EQUATORIAL SPORADIC E AND CROSS-FIELD INSTABILITY

BY R. G. RASTOGI

(Physical Research Laboratory, Ahmedabad-9)

and

(Indian Institute of Astrophysics, Kodaikanal-3)

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ABSTRACT

The occurrence of sporadic E at an equatorial station during magnetically quiet daytime conditions corresponds almost exactly to the time during which the horizontal component of the earth's magnetic field is above the mean night time level. Any large decrease of H below the night time level is accompanied by the disappearance of equatorial E_s-q reflections precisely for the period when the value of H remains below its night time level.

Such disappearance of E_s-q can be attributed to the reversal of the current equal to, or greater than, the normal eastward equatorial electrojet current. During magnetically disturbed conditions, however, the depressions in H are not always accompanied by the disappearance of E_s-q.

Whenever the normal E and sporadic E reflections can be resolved on the equatorial ionograms, the minimum virtual height of the normal E is seen to be clearly greater than that of the sporadic E layer.

The creation of E region irregularities at equatorial latitudes giving the appearance of an E_s-q layer in daytime ionograms is suggested to be due to cross-field (plasma gradient) instability. The horizontal magnetic field and the upward Hall polarisation (electric) field produce irregularities in the lower E-region where the rate of increase of ambient electron density is large and directed upward.

A temporary reversal of the electrojet current indicated by a decrease in H below the night time level and the disappearance of E_s-q are due to the temporary reversal of the vertical Hall polarisation field making it downward instead of upward which being opposite to the direction of the gradient of plasma density inhibits the cross-field instabilities.

EQUATORIAL ELECTROJET AND ASSOCIATED SPORADIC E LAYER

J. EGEDAL (1947) showed that an enhancemnet of the solar daily range of the horizontal geomagnetic field (H) occurs in a narrow zone near the magnetic equator. It was shown by Matsushita (1951) that a similar narrow belt of abnormally high frequencies of sporadic radio wave reflections from the E layer of the ionosphere (E_s) was also observed. Knecht and Mc-Duffie (1962) showed that the equatorial E_s occurs over a width of about 700 km around the magnetic equator which agrees well with the width of the equatorial geomagnetic field enhancements. This is attributed to the intensification of eastward flowing electric currents in the E-region of the ionosphere and is called the "Equatorial Electrojet".

The most notable feature of equatorial sporadic E is the high frequency of its occurrence during daytime; E_s was seen on about 93% of the records at Kodaikanal between 0600 and 1600 hr. during each of the seasons (Rangarajan, 1954). Lunar effects have been found at the time of dis-appearance of E_s in the evening (Matsushita, 1957), at their first appearance in the morning (Knecht, 1959), and in the total duriation of E_s (Bhargava and Subrahmanyan, 1963). These effects have been suggested to be due to the effect of lunar tides on the normal solar electrojet currents.

CHARACTERISTICS OF E_s IN IONOGRAMS AT EQUATORIAL STATIONS

The E_s reflections at equatorial stations have many characteristics which are different from those of mid-latitude E_s. Cohen *et al.* (1962) classi-fied the E_s echoes into two types: (1) equatorial q-type sporadic E ($E_s - q$) and (2) equatorial slant sporadic E ($E_s - s$). The $E_s - q$ occurs at a virtual height of 100 km while $E_s - s$ is seen as a diffuse trace emerging from the former at a low frequency and rising in equivalent height with increasing frequency.

Knecht (1959) has described the following main characteristics of $E_s - q$:

(1) it occurs only during day hours;

(2) it is always partially transparent to the probing radio waves and never blankets radio reflections from higher layers;

(3) it has usually a well-defined lower edge although scattered and diffuse echoes can be seen above the principal echo;

(4) in well-developed cases, the diffuse echoes start at about f_0E and increase in height with increasing frequency;

(5) multiple echoes of $E_s - q$ are not generally observed;

(6) the maximum frequency reflected from $E_s - q$ may extend beyond 13 MHz.

A few examples of equatorial E_s echoes are shown in Fig. 1 for Kodaikanal and in Fig. 2 for Huancayo.

Referring to Fig. 1, the ionogram at 1030 hr on 11 May 1954 shows E_s reflections within a triangular area starting from f_0E and having a sharp lower boundary at 100 km., the $E_s - q$ reflections extend upto 13 MHz. On the ionogram at 0745 hr on 1 February 1954, only the bottom and top boundaries of the triangular area are seen and both $E_s - q$ and $E_s - s$ are distinguishable.

On occasions when the scattered reflections are weaker, one can clearly see the q type E_s, the slant E_s as well as the normal E reflections (refer to the ionogram at 1500 hr on 25 August, 1954). On some occasions slant E_s is not seen and only $E_s - q$ and the normal E traces are recorded (refer to the ionogram at 1445 hr on December 30, 1958). It is important to note that whenever the normal E reflections can be seen resolved from the sporadic E reflections, the virtual height of the normal E-layer (h'E) is greater than that of the E_s layer ($h'E_s$).

In Fig. 2 are reproduced some examples of ionograms at Huancayo showing simultaneously both the normal E as well as sporadic E reflections. The ionogram for 12 January 1964, 1245 hr shows strong diffuse reflections from $E_s - q$ upto 8·0 MHz; the normal E region reflections are also clearly seen with f_xE equal to 4·4 MHz. The record for 18 January. 1964, 1600 hr. shows weak E_s reflections simultaneously with normal E and E_s reflections from higher levels. The records for 16 December 1957 and 30 December 1957 show both the O and X components at the E-region reflections above the level of E_s reflections. Thus it may be concluded that whenever the normal E as well as the $E_s - q$ reflections are simultaneously recorded and resolved in the ionograms, the virtual height of E-layer is greater than that of the sporadic $E_s - q$.

