Indian Journal of Radio & Space Physics
Vol. 15, February 1986, pp. 10-16

Post-midnight Equatorial Spread-F

R G RASTOGI
Indian Institute of Geomagnetism, Colaba, Bombay 400005

Received 3 *August* 1984; *accepted* 25 *October* 1985

The comparison of the scintillations of VHF radio beacons from geostationary satellite Geos-1 (74.9°W) and the vertical incidence ionograms at Huancayo (75.3°W) have shown that the diffused echoes observed on the ionograms during late night or early morning hours are not due to oblique reflections from new ionization but due to in situ plasma irregularities (bubbles) present on the path of satellite-to-ground radio path. These events are preceded with rapid rise of the F-layer. Multi-satellite and multi-station radio scintillation records indicate the presence of a westward movement of the bubbles corresponding on eastward electric field during these not very normal post-midnight events.

1 Introduction

Equatorial spread-F has been observed following the post-sunset rapid rise of the F-region at a number of low latitude stations, viz. Huancayo[1], Singapore[2], Kodaikanal[3], Ibadan[4] and at Thumba[5]. It has been shown that the peak in the nocturnal occurrence of spread-F at any equatorial stations occurs before midnight during high sunspots but gradually shifts to later hours with decreasing solar activity[6]. Studying the equatorial spread-F at Huancayo separately for the range and frequency types, Rastogi[7] showed that during the high sunspot years the nocturnal occurrence of range type spread-F is peaked at 20-21 hrs followed by a systematic decrease till sunrise hours. During the low sunspots, the premidnight peak is slightly lower but the mean occurrence of range spread-F at Huancayo continues at reasonably high level amost till sunrise periods. The occurrence of premidnight spread-F at Huancayo had a direct relation with sunspots while the post-midnight spread-F occurrence was more during low than during high sunspot years. Rastogi *et al.*[8] had shown that the geomagnetic activity had the effect of suppressing the occurrence of premidnight spread-F but it had a positive effect on the occurrence of post-midnight spread-F

The scintillation of radio waves during the night-time hours at low latitude stations has been known to be associated with equatorial spread-F[9-12]. Chandra *et al.*[13] showed that the scintillations at Ootacamund on 140 and 360 MHz radio beacons were associated with the range type of spread-F at Kodaikanal ionograms while frequency spread produced weak scintillations only on lower frequency beacon on 40 MHz. Rastogi and Woodman[14] showed that range type of equatorial spread-F can be generated at any of the hours of the night following the occurrence of an upward F-region drift corresponding to an eastward electric field. Rastogi and Aarons[15] showed that any abnormal reversal of the equatorial horizontal electric field at night is followed by the occurrence of intense VHF scintillations with a delay of about 1 hr. Thus the post-midnight hours seem to be a sensitive period for an equatorial ionosphere to generate unusual F-region irregularities and associated scintillations.

The long term average nocturnal variation of equatorial spread-F shows a single peak at premidnight hours and only a decrease or a minor broad peak at post-midnight hours[16,17]. But the plots of individual day scintillation index at Ootacamund on 327 MHz showed most frequent occurrence around 2200 hrs and another around 0400 hrs[18]. In this paper we study some of the properties of post-midnight spread-F and scintillations at the equatorial station, Huancayo.

2 Analysis of Spread-F and Scintillation Data

The data sets utilized are the vertical incidence ionograms and VHF scintillations at Huancayo. During the months of December 1974-January 1975, the radio beacons available at Huancayo were from satellite LES-6 on 254 MHz at an elevation of 46° and azimuth of 6°E of N and from ATS-6 on 140 MHz at an elevation of 64° and azimuth 30° E of N.

In Fig. 1 are shown mean and median values of the scintillation index (SI) as well as the number of occasions the SI exceeded peak-to-peak amplitude of 3 dB on 140 MHz beacons from ATS-6 received at Huancayo. It is seen that the mean and median values of SI showed the main peak around 2200 hrs and another smaller peak around 0230 hrs. During the peak occurrence around 2200 hrs both the mean and median values were of the same order of about 50% showing that the incidence of the scintillations was quite common. At another times, the mean was higher

