Equatorial Counter Electrojet & Interplanetary Magnetic Field

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The characteristics of equatorial counter electrojet events associated with the reversal of the $B_z$ component of interplanetary magnetic field (IMF) are discussed and compared with those of events associated with semi-diurnal luni-solar tides. The counter electrojet events due to luni-solar tides are preceded by high forenoon peaks of $\Delta H$ and very slow and smooth depressions of $\Delta H$ in the afternoon, and these events occur on a succession of days. The counter electrojet events due to the reversal of $B_z$ component of IMF from south to north show fast and shorter period variations in $H$ and occur at any time on some isolated days. At times these effects may be superposed on already existing counter electrojet of tidal origin. The relative importance of the two sources can be easily estimated by examining the magnetograms of two neighbouring electrojet stations separated in longitude by a couple of hours. The counter electrojet events due to tides are seen on the $H$ magnetograms of only the electrojet stations while the events due to the reversal of $B_z$ have their signatures at equatorial stations over an extended longitude zone as well as at non-equatorial stations and occur at the same universal time at all stations. It is the rapid change of the latitude ($\theta$) of the IMF from the southward to the northward direction in the presence of large and rather steady value of the scalar field $B$ which is effective in decreasing the equatorial electric field resulting in the counter electrojet event. Thus a comparison of the electrojet current or the equatorial electric field with hourly mean values of $B_z$ has led to misleading conclusions by some workers. The changes in the equatorial electric fields due to the reversal of IMF latitudes are seen both in the dayside and the nightside of the earth and are associated with similar changes in the auroral electric fields.

1. Introduction

The abnormal features in the solar daily variations of the horizontal magnetic field ($H$) at an equatorial station, Huancayo, were first noted by Bartels and Johnston. They demonstrated that the lunar tide in $H$ at Huancayo on certain days is so large that it modifies the solar daily variation of $H$ on a single day to such an extent that large depressions of the $H$ field are noticed in the afternoon hours. Gouin reported an event in which the daily variation of $H$ at Addis Ababa (within the electrojet) was depressed during the noon hours below the nighttime level; he attributed it to the lunar modulation of $\text{Sq}(H)$. Onwumechilli studied the lunar modulation of $\text{Sq}(H)$ at Ibadan and confirmed the existence of “big $L$” days, and also found that the intensity of $L(I)$ at two different hours of the same day could differ by a substantial amount.

This phenomenon of the decrease of $H$ field during the daytime at an equatorial station was named “counter electrojet” by Gouin and Mayaud. Hutton and Oyinloye suggested that there is no connection between the occurrence of counter electrojet and the moon as the phenomenon has been observed at all times of the lunar day, even though they found that the counter electrojet are most frequent around 0300 and 1500 lunar hours. Sastri and Jayakar showed that major afternoon counter electrojet events at Trivandrum occurred most frequently around lunar age 0000 and 1200 hrs (new and full moon days) and were practically absent around lunar age 0600 and 1800 hrs (first and third quarter moon days). Rastogi explained the observed solar and lunar times of maximum occurrence of counter electrojet events to be the result of the superimposition of the $L$ field on that particular day over the average $\text{Sq}$ field. On the same model, he predicted that the morning counter electrojet events would be most frequent around lunar ages 0600 and 1800 hrs which was later confirmed from the analysis of Huancayo data.

After studying the magnetograms of all equatorial stations for over two solar cycles, Rastogi showed that the afternoon counter electrojet events at Huancayo are about seven times more frequent in summer (December) than in winter (June); while for Kodaikanal the ratio is only two; the counter electrojets at any station are more frequent during low than during high sunspot years. All these observational facts were shown by Rastogi to be consistent with the suggestion that, on the average, the counter electrojet events are the results of the superimposition of lunar tidal wave over the solar daily variation of $H$ appropriate for the concerned longitude and epoch of the year and solar cycle. Marriott noted that the afternoon counter electrojets occur most often at all stations when the lunar phase is 1 hr and the morning
counter electrojets occur most frequently for phases 5,6 and 7 hr.

Schieldge et al.\textsuperscript{12} simulated worldwide magnetic variations observed at four universal times of a quiet day on the basis of coupled numerical models of the global ionospheric dynamo consisting of a tilted dipole field within realistic conductivity contributions and height varying tidal winds and allowed for the field aligned currents. They found that in addition to the diurnal tidal wind component, the semi-diurnal component played a prominent role in generating electric fields and currents.

Recently, Bhargava and Sastri\textsuperscript{13} showed that the electrojet field in the Indian region on days when counter electrojet afternoon event occurs is composed of two components, a normal quiet-day electrojet field and an additional field superposed on it. The additional field showed a northward component with its maximum at about 1000 hrs LT followed by a rapid decay and reversal of direction shortly after local noon reaching the maximum southward component around 1500 hrs LT which also decays rapidly and vanishes well before sunset. They found the northward additional field in the forenoon to be present on most of the days of counter electrojet afternoon event. This forenoon northward additional field is evident in the normal magnetogram because it would simply modify the intensity of the diurnal peak, while the afternoon southward field being opposite in nature to the normal $Sq$ field causes the net field to become negative giving rise to the counter electrojet event evident on just the usual perusal of the magnetograms. Earlier, Sastri and Jayakar\textsuperscript{6} had shown that the occurrence of major counter electrojet events was strongly controlled by the phase of the moon. It is thus quite reasonable to conclude that the additional field on days with the afternoon counter electrojet events detected by Bhargava and Sastri\textsuperscript{13} is of lunar tidal origin. Thus, it is very clear that a significant proportion of the counter electrojet events are associated with the lunisolar tidal wind system. Therefore, any study of counter electrojet in association with other solar or geophysical event should take care to avoid the days with distinct tidal effects.

A great interest was aroused in the studies of counter electrojet after Rastogi et al.\textsuperscript{14} showed that the depressions in $H$ at Kodaikanal were associated with simultaneous reversal of the drift velocities of the ionospheric irregularities over the equator and the sudden disappearance of the $q$-type of equatorial Es. Later, it was confirmed that the counter electrojet events at Huancayo were associated with the simultaneous reversals of the electron drift velocities measured by VHF backscatter radar at Jicamarca\textsuperscript{15}. Such an association has been shown to be true on a very small time scale of a minute or so and even during the geomagnetically disturbed periods\textsuperscript{16}.