The Diurnal Variation of $E_s - q$ Occurrence

In Fig. 3 are shown the variations of f_0E_s and the H component of the magnetic field at Kodaikanal on 20 and 23 May, 1965. Both these days were magnetically quiet, the A_p value being 4 on the 20th and 5 on the 23rd. At none of the three hourly intervals on these days did the K_p figure reach even 3. The symmetrical ring current effect on these days, according to Sugiura and Cain (1970), was not more than 15 γ. Thus it is reasonable to assume that the geomagnetic field changes on these days, were primarily due to currents flowing in the ionospheric dynamo region.

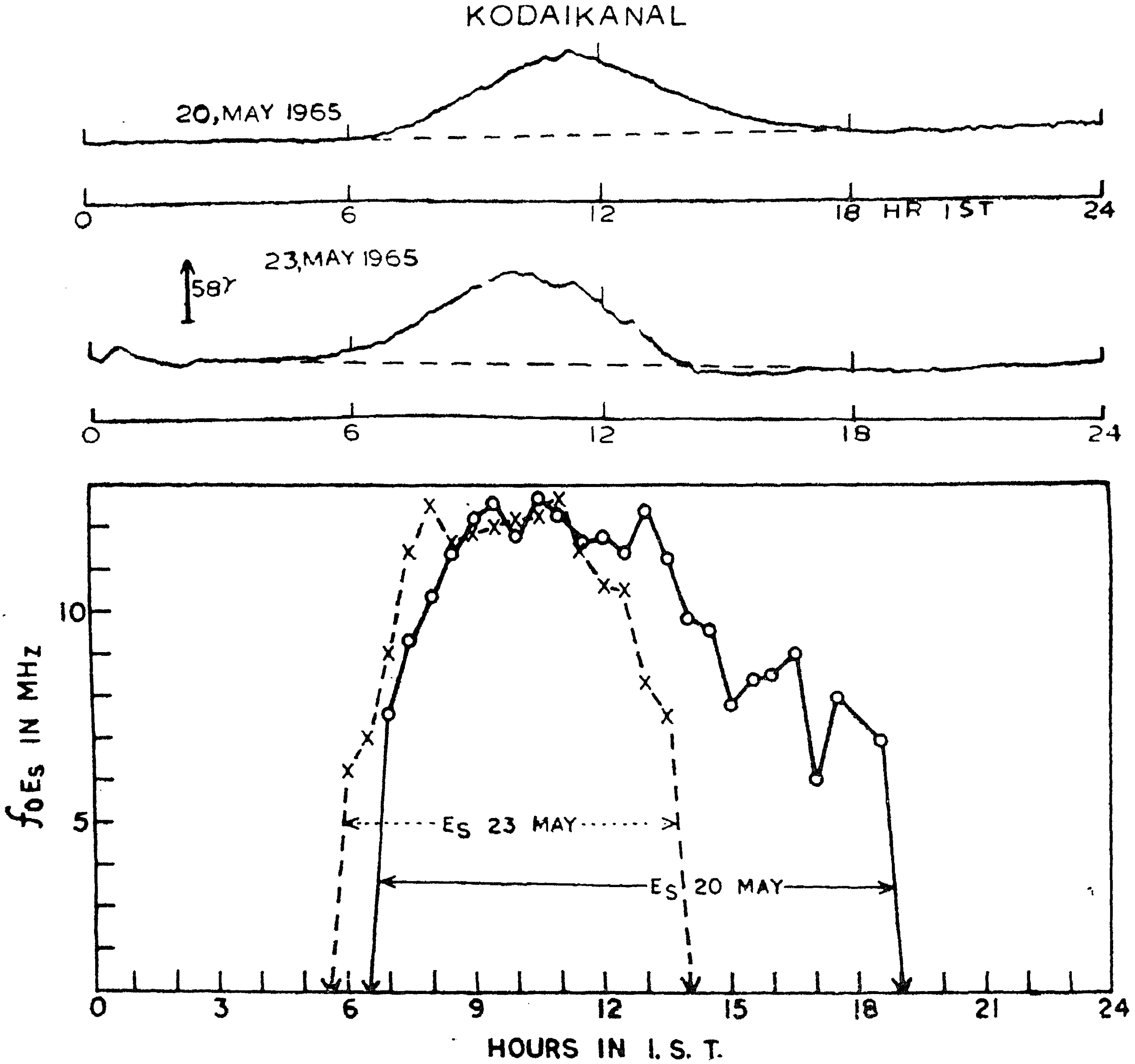

FIG. 3. Daily variations of f_0E_s at Kodaikanal on two magnetically quiet days with different periods of duration of the eastward equatorial electrojet current.

It is seen from the figure that on the 20th May, E_s appeared at about 0700 hr. and disappeared after 1800 hr. while on the 23rd it appeared at about 0500 hr. and disappeared after 1330 hr. Referring to the magnetograms the H field was above its night time level from about 0630 to 1800 hr on

20th May and from 0530 to 1400 hr on 23rd May. These periods, when H is above night time levels of H, correspond to the periods of eastward electrojet current. Comparing these two periods and similar occasions on other days, it can be inferred that the $E_s - q$ at equatorial stations occurs during the period when the electrojet is eastward, *i.e.*, when the electrostatic field during the dynamo current is eastward.

Equatorial Sporadic E and Geomagnetic Field Variations

The backscatter radar studies at Jicamarca have shown that the thin stratum of magnetic field-aligned irregularities embedded in the E-region is closedly associated with the equatorial electrojet currents (Bowles and Cohen, 1962). Cohen *et al.* (1962) have shown that the increased equivalent ranges of slant E_s are due to obliquely scattered radio wave reflections from field-aligned irregularities.

