Ground-based Measurements of Ionospheric Phenomena Associated with the Equatorial Electrojet

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Manuscript received 4 February 1972

The paper first describes the morphology of the equatorial electrojet current at different latitudes. The effects of geophysical disturbances like solar flares and geomagnetic storms as well as the regular changes like lunar tidal effects on the electrojet currents are then reviewed. The effects of equatorial electrojet on the horizontal and vertical drifts in the ionosphere near the magnetic equator and on the occurrence of sporadic E reflections near the magnetic equator, are discussed. The origin of equatorial anomaly in the F-region and the diurnal variation of \( f_0F \) at low latitudes are shown to be directly related to the electrojet. The storm time and the lunar diurnal variation in the Fa-region at low latitudes are found to be sympathetic to the corresponding variations in the electrojet. It is concluded that the F-region between ±30° dip as well as the E-region between ±7° dip is very closely connected with the equatorial electrojet currents.

1. Electrojet

1.1 Temporal and Spatial Variations during Quiet Conditions

The establishment of a magnetic observatory at Huancayo in 1922 showed, for the first time, the existence of abnormally large amplitude of the daily variation of horizontal component of the earth's magnetic field (\( H \)) near the dip equator and this was suggested as due to strong eastward current flowing over the magnetic equator. The data from magnetic observatories at Kodikanal and Madras led to the discovery that the latitudinal variation of diurnal range of \( H \) is a sharply peaked curve symmetrical about the dip equator. The enhancement of the daily variation of \( H \) has been later observed at other longitudes. This band of strong eastward current has been named as 'equatorial electrojet' by Chapman.

The strength of the equatorial electrojet as deduced from the amplitude of solar daily variation of \( H \) showed that the electrojet is maximum during the equinoctial months. A plot of the daily ranges of \( H \) as a function of magnetic latitude is shown in Fig. 1 for stations near the dip equator in the American, African and the Indian zones. The strength of the equatorial electrojet current is seen to have large longitudinal variations, being strongest in the American zone and weakest in the Indian zone.

The half-width of the electrojet in 1958 was found to be 200-300 km with no significant seasonal changes. The position of the axis was found to be at dip 1°S in Nigeria, slightly north in Philippines, very close to the dip equator in Ghana and 0-5°N of dip equator in Central Pacific. Thus it can be inferred that the position of electrojet axis is very close to that of the dip equator. An excellent review of the \( Sq \) current has been recently given by Hutton. A reversal of midday peak in \( Sq(H) \) variation was noticed at Addis Ababa (magnetic dip, 0-5°S) and this was suggested to be due to the large \( L \) variation. No such reversals are reported at Trivandrum and Annamalainagar. However, we have found the occurrence of daily variations in \( H \) at Indian stations very similar to those reported at Addis Ababa.

The existence of equatorial electrojet current at different longitudes has been confirmed by rocket-borne magnetometers. It was also found that the electrojet current near the coast of Peru is about twice that at Thumba confirming the longitudinal variation of the electrojet.

Fig. 1 — Latitudinal variations of the solar daily range of \( H \) component of geomagnetic field near the equator at Indian, African and American longitudes. The most prominent enhancement of range \( H \) at American longitude may be noted.
1.2 Electrojet during Disturbed Conditions

An enhancement of the amplitude of the sudden commencement (SC) of magnetic storms in $H$ during the daylight hours has been found at equatorial stations. This enhancement of SC is more pronounced in the American zone than in the Indian zone, similar to the pronounced enhancement of the solar daily variation of $H$ in the American zone. Later, it was shown that during the night, there is a small enhancement of SC($H$) amplitude in the American zone only. The amplitude of solar flare effects (s.f.e.) in $H$ was shown to be enhanced over the magnetic equator similar to that of the daily range itself. The equatorial enhancement of s.f.e. in $H$ is more pronounced in the American zone than in the Indian zone. For a particular zone, the equatorial enhancement of $H$ is more pronounced for s.f.e. than for SSC's. It was thus concluded that the current systems for s.f.e. and SSC are qualitatively similar but are located at different levels — that for s.f.e. being lower — confirming the earlier suggestions. These results indicate that both the solar flare effects and SC's at low latitudes are associated with the equatorial electrojet.

1.3 Lunar Tides in the Electrojet

Abnormally large lunar tidal amplitudes in $H$, and in the range of $H$, are found to occur at equatorial stations. This enhancement of lunar tides in the range of $H$ is confined within a narrow belt over the magnetic equator similar to the latitudinal variation of solar daily range itself, the enhancement being most pronounced in the American zone.

Lunar daily variations in $H$ at Huancayo for each lunar age have been calculated and it has been shown that the lunar-solar oscillations follow the well-known Chapman phase law, namely the phase of the lunar semi-diurnal oscillation is independent of the lunar age, phases of the lunar diurnal and terdiurnal oscillations decrease and increase respectively, through 360° during the course of a lunar motion. The ratio of lunar semi-diurnal to solar semi-diurnal oscillation decreases with increasing solar activity. The detailed analyses of the lunar-solar tides in $H$ at all the equatorial stations have shown that the yearly mean amplitude of the lunar semi-diurnal or semi-monthly oscillation is directly proportional to the mean solar daily range of $H$.

2. Ionospheric Drift at Low Latitudes

Soon after the evolution of the method of measuring ionospheric drifts by spaced receiver technique by Mitra and Krautkramer, measurements were made at a number of high latitude stations. The drift measurements have been made in India at a number of locations, viz. Ahmedabad (dip. lat., 20°N), Delhi (dip. lat., 19°N), Banaras (dip. lat., 21°N), Calcutta (dip. lat., 18°N), Waltair (dip. lat., 11°N), Thumba (dip. lat., 0-6'S), and recently at Udaipur (dip. lat., 20°N). It may be noted that out of all these stations only Thumba is within the equatorial electrojet region.

