of association and definitely the third type of association needs further scrutiny. Let us examine the features of partial counter-electrojet in the light of suggestions for the disappearance of *Es–q*.

It may be interesting to note here that Cohen and Bowles (1963) showed that the strength of radar echoes of 50 MHz radio waves from the electrojet irregularities over Jicamarca varied during the course of a day not in proportion to ΔH at Huancayo (close to Jicamarca) but in proportion to the difference of ΔH between the equatorial station–Huancayo, and the non-equatorial station in the same longitude zone—Fuquene. This further suggests that the strength of ionospheric irregularities in the electrojet region scattering VHF radio waves is proportional to the difference of the *H* field between an equatorial and a non-equatorial station. This procedure has a further advantage that the disturbance field effects not associated with ionospheric currents are eliminated.

The fact that ΔH at equatorial station, during partial counter-electrojet, is significant above the nighttime level indicates the presence of eastward current at certain levels of the ionosphere whose effect is larger than any other westward current at any of the levels. The disappearance of *Es–q* would occur when the plasma gradient and the Hall polarization field are not in the same direction; this means either the reversal at 100 km level of the plasma gradient or the E–W electrostatic field. The *Es–q* is shown to disappear very quickly with the decrease of *H* and follows very sympathetically the variations of the *H* field (Rastogi 1972 *b*), it is unlikely that the electron density profiles are suddenly changed during the repeated disappearances and appearances of the *Es–q*. Further the normal *E*-layer traces during the disappearances of *Es–q* do not indicate any negative gradient with height. Thus the only explanation left for the disappearance of *Es–q* during the partial counter-electrojet is the reversal of the polarization field which itself is consequent to the reversal of horizontal electrostatic field to westward direction. The consequent westward current at 100 km level is the cause of depression in the *H* field.

The daily variation of the *H* field outside the electrojet region remains unaltered during the counter-electrojet events which means that the *Sq* current system does exist as under normal conditions and the current at tropical latitudes must be completing its circuit over the magnetic equator. The rocket-borne magnetometers have shown that the normal electrojet current flows at the height of about 107 km (Maynard 1967; Davis *et al.* 1967; Sastry 1968).

Thus, it is suggested that there are two current systems existing during the periods of counter-electrojet events such that over the magnetic equator eastward current flows at the height of about 107 km and westward current at about 100 km. It is the net effect of these two currents, that is recorded in ground magnetograms. It may be that during strong counter-electrojet events the westward current may extend over the entire height range of the enhanced conductivity in the *E*-region over the magnetic equator.

During the first type of counter-electrojet, the development of the westward current at 100 km is rather rapid and it more than balances the normal current at higher level causing the *H* field measured at ground to show a depression. During the second type of counter-electrojet, the westward current at 100 km develops rather slowly such that the H field observed at ground decreases to the nighttime level sometime after the disappearance of Es–q. During the third type of counter-electrojet, westward current at 100 km is smaller in magnitude than the normal current at 107 km and is not able to cause a depression of the H field at ground level below the nighttime level but the reversal of electrostatic field causes the disappearance of the Es–q layer.

Regarding the sources of the reversed current in the E-region of the ionosphere, Bartels and Johnston (1940) were the first to suggest a prominent effect of the moon on the geomagnetic field variations near the equator. The control on the occurrence of counter-electrojet of the moon has been clearly demonstrated by Hutton and Oyinloye (1970), Sastri and Jayakar (1972), and Rastogi (1973 *a*, 1974 *b*). Similarly the disappearance of the equatorial Es has been shown to be significantly affected by the moon (Matsushita 1951; Bandyopadhyay and Montes 1963). These lunar current systems have comparatively large periodicities and may be caused by the second type of counter-electrojet described earlier.

Rastogi (1973 *b*) has shown the association of some events of Es–q disappearance with the DP_2 type of polar substorms. This type of substorm is suggested by Nishida (1971) to be associated with the magnetospheric electric field. The third type of counter-electrojet could be associated with these relatively shorter period of Es–q disappearance events.

The very sharp changes in the electrojet, exemplified by the first type of counter-electrojet, have to be caused by very sudden reversals of the electrostatic field. One of the possible sources of such changes have been suggested by Patel and Rastogi (1974) that the sudden disappearance of the Es–q at Huancayo was associated with the sudden reversal of the interplanetary magnetic field component perpendicular to the ecliptic (B_z) from the southward to the northward direction. It was suggested by them that the electric field $E = - V \times B$ associated with the solar wind interacting with the B_z field is responsible for causing these sudden changes in the equatorial ionosphere.

Onwumechilli *et al.* (1973) have shown that the suppression of the H field on moderately disturbed days, the daily variation $S_q{}^p$ is enhanced in the polar cap region and the electric field associated with the enhanced $S_q{}^p$ influences the equatorial electrojet by suppressing it. They suggested that the magnetic variations along the dip equator are influenced by a number of processes in the magnetosphere.

The large day-to-day variations of the daily range of the H field at equatorial latitudes uncorrelated with the variations of the H field at regions outside the electrojet latitudes may be due to independent sources for the variations in the two current systems.

Conclusions

1. There are basically three types of associations between the decrease in the *H* field and disappearance of *Es–q* near the magnetic equator. The *Es* may disappear almost at the instant when the ΔH becomes negative or slightly before the period of negative ΔH values or even during a depression of ΔH which does not decrease below the night level.

2. The value of ΔH at the equator may be positive during the period of *Es–q* disappearance but the difference of ΔH between an equatorial and a non-equatorial station definitely shows a negative value.

3. The ionospheric drifts are definitely reversed towards eastward during the period of the disappearance of *Es* whether the counter-electrojet is complete or partial.

4. The reversal of drift and disappearance of the *Es–q* in any of these events indicate a reversal of the current or the electric field at the base of the *E*-layer where *Es–q* is seen to occur, *i.e.*, at about 100 km level.

5. Events where *H* does not decrease below the nighttime level and *Es–q* disappears indicate a net eastward current besides the westward current at 100 km. This eastward current is suggested to be normal *Sq* current at about 107 km level.

6. The source of the upper current is suggested to be the *Sq* dynamo current system. The lower current may be associated with the lunar current system or due to the electric fields generated by the interaction of solar wind with the magnetosphere or by the various polar substorm processes.

7. The relative independent variations of the geomagnetic *H* field at the equator and at latitude outside the electrojet region may be due to combined effects of these two rather independent current systems.

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