Cohen *et al.* (1962) have also shown a case of disappearance of $E_s - q$ coincident with the diminution of geomagnetic H component. Bandyopadhyay and Montes (1963) have examined the Huancayo magnetograms and ionograms of 1958 and found that 82% of the cases of the disappearance of E_s were associated with troughs in the H trace. Bandyopadhyay and Montes (1964) have also noted a simultaneous decrease of field strength of the VHF forward scatter with the disappearance of $E_s - q$ layer at Huancayo.

Skinner and Wright (1957) found that the mean fE_s at Ibadan (dip 6° N) during daytime hours was lower on disturbed than on quiet days. Further, on a few occasions, abnormally low values of fE_s were seen simultaneously with the decrease of H. Bhargava and Subrahmanyan (1961) observed that E_s at Kodaikanal disappeared for several hours during the main phase of magnetic storms. Rastogi *et al.* (1971) have shown that at stations close to the dip equator a large decrease of H during the daytime is accompanied by the disappearance of E_s and a reversal of the direction of electron drifts from westward to eastward. They suggested that the temporary disappearance of equatorial E_s during the daytime hours is due to the suppression or reversal of the electrojet current caused by the imposition of an additional electrostatic field opposite in direction to that of the normal S_q field.

In this paper are discussed the relation between the changes in the H component of the geomagnetic field, the disappearance of E_s based on observations of rapid soundings of the ionosphere over the magnetic equator and a possible mechanism for the formation of $E_s - q$. The observations refer to the equatorial stations Kodaikanal (Geog. long. 77·5° E, magnetic dip 3·5° N) and Huancayo (Geog. long. 75·3° W, magnetic dip 2·0° N).

On magnetically quiet days the H component of the geomagnetic field at low latitudes remains fairly constant during the night; it starts to increase at about sunrise attaining a maximum between 11 and 12 hr local time and returns to the night time value by sunset. On certain occasions during low sunspot years a significantly large depression of H is noticed for several hours in the afternoon.

An example of such an event observed at Kodaikanal on 16 January 1967 is shown in Fig. 4. The value of A_p for the day was 9 and C_p 0·5. There was a s.s.c. type of geomagnetic storm on 13th January at 1202 UT which ended on 14th January at about 15 hr UT. Thus the 16th January could be considered a magnetically quiet day. The magnetogram for the day shows the usual increase of H after sunrise with a peak at 10–11 hr local. Between 14 and 16 hrs. local the H field decreased to a level lower than the night time level. The corresponding ionograms show $E_s - q$ upto 1430 hr but from 1445 hr to 1630 hr, $E_s - q$ was absent and only the normal E layer reflections were seen in the ionograms. The sporadic E reflections reappeared at 1645 hr. Thus the disappearance of $E_s - q$ corresponds to the period of the decrease of H below its base level.

Another extremely interesting example of the disappearance of $E_s - q$ during the decrease of H field is shown in Fig. 5 for Huancayo on 15th January 1964. Some of the ionograms which showed the reflections from E_s layer are also reproduced. The diagram also shows the equatorial D_{st} values computed by Sugiura and Cain (1970). 15th January 1964 was one of the five International Quiet days of the month, the value of A_p for this day was 2 and magnetic character figure (C_p) was 0·0. Thus it is seen that the day was a classified quiet day, and as such the variations of H on this day were not affected by super-ionospheric currents. The depression of H around 14–15 hr could only be due to ionospheric currents flowing in a direction opposite to the normal ones. If the line joining the early and last parts of the day s considered as the base value of the magnetic field, the magnetogram above this line would indicate an eastward current while the portion below, shown shaded, would indicate a westward current. According to this, a reversal of the current occurred between 1220 hr and 1640 hr.

The ionograms at 1,000 hr, 1100 hr, and 1200 hr clearly show the presence of strong equatorial sporadic E with fE_s about 8·0 MHz. At

1215 hr, although fE_s has not decreased, the amount of scattered echoes are less. At 1220 hr there are only very weak E_s echoes while at 1230 hr there are no E_s echoes at all. It is to be noted that the minimum virtual height of the normal E layer is slightly greater than that of E_s layer. The E_s reflections were not seen on all ionograms till 1600 hr. At 1630 hr, weak E_s echoes appeared and at 1640 hr strong E_s reflections were recorded. At 1700 hr fE_s exceeded 8·0 MHz. It is interesting to note that the times of the beginning and end of no-E_s condition coincide fairly well with the times of the reversal of the current.