The very first results obtained at Thumba showed that drift direction is predominantly westward (about 80%) during daytime and eastern during night. During 1964, the average drift speed was found to be 132 m/sec in the E-region and 161 m/sec in the F-region, both values being much higher than for any mid-latitude station. The elongation of the irregularities in the F-region at Thumba were found to be very high being along the north-south direction. It was suggested that abnormally large value of the drift speed, consistent westward direction of drift during the day-time and the extreme elongation of the irregularities are characteristics of the magnetic equatorial zone. It has been shown that the daily, seasonal and latitudinal variations of the drift near the magnetic equatorial zone are associated with the equatorial electrojet.

The average histograms of the apparent drift speed and direction during the day-time during high sunspot years at the Indian stations are shown in Fig. 2. The histogram of drift direction at Thumba differs from the same at other stations. At Delhi, which is nearest to the Sq focus, the direction has a very broad maximum. At Ahmedabad, the directions of the drift is mostly towards north-west and south-east. At Waltair, the drift direction has significant components towards south (S) and west (W). At Thumba, the direction of the drift is predominantly towards west (W).

Referring to the histograms of the drift speeds, it is seen that the speeds at Thumba are significantly higher than at other stations. The median value of the speed at Delhi, Ahmedabad or Waltair lies in the range 60-80 m/sec whereas at Thumba it lies in the range 100-120 m/sec. These two properties single out the ionospheric drift measurements at Thumba. Similar high values of the drift speed and consistent westward directions have been noticed at Tamale, Ibadan and Dapango, all of these stations being within the equatorial electrojet region.

Fig. 2 — Histograms of percentage occurrences of the apparent drift speed and direction in the F-region over the Indian stations Delhi, Ahmedabad, Waltair and Thumba during the high sunspot years.
With all the available data, the latitudinal variations of the apparent drift speed, axial ratio and the orientation of the characteristic ellipse are obtained and shown in Fig. 4. It is seen that the drift speed \( V' \) is approximately 80 m/sec at all stations with magnetic latitudes greater than 10°. It increases towards the equator; within 3° from the equator, the speed increases from 100 m/sec to about 150 m/sec. This enhancement is characteristic of the equatorial electrojet currents. The latitudinal variation of the axial ratio also shows a sharp enhancement within a few degrees of the magnetic equator. At stations within the equatorial electrojet, the orientation of the characteristic ellipse is precisely along the magnetic north-south direction, whereas with increasing latitude it tends to depart towards west of north.

These results indicate beyond doubt that radio waves are reflected from the ionosphere near the magnetic equator from pencil-like irregularities elongated along the field lines, and the drifts observed by spaced receiver technique indicate the movement of irregularities perpendicular to the field lines.

Combining the data for the period 1964-69, it was found that the apparent drift speed to some extent, and the true drift speed to a larger extent, decreases with increasing solar activity \( S \). It has been shown that the sensitivity of the E-region electron density and the daily range of \( H \) near the magnetic equator to sunspot number are nearly the same in the two cases, both increasing with the solar cycle. The decrease of drift speed with increasing solar activity is suggested to be due to the increasing contribution of electric field reversed to the normal Sq field.
The blanketing type of Es is known to be inhibited in a much narrower belt (within 2-4° dip) centred on the magnetic equator. The occurrence of this type of Es (Es-b) at Kodaikanal is maximum between 0730 and 0830 hrs, minimum at 1100 hrs and has a large maximum between 1700 and 1830 hrs local time. The diurnal variation is thus very similar to that of $f_{F2}$. The occurrence of Es-b is more common in the Asian zone than in the American zone. Other ionospheric and geomagnetic features which are observed under the influence of the electrojet are found to be suppressed during blanketing Es events, and it has been suggested that an electric current probably directed

3.2 Characteristics of Equatorial Es

The Es at Kodaikanal occurs for nearly 93% of half-hourly records during the day-time. At Kodaikanal two main types of Es are observed, namely (1) the patchy type with well-marked daily variation and (2) the blanketing type which occurs mainly in the afternoon hours.

An ionogram at Kodaikanal showing the special characteristics of Es, at the magnetic equator is reproduced in Fig. 5. The q-type of Es is characterized by the minimum height of reflection being independent of frequency, and the maximum frequency reflected by the layer being even higher than $f_{F2}$. The slant Es, which is also a characteristic of the region close to the magnetic equator consists of diffused reflections starting from $f_{E}$ and $f_{Es}$ and increasing in apparent height with frequency. The increased equivalent range of slant Es is due to oblique propagation in the E-W plane orthogonal to the irregularities. The reflections from the normal E-layer are generally embedded within the diffused echoes, but on certain occasions, normal E traces can be seen clearly or inferred without doubt.

It has also been shown that the drift speed is decreased during disturbed days; the drift speed of either the E- or the F-region decreases linearly with increasing magnetic activity, the effect being more in the E- than in the F-region. It is suggested that with increasing magnetic activity the electrostatic field of magnetospheric origin would decrease while the normal Sq fields remain unaffected; accordingly the total electrostatic field at low latitudes would decrease with increasing magnetic activity.

3.3 Blanketing Type of Es

The blanketing type of Es is known to be inhibited in a much narrower belt (within 2-4° dip) centred on the magnetic equator. The occurrence of this type of Es (Es-b) at Kodaikanal is maximum between 0730 and 0830 hrs, minimum at 1100 hrs and has a large maximum between 1700 and 1830 hrs local time. The diurnal variation is thus very similar to that of $f_{F2}$ at Kodaikanal. The occurrence of Es-b is more common in the Asian zone than in the American zone. Other ionospheric and geomagnetic features which are observed under the influence of the electrojet are found to be suppressed during blanketing Es events, and it has been suggested that an electric current probably directed
westward is introduced during the events of occurrence of blanketing $E_s$.

3.4 Lunar Tidal Effects in $E_s$-$q$

The $E_s$-$q$ at Huancayo often disappears around noon or early afternoon solar local time if these times lie between 0000 and 0300 or 1200 and 1500 hrs lunar time. At new and full moon, a westward electrojet flow is in the magnetic equatorial zone during 0000-0300 and 1200-1500 hrs lunar time. This disappearance of $E_s$-$q$ was suggested as due to the westward electrojet of the lunar current system. At Huancayo, the $E_s$ was shown to appear earlier during new and full moon.

Significant lunar control has been shown on the time of first appearance, the last disappearance as well as the duration of the $E_s$-$q$ at Kodaikanal. The duration of $E_s$ occurrence during the day was 37 min longer during new and full moon than during first and the third quarter. Similarly $E_s$ appeared 115 min after ground-sunrise on first and third quarters but only about 85 min after ground-sunrise on new and full moon days. Lunar tidal amplitude in $f^2E_s$ has been found to be 0.3-0.4 MHz and in $k^2E_s$ about 0.2 km (ref. 74-76), the phases being in close agreement with those of $H$ component. The lunar tidal amplitudes in $f^2E_s$ are greater in D-months than in J-months. An appreciable lunar-solar variation of the tide at Ibadan and Huancayo was also noticed, the amplitude during day-time being greater than that during nighttime.

3.5 Magnetic Disturbances and $E_s$-$q$

The average noon $f^2E_s$ at Ibadan was found to be lower on disturbed than on quiet days by about 1 MHz. Close correlation was seen between the dips in $f^2E_s$ and $H$ components of the magnetic field. The $E_s$ at Kodaikanal is known to disappear over several hours during the main phase of the magnetic storm. The $f^2E_s$ on quiet days at Indian stations is found to be greater by an average value of 0.5 MHz than on disturbed days. The occurrence of $E_s$-$q$ was shown to be not affected by the magnetic activity. During the main phase of a magnetic storm there is a general reduction in the $f^2E_s$ (ref. 82). The disturbance diurnal variation of $f^2E_s$ consists of a large reduction of $f^2E_s$ at about 0800 and 1400 hrs and only a small reduction at 1100 hrs.

3.6 Sudden Disappearance of Equatorial $E_s$ during Day-time

Based on the simultaneous observations of $H$, $E_s$-$q$ and east-west electron drift at stations within the equatorial electrojet region, it has been found that on quiet days, and sometimes on disturbed days, when there is abnormally large decrease in $H$ during day-time, there is a simultaneous disappearance of $E_s$ and a reversal of the direction of drift of electrons from westward to eastward direction. The equatorial $E_s$ is also found to disappear during the negative DP changes at the equator. $E_s$ has been found to disappear during the depression of the magnetic field on magnetically quiet days, an example of which is shown in Fig. 6. It is suggested that the disappearance of equatorial $E_s$ during day-time is due to the temporary reversal of the equatorial electrojet, which is caused by the imposition of an additional electrostatic field opposite in direction to that of the normal $S_q$ field.

3.7 Mechanisms Proposed for Equatorial $E_s$

One of the most favourable mechanisms of producing field-aligned irregularities and characteristics of $E_s$-$q$ as suggested by Farley is the so-called two-stream instability. This instability is produced only when the electron drift velocity exceeds the ion acoustic velocity which is about 360 m/sec.

This velocity could be attained in the American zone near the midday hours when the electrojet currents are large. In the Indian zone where electrojet current strength is approximately half of that in the American zone, it is rather unlikely that the electron drift velocity would exceed the ion acoustic velocity even when the electrojet current is maximum. On certain occasions, the characteristics of back-scatter echoes at Jicamarca do not support the presence of two-stream instabilities. Another mechanism for generating an instability in the ionospheric plasma is the gradient or cross-field instability. This instability has been studied in relation to the mid-latitude $E_s$ and spread-F. Some fluctuations in the ambient electron density, measured by rocket-borne probes, are also identified as due to the cross-field instability.

4. Quiet $F_2$-Region at Low Latitudes and the Electrojet

4.1 History and Nature of the Equatorial Anomaly

The establishment of an ionospheric station at Huancayo in November 1937 by the Carnegie Institute of Washington revealed for the first time that $f_2F_s$ at low latitudes reached a maximum in the morning and again decreased in the afternoon. This increase was also accompanied by a valley near noon. Similar build-up of $f_2F_s$ during the midday was noticed at Guam, Kwajalein Atoll and Christmas Island which were widely separated in geographic latitude and longitude. This similarity of the daily variation was explained on the basis of almost equal geomagnetic latitude of these stations. Similar differences in $f_2F_s$ stations with the same geographic but different geomagnetic latitudes were noticed earlier by other authors.
Appleton was the first to show that a plot of noon values of $f_0F_2$ at different stations in the world against the magnetic dip angle is a smooth curve showing two maxima around 28$^\circ$N and 28$^\circ$S with a trough around the equator. This behaviour of the F2-layer is often referred to variously as the geomagnetic anomaly, geomagnetic distortion, equatorial anomaly or Appleton anomaly of the F2-region.

4.2 Diurnal Development of the Equatorial Anomaly

It was later found that $f_0F_2$ versus dip plot for 0900 hrs has a single maximum around the magnetic equator; for 1200 hrs there were two maxima on both sides of the equator, and at 2100 hrs again a single maximum around the equator. The study of the anomaly during the different hours of the day in the minimum sunspot year showed that sub-tropic maximum first develops in the morning at low latitudes and later shifts polewards with the progress of the day, the course being reversed in the evening hours. Using topside ionospheric data, it was shown that the equatorial anomaly first appears at the peak of the F-layer at about 0800 hrs near the equator, and thereafter the maximum travels polewards. The equatorial anomaly was suggested to develop as well as to die out 3 hr later in sunspot maximum than in sunspot minimum years. The equatorial anomaly during sunspot maximum years has been studied by various authors and it has been found that during high sunspot years, it continues till even after sunset.

4.3 Seasonal and Solar Cycle Variations of the Equatorial Anomaly

The latitudinal variation of noon $f_0F_2$ for different years of the solar epoch showed that the two maxima of $f_0F_2$ occur at $\pm 30^\circ$ dip during low sunspot years and at about $\pm 35^\circ$ dip during high sunspot years: the proportionate depression of the equatorial trough decreases with increasing solar activity. The earlier studies of the equatorial anomaly were made for the equinoctial months. From a study of the equatorial anomaly for different seasons, it was suggested that the position of the $F_2$ peak is shifted towards the pole in the summer hemisphere. Study of the daily variation of $f_0F_2$ at stations close to the peak of $f_0F_2$ in the Indian zone has shown that the peak occurs at about $35^\circ$ dip during equinoxes and at about $25-30^\circ$ dip during solstices. The shift of the region of maximum $f_0F_2$ with month is clearly seen in the contour plot of $f_0F_2$ shown in Fig. 7. It was further shown that the northern peak is confined within $30^\circ \pm 5^\circ$ but the shift of the southern peak with season is much larger, being between $30^\circ \pm 10^\circ$. Other features of the equatorial anomaly have been discussed in a recent review.

4.4 Theoretical Explanation of the Equatorial Anomaly

The first explanation for the tropical maxima of $f_0F_2$ was given by Mitra. He suggested that in the upper part of the F2-region the electrons and ions produced by solar ultraviolet rays have very long free paths. These are thus free to spiral around the magnetic lines of force and at the same time are guided along them. At the magnetic equator the lines of force rise highest and slope north and south. The ionization formed in the high atmosphere in a belt along the magnetic equator is, therefore, guided north and south and when it comes down to lower levels contributes to the ionization density of the F2-region. Martin suggested that the electric field arising from the dynamo region causes F2-region to drift across the geomagnetic field lines, thereby reducing the maximum electron density over the equator. Hirono and Maeda showed that the vertical drifts caused by the electric field in the F-region and the Sq electric current were sufficient to account for the equatorial anomaly. It was further suggested that the diffusion of ionization from the equator towards the high latitudes takes place along the lines of force. The systematic change in the daily variations of $f_0F_2$ at low latitudes, the decrease in the $F_2$ anomaly during high sunspot years and the latitude of maximum $f_0F_2$ being greater than the maximum of $f_0F_2$ can be explained by the simultaneous uplift of the ionization at the equator and the diffusion of the same along the lines of force. This so-called 'fountain' theory has been later developed mathematically. This brings about a direct relationship of the equatorial electrostatic field, and thereby equatorial electrojet currents, with the equatorial anomaly.

4.5 Equatorial Anomaly and the Electrojet Strength

It has been shown that the product of the latitudinal extent and the magnitude of the anomaly is proportional to the solar daily range of $H$ near the magnetic equator. The ratio of $f_0F_2$ at Bogota (temperate latitude station) and at Huancayo (equatorial latitude station) showed a linear relation with the electrojet range, thereby indicating a relationship between the equatorial anomaly and the electrojet. It may be mentioned here that the equatorial electrojet strength is maximum during equinoctial months. This suggests that the extent of the equatorial anomaly is larger in the season when the electrojet currents are stronger. The study of $f_0F_2$ at stations close to the crest and trough of the equatorial anomaly in the Indian zone in relation to the equatorial electrojet has shown that the midday bite-out of $f_0F_2$ at an equatorial
station and the afternoon peak of $f_a F_s$ at mid-latitude station are greatly enhanced on days of strong electrojet; on some weak electrojet days the noon bite-out of $f_a F_s$ at Kodaikanal is completely absent. As an example of the association of equatorial $f_a F_s$ anomaly with the equatorial electrojet current, in Fig. 8 is shown the relationship between the differences of the noon $f_a F_s$ at Kodaikanal and the evening $f_a F_s$ at Ahmedabad, with differences in solar daily range of $H$ at Trivandrum and Alibag. $\Delta H_T - \Delta H_A$ is suggested to be a better index of current at the ionospheric heights. It is seen that for the quiet as well as for disturbed days the equatorial $F_s$ anomaly increases with increasing ionospheric current. To show the effect of equatorial electrojet current strength on the whole structure for the $F_s$-region, electron density contour diagrams at Kodaikanal are shown for two different days of the same month having widely different electrojet current strength (Fig. 9). On 6th of August the daily range of $H$ is very small, of the order of 40 Y only. The $N_{max}$ at Kodaikanal is very high being about $120 \times 10^4$ electrons cm$^{-3}$ and the curve being very much like that of mid-latitude station with the peak at 1400 hrs. On 25th August when the diurnal range is large (120 Y), the $N_{max}$ has two maxima, one in the morning and another in the evening hours with a deep bite-out, and the maximum value of $N_{max}$ is about $80 \times 10^4$ electrons cm$^{-3}$. It is interesting to note that most of the changes in the electron density on the weak and strong electrojet days occur above the height of 200 km. Hence, it is suggested that below 180 km the regions are not affected by vertical drifts and diffusion processes, and changes of electric fields affect only the upper $F_s$-region above 200 km.

4.6 General Studies of $F_s$-Region in India

One of the first studies of $f_a F_s$ data at Indian stations showed that Kodaikanal, Tiruchirapalli and Madras form the equatorial group and Bombay, Calcutta, Ahmedabad and Delhi form the non-equatorial group. Using the ionospheric data at Indian and Japanese stations, special features of the ionosphere near the regions of maximum electron density, viz. the early morning disappearance, $f_a F_s$ midday bite-out of the ionosphere at mid-latitudes and sunset effects in the $F_s$-region at mid-latitudes, have been described. The general features of the $F_s$-region at equatorial stations in India have also been studied.
The study of \( f_0F_2 \) and \( h_pF_2 \) near equatorial trough (Kodaikanal), near peak \( f_0F_2 \) (Ahmedabad) and beyond the anomaly (Kokubunji) indicated that the rate of increase of \( f_0F_2 \) and \( h_pF_2 \) with solar activity depends on the local time; the greatest change in \( f_0F_2 \) occurs for the hour of minimum \( h_pF_2 \) and vice versa. Hence quantitative studies of \( f_0F_2 \) variations at low latitudes should be done in conjunction with the corresponding variations of \( h_pF_2 \) (ref. 136).

4.7 Upward-moving Kinks over the Magnetic Equator

The apparent movement of ionospheric irregularities on fixed frequency (h'-f) records at spaced stations was first detected by Munro137. Irregularities on P'-f records moving down the frequency and height scale have been detected138,139. The downward velocity of the disturbances was estimated to be about 80-150 m/sec140.

Disturbances moving upwards in the h'-f trace were first detected by Rastogi141 at Thumba, the upward drift velocity being about 15 m/sec. Examination of the ionograms at Kodaikanal revealed that such events (kinks) occur frequently throughout the solar cycle. The seasonal variation of its occurrence shows a maximum in summer months142. The vertical drift thus calculated ranged from 10 to 40 m/sec.

Daily variations of the occurrence frequency of such events is shown in Fig. 10 along with the daily variations of \( H, F \)-region horizontal drift, \( f_0F_2 \) and \( h_pF_2 \). It is remarkable that the maximum occurrence is at about 1000 hrs local time when the westward drift is maximum, \( h_pF_2 \) is maximum and \( f_0F_2 \) is least. The occurrence of these kinks is suggested to be a consequence of the vertical drift produced by \( E \times B \) effect.

The magnitude of the vertical drift calculated from such events agrees fairly well with those obtained by the measurements made at Jicamarca57 by back-scatter radar, and calculated theoretically for explaining the daily variation of F2-region near the equator125,132,133. Those kinks have been detected at equatorial stations in different longitude zones and the phenomenon seems to occur only at stations within the equatorial electrojet.

4.8 Spread-F at Equatorial Stations

Diffuse reflections from the F-region, known as spread-F or F-scatter, were first observed at the equatorial station Huancayo145 and later at other stations Singapore146, Ibadan147 and Kodaikanal148. The spread-F at equatorial stations is mainly a night-time phenomenon and is closely associated with the rapid rise of the F-layers in the evening which precedes the onset of spread-F. The spread-F at equatorial stations is markedly inhibited during magnetically disturbed days147,149.

An equatorial belt of high occurrence of spread-F with a width of \( \pm 20^\circ \) latitude centred on the magnetic equator was detected during IGY150,151. The spread-F were studied from published \( f_0F_2 \) data at equatorial stations with \( \pm 5^\circ \) of magnetic equator and longitudinal differences were observed both for solar cycle and seasonal variations152.

There are mainly two types of spread-F at equatorial stations; the first type, called range-spread, occurs during the post-sunset period; it is well correlated with \( h_pF_2 \) rise, increases with sunspot activity and shows a marked reduction due to magnetic
disturbances. The second type, called frequency spread, occurs in the pre-sunrise period of summer months, is negatively correlated with sunspot activity and is not affected by height variations of F-layer or magnetic disturbances. It seems the mechanisms for the two types of spread-F are different. Annual average nocturnal variations of spread-F index, $k'F$, and E-W region drift at Thumba are shown in Fig. 11. The reversal of horizontal drift, $h'F$ variation and the onset of spread-F occur roughly at the same time. These results show that the onset of spread-F at equatorial stations is correlated with the reversal of the electrojet currents in the evening. Similar correlations between spread-F and drifts by backscatter technique have been observed at Jicamarca.

Studies of spread-F covering at least maximum to minimum solar activity periods have been made at low latitude stations Ahmedabad, Taipei, Baguio and Nairobi. Annual average nocturnal variations of spread-F index, $k'F$, and E-W region drift at Thumba are shown in Fig. 11. The reversal of horizontal drift, $h'F$ variation and the onset of spread-F occur roughly at the same time. These results show that the onset of spread-F at equatorial stations is correlated with the reversal of the electrojet currents in the evening. Similar correlations between spread-F and drifts by backscatter technique have been observed at Jicamarca.

5. Lunar Tides in the Equatorial Ionosphere

5.1 Analysis of Lunar Tide Data

The first evidence of the existence of lunar tides in the ionosphere was given by Appleton and Weekes, who showed that $h'F$ at Cambridge has a semi-diurnal oscillation of about 1 km. Later, Martyn showed that the lunar tide in the height of maximum ionization in the $F_2$-region at or near the equator could be as large as 30 km; the amplitude of $f_{oF_2}$ oscillation could be as much as 15% of the mean value. Geomagnetic control in the lunar tides in $f_{oF_2}$ was first pointed out by McNish and Gautier, who showed that the phase of lunar tides in $f_{oF_2}$ was reversed by about 180° between stations close to the geomagnetic equator and at about 20° geomagnetic latitude. This reversal of phase was confirmed from the analysis of the data collected at the Indian stations. The lunar tides in $f_{oF_2}$ at stations having same geomagnetic latitude were found to have large disagreement in phase at Leo-poldville having geomagnetic latitude 3.5°S, phase was found to be 10-5 hr, typical of a high latitude station. It was shown that these discrepancies disappeared if magnetic dip rather than dipole latitude is used. Analysing noon $f_{oF_2}$ data at a large number of stations, Rastogi showed that the reversal of phase of lunar tide in $f_{oF_2}$ from the equatorial type with a maximum at 0400 hrs to the high latitude type with maximum at 1000 lunar hrs occurred near ±11° magnetic latitude. The latitudinal variation of the amplitude showed a sharp maximum close to the magnetic equator and two broad maxima at about ±20 magnetic latitude. The equatorial maximum was suggested to be associated with the equatorial electrojet.

In Fig. 12 are shown the latitudinal variations of the solar daily range in $H$, lunar semi-monthly tides in range of $H$ and in midday $f_{oF_2}$. It is seen that the range in $H$ in the American zone as well as in the Indian zone increases sharply near the magnetic equator, but for any particular latitude the range is more in the American zone than in the Indian zone confirming the longitudinal inequalities of the electrojet strength. The lunar tide in the range of $H$, similarly, is greatly enhanced in both the zones, the amplitude of the tide being larger at American than at Indian stations. The lunar tide in $f_{oF_2}$ is at normally large at Trivandrum and Huancayo, the amplitude at Huancayo being about twice that at Trivandrum. This clearly indicates that the lunar tide in the $F_2$-region at the
The amplitude of the semi-monthly lunar oscillations in noon $f_2$ and solar daily range of $H$ plotted with dip showing equatorial enhancement of lunar tide in both parameters.

In Fig. 13 is shown the seasonal variation in the amplitude and phase of lunar tides in noon $f_2$ and range of $H$ at Huancayo for a large number of years. It is seen that the amplitude of tides in either parameter is minimum in June-July and maximum in January. The phase in either case varied over about 90° but keeping almost anti-phase relationship between the two parameters for any month. This indicates that although the amplitude of tide in $f_2$ ionization and electrojet current vary sympathetically, the oscillations remain in phase opposition.

Lunar tides in various parameters defining the structure of the ionosphere over Huancayo, viz. $N_{\text{max}}$, $h_{\text{max}}$, $Y_m$, $N_i$, and $H$ have been discussed. The annual average lunar tidal variations in these parameters are shown in Fig. 14. It is seen that the height of maximum ionization varies sympathetically with the variations in $H$ field; $h_{\text{max}}$ is raised or lowered with an increase or decrease of $H$ respectively. $N_{\text{max}}$ is found to vary in almost phase opposition with that of $h_{\text{max}}$. The variations of the semi-thickness are also similar to that of $h_{\text{max}}$, suggesting that the lunar tides are very small at the base of the $F$ region. These facts are explained as follows. An increase of $H$ which would be due to increase of eastward electric field $E$ would increase the $E \times B$ drifts thereby raising the height of the layer, which would be followed by decrease of $N_{\text{max}}$ with a time-lag dependent on the average recombination of the $F$ layer. A close association between the equatorial electrojet and the lunar tides in the $F$ layer is thus undoubtedly seen.

Equatorial Anomaly and Lunar Tides

It has been shown that the noon bite-out of $f_2$ at equatorial stations was very large on days with lunar age 3 or 15 hr, and almost absent on days with lunar age 9 and 21 hr. The difference between equatorial and tropical latitude $f_2$ for noon hours was least on lunar age 9 or 21 hr and large on lunar age 3 and 15 hr. It was thus suggested that the lunar tide in $f_2$ at low latitudes is a consequence of the lunar perturbation in the diurnal development of equatorial anomaly. The equatorial
5.4 Luni-Solar Tides in $f_{0}F_{2}$ and $H$

The lunar semi-monthly as well as lunar semidiurnal oscillations in $f_{0}F_{2}$ and $h_{0}F_{2}$ at Ahmedabad were computed by Rastogi and Alurkar. The lunar tides were found to be strong during daylight hours. Systematic changes in the lunar tides with solar time and with solar cycle were indicated. Lunar tides at the equatorial station Huancayo were also shown to be significantly larger during day-time than during night-time.

The Chapman phase law for the lunar tide in $H$ was shown to be valid for $f_{0}F_{2}$ also. The lunar semi-monthly tide in $H$ at Huancayo was found to increase after sunrise reaching a maximum around noon, while the tide in $f_{0}F_{2}$ starts increasing about 2 hr after sunrise and has a broad maximum between 1000 and 1600 hrs. The lunar daily variation of $f_{0}F_{2}$ and $H$ during any particular lunar age as well as averaged over the whole lunation was shown to be almost 180° out of phase with each other. The lunar daily variations of $f_{0}F_{2}$ or $H$ during the high sunspot years were similar in nature but the lunar semi-monthly tides in $H$ were greater in amplitude during the daylight hours and that in $f_{0}F_{2}$ remained large even during the periods after sunset. The luni-solar tide was shown to be different during December and June solstices.

5.5 Lunar Tides at Different Heights of the Ionosphere

Lunar semi-monthly tides were calculated for different heights of the ionosphere over Ahmedabad for the noon hours and it was shown that the amplitude increased uniformly with height while the phase remained constant. At any fixed height the amplitude was largest during winter and least during summer. Similar analyses were extended for the equatorial station Huancayo and mid-latitude station Puerto Rico. The tidal amplitudes were found to increase with height at both the stations. The lunar tidal analyses were extended for different heights for different hours of the day at the equatorial station Huancayo and the mid-latitude station Puerto Rico. To study the differences in lunar tidal effects during day and night, the amplitude of the tide ($r_{2}$) and phase (i.e. time of maximum positive deviation $\delta_{2}$) are averaged for solar day-time hours (0600-1800 hrs) and night-time hours (1900-0500 hrs) separately for each height. The variations with height of $r_{2}$ and $\delta_{2}$ during day-time as well as the night-time hours for Huancayo are shown in Fig. 15. At both the stations the tidal amplitude in the $F_{2}$-region (above 160 km) increases with altitude. The day-time phase at Huancayo is about 7-8 lunar hr for heights between 120 and 190 km and about 3-4 lunar hr for heights between 220 and 400 km. At Puerto Rico, the phase ($\delta_{2}$) is continuously retarded with increasing height, with no sharp changes occurring for any height range. Thus it is seen that besides the latitudinal reversal of phase between equatorial and tropical stations, there is also a phase change with height occurring at about 180-200 km at the equatorial stations. This phase reversal of the tidal oscillations with height during the day-time at the equatorial stations is due to the different processes causing these variations in regions below and above 180 km, which is thought to be the region...
separating the lower photochemical regime and the upper electrodynamical regime.

5.6 Lunar Tides in the D-Region

The results of the lunar tidal analysis in the ionospheric absorption for the equatorial stations Ibadan \(^{189}\) and Colombo \(^{188}\) have shown that the phase of the tide in the D-region near the equator undergoes a reversal compared to the phase at the high latitude stations. A similar analysis at Singapore \(^{182}\) accounts for the possibility of this reversal taking place at a slightly lower magnetic latitude in comparison to the F-region tide. There is no marked enhancement of the amplitude of D-region tide close to the magnetic equator \(^{188}\), showing thereby that the tidal amplitudes are not affected by the electrojet currents. The amplitude of the tide shows a maximum around 20° magnetic latitude\(^{188}\).

6. Ionospheric Storms and the Equatorial Electrojet

Berliner and Seaton \(^{188}\) were the first to show that the effect of geomagnetic disturbance at an equatorial region is different from that at high latitudes. At high latitudes \(f_0F_2\) was known to decrease with geomagnetic activity while at Huancayo it was shown, to increase steadily with the increase of magnetic activity. The geomagnetic storm effects in the ionosphere were first indicated by Martin \(^{184}\). The disturbance effect in \(f_0F_2\) at Ibadan, an equatorial station, was shown to be opposite to that at temperate latitudes, the average value of \(f_0F_2\) at the equator being higher during a disturbed day than a quiet day \(^{187}\). Matsushita \(^{188}\) studied ionospheric storms at a large number of stations and concluded that:

1. Saw latitude stations show an increase of \(f_0F_2\) in any season;
2. High latitude stations show a decrease of \(f_0F_2\) in any season;
3. Mid-latitude stations show a decrease of \(f_0F_2\) in summer and a tendency for increase in winter.

Analyzing the data of \(f_0F_2\) at Indian stations it was found that the change from positive to negative effects in \(f_0F_2\) during storms occurs at a latitude of 20°N dip\(^{189}\). The ionospheric storm effects were found to be similar at stations with same dip latitude rather than same geographic latitude\(^{188}\).

Significant longitudinal differences in equatorial ionospheric storms were indicated when it was found that the seasonal average disturbance daily variation of \(f_0F_2\) at Kodaikanal was always positive irrespective of the season and solar cycle epoch, while at Huancayo the average \(f_0F_2\) on D-days was lower than that on Q-days during the December solstice than same dipole latitude \(^{188}\). This anomaly was shown to occur in a region of low magnetic field, during the local summer months of the most active period of the sun when the height of the F2 layer was very much increased\(^{182}\). The storm effects in \(f_0F_2\) at Kodaikanal on some individual occasions are found to show a decrease\(^{189}\).

A north-south asymmetry in ionospheric storm behaviour was found to be marked for mid-latitude stations\(^{188}\). Both these are due to differing geomagnetic field configurations at the conjugate points, but the exact mechanism remains to be explained. These results show that not only the magnetic dip but the general spatial distribution of the geomagnetic field around that region controls the behaviour of the ionospheric disturbances.

A detailed study of storm effects in the ionosphere at a large number of stations covering all latitudes was made. It showed that the regions around ±30° dip experience a decrease of \(f_0F_2\) during storms, but mid-latitude in winter register a sharp increase in \(f_0F_2\) during storms, if magnitude larger than the equatorial enhancement\(^{189}\). In low sunspot years, the mid-latitude increase of \(f_0F_2\) is seen in the summer hemisphere as well; it is only the very high latitudes which show a decrease in \(f_0F_2\) during disturbances. The effect of the local time of the sudden commencement on the changes in \(f_0F_2\) at low latitude stations was also indicated\(^{197}\).

Fig. 16 shows the variations of the geomagnetic H-component at Trivandrum compared with \(f_0F_2\) at Kodaikanal and Ahmedabad around days of magnetic storms of January, March, and August 1964. The beginning and end of the storms are marked in the diagram. It has been earlier shown that a certain component of storm time variation depends on the storm time commencing from the time of S.S.C. It can be seen here that on the day on which the midday peak in H at Trivandrum is absent, \(f_0F_2\) at Ahmedabad is less than at Kodaikanal, and the noon bite-out at Kodaikanal is completely absent. This happens on the second day of the storm in January and March and on the third day of the storm in August. This phenomenon is suggested as due to a weakening of the equatorial electrojet with reduced \(E_XB\) vertical uplift over the equator resulting in less transport of ionization away from the equator. It has been mentioned\(^{190}\) that the major part of the ionospheric storm effects at low latitude stations is due to changes in the equatorial electrojet current which itself is controlled during storms by additional electrostatic fields imposed over the normal Sq electric field.

7. Electron Density Distributions during Storms

Studies of changes in \(N_{max}\), \(h_{max}\), \(Y_m\) and \(N_v\) have been made by using \(N-S\) profiles during disturbed days\(^{195}\). It was found that at the equatorial station Huancayo, storm time changes in electron density were confined to heights above 180 km\(^{192}\). It was also shown that during some severe geomagnetic storms, vertical transport velocity decreases with height in contrast to its increase with height on quiet nights\(^{202}\).

Topside ionosondes on board satellites have now enabled the study of electron density distributions in the upper half of the F2-region during geomagnetic storms\(^{202},204\). In situ measurements of electron density by satellites have shown the enhancement of ionization at mid- and high latitudes larger by day, and smaller by night\(^{205}\). These enhancements of electron density were later found to be prominent at the winter high latitudes\(^{206}\).