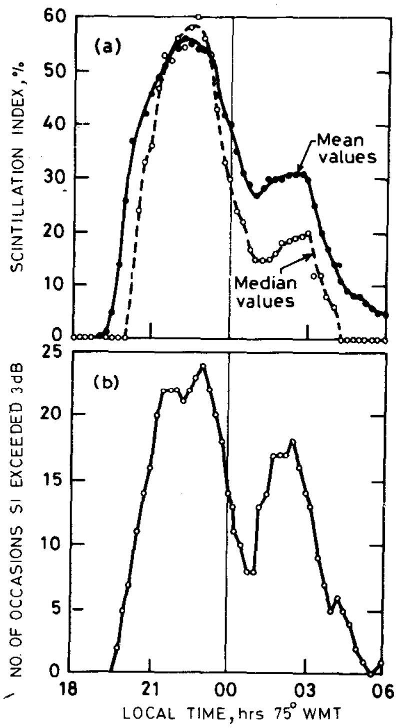

Fig. 1—Nocturnal variations of the mean and median values of the scintillation index as well as the number of occasions the index exceeded the level of 3 dB of the ATS-6 radio beacon on 140 MHz received at Huancayo for the period December 1974-January 1975

than median suggesting that the scintillation events on these hours were much infrequent than the weak scintillation or no scintillation events. Thus the post-midnight occurrence of spread-F is not a regular phenomenon but occurs on some special occasions, probably when the horizontal electric field is eastward.

In the nocturnal plot of the occasions when the scintillation index exceeded 3 dB, one notices the major peak at 2300 hrs but a significant peak at 0300 hrs with a definite minimum at 0100 hrs. The post-midnight peak after a definite minimum suggests a regeneration of new irregularities rather than the resurgence of the old irregularities.

The ionospheric (350 km) cross-over points of these transmission paths from LES-6, ATS-3 and ATS-6 were respectively about 340 km east, 10 km east and 150 km west of the longitude of Huancayo. The ionospheric irregularities at equatorial regions are highly elongated in the N-S direction and so the latitudinal difference of the cross-over points does not matter much when we are studying the movements of the spread-F patches in the east-west direction. If the event is associated with the local sunset then it should be felt first on LES-6 beacon, then on ATS-3 beacon and afterwards on ATS-6 beacon. If the event is universal time controlled then it would be observed at the same local standard time on all the beacons. Examining the scintillations of radio beacons from these satellites at Huancayo, Rastogi[19] has shown that during the initial stages of the development of spread-F in the post-evening hours the drift is generally westward associated with the movements of the sunset terminator while at later stages when the irregularities are fully developed the drift is eastward. From later study of these records it has been found that if the spread-F started well after sunset or late in the night hours, the development of scintillations was almost at the same time on all the three radio beacons. An example is shown in Fig. 2 from the nocturnal variations of the scintillations of beacons from LES-6, ATS-3 and ATS-6 on 11 and 18 Dec. 1974. It is seen that on 11 Dec. 1974 scitntillations started on LES-6 (254 MHz beacon) at 1930 hrs on ATS-3 (137 MHz beacon) at 2015 hrs and on ATS-6 (140 MHz beacon) at 2045 hrs. The delay between the start of scintillations on ATS-6 and ATS-3 beacons was roughly half that between ATS-3 and LES-6. This suggests a uniform west progression of the spread-F boundary after sunset. On 18 Dec. 1974, the scintillations started in the post-midnight hours at 0200 hrs on the radio beacons from any of the three satellites and no significant delay was noticed.

During the AFGL campaign of ionospheric irregularities in Peru in March 1977, the geostationary satellite Geos-1 was situated at 74.9°W longitude and the amplitude scintillations were recorded at Huancayo (75.3°W) where an ionospheric observatory was also located. Thus the propagation path of satellite-to-ground was practically along the geomagnetic meridian. The elevation of the satellite from Huancayo was 76°. Thus the volume of the ionosphere at an altitude of 400 km sampled by the scintillation of the satellite signal was only 100 km due north (along the same magnetic field line) of Huancayo ionospheric observatory. Thus these experiments provided an ideal data for the comparison of radio scintillations and vertical ionospheric soundings records.