Comparing the simultaneously recorded ionograms and magnetograms at Huancayo with the high resolution plots of interplanetary magnetic field (IMF) by Explorer 33, 34, or 35 satellites, Rastogi and Patel\textsuperscript{17} had demonstrated that a number of events of counter electrojet were associated with the IMF. They had concluded that large and quick changes in the latitude of IMF from its southward to northward direction would impose an electric field in the ionosphere from the evening to the morning sector of the earth, which would be superimposed on the $Sq$ electric field. Depending upon the magnitude of the magnetospheric electric field and the $Sq$ electric field at the concerned location and local time, the resultant electrostatic field on the equator may be decreased still maintaining the normal direction, or even reversed from its normal direction, causing a partial or complete counter electrojet events. It should be mentioned that the conclusions were arrived at after studying actual observatory records and the 81 second plots of IMF, and that no hourly mean data were used.

Fambitakoye et al.\textsuperscript{18} showed that the criterion for the disappearance of Es-$q$ is not necessarily that $H$ at the equator becomes negative but that the latitudinal profile of $AH$ and $AZ$ should reverse from its normal regular pattern. Rastogi\textsuperscript{19} showed that the condition for Es-$q$ disappearance and the reversal of ionospheric drift at Thumba was not the decrease of $AH$ at Trivandrum below its night level but $AH$ Trivandrum minus $AH$ Alibag should decrease below its night level. It was shown that the index $Sd$ as defined by Kane\textsuperscript{20} did not necessarily become negative at the counter electrojet event and is not the correct index to define the reversal of electric field at the Es-$q$ level. Rastogi et al.\textsuperscript{16} have shown that the criterion for the counter equatorial electrojet is $AH$ equatorial minus $AH$ non-equatorial stations in the same zone getting below the corresponding night level even on a very high time resolution data.

Comparing the ionospheric and magnetic data from Indian stations, Rastogi\textsuperscript{21} classified three types of counter electrojet events. He explained the observed magnetic field variations over the equator to be the result of the superimposition of two independent current systems over the dip equator, one the $Sq$ current system flowing always eastward at about 107 km and the other current system flowing at 100 km, the seat of E-region irregularities. The current system at 100 km could flow eastward or westward. The slow and large period (a few hours) depressions in the $H$-field at the equator were suggested to be caused by the lunar current system while the sharp changes (less than hour)
in the electrojet were suggested to be caused by the very sudden reversals of the electrostatic field associated with the sudden reversal of the $B_z$ component of IMF from southward to northward direction.

Patel\textsuperscript{22} re-examined the effect of IMF variations on the low latitude ionosphere by studying the simultaneous disappearance of equatorial Es-$q$ at Huancayo, the decrease or reversal of the equatorial electrojet as implied from Huancayo magnetogram signatures and a northward turning of the $Z$-component of IMF observed by Explorer 43 satellite. He quoted that the search for the simultaneous occurrence of these three phenomena met with partial success; because out of 20 events for which simultaneous data were available, 12 showed no significant change in the IMF near the disappearance of Es-$q$.

Kane\textsuperscript{23} studied about a dozen counter electrojet events and compared these with IMF data. Unlike the earlier studies by Rastogi and Patel\textsuperscript{17} and by Patel\textsuperscript{22} who used original ionograms, magnetograms and satellite IMF plots, Kane\textsuperscript{23} had used only the published hourly data of the Trivandrum $H$-field and IMF components. He noticed that only in three to four cases there was an association between counter electrojets and an excursion of $B_z$ from southward to northward. In other cases, no such association nor an association with $B_z$ gradient was noticed. He concluded that there is no clear-cut relationship between equatorial counter electrojet and IMF, and that the observed associations in a few cases could be accidental.

Recently, Fejer \textit{et al.}\textsuperscript{24} have re-examined the relationship between the equatorial electric field and IMF by comparing the E- and F-region electron drift velocities at Jicamarca with the hourly mean values of $B_z$. They noted that rapid reversals from south to north are sometimes correlated with reversals of the equatorial east-west electric field during both daytime and nighttime. However, they suggested that sometimes IMF may reverse without any apparent effect at the equator; and large equatorial field perturbations are sometimes observed when the IMF $B_z$ is large and southward but not varying drastically. It may be noted that all their curves of $B_z$ seem to be wrongly plotted with a shift of half an hour.

The equatorial counter electrojet events are not only associated with the disappearance of the E-region irregularities but also alter the mean ionization distribution over a large spatial extent at low latitudes\textsuperscript{25 - 29}. Further, even during nighttime, a reversal of the ionospheric electric field has been shown to cause the generation of spread-F and intense ionospheric scintillations\textsuperscript{30,31}. These nighttime reversals of the electric field generating the spread-F are shown to be associated with the reversal of the $B_z$ component of IMF\textsuperscript{32}.

Thus, due to the great importance of the counter electrojet in revealing the low latitude ionosphere both for the physicist as well as for the communication engineers, it was felt necessary to re-examine the data used by Patel\textsuperscript{22} and by Kane\textsuperscript{23} to determine the role of IMF in reversing the electrojet currents.

2. Analysis
First of all to obtain some statistics of the phenomenon of the disappearance of Es-$q$ at Huancayo in January 1973, the events seen on quarter hourly ionograms plotted on the grid of local time versus date are shown in Fig.1(a). In Fig.1(b) are shown the daily variations of the percent of time Es-$q$ had disappeared on the ionograms. The age of the moon is also indicated on the right-hand side of the chart. No ionograms were available for 23-31 Jan. 1973 due to equipment failure.

