Range and frequency spread-F at Kodaikanal

by

J. Hanumath SASTRI and K. SASIDHARAN
Indian Institute of Astrophysics
Kodaikanal-624 103, India

and

V. SUBRAMANYAM and M. Srirama RAO
Space Research Laboratories, Physics Department
Andhra University, Waltair-530 003, India

ABSTRACT. – *Using Ionogram data at Kodaikanal (Geo. Mag. lat. 0.6°N, Dip 3.5°N) over a seven year period: Jan 1957-Dec 1963, a study is made of the seasonal and sunspot cycle variations in the nocturnal occurrence of range and frequency type of spread-F configurations. It is found that the occurrence of both range and frequency type spread-F exhibits a positive dependence on the phase of the sunspot cycle. There is also a significant positive correlation between the occurrence patterns of range and frequency type spread-F. The Occurrence of range type spread-F shows a prominent peak around 20-22 hrs LT, irrespective of season and phase of the sunspot cycle, except during local summer months of low sunspot years when it is shifted to the postmidnight period around 00-03 hrs LT. The peak occurrence of range spread-F (for two hours around the peak) shows a semi-annual variation during years of moderate and low sunspot activity. A comparison of these results with those at other equatorial stations revealed a marked longitudinal dependence of the characteristics (nocturnal, seasonal and sunspot cycle changes) of range and frequency type spread-F.*

RESUME. – *On a étudié les variations saisonnières et de cycle solaire dans la production nocturne des configurations de l'élargissement F en amplitude et en fréquence d'après les données d'ionogrammes à Kodaikanal (Latitude géomagnétique 0,6°N, latitude dipolaire 3,5°N) sur une période de 7 années (Janvier 1957 jusqu'à décembre 1963). On a trouvé que les élargissements F en amplitude et en fréquence dépendent réellement de la phase du cycle solaire. Il existe aussi une réelle corrélation significative entre les modèles de production des élargissements F en amplitude à un pic net vers 20 à 22 h locale, quelle que soit la saison ou la phase du cycle solaire, à l'exception des mois d'été local des années de faible activité solaire, lorsque ce pic est décalé vers la période après-minuit, vers 00 à 03 h. locale. La production maximale de l'élargissement F en amplitude (pendant 2 heures autour du pic) montre une variation semi-annuelle pendant les années d'activité solaire faible et moyenne. Une comparaison de ces résultats avec ceux d'autres stations équatoriales a montré une dépendance longitudinale nette des caractéristiques (variations nocturne, saisonnière, et du cycle solaire), de l'élargissement F en amplitude et en fréquence.*

Introduction

The presence of diffuse traces (spread-*F*) is a commonly noticeable feature on ionograms at stations over a wide range of latitudes. Morphological studies of the phenomenon of spread-*F* on a global basis showed the existence of two belts of intense spread-*F* occurrence, one centred on the dip equator with a width of 40° and the other in the Cis-Auroral regions (Reber, 1956; Shimazaki, 1959; Wright, 1959; Singleton, 1960). In this paper, we mainly deal with spread-*F* as observed in the equatorial region, referred to as equatorial spread-*F*, which is essentially a night time phenomenon. Since the earliest observations of Booker and Wells (1938), the morphology of equatorial spread-*F* has been extensively studied by several workers mainly using published ionospheric data (refer to Clemesha and Wright, 1966 and the references in Skinner and Kelleher, 1971). The HF and VHF scatter experiments of Cohen and Bowles (1961) and Clemesha (1964) indicate that equatorial spread-*F* is due to partial reflections from small field aligned irregularities in *F*-region ionization. Calvert and Cohen (1961) and Pitteway and Cohen (1961) showed that the various types of spread-*F* configurations noticeable on equatorial ionograms could be produced by field aligned irregularities at various locations within or below the main *F*-layer trace, the irregularities either scattering or providing a duct for the radio waves. However, the physical mechanisms responsible for the production and sustenance of the field aligned irregularities still remain to be established, allthough some significant advances have been made in the recent times (Balsley *et al*, 1972., Beer, 1974., Haerendel, 1974 Hudson and Kennel, 1975., Rottger, 1976., Woodman and La Hoz, 1976., Morse *et al,* 1977, Jain and Das, 1978). In this brief communication, we present and discuss the salient results of a study of the sunspot cycle and seasonal trends in the nocturnal behaviour of spread-*F* configurations (range and frequency type of spread-*F*) in the Indian equatorial region.