Fig. 17 shows the electron density variations at true heights for the storm of June 15-17, 1965 at the stations Ahmedabad and Kodaikanal. On 15th June — treated as a control day — a clear midday bite-out in \(N_{max}F_2\) is seen at Kodaikanal, while Ahmedabad shows typical crest-type \(N_{max}F_2\) of (200 \(\times 10^4\) e/cm\(^3\)). Or 16th June — the main phase of the storm — \(N_{max}F_2\) at Ahmedabad falls to...
Fig. 16 — The variations of $f_0F_2$ at anomaly crest (Ahmedabad) and trough (Kodaikanal) compared with the corresponding variations of $H$ at the equator for three magnetic storms of 1964 (The value of $f_0F_2$ is smaller at Ahmedabad than at Kodaikanal on the days when there is no midday enhancement of $H$ at Kodaikanal)
Fig. 17 — Electron density variations at constant heights at anomaly crest (Ahmedabad) and trough (Kodaikanal) stations during different phases of the storm of 15th June 1965

\[(100 \times 10^4) \text{ el/cm}^2\] while midday bite-out at Kodaikanal decreases with increased \(N_{\text{max}}F_2\). Again the equatorial anomaly in \(f_p\) seems to vanish completely. On 17th June — the recovery phase of the storm — \(N_{\text{max}}F_2\) at Ahmedabad does increase to \((140 \times 10^4) \text{ el/cm}^2\) but it is still below the control-day value; at Kodaikanal \(N_{\text{max}}F_2\) has increased still further with less evidence of midday bite-out. These results conclusively show that during the main phase of a storm the equatorial electrojet is considerably weakened with less \(E \times B\) vertical uplift, and reduced transport of ionization from the equatorial to the anomaly crest regions. This phenomenon is effective only at heights above 180 km.

8. Conclusions

1. Electrojet

The existence of a strong eastward band of current at E-region heights over the magnetic equator as inferred from the ground-based geomagnetic field variations has been confirmed by rocket-borne magnetometers. The electrojet shows a strong longitudinal inequality, being strongest in the American and weakest in the Indian zone. The electrojet current is strongly influenced by the lunar age, the effect being most prominent during the midday hours. The electrojet is affected by geophysical disturbances like solar flares and storm sudden commencement.

2. Ionospheric Drifts and Electrojet

Ionospheric drifts near the magnetic equator show close relations with the electrojet in reference to diurnal as well as seasonal variations. Short period variations in the geomagnetic field are systematically reflected in ionospheric drift measurements. Day-to-day variations of drift speed are related to the corresponding electrojet intensity. The ionospheric drift and the electrojet decrease with increasing geomagnetic activity.

3. Sporadic E and the Electrojet

The sporadic E near the equator is known to be closely related with the electrojet. The lunar diurnal effects in the occurrence of \(E_s - q\) are the consequences of changes in the electrojet due to the lunar tides. \(E_s - q\) disappears suddenly during sudden decreases of \(H\), and is interpreted as the cause of the reversal of equatorial electrojet. \(E_s - q\) is suggested to be caused by cross-field instability rather than by two-stream instability.

4. Quiet \(F_2\)-Region and the Electrojet

The \(F_2\)-region of the ionosphere on quiet days is significantly distorted by the electrojet currents giving rise to the decrease of ionization at the equator and increase of the same at tropical latitudes. The magnitude of this distortion is shown to be proportional to the electrojet strength. The \(F_2\) anomaly is shown to almost disappear on days with weak electrojet whether magnetically quiet or disturbed.

The direct evidences of the \(E \times B\) upward forces existing in the equatorial ionosphere have been confirmed by the occurrence of the new kind of irregularities moving upward over the magnetic equator.
The occurrence of spread-F in the post-sunset period is shown to be related to the reversal of the electrostatic field.

The lunar tides in the F region near the equator are the consequences of the corresponding changes in the equatorial electrojet current and the west-east electric field. The lunar tides in the ionosphere and the electrojet are sympathetic to each other both in relation to diurnal, seasonal and solar cycle variations. The effects of transport phenomenon in the ionosphere due to the electrojet are prominent only at heights above about 200 km.

5. Ionospheric Storms and the Electrojet

In general, the ionospheric storms have the property of increasing $F_{\pi}$ near the magnetic equator. The changes in the ionosphere near to the magnetic equator during geomagnetic disturbances are explained as caused by the changes in the equatorial west-east electrostatic field. These changes affect the ionosphere even up to the tropical latitudes. The effect of the ionosphere at higher latitudes is due to the combined effects of the transport from the electrojet and as well as due to the equatorial winds and the changes in the composition of the atmosphere.

It is concluded that the ionosphere within about ±20° from the magnetic equator is very intimately connected with the changes in the electrojet currents which lie within a narrow band of ±3° centred around the magnetic equator.

Acknowledgement

The authors wish to acknowledge their indebtedness to Prof. K. R. Ramanathan who initiated ionospheric research at Ahmedabad. The major part of the work discussed in the present paper is due to the continued interest, discussions and guidance which he has been giving to the Ionospheric Group at Ahmedabad. The new information about the equatorial ionosphere has been possible due to the facilities provided at Thumba Equatorial Rocket Launching Station, Thumba, by late Prof. V. A. Sarabhai, Chairman, Indian Space Research Organization. His encouragement during the early stages of setting up of the ionospheric research station at Thumba was responsible for the rapid development of ionospheric research near the magnetic equator in India. Thanks are due to the authorities of the World Data Center for Upper Atmosphere Geophysics at Boulder, who have freely placed at their disposal the data collected at their center. The authors have great pleasure in expressing their thanks to Dr M. K. Vainu Bappu, Dr J. C. Bhattacharyya and other staff of the Indian Institute of Astrophysics, Kodaikanal, for providing facilities for studying the ionospheric and magnetic data collected at Kodaikanal. Thanks are also due to their colleagues at the Physical Research Laboratory, Ahmedabad, and at former Central Radio Propagation Laboratory, Boulder, USA, for helpful discussions and suggestions.

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