The Es-$q$ appeared first in the morning at 0600-0615 hrs LT, but on some days it appeared late or disappeared again and these events may be due to morning counter electrojets. During the hours 0815-1115 hrs LT, Es-$q$ was present on all the days on which observations were available. The absence of Es-$q$ in the afternoon hours was quite common, so much so that between 1500 and 1700 hrs LT these events occurred on about 70% of days. Around 1800 hrs LT there was a significant minimum in the per cent disappearance of Es-$q$, indicating that in some cases, Es-$q$ had appeared after the counter electrojet event was over. It is also very clear that on days close to the first quarter of the moon ($v=6$ lunar hours), Es-$q$ continued to exist late in the afternoon up to about 1400 hrs LT while on days close to the new and full moons ($v=0$ or 12 lunar hours), Es-$q$ disappeared even before 1200 hrs LT. Thus on even one month's data, a strong lunar control on the phenomenon of disappearance of Es-$q$ could be clearly seen.

Next, the Es-$q$ disappearance events were noted during the six summer months of 1963-64 and 1964-65 and the number of events observed was plotted on a grid of local solar time and lunar age in Fig.2. Within this period of six months, any particular lunar age would occur at the most on eight days and thus a number 8 occurring at any space indicates that Es-$q$ was absent during each of the cases with that local time and lunar age. The points indicate a very regular pattern; the Es-$q$ disappearance started earlier in the day (around 1200 hrs LT) on days with lunar age 0900-1200 lunar hours or around 2100-2300 lunar hours. There were least cases of Es-$q$ disappearance on days around $v=7$.

Thus it is concluded that the disappearance of Es-$q$ is
a fairly commonly occurring phenomenon during certain months of low sunspot years and the occurrence of the phenomenon is very strongly controlled by luni-solar tides in the ionosphere.

The disappearance of Es-q associated with the counter electrojet is observed at other equatorial stations around the world, viz. Ibadan, Huancayo, Jicamarca and Natal. Large lunar tidal effects on the geomagnetic H-field at a number of equatorial stations, viz. Huancayo, Koror, Jarvis, Addis Ababa and Trivandrum have been shown by Rastogi and Trivedi. Thus, it is quite likely that on some of the days, the tidal effects are strong enough to cause the counter electrojet in the local afternoon hours and this tidal wave may travel with the sun round the world and be observed at equatorial stations at widely separated longitudes.

One such event is evidenced in Fig.3 showing the H magnetograms on 16, 17 and 18 Jan. 1971 recorded at equatorial magnetic observatories Huancayo (75°W),

![Fig. 1](image1.png)

**Fig. 1**—(a) Chart showing the events of the disappearance of Es-q on the quarter hourly ionograms of Huancayo in January 1973 (Note that the disappearance of Es-q during this month was fairly common during the afternoon hours); and (b) daily variation of per cent of time Es-q disappeared on Huancayo ionograms in January 1973 (Between 1500 and 1700 hrs LT the Es-q was absent for about 70% of time.)

![Fig. 2](image2.png)

**Fig. 2**—Chart showing the number of events of the disappearance of Es-q on the quarter hourly ionograms of Huancayo as a function of local solar time and the lunar age, averaged over the six summer months Nov. 1963-Jan. 1964 and Nov. 1964-Jan. 1965 (Note prominent lunar control on the disappearance, being more frequent on couple of days before new and full moons.)
Fort Archambault (18°E), Addis Ababa (39°E), Trivandrum (77°E) and Davao (126°E). On 16 January, a small depression in $H$ was seen at Davao around 0730 hrs UT (1600 hrs LT). Significantly strong counter electrojet was recorded at Trivandrum around 1000 hrs UT (1530 hrs LT), at Addis Ababa around 1230 hrs UT (1600 hrs LT), at Fort Archambault around 1430 hrs UT (1530 hrs LT) and a comparatively weak depression at Huancayo around 2100 hrs UT (1600 hrs LT). Thus the counter electrojet event moved progressively westward occurring at about the same local time at all the stations on the equator around the world. Similar progression of the counter electrojet is evidenced to have been on 17 Jan. 1971 also. On the next day 18 Jan. 1971 the depression was shallower at Davao and Trivandrum but at Addis Ababa and Fort Archambault the afternoon depression was superposed by the disturbance occurring simultaneously at all stations and hence of non-local origin. There was an interesting depression of the $H$ field between 1400 and 1500 hrs UT on 18 Jan. 1971. The $\Delta H$ at Huancayo was about 150 nT, at Fort Archambault it was about 70 nT and at Addis Ababa only 30 nT. Thus, the depression was largest at a station situated closest to local noontime. However, the depression at Fort Archambault was associated with the disappearance of $Es-q$ but $\Delta H$ at Huancayo even though larger could not reverse the normal $Sq$ electric field and cause $Es-q$ to disappear. The counter electrojet events on 16 and 17 Jan. 1971 are clearly of tidal origin and any attempt to correlate these with IMF would not be proper. It is the 18 Jan. 1971 type of depressions in $H$ that are likely to be associated with magnetospheric changes caused by its interaction with solar wind. The IMF data are available for the period to check this event.

In Fig. 4 are reproduced the magnetograms at Huancayo for the days considered to be associated with the reversal of IMF by Patel. The time of disappearance of $Es-q$ in the ionogram is indicated by an arrow with $Es$. Similarly, the arrow with $Bz$ indicates the time of the reversal of the $Bz$ component of IMF as observed on-board Explorer 43 satellite. It is seen that most of these days had large tidal effects showing slow afternoon counter electrojet depressions in the $H$ magnetograms. The changes in the electric field due to the reversal of $Bz$ were superimposed on already existing counter electrojet field due to tides and hence distinct associations between the disappearance of $Es-q$ and $Bz$ component of IMF could not be ascertained from these data.

In Fig. 5 are reproduced the magnetograms at Trivandrum for the days 31 July-9 Aug. 1966 and for the days 1-9 July 1968. The age of the moon on each of the days is also indicated on the right-hand end of the magnetogram tracing.
Fig. 4—H magnetograms at Huancayo on the days studied by Patel for examining association of counter electrojet with the reversal of Bz (The arrows with Es denote the time of disappearance of Es-q on ionogram and the arrow with Bz denotes the time of the reversal of Bz component of IMF)

Kane has mentioned the counter electrojet on 7 Aug. 1966 and a change of Bz from negative to positive value. He, however, noted similar change in Bz on 6 August with very small counter electrojet. These diagrams show the tracings from actual magnetograms and not the curve derived from hourly average data. These sets of magnetograms show a strong semi-diurnal variation of H and the afternoon counter electrojet events were of tidal origin. The new moon was on 7-8 Aug. 1966 and as such the lunar age was very favourable for producing large afternoon depressions in H.