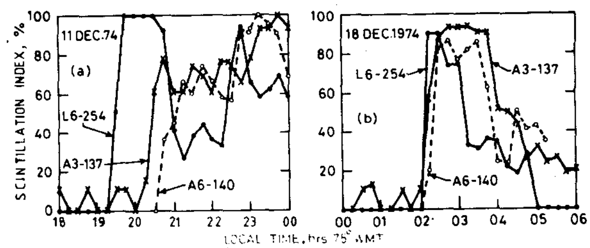

Fig. 2—Plots showing: (a) temporal variation of the pre-midnight scintillation event on 11 Dec. 1974 and (b) the post-midnight scintillation event on 18 Dec. 1974

In Fig. 3 are shown the ionograms at Huancayo on the night of 8-9 March 1977 when post-midnight scintillations were recorded on the radio beacons transmitted from Geos-1 received at Huancayo. The temporal variations of the scintillation index are compared with the variations of the critical frequency of the minimum heights of the F-layer at Huancayo in Fig. 4. It is seen from Fig. 3 that there were no post-sunset spread-F recorded on the ionograms and the critical frequency traces were clearly seen. The ionogram for 0303 hrs LT showed some multiple traces near the critical frequency and the ionogram for 0403 hrs LT showed complete spread. At 0503 hrs LT the echoes were scattered strongly from two altitudes of 300 and 400 km. Referring to Fig. 4 it is seen that range type of spread-F was seen between 0315 and 0545 hrs LT. This spread-F event was preceded by a large increase of the F-region base from 200 to 300 km between 0200 and 0330 hrs LT. The radio beacon from Geos-1 to Huancayo had no scintillations at 0300 hrs LT but the fluctuations were of peak-to-peak magnitude of 6.7 dB at 0315 hrs LT. The scintillations were high during the spread-F activity and decreased following the sunrise. The rise of the F-region prior to the spread-F and scintillation event indicates that the phenomenon was due to the eastward electric field at about 0200 hrs LT causing **E** × **B** uplift of the F-layer, but no drift data are available during the period. Sometimes, the occurrence of post-midnight scintillation event is suggested to be

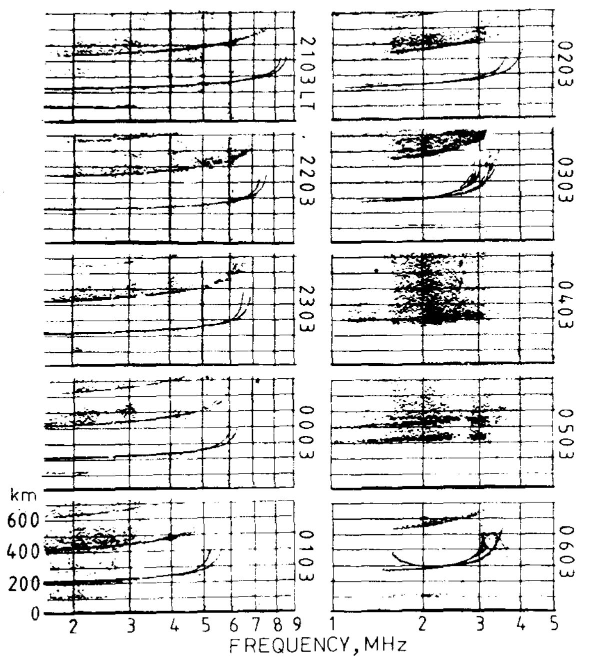

Fig. 3—Ionograms at Huancayo on the night of 8-9 Mar. 1977 showing spread-F occurring only after midnight hours at 0300 hrs LT

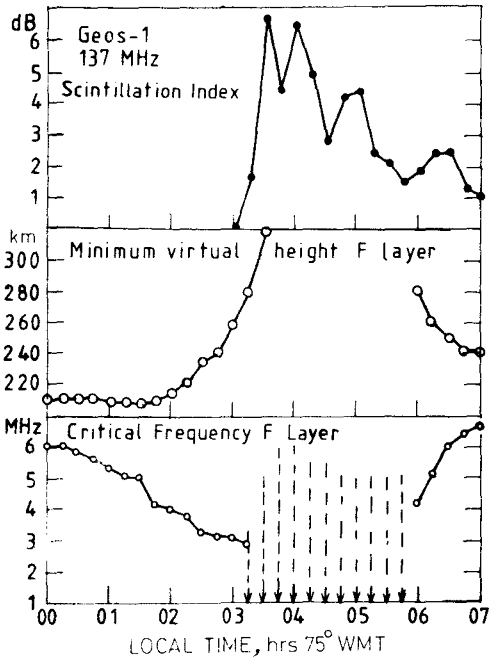

Fig. 4—Comparison of the sudden onset of scintillations of Geos-1 (137 MHz) radio beacon received at Huancayo with the variations of the critical frequency and height of the F-region during the same period on 9 Mar. 1977

due to the reactivation of the post-sunset spread-F irregularities or bubbles or due to the movement of the bubble from other longitudes. The complete absence of the spread-F during the night up to 0300 hrs LT excludes the suggestion of the evening bubbles drifting along the path of satellite radio beacon by the morning hours. This is definitely a case of freshly generated bubble in the morning hours near the vicinity of Huancayo itself.