Data and analysis

The study is based on the ionogram data at Kodaikanal (Geo. Lat. 10.2°N, Geog. Long. 77.5°E, Dip 3.5°N) over a seven year period from January 1957 to December 1963, covering the maximum and descending phase of the 19th solar cycle. This particular period is felt to be very suitable for examining the sunspot cycle trends as it encompasses periods of high (1957-59, Mean R_Z = 177), moderate (1960-61, mean R_Z = 83) and low (1962-63, mean R_Z = 33) sunspot number. Ionograms for each night over the seven period have been carefully examined to note down the presence of spread-*F* and if so, the type of configuration. As presented in our earlier paper (Sastri *et al,* 1975), spread-*F* on Kodaikanal ionograms usually manifests in three basic configurations which may be described as follows. The first one is characterised by the presence of spread only at the low frequency and of the *F*-layer trace with clear cut foF2 cusps. The second one is the well known equatorial or range type of spread-*F* where in spread exists over the entire frequency range of the *F*-layer trace. These two configurations have been coupled together and taken to represent range type of spread-*F*. The third one is characterised by the presence of spread only at and around the critical frequency of the *F*-region and represents the temperate latitude or frequency type spread-*F*. Following this classification procedure, the frequency of occurrence of either type of spread-*F* configuration i.e. range or frequency is inferred at half-an-hour intervals from 1800 hrs to 0600 hrs LT for every month over the entire seven year period. From this material, the seasonal and solar cycle trends in the nocturnal behaviour of spread-*F* configurations have been examined by clubbing together the data according to season and sunspot activity level and evaluating the mean percentage occurrence (defined as the ratio of the number of ionograms exhibiting spread-*F* to the total number of ionograms examined multiplied by 100) of either type of spread-*F* configuration, as a function of the local time of the night. The monthly mean percentage occurrences (for the whole night) of either type of spread-*F* has also been calculated to facilitate a quantitative study of the association of either type of spread-*F* with sunspot activity. It is known that rather unusual forms of Spread-*F* exist on equatorial ionograms (Chandra and Rastogi, 1972[a]; Sastri and Murthy, 1975[a]) and these have not been taken into consideration in the analysis.

Results

In Figure 1 is shown the variation of the monthly mean percentage occurrence (for the whole night) of range and frequency type spread-*F* over the period Jan 1957-Dec 1963, together with that of the monthly mean sunspot number. The cross-correlation coefficients between the three variables are also indicated in the figure. It can be clearly seen that the occurrence of both range and frequency spread-*F* exhibits a significant positive correlation (P > 0.01) with sunspot number.

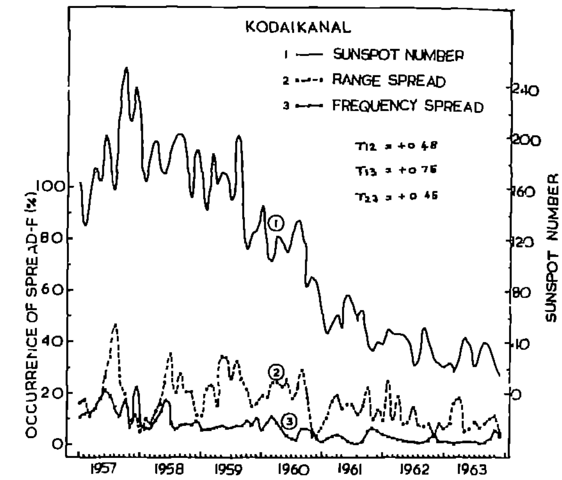

Fig. 1

Variation of the monthly mean percentage occurrence of range and frequency type of spread-*F* at Kodaikanal over the period Jan 1957 – Dec 1963, in comparison with that of the monthly mean sunspot number. The cross-correlation coefficients between the variates are also shown.

There is also a significant positive correlation (P > 0.01) between the monthly occurrence patterns of range and frequency type spread, a feature that is in good agreement with our earlier results for the period 1964-69 (Sastri *et al,* 1975). To bring out clearly the sunspot cycle influence on the nocturnal behaviour of spread-F configurations, in Figure 2 is shown the variation of the occurrence of range and frequency type spread-*F* as a function of local time, for years of high (1957-59) moderate (1960-61) and low (1962-63) sunspot number. It is quite evident that the solar cycle effect is most conspicious during the premidnight period for range type of spread-*F* and during the postmidnight period in the case of frequency type of spread-*F*. These solar cycle trends in the behaviour of equatorial spread-*F* configurations are in conformity with the results of our earlier study for period 1964-69 (Sastri *et al,* 1975) and establish beyond doubt that at Kodaikanal, the occurrence of both range and frequency type of spread-*F* exhibits a positive association with the phase of the sunspot cycle. With a view to bring out clearly the time domains of the occurrence of range and frequency type spread-*F*, in Figure 3 is shown the nocturnal

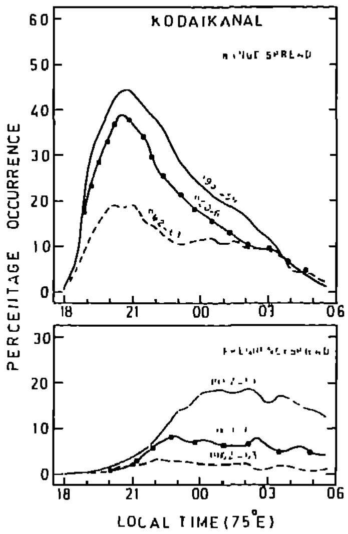

Fig. 2

Nocturnal Variation of the mean percentage occurrence of range and frequency type spread-F for years of high (1957-59), moderate (1960-61) and low (1962-63) sunspot activity.

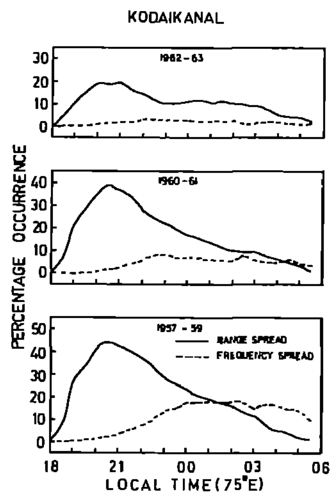

Fig. 3.

Plots showing the mean percentage occurrence, in comparison, of range and frequency type spread-F as a function of local time for periods of varying sunspot activity.

behaviour, in comparison, of range and frequency type spread-F, for periods of varying sunspot activity. It is seen that during periods of high sunspot activity, range spread-F is more frequent during premidnight period, while frequency type spread-F is more frequent during the postmidnight period, in particular, in the presunrise period. However, with decrease in sunspot activity, the occurrence of range type spread-F gains prominence over frequency type spread-F and it is the most dominant spread-F configuration at any particular time of the night for periods of low sunspot activity, as can be seen from Figure 2.

A comparison of the above results with the recent ones of Rastogi and Vyas (1977) for Huancayo (Geog. Lat. 12.0° S. Geog. long. 75.3° W, Dip 2° N) in the American zone, revealed the existence of marked differences in the solar cycle and nocturnal behaviour of spread-F configurations between the two longitude zones. As this longitude dependence represents as interesting aspect of the phenomenon of equatorial spread-F, the points of difference, considered to be poignant, will be highlighted. Firstly, unlike at Kodaikanal where both range and frequency type of spread-F exhibit a positive association with the phase of the sunspot cycle ; at Huancayo, the range type of spread-F shows an inverse relationship with sunspot cycle and the frequency type of spread-F is practically independent of the sunspot cycle. Secondly, during high sunspot activity, while at Kodaikanal the range spread-F is prominent during premidnight period and frequency spread-F is prominent during premidnight period ; at Huancayo, frequency spread-F is the most dominant configuration at any particular of the night. On the other hand, during low sunspot activity, while at Kodaikanal the range spread-F is the dominant configuration at any hour of the night ; at Huancayo, range spread-F is more frequent during the premidnight period and frequency spread-F in the postmidnight period. It is also pertinent to point out here that the work of Huang (1970) showed that at Taipei (Geog. Lat. 25.0°N, Geog. Long. 121.2°E, Dip 19.0°N), a "non-electrojet" equatorial station in the 120°E meridian, range spread-F shows a strong positive correlation and the frequency spread-F a strong negative correlation with sunspot number.

Figure 4 depicts the seasonal behaviour of the nocturnal occurrence of range and frequency type of spread-F, for periods of high, moderate and low sunspot activity seperately. The seasonal break-up adopted is D-months (Nov, Dec, Jan, Feb), E-months (Mar, Apr, Sept, Oct) and J-months (May, June, July, Aug). The following features may be noticed. During D and E-months i.e.local winter and equinoxes respectively, the occurrence of range spread-F exhibits a prominent peak around 20-21 hrs L.T. and this peak is well maintained irrespective of the phase of the sunspot cycle. On the other hand, the occurrence of frequency type of spread-F shows a prominent peak around midnight period and this feature is conspicuous only during years of high solar activity. During J-months, although the range spread-F shows a peak around 20-22 hrs L.T. as in D and E-months for periods of high and moderate solar activity, it persists for a longer time i.e. into the post-midnight period. Further, it is interesting to note that during periods of low sunspot activity, the range type of spread-F shows a rather broad peak around 00-03 hrs LT, instead of around 20-22 hrs LT. It is known from earlier work that at Kodaikanal, spread-F activity persists for a longer time and shows a peak around

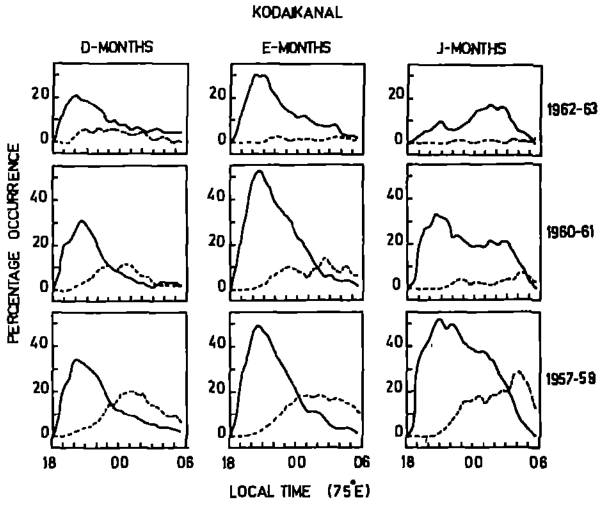

Fig. 4.

Nocturnal variation of mean percentage occurrence of range and frequency type spread-F for each season of years of high, moderate and low sunspot activity.

03 hrs LT, during J-months of low sunspot years (Chandra and Rastogi 1972^b). The present study thus revealed that these features are basically representative of the range type of spread-F and not of the frequency type of spread-F. Careful scrutiny of the data further showed that the postmidnight peak in the occurrence of the range type spread-F during this period receives substantial contribution from the occurrence of a number of days on which there occurred a sudden onset of range spread-F in the postmidnight period, with no range spread-F whatso ever in the preceeding part of the night. It is further noticed that the sudden onset of range spread-F in the postmidnight period usually occurs in association with a prominent rise in F-region height (represented by $h'F$) and that most of the days on which such a behaviour is noticed pertain to geomagnetically quiet conditions. The results presented in Figure 4 also show that there is a seasonal variation, that is dependent on sunspot activity, in the peak occurrence of range type of spread-F (for two hours around the peak). During periods of high sunspot activity, the peak occurrence is high and more or less the same during summer and equinoxes and low in winter. However, with decrease in sunspot activity, the occurrence during equinoxes becomes prominent and a semi-annual variation with maximum in equinoxes and minima in winter and summer is evident for years of moderate and low sunspot activity. A similar semi-annual variation in the peak occurrence of range type of spread-F has also been noticed by Rastogi and Vyas (1977) at Huancayo for low sunspot conditions, allthough the semi-annual trend is more marked at Huancayo than at Kodaikanal.

Discussion

It is well documented in literature that the onset time and intensity of equatorial spread-F are closely associated with the post sunset rise of the equatorial F-region. The postsunset height rise is partly apparent due to the loss of ionization by recombination and diffusion at that time. The measurements of F-region vertical drift by radar Doppler techniques at Jicamarca however showed the existence of a peak in the upward F-region vertical drift just around the time of the sunset reversal, sometimes as large as 40-60 msec^{-1} (Balsley and Woodman 1969 ; Woodman, 1970). This experimental evidence clearly indicates the involvement of a true vertical drift in the postsunset rise of equatorial F-region. One consistent pattern evident from the present study is that the occurrence of range type spread-F shows a prominent peak around 20-22 hrs LT irrespective of season and phase of the sunspot cycle (except during J-months of low sunspot activity). This clearly indicates that the occurrence of range type of spread-F on equatorial ionograms is closely associated with the height rise and pre-reversal peak of upward vertical drift of F-region around the sunset period. It is well known that the postsunset rise of equatorial F-region is dependent on the phase of the sunspot cycle being more marked during high sunspot activity, and the recent observations of Woodman *et al.* (1977) also show the pre-reversal peak in upward vertical drift to be positively correlated with the sunspot cycle. Thus, one would expect a positive correlation of the occurrence of range spread-F with sunspot activity. This indeed is the behaviour at Kodaikanal as the results of the present study showed and also at Taipeh as already mentioned. The inverse relationship reported by Rastogi and Vyas (1977) for Huancayo however defies an understanding on these terms. Further, the results of the present analysis show that the sunspot cycle effect in the occurrence of frequency type spread-F is also different at Kodaikanal, Huancayo and Taipei. These observations clearly indicate a marked longitudinal dependence of the long term trends in the occurrence of range and frequency type spread-F, the cause (*s*) for which merits further critical examination.

Several theories have been put forward in the past to account for the generation of irregularities responsible for equatorial spread-F based on the changes that occur around the sunset period (refer to Farley *et al*, 1970 for a discussion of the earlier theoretical work). New information on equatorial spread-F irregularities has been obtained in the recent times from a variety of potential experimental techniques : in situ measurements by rockets and satellites (Hanson and Sanatani, 1971, 1973 ; Dyson *et al*, 1974 ; Kelley *et al*, 1976 ; Morse *et al*, 1977) ; *HF* forward scatter (Rottger, 1973) and *VHF* backscatter measurements (Woodman and La Hoz, 1976). It is now being increasingly felt that there could be more than one physical mechanism involved in the production of the wide spectrum of spread-*F* irregularities (Woodman and La Hoz, 1976 ; Morse *et al*, 1977). As regards spread-*F* on bottomside ionograms is concerned, it appears that during the postsunset period (the time domain of range spread-*F*) where the spread-*F* usually manifests on the steep bottomside of the *F*-region, the Rayleigh – Taylor instability (Originally proposed by Dungey, 1956 and revived in recent times by Balsley *et al*, 1972 ; Jain and Das, 1978 Haerendel, 1974 ; Beer, 1974 ; Hudson and Kennel, 1975) and the drift instability (Hudson and Kennel, 1975) which is independent of electric field, could be the probable mechanisms responsible for the generation of irregularities. This inference stems from the observational evidence available. To elaborate, the UHF backscatter measurements of Farley *et al* (1970) showed the presence of an altitude threshold rather than a vertical drift velocity threshold for the onset of spread-*F* in the postsunset period (although the backscatter measurements refer to irregularities at a wavelength of 3 m in contrast to ionosonde observations which pertain to irregularities at wavelengths ranging from 100 m to a few Km, when the radar backscatter signal is strong, spread-*F* is noticed to be always present on ionograms). The recent observations of Woodman and La Hoz (1976) also showed that spread-*F* occurrs at the steep bottom of *F*-region when vertical drift is down, zero or upward. On the otherhand, the observations of Rastogi (quoted in Rastogi and Woodman, 1978) indicate the presence of a vertical drift threshold for the postsunset onset of spread-*F*. Our recent studies using ionogram data at Kodaikanal showed considerable scatter in the values of $h'F$ at the time of the postsunset onset of spread-*F* clearly indicating the the onset is not uniquely dependent on the altitude attained (Sastri and Murthy, 1978 ; Sastri *et al.* 1978). Since the altitude attained depends on the vertical drift velocity, recombination and perhaps diffusion, the scatter in the values of $h'F$ suggests considerable day-to-day changes in the vertical drift behaviour around the sunset period which is infact observed in the backscatter measurements.

As already mentioned, the frequency type spread-*F* on equatorial ionograms has been explained as due to ducting by thick field aligned ionization irregularities (Pitteway and Cohen, 1961). However, the understanding of the Physical mechanisms involved in the production of such irregularities is poor at the moment. It is quite pertinent to mention here that King (1970) asserted that both range and frequency spread-*F* on ionograms is due to one and the same cause namely, total reflection from sharp tilts in the isoionic contours. The results of the present analysis (for the period 1957-63) and those of our earlier study (for the period 1964-69) consistently showed a significant similarity in the monthly mean occurrence patterns of range and frequency spread-*F* at Kodaikanal. Such a similarity is also apparent in the monthly mean occurrence patterns of range and frequency spread-*F* at Huancayo (Figure 1 of Rastogi and Vyas, 1977) although not explicitly studied. This feature clearly suggests that the occurrence of range and frequency spread-*F* in the equatorial region could not be entirely due to unrelated causative mechanisms. Further studies, both theoretical and experimental, are very much required to throw light on the physical processes responsible for the frequency type of spread-*F* on equatorial ionograms.

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Références

Balsley B.B. and R.F. Woodman, On the control of the *F*-region drift velocity by the *E*-region electric field experimental evidence", *J. Atmos, Terr. Phys.*, 31, 865-867,1969.

Balsley B.B., G. Haerendal and R.A. Greenwald, "Equatorial spread-*F* : recent observations and a new interpretation", *J. Geophys. Res.*, 77, 5625-5628, 1972.

Beer, T., On the dynamics of equatorial spread-*F*, *Aust. J. Phys.*, 27, 391-400, 1974.

Booker H.G. and W.H. Wells, "Scattering of radio waves by the *F*-region of the ionosphere", *Terr, Magn. Atmos. Electr.*, 43, 249-256, 1938.

Calvert W. and R. Cohen, "The interpretation and synthesis of spread-*F* configurations appearing on equatorial ionograms", *J. Geophys. Res.*, 66, 3125-3140, 1961.

Chandra H. and R.G. Rastogi, Spread-*F* at the magnetic equatorial station, Thumba", *Ann. Geogphys.*, 28, 37-44, 1972a.

Chandra H. and R.G. Rastogi, "Equatorial spread-*F* over a solar cycle", *Ann. Geophys.*, 28, 709-716, 1972b.

Cohen R. and K.L. Bowles, "On the nature of equatorial spread-*F*", *J. Geophys. Res.*, 66, 1081-1106, 1961.

Clemesha B.R., "An investigation of the irregularities in the *F*-region associated with equatorial type spread-*F*", *J. Atmos. Terr. Phys.*, 26, 91-112, 1964.

Clemesha B.R. and R.W.H. Wright, "A survey of equatorial spread-*F*, in spread-*F* and its effects upon radio wave propagation and communication", edited by P. Newman, P 3-27, Technivision, Maidenhead, England, 1966.

Dyson P.L., J.P. Mcclure and W.B. Hanson, In situ measurements of the spectral characteristics of *F*-regionionospheric irregularities, *J. Geophys. Res*, 1497-1502, 1974.

Dungey J.W., Convective diffusion in the equatorial *F*-region, *J. Atmos. Terr. Phys.*, 9, 304-310, 1956.

Farley D.T., B.B. Balsley, R.F. Woodman and J.P. McClure, "Equatorial spread-*F* implications of *VHF* radar observations", *J. Geophys. Res.*, 75, 7199-7216, 1970.

Fejer B.G., D.T. Balsley, B.B. Balsley and R.F. Woodman, "Radar studies of anomalous velocity reversals in the equatorial ionosphero", *J. Geophys. Res.*, 81, 4621-4626, 1976.

Haerendel G., *Theory of equatorial spread-F*, preprint, Max-Planck- Institut fur Physik und Astrophysik, Garching, West Germany, 1974.

Hanson W.B. and S Sanatani, Relationship between F_c^+ ions and equatorial spread-*F*, *J. Geophys. Res*, 76, 7761-7768, 1971.

HansonW.B. and S. Sanatani, Large N_i gradients below the equatorial *F*-peak, *J. Geophys., Res.* 78, 1167-1172, 1973

Huang C.M., "F-region irregularities that cause scintillations and spread-*F* echoes at low latitudes", *J. Geophys. Res.*, 75, 4833-4841, 1970.

Hudson M.K. and C.F. Kennel, Linear theory of equatorial spread-*F*, *J. Geophys. Res*, 80, 4581-4590, 1975

Jain R.K. and A.C. Das, Non linear Rayleigh – Taylor instability in partially ionised plasma and the equatorial spread-*F*, *Proc. Indian Acad. Sci*, 87A, 1-12, 1978.

Keller M.C., G. Haerendel, H. Kappler, A. Valenzuela, Balsley B.B., D.A. Carter, W.L. Ecklund, C.W. Carlson, B. Hausler and R. Torbert, Evidence for a Rayleigh – Taylor type instability and upwelling of depleted density regions during equatorial spread-*F*, *Geophys. Res. Lett.*, 3, 448-450, 1976.

King G.A.M., Spread-*F* on ionograms, *J. Atmos. Terr. Phys*, 32, 209-221, 1970.

Morse F.A., B.C. Edgar, H.C. Koons, C.J. Rice, W.J. Heikkila, J.H. Haffman, B.A. Tinsley, J.D. Winningham, A.B. Christensen, R.F. Woodman, J. Pomalaza and N.R. Teixeira, "Equion, an equatorial ionospheric irregularity experiment", *J. Geophys. Res.*, 82, 578-592, 1977.

Pitteway M.L.V. and R. Cohen, "A wave-Guide interpretation of temperate latitude spread-*F* on equatorial ionograms" *J. Geophys. Res.*, 66, 3141-3156, 1961.

Rastogi R.G. and G.D. Vyas, "Range and frequency type spread-*F* at Huancayo", *Proc. Indian. Acad. Sci. A*, 86, 417-421, 1977.

Rastogi R.G. and R.F. Woodman, "Spread-*F* in equatorial ionograms Associated with reversal of horizontal *F*-region electric field", *Ann. Geophys.* 34, 31-36, 1978.

Reber G., Worldwide spread-*F*", *J. Geophys. Res.*, 61, 157-164, 1956.

Rottger J., Wave-like structures of large scale equatorial spread-*F* irregularities, *J. Atmos. Terr. Phys*, 35, 1195-1206, 1973.

Rottger J., The macro-scale structure of equatorial spread-*F* irregularities, *J. Atmos. Terr. Phys*, 38, 97-101. 1976.

Sastri J.H. and B.S. Murthy, "Spread-*F* at Kodaikanal", *Ann. Geophys.*, 31, 285-296, 1975a.

Sastri J.H., B.S. Murthy and K. Sasidharan, "On the characteristics of spread-*F* configurations at Kodaikanal", *Ann. Geophys.*, 31, 409-414, 1975b.

Sastri J.H. and B.S. Murthy, "On the onset of equatorial spread-*F*", *Ann. Geophys.*, 34, 47-49, 1978a.

Sastri J.H., V. Subramanyam, K. Sasidharan and M. Srirama Rao, "On the height control of the onset of equatorial spread-*F*", *Curr. Sci.*, 47, 451-452, 1978b.

Shimazaki R., "A statistical study of world – wide occurrence probability of spread-*F*, I. Average state", *J. Radio. Res. lab. Japan* 6, 669-687, 1959.

Singleton D.G., "The geomorphology of spread-*F*", J. Geophys. Res., 65, 3615-3524, 1960.

Skinner N.J. and R.F. Kelleher, "Studies of *F*-region irregularities at Nairobi-1, From spread-*F* on ionograms 1964-1970", *Ann. Geophys.*, 27, 181-194, 1971.

Woodman R.F., "Vertical drift velocities and east west electric fields at the magnetic equator", *J. Geophys. Res.*, 75, 6249-6259, 1970.

Woodman R.F. and C. La Hoz, "Radar Observations of *F*-region equatorial irregularities", *J. Geophys, Res.*, 81, 5447-5466, 1976.

Woodman R.F., R.G. Rastogi and C. Calderon, "Solar cycle effects on the electric fields in the equatorial ionosphere", *J. Geophy. Res*, 82, 5257-5261, 1977.

Wright R.W.H., Geomorphology of spread-*F* and characteristics of equatorial spread-*F*", *J. Geophys. Res.*, 64, 2203-2207, 1959.