Another counter electrojet event discussed by Kane was on 6 July 1968, which he found was not associated with any change of Bz component. He reported a south-to-north change with very small counter electrojet. The lunar age on 6 July 1968 was 22 lunar hours, the most appropriate for producing large tides in the afternoon causing the counter electrojet.

Following Bhargava and Sastri, the additional field on 6 July 1968 was separated by subtracting from it the mean H-field on non-counter electrojet days with low disturbance activity. The control days chosen were 21, 22 June and 15, 20 and 30 July with mean Ap value equal to 5.4. The daily variation of H-field on 6 July 1968 for the control days and the difference field are shown in Fig.6. It is clearly seen that there was an additional northward field of about 30 nT around the noon of 6 July 1968 followed by the afternoon southward field of about 50 nT around 1500 hrs LT. Thus the counter electrojet event of 6 July 1968 at Trivandrum is suggested to be due to a strong semi-diurnal wave superimposed on the normal daily variation and not due to any changes of IMF.

Statistically, to some extent, one can guess the most favourable lunar ages for large tidal effects in H at a particular station. For a particular day, a comparison of the magnetogram for the neighbouring days would also indicate the persistent semi-diurnal tidal effects, if present. The magnitude of tidal effects in H for any of the solar daytime hours is known to be enhanced over the dip equator and as such the tidal effects in the electrojet at an equatorial station (say Trivandrum) on an individual day may not be seen in the magnetogram at a station outside the equatorial electrojet belt (say Hyderabad). It is suggested that the tidal wave being progressive and moving with the sun due to strong luni-solar coupling would move westward with time and would be clearly evident on two electrojet stations separated by a couple of hours in longitude, roughly at the same local times. If the two stations are too far separated, the wave could change itself due to

Fig. 5—(a) Reduced H magnetograms at Trivandrum during the period 31 July-9 Aug. 1966 (Note the afternoon depression in H on each of the days reaching a maximum effect around new moon day); and (b) reduced H magnetograms at Trivandrum during the period 1-9 July 1968 (Note the slow period counter electrojet effects on days near new moon and short period counter electrojet effects on 3 July 1968)
significant longitudinal effects in the geomagnetic lunar tides caused by the large variation of average electrojet current with longitude itself24. Trivandrum is probably the only electrojet station having another electrojet station west of it at similar geographic latitudes (Addis Ababa, dip = 0.5°S) and a northward non-electrojet station (Hyderabad) at similar geographic longitudes.

Let us examine the magnetograms at these three stations Trivandrum, Addis Ababa and Hyderabad on each of the days from 31 Dec. 1967 to 6 Jan. 1968 as reproduced in Fig. 7 on uniform time as well as the sensitivity scales. The tracings are reproduced from the microfilm copies of the actual magnetograms reproduced to a uniform sensitivity scale for all the stations with the help of a Bausch and Lomb Zoom Transfer Scope. Thus, all the finer resolutions in the original magnetograms are truthfully reproduced in these tracings.

Let us compare the magnetograms for 3, 4 and 6 Jan. 68 at all these three stations. On 6 Jan. 1968 a large afternoon counter electrojet was recorded at Trivandrum around 1000 hrs UT (1500 hrs LT) with almost no appreciable effect at Hyderabad. At Addis Ababa a comparatively weaker counter electrojet was evident again around 1500 hrs LT (1200 hrs UT). Some magnetospheric changes around 1400-1600 hrs UT were recorded at all the three stations at the same time and with same magnitude. The afternoon (1500 hrs LT) event of counter electrojet on 6 Jan. 1968 seen at Trivandrum and Addis Ababa is suggested to be of tidal origin and not due to any IMF changes. Similarly, the large semi-diurnal variation of the H-field at Trivandrum on 3 and 4 Jan. 1968 with the counter electrojet in the afternoon hours is repeated at Addis Ababa at the same local times with no effects at Hyderabad. Thus, the counter electrojet events between 3 and 6 Jan. 1968, discussed by Kane23 seem to be of lunar tidal origin and no correlation with the magnetospheric changes should be expected from these events.

On 2 Jan. 1968 a large depression in H-field is seen at Trivandrum in the afternoon hours which when seen in the hourly mean plot looks similar to the type of counter electrojet caused by the tidal effects. Comparing the Trivandrum magnetogram with that at Hyderabad it is seen that both the stations recorded very similar daily variations and the depressions of the H-field at the two stations were almost of the same order. The hourly plot of Sd, in Kane's paper did not show any negative value but the finer data of ΔH...
Trivandrum minus $\Delta H$ Hyderabad indicate brief periods of counter electrojet. The daily variation of $\Delta H$ at Addis Ababa was in general similar to that at Trivandrum with a number of sudden changes recorded simultaneously at the two places but the minimum of $\Delta H$ occurred more than an hour later at Addis Ababa than at Trivandrum. This particular event of counter electrojet is a mixture of both tidal as well as magnetospheric effects.

The $H$ magnetograms on 31 Dec. 1967 at Hyderabad, Trivandrum and Addis Ababa were very similar to each other. Any individual fluctuation at all of the stations was recorded at the same absolute time. This is, therefore, an excellent example when the daily variations of $H$ for Addis Ababa and Trivandrum one can detect the magnetospheric origin. Examining closely the curves but were due to currents outside the ionosphere—either the ring current or the currents of magnetospheric origin. Examining closely the curves for Addis Ababa and Trivandrum one can detect the presence of normal $S_y$ current.

Now referring to the magnetograms for 1 Jan. 1968, it is clear that Trivandrum recorded a weak and slow depression of the $H$-field around 1400 hrs LT, whereas no effect was seen at Hyderabad. Short period fluctuations in $H$ were recorded simultaneously at Trivandrum and Hyderabad suggesting the non-ionospheric disturbances present even on this day. Now, comparing Trivandrum and Addis Ababa, one finds short period fluctuations simultaneously at the two places but the general variations of $\Delta H$ were delayed by a few hours at Addis Ababa suggesting a pre-dominant local time component. Hence, one can suspect significant tidal effects on 1 Jan. 1968 similar to and smaller than those more clearly seen on succeeding days. Thus, the event on 1 Jan. 1968 cannot be taken to disapprove the association of counter electrojet event with the reversal of $B_z$ component of IMF.