We examine a case of spread-F and associated scintillations starting after midnight hours on 10 Mar. 1977. The vertical incidence ionograms at Huancayo and the temporal variations of the height of the scintillation index of 137 MHz beacons from Geos-1 satellite to Huancayo are shown in Fig. 5. It is seen that the ionogram for 0300 hrs LT was extremely clean with both the ordinary and extraordinary critical frequencies of the F2-layer recorded very clearly. At 0345 hrs LT, weak spread echoes had developed at the base of the F2-layer and some diffused echoes were recorded at different heights but the first order *h'-f* trace was clearly identified without any ambiguity in the critical frequencies. At 0400 hrs LT, the ionogram indicated complete spread with no *h'-f* trace discernible. The sunrise at the F-region heights was at about 0430 hrs. The ionogram at 0530 hrs LT showed a number of layers of strong reflections without any group retardation suggesting these echoes to be due to scattering processes at sharp plasma gradient levels rather than due to reflections corresponding to the plasma frequency at that level. At 0600 hrs LT, fresh ionization had been generated due to the sunrise and an intermediate critical frequency was recorded at 3 MHz; spread echoes were recorded at higher frequencies up to 8 MHz. The echoes beyond f_0F2 showed clearly the effect of the group retardation by the underlying intermediate layer. At 0615 hrs LT the critical frequencies of the F2-layer had further increased and the group retardation in the spread echoes was still seen. Such spread echoes close to the F2-layer critical frequencies were seen up to 0830 hrs LT after the sunrise.ı

The variation of *h'-f* shows that the base of the F2-layer had started rising even at 0200 hrs LT and reached the maximum value at about 0400 hrs LT, most probably due to a reversal of electric field in the ionosphere to the eastward direction. The scintillations of Geos-1 (137 MHz) were absent until 0315 hrs LT and increased to a value exceeding 10 dB thereafter. The scintillations continued up to 0800 hrs LT corresponding to the time during which spread-F were recorded on the ionograms. This shows that plasma irregularities in the F-region may remain in view for a few hours after sunrise on certain occasions.

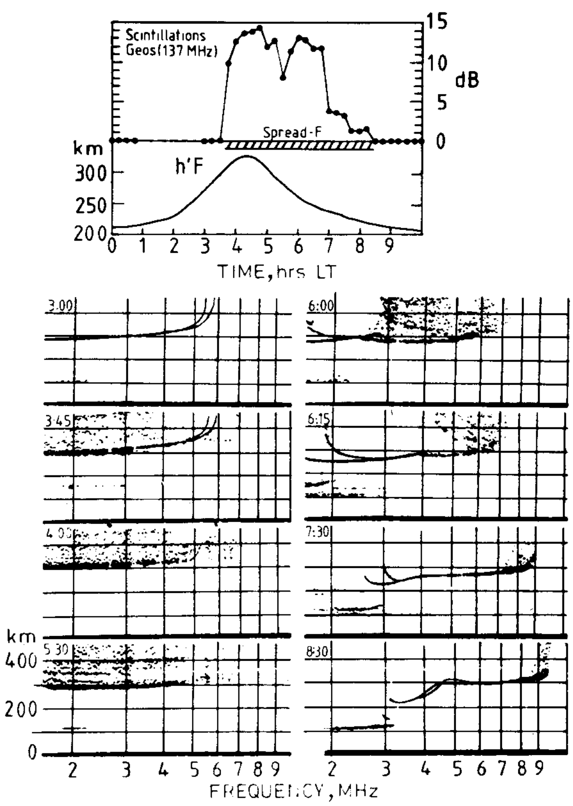

Fig. 5 -Ionograms at Huancayo on 10 Mar. 1977 showing post-midnight spread-F compared with the temporal variations of *h'*F and of the scintillation index of Geos-1 (137 MHz) radio beacon received at Huancayo

On certain events long-lived irregularities could have moved out of view of the ionosonde or scintillation path.