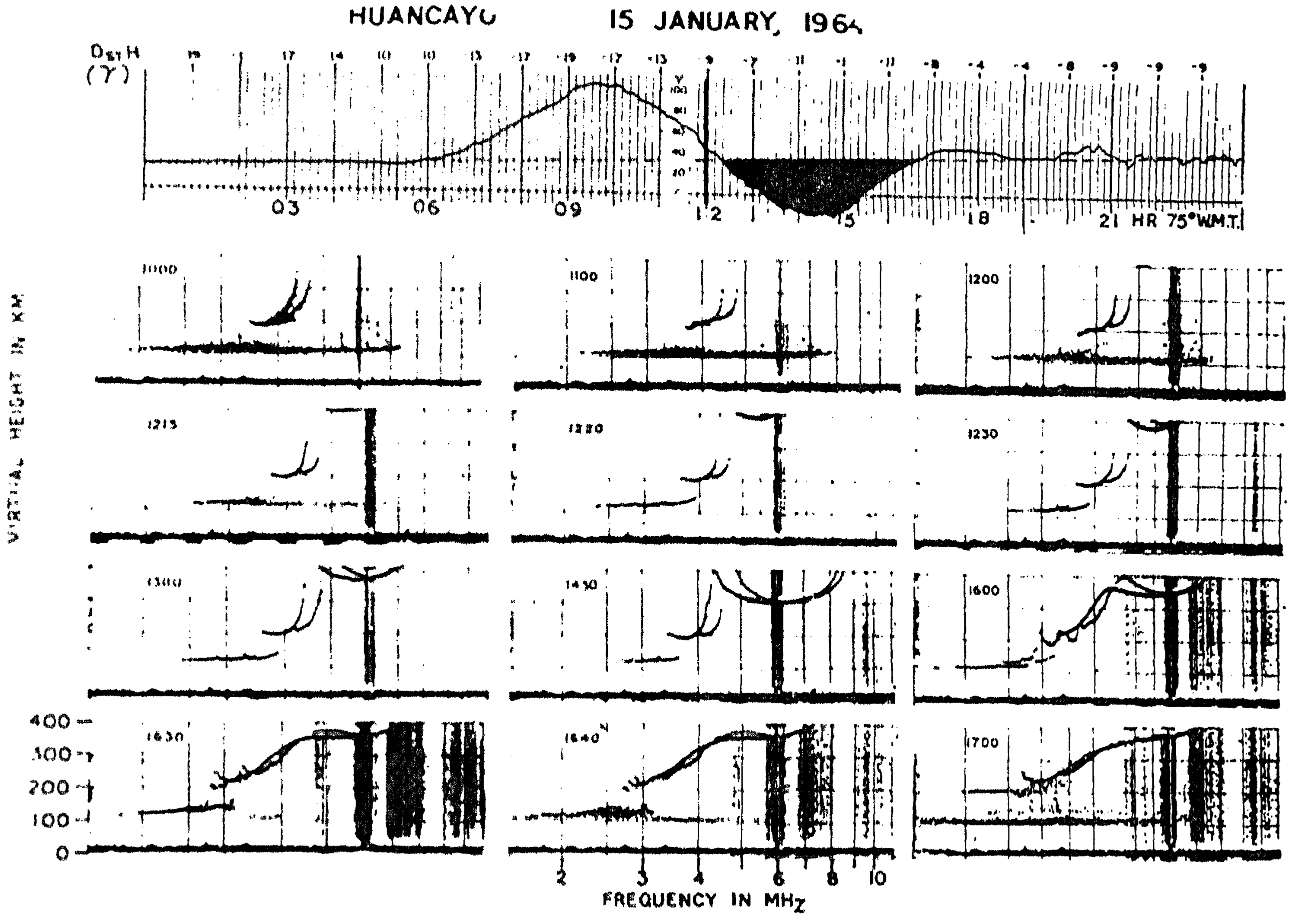

FIG. 5. Magnetogram and ionograms of Huancayo on a magnetically quiet day (15th January 1964) showing a temporary depression in H and disappearance of E_s.

An example of equatorial ionograms during a magnetic disturbance on 13th December 1958 is shown in Fig. 6. This day was one of the five International Disturbed days of the month; A_p and C_p being equal to 50 and 1·6 respectively. An SC type geomagnetic storm has started at 1000 hr UT (*i.e.*, 1901 hr, 75° L.T) on 12th December 1958. The magnetograms show large fluctuations in H during the whole day; the values of H after 1400 hr were generally lower than the night time level indicating the main phase of the storm. The D_{st} values taken from Sugiura (1964) indicate that the ring currents had significant effects in the H variation after about 1000 hr. The ionograms taken during the period are also reproduced. To compare an individual ionogram with the corresponding geomagnetic field H variation, various depressions on the magnetograms are labelled by the letters A, B, C., etc., upto I.J. The letter enclosed within circles correspond to the absence of sporadic E and those inside squares indicate the presence of E_s reflections at that time.

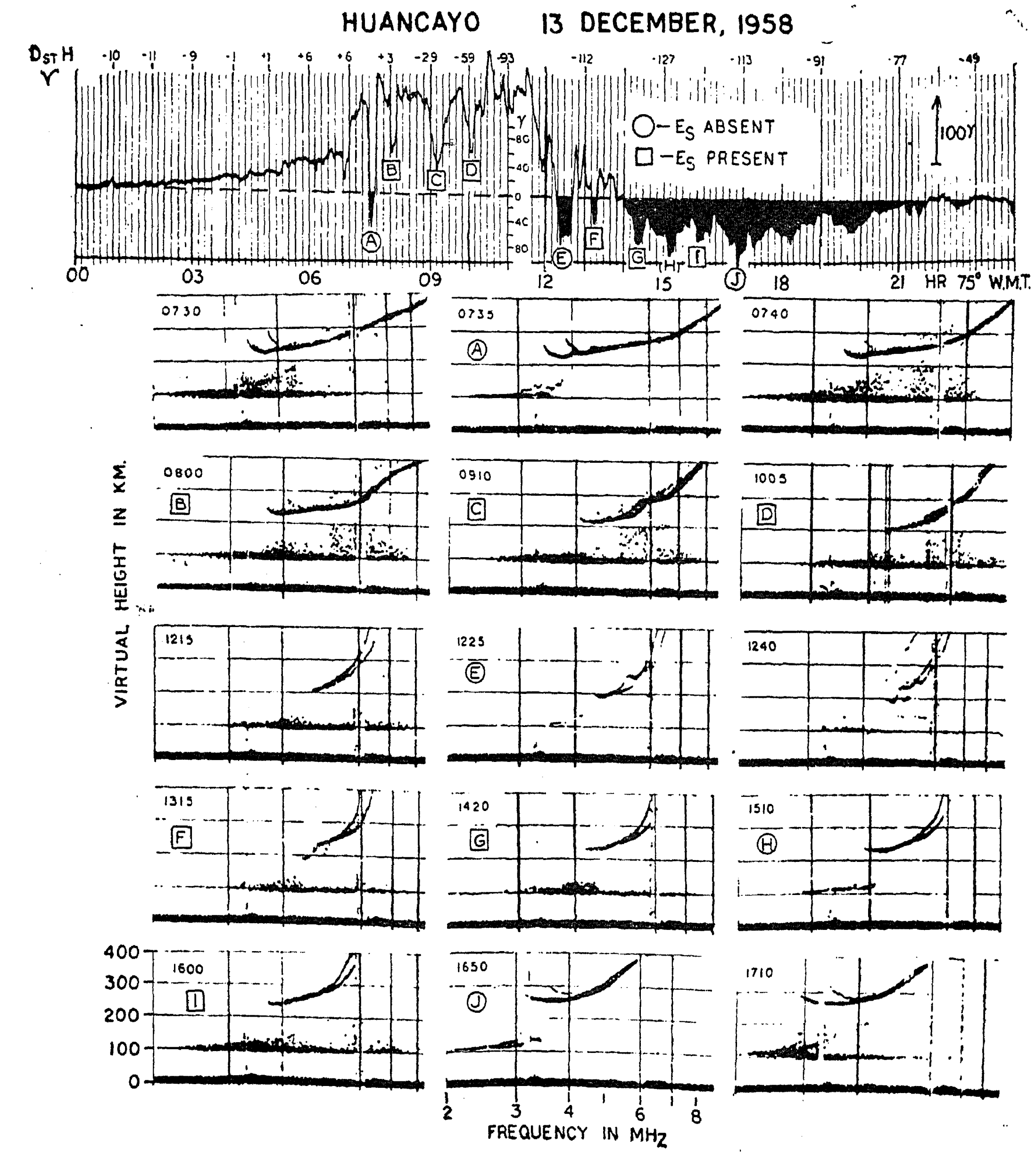

FIG. 6. Magnetogram and ionograms at Huancayo on a magnetic disturbed day (13th December 1958) showing the disappearance of E_s at the times of sharp decreases of H.

Between 07 and 08 hr, D_{st} values are low and a very sharp and large depression in H component is seen between 0730 hr and 0740 hr; the mini-

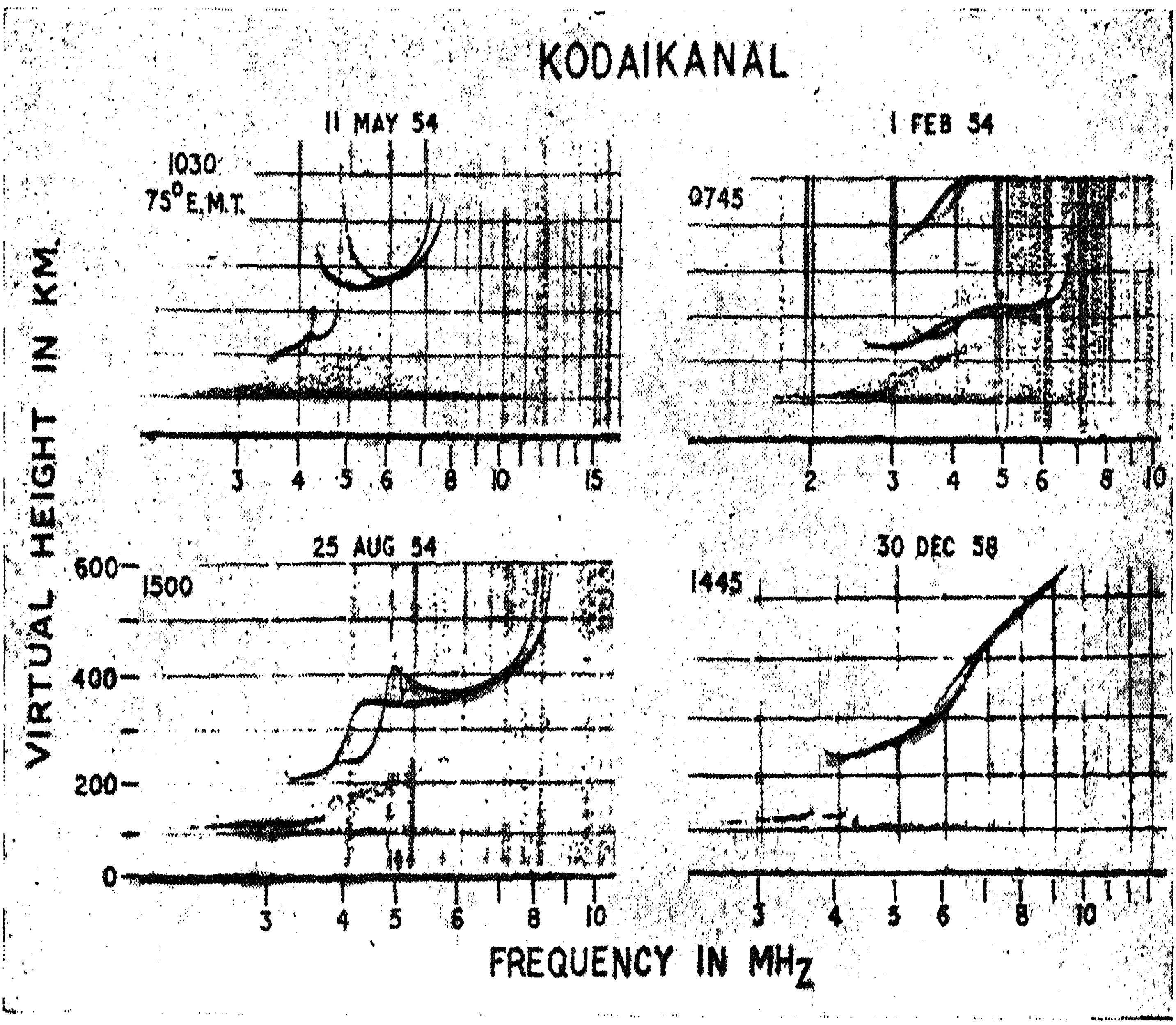

FIG. 1. Few examples of E_s reflections at the equatorial station Kodaikanal showing normal E, slant and *q* type E_s reflections.

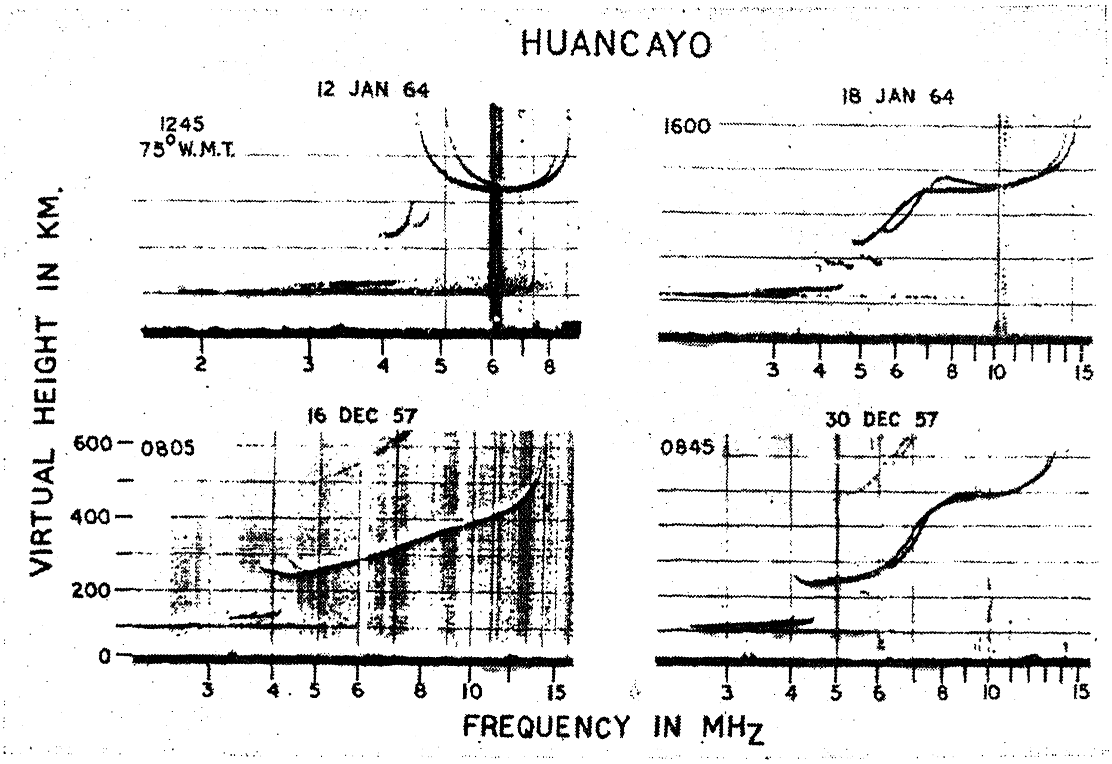

FIG. 2. Few examples of E_s reflections at the equatorial station Huancayo showing the traces due to normal E as well as $E_s - q$ layers simultaneously seen. Note $h''E$ is greater than $h'E_s$ in each of the cases.

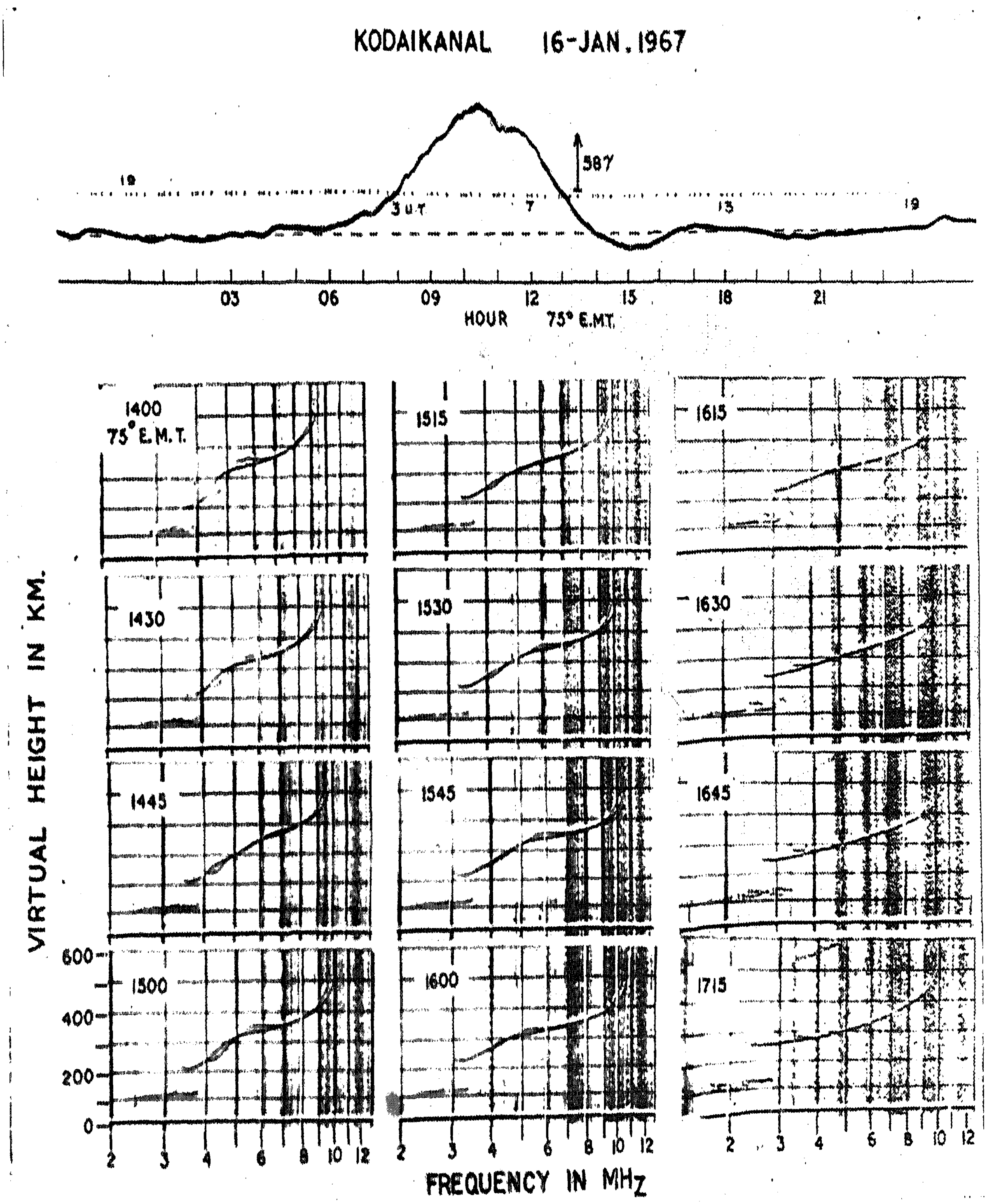

FIG. 4. Magnetogram and ionograms at Kodaikanal on a magnetically quiet day (16th January 1967) showing a temporary depression in H and the disappearance of $E_s - q$ layer.

mum reaching a level below the night time level occurred at 0730 hr (A). The corresponding ionograms show strong E_s reflections at 0730 hr and 0740 hr but the E_s was completely absent at 0735 hr Large depressions in H occurred at 0800 hr (B), 0910 hr (C) and 1005 hr (D); one of these (C) reached almost the night level of H. The corresponding ionograms show strong E_s reflections at all these times. The next depression occurred at 1225 hr (E); the minimum value reached much below the nigh time level. E_s was present at 1215 hr and 1240 hr but was completely absent at 1225 hr. There were other depressions at 1315 hr, 1425 hr, 1510 hr, 1600 hr, 1650 hr and 1710 hr, but only a few of these were associated with the absence of E_s. During this period the main phase had set in and many of these fluctuations could have been due to the magnetospheric current variations.

These observations indicate that depressions of H which occur even during quiet conditions can inhibit the $E_s - q$ layer at equatorial stations. The value of H should decrease below a threshold value which is nearly the night time level of H. Rastogi *et al.* (1971) have shown that the occasional absence of E_s during the daytime hours are associated with the reversal of the ionospheric electron drift direction and consequently with the reversal of the electrojet currents.

Mechanism of Producing Irregularities in the Equatorial E-Region

Cohen and Bowles (1963) working at Jicamarca showed that enhanced scattering of VHF radio waves of frequency greater than 50 MHz from the equatorial ionosphere occurred at heights and latitudes in which the electrojet flows. The scattered intensity is not perceptible until a minimum threshold of electrojet current is reached; above this value the scattered signal intensity is closely related to the strength of the electrojet. Secondly, the echoes are aspect-sensitive, *i.e.*, the direction of the radar beam must be nearly perpendicular to the magnetic field. Bowles *et al.* (1963) showed that the frequency spectrum of the echoes, when the radar is not pointing vertically, usually consists mainly of a fairly sharp peak showing a discrete Doppler shift. The magnitude of this shift is roughly independent of the angle between the beam and the jet current, while the direction of the shift depends on whether one is looking east or west. The Doppler shift for 50 MHz signal is found to be 120 ± 10 c/s which corresponds to a line-of-sight velocity of 360 meters per second. The irregularities responsible for these reflections are called type I irregularities.

Fairley (1963) suggested that the scattering of VHF signals from the equatorial ionosphere is due to electron density fluctuations generated by two-stream instability that occurs when there is sufficient relative velocity of the electrons with respect to the ions. By extending the theory to allow for the presence of the magnetic field, and for collisions with neutral particles, he explained the aspect sensitivity of the received signals and the association of the signal strength with the change in magnetic field. The discrete Doppler shift corresponds to the speed of the acoustic wave in the medium.

Cohen and Bowles (1967) showed the existence of another type of irregularities in the equatorial electrojet which are resolvable in the spectrum when the radar is directed either nearly vertical or at most of the angles when the electrojet is comparatively weak. These irregularities, known as type II irregularities, were shown to move with approximately the electron drift velocity, and were suggested to exist when the electron drift is insufficient to produce type I irregularities. Using radar measurements of the electrojet at about 16, 50 and 146 MHz, Balsley and Farley (1971) found that the strength of type II irregularities decreases more rapidly with increase in frequency than the strength of type I irregularities. As a result the signals on 16 MHz is predominantly from the type II irregularities while the 164 MHz signals are only due to type I irregularities.

Cohen and Bowles (1963) extended the results of VHF radar studies to the frequencies used in ionospheric sounding radars (1–25 MHz) and suggested that the irregularities responsible for the equatorial sporadic E configuration were due to plane waves of electron density aligned with the magnetic field but moving perpendicular to it. In view of the recent results by Balsley and Farley (1971), the scattered signals responsible for the equatorial E_s would be mostly type II even at the time of strong electrojet current due to the longer wavelength of radio waves used in normal ionospheric soundings.

One of the possible mechanisms of producing irregularities in the equatorial E-region seems to be the plasma gradient or cross-field instability. Simon (1963) was the first to show theoretically that in the presence of an external d.c. electric and a d.c. magnetic field directed at an angle to each other, a weakly ionized plasma is subjected to an instability if there exists an appreciable gradient of plasma density. This mechanism was applied by Maeda *et al.* (1963), Tsuda *et al.* (1966) and Reid (1968), to the mid-latitude ionosphere to explain E_s and spread-F.

Knox (1964) showed that in typical conditions obtained in the equatorial electrojet, field-aligned, plane wave irregularities in ionisation density of angular wave number less than 1 ms^{-1} grow in amplitude. The velocities all have an east to west component. This mechanism explains some features of the observed irregularity pattern not predicted by the Farley theory of two-stream instability. At night the direction of flow of electric current is opposite to the daytime direction and the vertical electric field is downward. The gradient of ionisation remains in the same direction and the irregularities are damped instead of being amplified as during the day. Thus he showed that this part of the ionosphere should be smoother than the neighbouring regions.

Rogister and D'Angelo (1970) examined different mechanisms for the production of type II irregularities in the equatorial electrojet and showed that the vertical gradient in the plasma density is essential for the excitation of these irregularities.

Whitehead (1971) has considered a model in which the ion collision to gyrofrequency (ν_i/ω_i) changes from 50 to 1 as the height increases from 95 to 120 km. and the electron density varies in different ways. If the upward ionisation drift velocity during daytime exceeds 3 m $sec.^{-1}$ or downward velocity during night time exceeds 0·1 m $sec.^{-}$ the ionosphere should be unstable.

During a rocket flight with langmuir and plasma noise probes over the magnetic equator, Thumba, during the night time hours Prakash *et al.* (1970) detected plasma density fluctuation irregularities with scale size 30–300 m. During the daytime hours these irregularities were seen in the height range where the electron density gradient was upward while during the night time hours these irregularities were detected only in the region where the electron density had negative gradient with height. They ascribed these irregularities to cross-field instability in the ionosphere.

EQUATORIAL E_s AS THE CAUSE OF CROSS-FIELD IRREGULARITIES

In the presence of d.c. electric and magnetic fields at right angles to each other within a plasma, cross-field irregularities can be produced only when there exists a gradient of plasma density in the same direction as the electric field.

In the presence of an east-west electrostatic field (E) in the equatorial E-region the horizontal electron velocities are due to Pedersen mobility

(σ_1) due to E, a Hall mobility (σ_2) due to polarization field $E_p = (\sigma_2/\sigma_1)$ E. Within the electrojet region, σ_2 is roughly 20–30 times σ_1. During the daytime the horizontal electrostatic field (E) is eastward causing the Hall polarisation field (E_p) to be directed upward. As shown earlier the sporadic E ionization near the magnetic equator occurs at the base of the E-region where the electron density gradient is directed upward. Thus the situation near the magnetic equator presents favourable conditions for the creation of cross-field instabilities; the magnetic field being northward and the plasma gradient and the polarization field both being upward. During the night time the horizontal electric field becomes westward causing the vertical polarisation field to be downwards, inhibiting the cross-field instabilities, this is confirmed by the absence of E_s at night near the magnetic equator when the gradient in electron density is still upward.

The absence of E_s during the temporary decrease of H is caused by the imposition of an additional westward horizontal electric field of significant magnitude over the original eastward S_q field.

CONCLUSIONS

1. The duration of equatiorial sporadic E ($E_s - q$) during the daytime corresponds to the period when the geomagnetic H component is above the night time level, *i.e.*, during which the electrostatic field in the E-region is eastward.

2. The $E_s - q$ occurs at the base of the E-region, and not near the peak of E-region ionisation density.

3. During magnetically quiet conditions, the $E_s - q$ can disappear suddenly even during the daytime when the H-field decreases below the night level.

4. During magnetically disturbed conditions, the $E_s - q$ does not always disappear during large decreases of H. It seems that the changes in H caused by currents outside the ionosphere during disturbed conditions of the magnetic storm-type do not affect $E_s - q$.

5. The disappearance of $E_s - q$ on quiet or disturbed conditions is accompanied by the reversal of ionospheric E-region drift. The reversal of electrojet current is caused by temporary imposition of additional westward electrostatic field equal to or greater than the normal eastward S_q field.

6. The $E_s - q$ is shown to occur near the base of the E-region (100 km) where the vertical gradient of electron density as well as the Hall polarisation field is maximum and not at the height of maximum electron drift velocity which is about 108 km.

7. The creation of irregularities giving $E_s - q$ reflections on ionograms is identified as cross-field (or plasma gradient) instability. The horizontal northward magnetic field interacting with the plasma having vertically upward gradient in presence of vertically upward Hall polarization field makes the plasma unstable causing E_s irregularities.

8. The temporary disappearance of $E_s - q$ during daytime is caused by the imposition of additional westward electric field, causing the Hall polarisation field to become vertically downward which being opposite to the direction of plasma gradient, causes the inhibition of the irregularities.

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