Now let us examine the changes in $\Delta H$ field on 3 July 1968 mentioned earlier when counter electrojets were noticed at Trivandrum. (The days preceding and following 3 July 1968 were definitely non-counter electrojet days.) In Fig.8(a) are reproduced the $H$ magnetograms at Hyderabad, Trivandrum and Addis Ababa, all in the dayside hemisphere; all the magnetograms are traced on the same time and sensitivity scales. In Fig.8(b) are reproduced expanded versions of the $H$ magnetograms at Trivandrum and Addis Ababa on the same scales, showing finer details of the fluctuation in $H$. These are compared with the variations in the magnitude $B$ and latitude $\theta$ of the IMF as recorded aboard Explorer 35 situated at $X_{SE} = 2R_E$ and $Y_{SE} = +59R_E$. The fluctuations in $H$ at Trivandrum between 0800 and 1200 hrs UT (local afternoon) were also recorded at Hyderabad but the magnitudes of excursions were greatly reduced. The fluctuations were simultaneous at Addis Ababa, but the magnitude of the excursions were greatly increased as these occurred at local noon for Addis Ababa. The fluctuations were recorded at Huancayo at the same UT even though the station was in the pre-sunrise sector. The simultaneous recording of the fluctuations at widely separated longitudes and at latitudes strongly suggests the origin to be not in the ionosphere (like tidal effects) but at the magnetosphere levels. In the diagram, comparing the $H$ at the electrojet region with IMF components, it is seen that large depression in the $H$-field at 0830 hrs UT in the Addis Ababa and Trivandrum magnetograms is associated with similar changes of IMF latitude from southward to northward direction. It is to be noted that in the IMF the negative latitudes (southward) are plotted increasing upwards, reversed to that in the original plots of Explorer 35 data. The satellite was at $Y_{SE} = +59R_E$ and was well outside the magnetosphere. Further $X_{SE}$ being very low ($=2R_E$) the changes in the IMF parameters were observed almost at the same time at the earth and at the satellite. It is further important to note that we are discussing rather sudden changes in the latitude, in this particular case $\theta$ changed from its value of $-70^\circ(S)$ at 0830 hrs UT to $+50^\circ(N)$ at 0840 hrs UT. If these events are studied on the basis of hourly mean values of $H$, $\theta$
or $B_z$, one would not even expect a definite correlation. The hourly average value of $B_z$ was $+2.8$ nT at 8.5 hrs UT and $+4.9$ nT at 9.5 hrs UT.

Next, we would like to present an example of $H$ variation at low latitudes showing the characteristics of the effects of the IMF latitude reversal. In Fig.9(a) are shown the variations of $H$ for 25 June 1969 recorded at the electrojet station Huancayo and at the non-electrojet station Fuquene both situated on the same longitude. In Fig.9(b) are plotted the $\Delta H$ values at Huancayo between 1630 and 1900 hrs UT and are compared with corresponding variations of IMF magnitude ($B$), latitude ($\theta$) and component perpendicular to the ecliptic ($B_z$) as observed aboard Explorer 35. Note that the $\theta$ and $B_z$ plots are inverted, positive values increasing downwards. The daily variation of $H$ at Huancayo showed the usual maximum slightly before noon but a significant decrease of $H$ was noticed between 1230 and 1400 hrs LT. A relative smaller decrease of $H$ was recorded at Fuquene, too, at the same time. The decrease of $H$ at Huancayo and Fuquene are shown to be associated with the change of the IMF latitude from its value of $-75^\circ$(S) to $+15^\circ$(N) within about five minutes. During the same period there was a decrease of $B$ from 15 to 13 nT, but the component $B_z$ changed from $-13$ to $+4.5$ nT. Thus the major cause of the depression in $H$ at Huancayo is to be associated with the change in $\theta$ and not with the change of $B$ just as first suggested by Rastogi and Patel.\(^{17}\) The hourly mean values of $B_z$ were $-13.0$ nT at 16:5 hrs UT, $-11.4$ nT at 17:5 hrs UT and $-5.9$ nT at 18:5 hrs UT. It is seen that the change in the hourly values of $B_z$ is much smaller than the corresponding change in the 81 sec mean values of $B$. Thus, it should again be emphasized that for studying associations between electrojet and IMF, the original data rather than hourly mean values are to be compared.

In Fig.10 are reproduced the magnetograms at Huancayo, Fuquene and Addis Ababa as well as the daily variations of $\Delta H$ (Huancayo minus Fuquene) on 21 and 19 Jan. 1973. The corresponding variations of the IMF components $B$, $\theta$ and $B_z$ are also plotted in Fig.10. The value of $\Delta H$ (Huancayo minus Fuquene) shows negative values in the afternoon suggesting counter electrojet currents during that period. The ionograms at Huancayo indicated the absence of Es$-$ confirming the presence of westward electric field during that period. The depression of $H$ at Huancayo on 21 January was slow and was not associated with any depression at non-equatorial station Fuquene in the same longitudes or with equatorial station Addis Ababa in another longitude. On the other hand the depression of $H$ at Huancayo on 19 Jan. 1973 was associated with simultaneous though weaker depressions of $H$ at Fuquene and at Addis Ababa. This event was thus not local in character. This seems to be associated with the northward turning of $\theta$. A relatively large change of $\theta$ had occurred on 21 Jan. 1973 but it did not produce any effect on $H$ at Huancayo because of low value of $B$. Assuming the solar wind velocity of 500 km/sec the equivalent electric field associated with the change of $\theta$ was 0.9 mV on 21 Jan. 1973 and 6.1 mV on 19 Jan. 1973 event.

Rezhenov and Fel'dshteyn\(^{35}\) have shown that the fluctuations in the $B_z$ component with an amplitude of 5y produce an average fluctuations at the equator of 20y. Further, $B_z$ fluctuations with an amplitude of less than 5y most frequently observed in the solar wind do not cause noticeable changes in the magnetograms of low latitude observatories.

Fejer et al.\(^{24}\) have cited two cases of afternoon counter electrojet events at 1600 hrs LT on 12 Dec. 1968 and at 1300 hrs LT on 6 Mar. 1969 to be associated with the reversal of $B_z$. In both these cases the change of the hourly mean value of $B_z$ have been shown by them to be less than 3y. These events are re-examined to clarify the type of associations between counter electrojet and $B_z$.

In Fig.11(a) are reproduced the $H$ magnetograms at Huancayo on days 6-14 Dec. 1968 and Fig.11(b) shows the variation of the magnitude ($B$) and latitude ($\theta$) of IMF aboard Explorer 35 which was at coordinates $X_{SE} = -5R_E$ and $Y_{SE} = -60R_E$ and thus was outside the magnetosphere. The daily variation of the F-region

\[\begin{align*}
210° - 75°(S) & to \ & +15°(N) \\
1630 & & 1900 \\
-13 & & +4.5 \\
15 & & 13 \\
\end{align*}\]
velocity on 12 Dec. 1968 had been decreasing slowly leading to the afternoon counter electrojet. This is more clearly seen in the magnetogram. The depression of $H$ in the evening hours on 12 Dec. 1968 had been the normal characteristic on the days neighbouring to 12 Dec. 1968 and are clearly demonstrated in the $H$ magnetograms of 6-14 Dec. 1968. Thus the counter electrojet in the afternoon of 12 Dec. 1968 is of normal tidal origin and its origin should not be sought for in IMF variations. The magnitude of IMF on 12 Dec. 1968 was just normal being around 5-6 nT and the latitude ($\theta$) was around 0° with only minor fluctuations. It is interesting to note that on 11 Dec. 1968 there was an abnormal decrease of $H$ between 1230 and 1400 hrs LT. The magnitude of IMF around that period was high (> 10 nT) and there was a rapid reversal of the latitude at about 1230 hrs LT from a value of $-75^\circ$ to $+65^\circ$ within a few minutes. Thus the midday depression of $H$ (not leading to counter electrojet) on 11 Dec. 1968 was due to rapid northward turning of $\theta$ and hence of $B_z$. Thus the counter electrojet in the afternoon of 12 Dec. 1968 at Huancayo was of tidal origin and not due to the northward turning of $B_z$ as suggested by Fejer et al.24.

In Fig. 12 are reproduced the $H$ magnetogram on 6 Mar. 1969 together with the variations of the hourly mean values of IMF latitude ($\theta$), magnitude ($B$) and of $B_z$ derived from Heos-2 data. The figure in the work by Fejer et al.24 shows a change of only 3° in $B_z$ to be associated with the event, a value normally too small to affect the daytime counter electrojet. This event was discussed by Rastogi and Patel17 who noted that the value of $\theta$ aboard Explorer 35 had changed from almost southward to almost northward direction at 1300 hrs (75° W); the satellite was behind the earth with respect to sun causing the event at satellite to be delayed with respect to the event at ground. Examining the hourly mean value of the IMF parameters from Heos-2 data, the event was associated with the change of $\theta$ from $-68^\circ$ to $+24^\circ$ and the value of $B_z$ changed from $-3.3$ to $2.0$ nT. Thus a change of $B_z > 5$ nT seems to be a reasonable value.

Fejer et al.24 have cited cases of no effects on equatorial electric field with apparent large changes of $B_z$. They noted that neither the large increase in the northward $B_z$ component at about 1600 hrs LT on 23 Mar. 1971 did affect the ionospheric drift, nor the northward turning of $B_z$ on 13 and 22 May 1971.
affected the ionospheric drift. Referring to 12-13 May 1971, the latitude $\theta$ had changed from $-31^\circ$ at 23:5 hrs (75°W) to $+7^\circ$ at 0:5 hrs (75°W) resulting in the change of $B_z$ from $-28$ to 0.6 nT. During this event the mean magnitude $B$ was just normal being equal to 5.6 nT and $B_z$ was also only $+3.4$ nT which was too small to affect the equatorial electrojet. On 22 May 1971 the northward turning of $\theta$ was indicated around 0000 hrs (75°W) from a value of $-36^\circ$ to $+66^\circ$. However, the value of $B$ was abnormally low being less than 4 nT and thus even with large change of $\theta$, the corresponding change in $B_z$ was only about 4 nT which was again too small to affect the equatorial electric fields. On 23 Mar. 1971, a large change of $B_z$ was indicated from $-2.2$ nT at 15:5 hrs (75°W) to $+6.0$ nT at 16:5 hrs (75°W). It is to be noted that the values of IMF at 16:5 hrs were derived from Heos-2 data and the values at 15:5 hrs were derived from Imp-6 data. There was a break in the Imp-6 data for a brief period and so the variations of IMF parameters on a short time scale could not be followed. The lack of any correlation in this particular case should be noted with caution due to the mixing of data from different satellites and need not be taken as an evidence against the phenomenon on IMF changes affecting equatorial electric fields.

Fejer et al.\textsuperscript{24} have also cited examples of equatorial drift reversals not associated with northward turning of $B_z$. They noted that on 9 Aug. 1972 the equatorial drift reversal occurred when $B_z$ was weakly southward and on 31 October to 1 November the reversal took place during a period of large and steady southward $B_z$. In Fig. 13 are reproduced the variations of Jicamarca drift velocity $V_{\phi}(F)$ together with the hourly mean values of $B_z$ (Imp-5) and the high time resolution data of $\theta$ for 8-9 Aug. 1972. Comparing the variations of $V_{\phi}(F)$ with the hourly mean values of $B_z$, it is clearly seen that the reversal of $V_{\phi}(F)$ after 0100 hrs (75°W) is well associated with the northward turning of $B_z$. The temporary reversal at 0000 hrs is not reflected in the hourly mean value of $B_z$. However, comparing $V_{\phi}(F)$ with 2.5 min values (derived from IMF microfilm data) of $\theta$, it is remarkable to note that even short period reversal at 0000 hrs is associated with large northward turning of $\theta$. The main reversal of $V_{\phi}(F)$ after 0100 hrs is also clearly evidenced by the large northward turnings of $\theta$. The lack of correlation obtained by Fejer et al.\textsuperscript{24} is partly due to the fact that they were using hourly mean value of $B_z$ and partly because the values of $B_z$ are shifted in time in the wrong direction. Regarding the event on 31 Oct.-1 Nov. 1972, a comparison could not be made between $V_{\phi}(F)$ and IMF data by the author. The satellite Imp-l(6) was in the magnetosphere during this period and so the data cannot be used to obtain IMF values. IMF data book published by NASA contains the data from 12:5 to 21:5 hrs (75°W) on 31 Oct. 1972. Thus, the reversal in $V_{\phi}(F)$ at 0100 hrs on 1 Nov. 1972 could not be checked with the IMF data.

Fejer et al.\textsuperscript{24} have noted that two large changes in $B_z$ occurred during 11-12 June 1975. The daytime perturbations produced no change in the F-region

Fig. 11.—(a) Magnetograms at Huancayo for number of days during 6-14 Dec. 1968 (Note that the afternoon depression of the $H$-field was a common feature around these days, while large depression at 1300 hrs LT on 11 Dec. 1968 was an abnormal event); and (b) variation of the magnitude ($B$) and latitude ($\theta$) of IMF on 11 and 12 Dec. 1968 (Note the large northward turning of $\theta$ at 1230 hrs LT on 11 Dec. 1968 and only small and slow fluctuations of $\theta$ on 12 Dec. 1968.)

Fig. 12.—$H$ magnetogram at Huancayo on 6 Mar. 1969 showing sudden decrease of $H$ at 1230 hrs LT leading to the counter electrojet event (The variations of IMF latitude ($\theta$), magnitude $B$ and of $B_z$ show the event to be associated with the change of hourly mean value of $\theta$ from $-68^\circ$ to $+24^\circ$, of $B_z$ from $-3.3$ to $+2.0$ nT.)
vertical drift but the northward turning during the night was associated with the reversal of the drift. There were three events of the northward turning of $\theta$ during this period, one around 1300 hrs (75°W) from $-28^\circ$ to $+32^\circ$, second around 2200 hrs from $-22^\circ$ to $+5^\circ$ and the third around 0300 hrs from $-11^\circ$ to $+33^\circ$. The daytime change of $\theta$ did not produce any large effect but both the nighttime changes of $\theta$ produced large changes in the F-region drift. This only suggests that somehow the equatorial electric fields are reversed more easily during the nighttime than during the daytime hours.

The daytime reversals of the equatorial electric field can be estimated from the $H$ magnetograms besides from the VHF electron drifts or from the HF ionospheric irregularity drifts. During nighttime any reversal of electric fields causes the reversal of electron or irregularity drift velocities but the $H$ magnetograms are not affected appreciably due to very low conductivities during night. The number of VHF electron drift measurements is very few to obtain any statistics of electric field reversals. However, reasonable continuous observations have been made of the E- and F-region irregularity drift measurements at equatorial stations in India since 1964. Chandra et al. have shown that the E-region ionospheric drifts at Thumba during the daytime hours was more than 90% of times towards west and only about 10% of times towards east. But, during the nighttime the E-region drift was on $65\%$ of occasions towards east and on about $35\%$ of occasions towards west. Thus, the direction of E-region drift in a direction opposite to that expected to normal $Sq$ current system was observed at least three times more frequently during the night than during the day.

Thus, it has been amply shown that the rapid reversal of the IMF latitude $\theta$ in the presence of high mean value of $B$ does affect the equatorial electric field resulting in the depression of daytime value of $H$ which may lead to the reversal of the equatorial electrojet current. The lack of correlation in the studies by Kane, Patel and Fejer et al. has been due to the choice of improper data of electrojet or the IMF.

Fejer et al. have criticized the relation between equatorial F-region horizontal drifts at Thumba and the average value of $Bz$. They suggested that the equatorial F-region drifts are determined by the vertical electric fields in the F-region and so the results did not refer to the normal (east-west) $Sq$ equatorial electric field. Their arguments may be correct for VHF electron drifts at Jicamarca but not for the HF ionospheric drifts in E- or in the F-region. The daily variations of the E- and the F-region ionospheric drifts at low latitude stations are very similar to each other on the average as well as on individual days. Further, both the E- and the F-region ionospheric drifts in E- or in the F-region. The daily variations of the E- and the F-region ionospheric drifts at low latitude stations are very similar to each other on the average as well as on individual days. Thus, the objections by Fejer et al. to the relationship between F-region drifts at Thumba and $Bz$ are not tenable.

Kane has expressed one baffling aspect of counter electrojet. "If the turning of $Bz$ from southward to northward causes a field reversal to the normal $Sq$ field and when superposed upon it gives a depression in the normal $H$ pattern why is this superposition effect confined to a narrow zone of latitudes and even very large individual counter electrojet events at Trivandrum have no effects at Alibag?" This statement is true only for the predominant slow mode of counter electrojet events which are produced by lunar tidal wave. Depending upon the particular mode of the tidal wave it is not surprising that the large changes in $H$ near the equator are not seen at non-equatorial latitudes.

The counter electrojet events due to changes at magnetospheric level are distinctly seen at non-equatorial latitudes as shown in the examples discussed earlier for 3 July 1968, 25 June 1969 and on 28 May 1969. Even the examples shown in the original paper by Rastogi and Patel indicated simultaneous changes in $H$ at Huancayo on 23 Apr. 1967 [Fig. 1(a) contained in Ref. 17] associated with the reversal of IMF latitude; this was also seen in the magnetograms at Fuquence, San Juan and Thule. Similarly, the event on 13 Sep. 1967 mentioned in their paper [Fig. 2(a) contained in Ref. 17] was evident on all the stations Fuquene, San Juan, Thule and Huancayo. Fluctuations in $H$ on 28 Nov. 1968 at Huancayo were
electric field through the electrostatic field (E) and electric field could be caused by changes in either solar electrostatic field is superimposed on the E, To have an appreciable change in prominantly seen only at the equator. conductivities would answer the question raised by the two fields at the equator coupled with the large effect in cancelling the magnetospheric electric field would have far less would be only at the dip equator where the two fields cancellation of the Sq would be antiparallel with any chance for the effects of IMF reversals are seen at non-equatorial region, of course greatly decreased in magnitude.

Regarding the large enhancements of counter electrojet events over the dip equator and the narrow latitude zone for its occurrence, it is clear that due to special geometrical conditions the conductivities over the dip equator are greatly increased as a consequence of the Hall polarization field which itself is generated by the eastward electric field over the equator. The ground measurements of H are due to the dynamo current overhead, and it is only at the equator that this current is either eastward or westward at any time of the day. At other latitudes, below the Sq focus the current is predominantly eastward only around noon and has substantial component along the meridian in the morning and evening hours. The Sq electric field at low latitude is basically along north-south direction in the evening hours. Rastogi and Patel had shown that the electrostatic field (E = -v × Bz) associated with the changes of Bz component of IMF would be along the dusk-dawn direction, i.e. eastward if ΔBz is negative and westward if ΔBz is positive. When this large-scale electrostatic field is superimposed on the Sq field, it would be only at the dip equator where the two fields would be antiparallel with any chance for the cancellation of the Sq field. At non-equatorial stations the magnetospheric electric field would have far less effect in cancelling the Sq field there. This parallelism of the two fields at the equator coupled with the large conductivities would answer the question raised by Kane as to why the counter electrojet effects are most prominently seen only at the equator.

The coupling between the IMF and equatorial electric field through the electrostatic field (E) associated with the interaction of solar wind velocity (v) and Bz is given by E = -v × Bz. Any changes in the electric field could be caused by changes in either solar wind velocity v, IMF magnitude B or IMF latitude θ. To have an appreciable change in E, there should be a large change in any one of the three parameters. A large change in solar wind velocity would cause a compression of the magnetosphere resulting in an increase of the ground magnetic field at most of the places on earth. A change in Bz could be produced by either B or θ. A change of B would again correspond to a corresponding change of ground magnetic field. A change of θ would have pure electric field effects and would be most sensitive for equatorial latitudes. Thus, the most appropriate period when IMF would have effects in the equatorial electrojet current is when large changes in θ occur in the presence of high and steady value of B and of the solar wind velocity v. Rastogi et al. have shown that it is the sudden change of θ that causes an instantaneous change in ΔH at the equatorial station and not the change in B.

Besides the lunar tidal effects and magnetospheric effects, the equatorial electrojet current is closely associated with other geophysical phenomena. Solar flares are shown to produce changes in E-region ionization and thereby conductivities in the dynamo. Van Saben has shown the presence of small reversed vortices in the representative ionospheric current systems of solar flare effects in the morning and evening sectors of the equatorial electrojet regions. Akasofu and Chapman have suggested that part of the return current from the auroral zone can extend even up to the low and middle latitudes.

Nishida was the first to show a relationship between the IMF and the equatorial magnetic field variations. Rastogi showed that these so called disturbances in the H-field coherent at the equatorial and polar regions were associated with the disappearance of Es-q layer and hence with the counter electrojet. Comparing the DP2 disturbance in H and the E-region electron drifts at Jicamarca, Matsushita and Balsley have shown that the DP2 disturbance is due to the westward current at the equator. It has been later shown by Rastogi that large sudden decreases of H at Huancayo associated with the reversals of IMF (Bz) are accompanied by large bursts of auroral AE index suggesting coupling between the IMF and equatorial counter electrojet through the polar electrojets.

Kelley et al. showed a close similarity in the variations of east-west electric field in the Alaskan region measured by balloon-borne experiments and the east-west equatorial electric field measured by Jicamarca VHF radar during the night of 8-9 Aug. 1972. Comparing these data with the magnetic field variations at a number of low latitude stations, Rastogi showed that besides the close coupling between the auroral and equatorial electric fields, the nighttime equatorial electric fields at Jicamarca (at intervals of 10 min) were closely related to ΔH (Kodaikanal minus Alibag, the stations in the dayside electrojet region) the equatorial electric field perturbations were of opposite sign at the dark and sunlit hemispheres. It has been shown that the equatorial electric field perturbations on 8-9 Aug. 1972 were closely correlated with the perturbations of the IMF latitude (θ). The worldwide nature of such electric
field perturbations has been later confirmed by Gonzales et al. in the case of other events on 17-18 Feb. 1976, 21-22 Jan. 1976 and 13-14 Apr. 1978.

Mackawa and Maeda have shown that the distribution of the electric field in the ionosphere due to the field aligned currents of magnetospheric origin is of the same order of magnitude at middle and low latitudes as the polarization electric fields derived from the ionospheric-wind dynamo theory. They thus suggested that the $q_e$ electric field is much influenced by the field aligned currents to the extent that the electric field is sometimes reversed at low latitudes. Kikuchi et al. have shown that an electric field originating in the magnetosphere at high $L$-values communicates to the polar ionosphere along the geomagnetic field lines and then propagates instantaneously to the equator as the zero order transverse magnetic waveguide mode, resulting in geomagnetic variations similar to those in the polar regions.

Kelley et al. have proposed a model for the direct penetration of the magnetospheric electric field suggested by Rastogi and Patel. They suggested that during the recovery phase of a magnetospheric substorm, the observed equatorial perturbations may be due to a temporary imbalance of convection related charge density and shielding charges built up by the ring current. If the convection suddenly drops for example during a northward turning of $B_2$ with a consequent end to the reconnection process, the external field would vanish but the shielding would remain. This would correspond to a dusk-dawn perturbation which is eastward at night and westward during the day. The ring current which establishes these charges has a time scale of a few hours.

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References

11. Marriott R T, Richmond A D & Venkateswaran S V, J Geomagn Geoelectr (Japan), 31 (1979), 311.
40. Van Saben D, J Atmos & Terr Phys (GB), 30 (1968), 1641.
42. Nishida A, J Geophys Res (USA), 73 (1968), 5549.
43. Rastogi R G, Ann Geophys (France), 28 (1972), 717.
46. Kelley M C, Gonzales C, Mozer F S & Woodman R F,
Simultaneous measurements of the electric field in the auroral zone and at the equator during intense magnetic activity, Paper presented at fifth international symposium on equatorial aeronomy, Townsville, 25-31 Aug. 1976.