In Fig. 6 are shown the ionograms at Huancayo and the variation of scintillation index of 137 MHz signal from Geos-1 satellite to Huancayo around sunrise period on 12 Mar. 1977. It would be seen from the ionograms, that there was no spread at Huancayo during the post-midnight hours of 12 Mar. 1977; both the *o* and *x* components of the F-layer critical frequencies were clearly recorded. At 0530 hrs LT, some oblique scatter echoes were recorded on the ionograms but the critical frequencies were clear. At 0545 hrs LT, the spreadiness grew to be stronger. At 0600 hrs LT sunrise effects were clear by the increase of F-layer critical frequencies as well as by the appearance of group retardation at the start of *h'-f* trace for the F-layer. At 0615 hrs LT, the spread-F had disappeared on the ionograms. The spread-F was seen on the bottomside ionogram only between 0545 and 0600 hrs LT. The recordings of Geos-1 (137 MHz) signals received at Huancayo showed complete absence of scintillations up to 0530 hrs LT and had suddenly appeared at 0545 hrs LT (magnitude 3 dB). The scintillations continued up to 0630 hrs LT and it was more than 4 dB at 0615 hrs LT.

In Fig. 7 are shown another case of post-sunrise

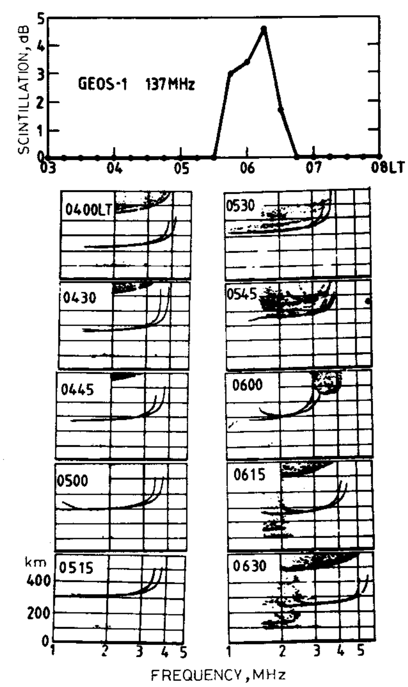

Fig. 6—Ionograms at Huancayo on 12 Mar. 1977 showing spread echoes above the F2-layer during sunrise period and the scintillations of Geos-1 (137 MHz) radio beacons received at Huancayo

spread-F and associated scintillation activities. Fig. 7 shows ionograms at Huancayo and the variations of scintillation index of Geos-1 (137 MHz) signals received at Huancayo (11.97°S, 75.34°W) and at Ancon (11.71°S, 77.15°W) on 14 Mar. 1977.

The ionograms at 0400 hrs LT showed clean *h'-f* trace without any spread-F. At 0415 hrs LT some spread echoes did appear at the base of the F-layer but the *h'-f* trace was perfectly clear; the scintillation indices of the satellite signals were zero at both Huancayo and at Ancon. At 0445 hrs LT, spread-F at Huancayo increased in intensity, but the *h'-f* trace was still clear; scintillations at Huancayo were weak, of about 1 dB, while at Ancon there were no scintillations. At 0500 hrs LT, the spread-F had developed to the stage of obscuring the *h'-f* trace and the scintillations at Huancayo started increasing thereafter reaching a value of 10 dB at 0530 hrs LT. At 0600 hrs LT, fresh ionization had been generated in the F2-region giving f_0F2 = 2.9 MHz, but spread echoes were still strong on frequencies beyond f_0F2; scintillation index at Huancayo remained high (10 dB). At 0615 hrs LT, f_0F2 increased to 4.1 MHz and spread echoes continued to be seen on frequencies beyond f_0F2. It is to be noted that the spread-F configuration above f_0F2 clearly shows group retardation; thus these scattered radio waves have traversed through a region having fresh ionization. This clear F2 trace and the spread echoes are not from different regions of the ionosphere. By 0615 hrs LT scintillation index at Huancayo had decreased to 5 dB. Both the spread-F and scintillations at Huancayo continued up to 0645 hrs LT. The scintillations at Ancon, situated about 100 km to the west of Huancayo started increasing only after 0530 hrs LT, about half an hour after the start of scintillations at Huancayo. Similarly, the scintillation activity at Ancon continued till 0745 hrs LT while that at Huancayo continued up to 0645 hrs LT. In Fig. 8 are reproduced the variations of the scintillation of Geos-1 (137 MHz) and LES-6 (245 MHz) radio beacons received at Huancayo on 14 Mar. 1977 after AFGL publication by Whitney *et al.*[20] With respect to Huancayo the satellite LES-6 was east while Geos-1 was slightly west of Huancayo.

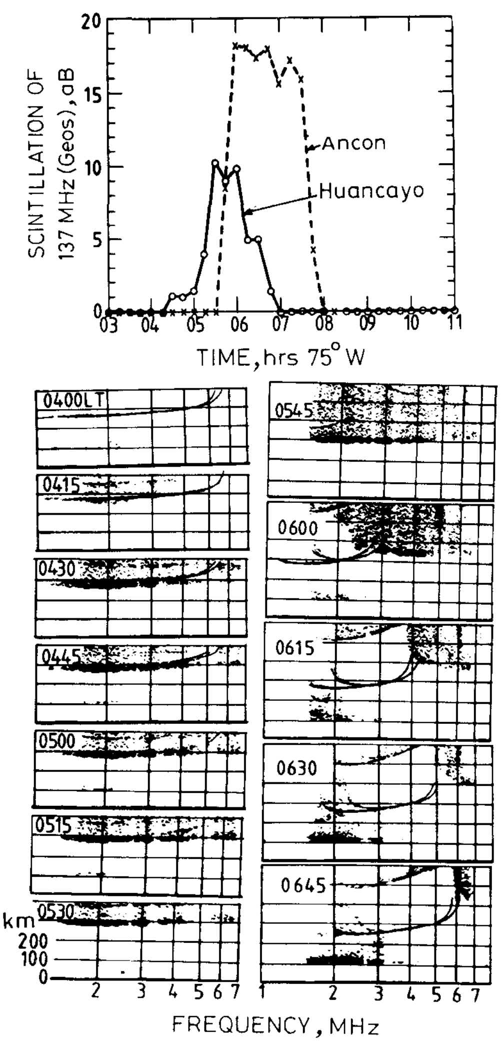

Fig. 7—Comparison of spread-F on the ionograms at Huancayo with the scintillations of Geos-1 (137 MHz) beacon received at Huancayo on 14 Mar. 1977

It is seen from the diagram that scintillations on LES-6 signals started about an hour earlier than on Geos-1 signals. Thus this event of spread-F and scintillations observed at Huancayo was due to a westward movement of the bubbles which suggests a strong eastward electric field associated with the generation of fresh bubbles in the late night or the early morning hours.

3 Discussion

The very first observations of equatorial spread-F at Huancayo by Booker and Wells[1] in 1938 and at Singapore by Osborne[2] in 1952 had clearly indicated the importance of rapid rise of the F-region at post-sunset hours preceding the onset of spread-F. Osborne's observations on the occurrence frequency

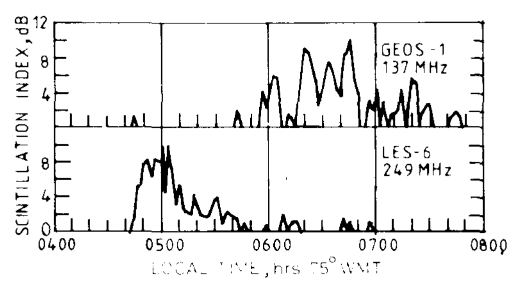

Fig. 8—Temporal variations of the scintillation of radio beacons Geos-1 (137 MHz) and LES-6 (245 MHz) received at Huancayo on 14 Mar. 1977

of spread-F and on the rate of rise of the F-region had given a convincing effect of the F-region movement on the generation of the spread-F. Any source causing a vertical drift of the irregularities against an overdense plasma would result in the amplification of the irregularities. Martyn[21] had suggested that the east-west electrostatic field causes both the ionosphere and its irregularities to drift vertically with slightly different speeds; and under this mechanism the F-region would be most unstable at the base of the F-layer where the logarithmic gradient of ionization is high. Martyn had suggested that the electric field driving the daily *Sq* current system in the E-region would be an adequate source for the amplification. This idea was not accepted those times because the spread-F was often observed after the reversal of the electric field direction in the evening. Rastogi[22] has shown that the prominent effect of the daytime *Sq* field extending after ground sunset is responsible for the generation of spread-F irregularities. Thus, the Martyn's theory is still tenable as far as the amplification of the irregularities is concerned.

An alternative to Martyn's theory is based on the cooling of the atmosphere after sunset. Clemmow *et al.*[23] had suggested that the motion of irregularities relative to the ambient ionization should occur when there is a wind of the neutral atmosphere across the geomagnetic field. According to the predictions of Lowan[24] and the observations of Serbu *et al.*[25] the upper atmosphere cools abruptly after sunset. Calvert[26] suggested that the wind occurring as the atmosphere cools after sunset, i.e. the thermal contraction wind, may give rise to instabilities in the F-layer.

The neutral atmosphere movement across the contours of ionization levels may be caused by the gravity waves. Such gravity waves excited during sunset might well explain the motion of spread-F irregularities. Whitehead[27] suggested that in the presence of an electrostatic field and background neutral wind, the internal gravity waves can create a spatial resonance in the F-region plasma when the natural drift of ionization irregularities equals the phase velocity of the gravity wave. Beer[28] suggested a self induced spatial resonance where the ionization perturbations produced by the gravity waves drift velocity match the gravity waves phase velocity. Klostermeyer[29] suggested that the polarization field generated by the electric currents driven by the gravity waves is the cause of plasma irregularities. Prakash and Pandey[30] pointed that the perturbation electric fields would be shorted out if magnetic field lines can link the regions of positive and negative charges and for a finite meridional components of the gravity wave number, the process would be limited to very near the dip equator.

Dungey[31] was the first to suggest the equatorial spread-F to be caused by Rayleigh-Taylor instability driven by gravity anti-parallel to the plasma density gradient and perpendicular to the magnetic field. This theory could not explain the generation of irregularities on the topside where the density gradient and the gravity are in the same direction. Balsley *et al.*[32] and Haerendel[33] suggested collisional Rayleigh-Taylor instability with field line averaging for the generation of equatorial spread-F. Hudson *et al.*[34] suggested a two-step generation of smaller scale size irregularities on the top of large scale sizes in the equatorial spread-F. The non-linear numerical simulation of the collisional Rayleigh-Taylor instability for the equatorial spread-F by Scannapieco and Ossakow[35] showed that the plasma density depletions (bubbles) on the bottomside of the F-region subsequently rose beyond the F peak by non-linear polarization induced $\mathbf{E} \times \mathbf{B}$ forces. The results have been in accord with the experimental data of Woodman and La Hoz[36], Kelley *et al.*[37] and McClure *et al.*[38] The Rayleigh-Taylor instability mechanisms theory modified by various workers remarkably confirms the observations of equatorial spread-F but no explanation has been attempted on the morphology of the spread-F or on the generation of the late night spread-F on certain cases specially associated with the abnormal reversals of the equatorial electric fields.

Reid[39] and Cunnold[40] suggested the density gradient driven plasma instability for the generation of spread-F irregularities. Reid[39] showed that irregularities scale sizes in the range of some hundreds of metres to a few kilometres can develop in the F-region in a time of the order of an hour by an eastward electric field. Cunnold[40] suggested that the irregularities in the lower ionosphere could be connectively amplified by the drift instabilities. Rastogi and Woodman[41] have shown that the sudden reversal of the horizontal electric field to eastward direction at any time of the night is followed by the occurrence of range type of spread-F with delay of about an hour confirming the growth time required by Reid's calculations. Rastogi[42] explained the seasonal and longitudinal variations of the occurrence of spread-F on the basis of the initiation of irregularities by gradient drift instability and its vertical extension by Rayleigh-Taylor instability. Rastogi[43] has shown that the predominantly strong control of the eastward electric field in the ionosphere is responsible for producing the evening spread-F. The present observations further support these ideas.

Acknowledgement

Grateful thanks are due to National Research Council of USA for the award of Senior Research

Associateship and to Air Force Geophysics Laboratory Bedford, Massachusetts, USA, for the facilities provided to the author. Thanks are due to J Aarons, J A Klobuchar and other colleagues for useful discussions and suggestions. Research at the Indian Institute of Geomagnetism is supported by the Ministry of Tourism and Civil Aviation, Government of India, New Delhi.

References

1 Booker H G & Wells H W, *Terr Magn & Atmos Electr* (*USA*), **43** (1938) 249.

2 Osborne B W, *J Atmos & