Duration of equatorial spread-F

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ABSTRACT. From an analysis of ionogram data of Kodaikanal (dip 3.5° N) for a 3-yr period of high sunspot activity, it is shown that the duration of equatorial spread-F (ESF), on the average, bears a direct relationship to the peak amplitude as well as duration of the post-sunset enhancement in F-region upward vertical drift in all seasons. The duration of ESF is also found to exhibit a significant positive correlation with the altitude of bottomside F-region at the time of onset of ESF but only during equinoxes and northern winter (D) months.

Key words : equatorial F-region, vertical drift, spread-F, duration.

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INTRODUCTION

The presence of diffuse traces is a commonly noticeable feature on night-time ionograms at locations in a belt of width of about 40° centred on the geomagnetic equator (Wright, 1959 ; Shimazaki, 1959) and is referred to as equatorial spread-F (ESF). It has been well-known that the onset of ESF is closely related to the vertical uplift of F-region that conspicuously occurs in the post-sunset equatorial ionosphere (Farley *et al.*, 1970; Skinner and Kelleher, 1971 and references therein). VHF radar backscatter observations demonstrated that in the vicinity of dip equator, the F-region plasma drifts upward (downward) during day (night) under the influence of the eastward (westward) electric field associated with the E-region dynamo, and the reversal in drift direction from upward to downward (downward to upward) occurs around sunset (sunrise) (Woodman, 1970; Farley *et al.*, 1970). Further, the daytime upward vertical drift (V_z) undergoes a short-lived enhancement in the evening hours before reversing to downward, particularly during high sunspot activity years (Woodman *et al.*, 1977; Fejer *et al.*, 1979). Build-up of polarization electric fields in the F-region (F-region dynamo effect) due to the sudden decrease of E-region conductivity at sunset is considered to be responsible for the enhancement in the eastward electric field (Rishbeth, 1971; Heelis *et al.*, 1974). The recent finding of a dependence of the peak amplitude (V_{zp}) and width of the prereversal peak in V_z on the duration of sunset between the conjugate E-regions over the equatorial stations, Fortaleza and Jicamarca by Abdu *et al.* (1981*a*) lends support to this understanding.

ESF manifests on ionograms usually around the time of reversal of F-region upward motion (time of maximum height) in the post-sunset hours and grows in intensity during the subsequent downward motion (Clemesha, 1964; Rao, 1966; Rastogi, 1978). The duration of ESF is however quite variable on individual nights. After onset, ESF sometimes lasts for only a few hours and sometimes persists throughout the night. On some nights ESF occurrence is discontinuous in that it reappears after manifesting for a few hours in the pre-midnight period. The local ionospheric conditions necessary and/or sufficient for the onset of ESF and, especially, those underlying the marked day-to-day variability of ESF duration are yet to be well understood. Rao (1966) and Farley *et al.* (1970) presented evidence to show that the bottomside of F-region has to attain a threshold height for the generation of irregularities associated with ESF. Our recent studies of Kodaikanal ionogram data, however, did not reveal the presence of any particular threshold height for the bottomside of F-region at the time of onset of ESF (Sastri and Murthy, 1978*a*; Sastri *et al.*, 1978*b*). It is pertinent to mention here that the observations of Farley *et al.* (1970) also showed the concept of threshold height to be not always valid. The altitude of equatorial F-region in the evening hours depends on the duration as well as peak amplitude (V_{zp}) of the enhancement in V_z, besides on chemical recombination and perhaps diffusion. The relative role of the altitude and parameters of the prereversal enhancement in V_z, in relation to other factors, in the initiation, growth and sustenance of ESF remained by and large an unsettled question. The data presented and discussed by Woodman (1970) and Rastogi (1978) suggested a prereversal peak in V_z to be a necessary condition for the onset of ESF. The ionogram analysis of Abdu *et al.* (1982) showed that local ionospheric parameters such as the bottomside electron density scale length and the ion-neutral collision frequency at the base of the layer determine the post-sunset gene-

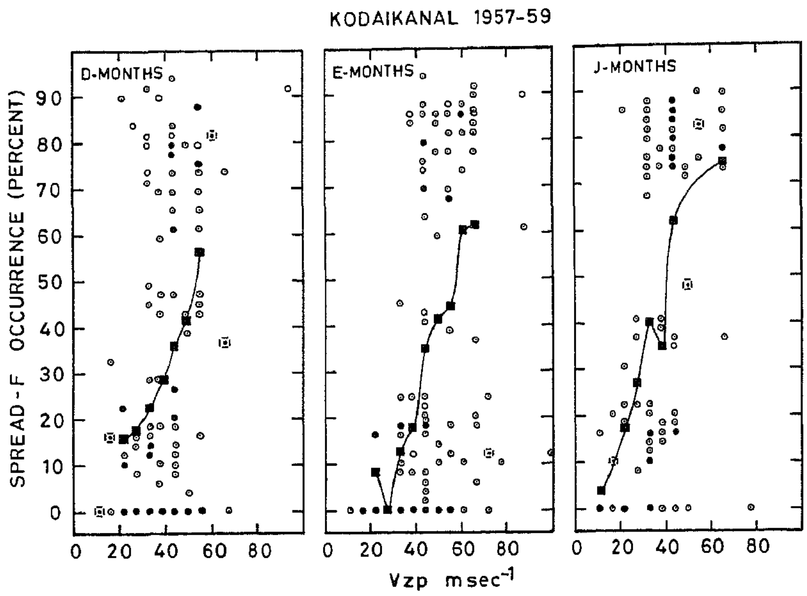

Figure 1
Scatter plots of the duration of spread-F against the pre-reversal maximum in F-region vertical drift (V_{zp}) deduced from ionograms. The open and solid circles indicate single and more than one observation respectively. The squares represent the mean values of spread-F occurrence for a given V_{zp} (open squares indicate average values deduced from less than four individual observations).

ration of ESF irregularities. Very recently, Abdu *et al.* (1983) reported a significant positive relationship between the range type spread-*F* indices (degree of range spreading) in the pre-midnight period and V_{zp} at Fortaleza valid for equinoxes and southern solstice. The problem as to the factors that influence the duration of ESF has not received due attention so far. Somayajulu *et al.* (1975) contended that fluctuations in east-west electric field are a prerequisite for the generation and maintenance of ESF, based on a comparative study of $h'F$ variations on nights with short (2-3 hr) and long duration spread-*F* activity. The analysis of Abdu *et al.* (1981*a*) suggested the occurrence rate of ESF to increase in general with increase in V_{zp}. In this paper, we present and discuss the relationship between the parameters of the post-sunset enhancement in V_z and the onset and duration of spread-*F* over the magnetic equatorial station, Kodaikanal (10° 14′ N, 77° 28′ E, Dip 3.5° N).

OBSERVATIONS

Quarter-hourly ionograms covering a 3-yr period of high sunspot activity (1957-59) constitute the basic data used for the present study. Values of $h'F$, the height of bottomside *F*-region are scaled at 15 min intervals from ionograms on individual nights and the time history of V_z is evaluated taking V_z as $d(h'F)/dt$. The time derivative of $h'F$ has been shown recently by Bittencourt and Abdu (1981) to accurately represent V_z in the evening equatorial ionosphere provided $h'F$ is above 300 km, a condition that is usually satisfied at Kodaikanal during high sunspot activity years. The present analysis, in fact, is restricted to high sunspot years because of this limitation in deriving V_z from ionograms. The ionogram data are carefully scrutinised for the presence of spread-*F* and the percentage occurrence of spread-*F*, defined as the ratio of number of ionogram frames exhibiting spread-*F* to the total number of ionogram frames examined multiplied by 100, has been evaluated for individual nights. Only those nights on which spread-*F* condition was continuously seen are taken into consideration in evaluating the percentage occurrence of spread-*F*, which thus indicates the duration of spread-*F*. It is well documented in the literature that spread-*F* manifests in three basic configurations in equatorial ionograms (Chandra and Rastogi, 1972; Sastri and Murthy, 1975; Abdu *et al.*, 1981*b*). In the first one, which usually manifests during the onset phase of ESF in the post-sunset hours, spread is seen only at the low frequency end of the *F*-layer trace with clear cut f_0F_2 cusps. The second one is the well-known equatorial or range type spread-*F* wherein spread exists over the entire frequency range of the *F*-layer trace and this configuration usually develops from the first one. These two types are clubbed and taken to represent range type spread-*F* which occurs predominantly in the pre-midnight period during years of high sunspot activity in the Indian equatorial region (Sastri and Murthy, 1975; Sastri *et al.*, 1979). The third type is characterised by the presence of spread only at and around the critical frequencies of *F*-layer trace and represents the temperate latitude or frequency spread-*F*, which most usually manifests in the post-midnight period in the Indian equatorial region during years of high sunspot activity (Sastri and Murthy, 1975; Sastri *et al.*, 1979). Rastogi and Woodman (1978) suggested that range spread-*F* is due to reflection of radio waves from large-scale irregularities around the base of *F*-layer, while frequency spread-*F* is due to scattering from large scale irregularities near the peak of *F*-layer. As the nature of spread-*F* usually changes during the course of a night at Kodaikanal, we have not paid particular attention to the type of spread-*F* while examining the dependence of the duration of ESF on the parameters of the post-sunset enhancement in V_z. An attempt is, however, made to infer the changes in the development of the post-sunset enhancement in V_z on nights with predominantly either range or frequency type spread-*F*, to enable a comparison of the trends with those reported for the American equatorial region by Abdu *et al.* (1981*a*).

Mass plots depicting the relationship between the duration of spread-*F* and V_{zp} based on data for 324 nights are presented in figure 1. The plots are drawn separately for the three seasonal groups of months : D months (Jan., Feb., Nov., Dec.), E months (Mar., Apr., Sept., Oct.) and J months (May through Aug.). Data pertaining to nights without spread-F are also included in the mass plots to infer the role of V_{zp} in the onset of ESF. That there is a large scatter in the duration of spread-F for a given V_{zp} and in V_{zp} for a given rate of spread-F occurrence is quite evident from figure 1. On the average, the duration of spread-F, however, bears a positive relationship to V_{zp} in all seasons as can be seen from the solid lines in figure 1, which represent the variation of the average level of spread-F occurrence with V_{zp} (nights without spread-F are included while calculating the average level of spread-F occurrence for a given V_{zp}). The data of figure 1 also show that on nights with spread-F activity (irrespective of duration) V_{zp} is above 20 ms^{-1} during D and E months and above 10 ms^{-1} during J months. Following the usual practice, these values may be taken to represent the thresholds for V_{zp} for the onset of spread-F over Kodaikanal valid for high sunspot activity years. It is nevertheless important to note that V_{zp} varies over the wide range of 10-75 ms^{-1} on nights without spread-F. This feature reveals that the mere presence of an upward V_z in the evening hours does not always constitute a sufficient condition for the initiation of ESF and that other factor(s) play a definite role. With a view to see if the onset and duration of ESF depend not only on the peak amplitude but also on the duration of the enhancement in V_z, we have examined the data by separating them into nights with short duration spread-F (span of activity less than 30 % of the night-time) and long duration spread-F (span of activity more than 60 % of the night-time). The time histories of average V_z corresponding to these two groups of nights are shown in figure 2 separately for the three seasonal groups of months. The behaviour of average V_z on nights devoid of spread-F is also shown in figure 2 for comparison. It is apparent from figure 2 that the amplitude of V_{zp} and the duration of the enhancement in average V_z are significantly larger on long duration spread-F nights compared to the ones on nights with short duration spread-F which, in turn, are larger than the ones corresponding to no spread nights. Perusal of the temporal variation of V_z on individual nights showed that although on several of the nights without spread-F V_{zp} occurs earlier and/or is sharper compared to short and long duration spread-F nights (the time profiles of average V_z shown in figure 2 reflect these trends), a plot (not shown here) of the percentage occurrence of spread-F *versus* the duration of the post-sunset enhancement in V_z exhibits appreciable scatter. This feature suggests that the duration of spread-F does not uniquely depend on the duration of the enhancement in V_z and that V_{zp} as well as the duration of positive V_z influence the onset and maintenance of ESF.

Because V_{zp} and the duration of the enhancement in V_z effectively determine the peak altitude of bottomside F-region in the post-sunset period, it seems that the F-region height plays a prominent role in the onset and persistence of ESF. Since, as already mentioned, the onset of ESF usually occurs around the time of maximum height of bottomside F-region, it is felt necessary

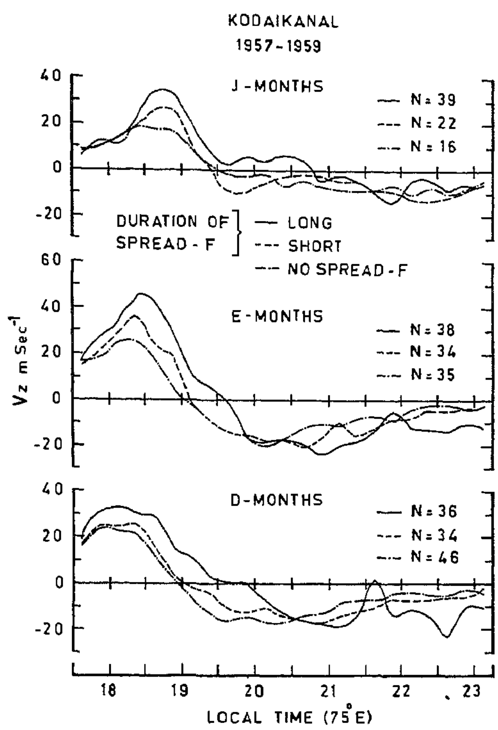

Figure 2
Variation of the mean F-region vertical drift (V_z) on short and long duration spread-F nights over Kodaikanal. The variation of mean V_z on nights without spread-F condition is also shown. The number (N) of nights without spread-F, with short and long duration spread-F is indicated for the three seasonal groups of months.

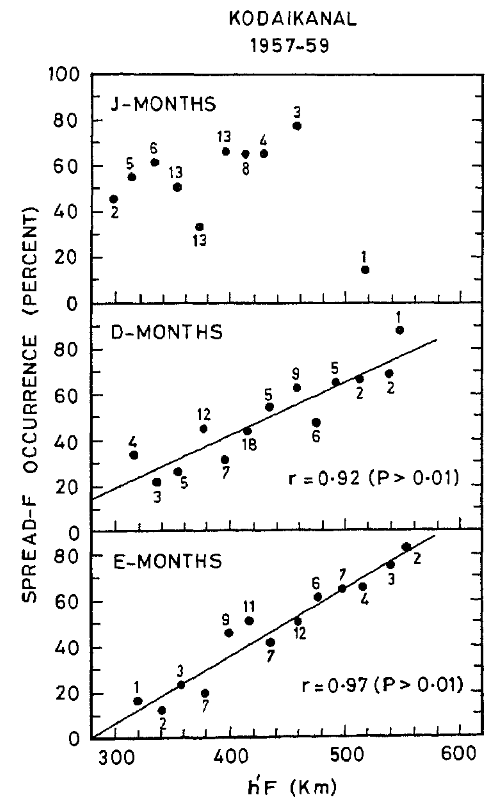

Figure 3
Variation of duration of spread-F with the altitude of bottomside F-region at the time of post-sunset onset of spread-F over Kodaikanal. The numbers around the points indicate the number of individual observations used for obtaining the averages. The correlation coefficient (r) with it's level of significance and the regression line obtained by least-squares fitting are also shown.

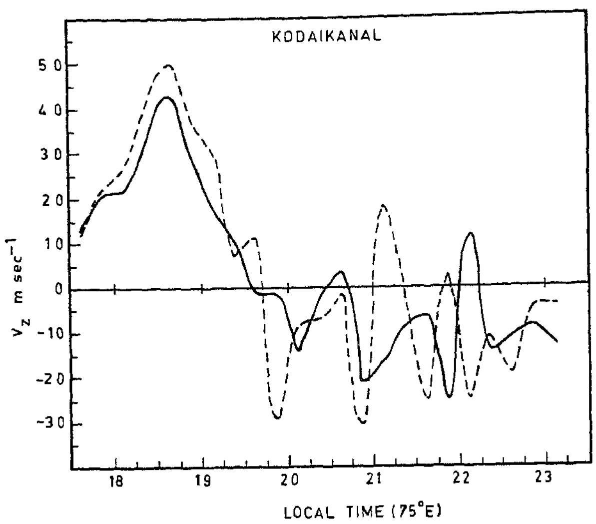

Figure 4
Variation of mean V_z on long duration spread-F nights with a predominance of range type spread-F (—) and frequency type spread-F (— — —).

and worthwhile to attempt a correlative study of the duration of spread-*F* to the altitude of bottomside *F*-region at the time of onset of spread-*F*. For this purpose, *h' F* values corresponding to the onset time of ESF on individual nights are collated and separated into bins of 20 km size, and the corresponding values of the duration of spread-*F* are noted. A graphical representation of the average values of *h' F* and duration of spread-*F* in each of the bins is then made to examine the correlation. The results presented in figure 3 demonstrate that a significant positive correlation indeed exists as anticipated, but only in equinoxes and local winter (*D*) months. The break-down of the correlation in local summer (*J*) months is found to be due to the invalidity of the assumed relationship of the onset time of ESF to the post-sunset peak in *F*-region height. In *J* months, unlike in *D* and *E* months, the onset of spread-*F* is noticed to occur well removed from the post-sunset peak in *F*-region height and/or the height exhibits a secondary maximum in the pre-midnight period, on a sizeable number of long duration spread-*F* nights. The latter feature is similar to the one reported by Somayajulu *et al.* (1975) on long duration spread-*F* nights at Trivandrum, a station south of Kodaikanal in the Indian equatorial region. The nocturnal variation of average V_z on long duration spread-*F* nights in *J* months shown in figure 2 mirrors these trends in the form of a sharper V_{zp} and prolonged positive values of V_z. A statistically significant positive correlation ($P > 0.01$) is however noticed (not shown here) between the duration of spread-*F* and the post-sunset peak in *F*-region height in *J* months.

The principal finding of the present study is that, in gross behaviour, the post-sunset time history of *F*-region vertical drift and hence the peak altitude of bottomside *F*-region in the evening hours significantly influence the onset and sustenance of ESF on ionograms. Although earlier statistical studies suggested a height control of ESF, explicit evidence of the type obtained here had not been reported so far for the Indian zone. For the American zone, the recent study of Abdu *et al.* (1981*a*) indicated a dependence, on the average, of the nature and duration of ESF on V_{zp} and its width. They reported that while the duration of ESF bears a direct relationship to V_{zp}, the width of V_{zp} is sharper (broader) if the occurrence of range type spread-*F* (frequency type spread-*F*) is high. To facilitate a comparison as already mentioned, we have further examined the post-sunset behaviour of V_z at Kodaikanal on nights with a preponderance of either range type spread-*F* or frequency type spread-*F*. Out of the 113 long duration spread-*F* nights studied, on 17 nights the spread-*F* configuration was essentially of range type and only on 4 nights it was essentially of frequency type (on the remaining 92 nights a combination of range, frequency and complex configurations was seen; see Chandra and Rastogi, 1972 and Sastri and Murthy, 1975 for complex spread-*F* configurations). That V_{zp} is sharper (broader) when range type spread-*F* (frequency type spread-*F*) predominates on a night may be seen from figure 4 which shows the V_z variation for the two categories of nights. The relationship between the post-sunset evolution of V_z and the type and duration of ESF thus seems to be similar in the Indian and American equatorial regions.

DISCUSSION

Extensive theoretical and experimental studies made over the past decade have indicated that the generation and growth of ESF occurs in stages involving both the neutral and the ionized component of the equatorial upper atmosphere. The equatorial *F*-region rises in height accompanied by steepening of electron density gradients on its underside following sunset, due to chemical recombination and electrodynamic effects associated with the enhancement of the eastward electric field. Such physical conditions render the steep plasma density gradients on the bottomside unstable to either collisional Rayleigh-Taylor (R-T) instability (Dungey, 1956; Haerendel, 1974; Hudson and Kennel 1975) or EXB gradient drift instability (Martyn, 1959; Simon, 1963). The initial perturbations in plasma density necessary to trigger the R-T or EXB instability are widely attributed to internal gravity waves (Rottger, 1973, 1976, 1978; Booker, 1979). The subsequent growth, under favourable altitude and gradient conditions, of irregularities leads to the formation of depletions in plasma density on the bottomside which then rise non-linearly into the topside (Ossakow *et al.*, 1979). These depletions are referred to variedly in the literature as holes, bubbles and plumes depending on the experimental technique adopted to detect their signatures. ESF as seen on ionograms is considered to be due to secondary plasma instabilities on the walls of the plasma bubble (Woodman and La Hoz, 1976; Tsunoda, 1980). Numerical simulation studies of Ossakow *et al.* (1979) showed that the altitude of *F*-layer peak and the bottomside electron density scale lengths play an important role in the linear and non-linear evolution of the plasma bubble under conditions of collisional R-T instability. For example, for the same bottomside electron density gradient scale length of 10 km, an increase of altitude of *F* peak from 344 km to 434 km has been shown to transform a weak bottomside spread-F condition to a strong spread-F condition both on the bottomside and topside. It is known that the equatorial F-region rises as a whole in the evening hours without significant changes in its semi-thickness (Rastogi, 1978). A high altitude of F therefore implies a high altitude of its underside as well. Now, in the absence of any other sustaining mechanism the lifetime of ESF irregularities depends on their initial strength and the chemical loss rate. Since the chemical loss rate decreases and strength of ESF irregularities increases with increase in altitude, one would expect a positive dependence, in general, of the duration of ESF on the amplitude and width of the post-sunset enhancement in V_z, a feature that is clearly seen in the results of the present study. It is quite relevant to add here that on a majority of the short duration spread-F nights, the usual intensification of ESF in the pre-midnight period was not evident. Out of the 90 short duration spread-F nights, on 35 nights ESF throughout its manifestation remained confined to the bottomside (i.e. at the low frequency end of the F trace), on 13 nights it was essentially of complex type and on another 35 nights a combination of these two types was seen. A well developed range type spread-F was seen only on 7 of the short duration spread-F nights. The statistical evidence obtained here thus seems to support the view that gravitationally driven collisional R-T instability plays an important role in the generation and growth of ESF irregularities. The appreciable scatter noticed in the plots of the occurrence of ESF *versus* V_{zp} (and also width of the enhancement in V_z) may be due to (a) day-to-day changes in the amplitude of the primary perturbations necessary to initiate R-T instability and/or (b) variations in the exospheric temperature and densities that determine the altitude profile of ion-neutral collision frequency (ν_{in}). It is pertinent to point out in this context that although the earlier work of Abdu *et al.* (1982, 83) as well as the current one demonstrated a definite influence of the local ionospheric parameters (ν_{in}, bottomside F-region electron density scale length, L and height of bottomside F-region) in the onset and duration of ESF on ionograms, the field line integrated values of these parameters, which are the more relevant ones to consider in an assessment of the role of R-T instability in ESF, could be quite different from the local ones. Coordinated experimental efforts at a chain of stations, in the same magnetic meridian, spanning the latitude region right from the dip equator to low latitudes are therefore very much required to throw light on the properties of the plasma characteristics on the field line and their role in the initiation, growth and maintenance of ESF (see Tinsley, 1982). Recent model calculations of Zalesak *et al.* (1982) revealed that besides the altitude of F-layer peak and electron density gradients on the bottomside, the presence of the E-region and other background plasma at higher latitudes connected along magnetic field lines to the F-region over the dip equator can retard the rate of plasma bubble evolution. It has also been shown that a high altitude of F-region favours the onset of bottomside spread-F through R-T instability by reducing the E-region Pedersen conductivity (Hanson *et al.*, 1983). To conclude, the altitude dependence of the duration of ESF evidenced in the present statistical study is in accordance with the current understanding of ESF.

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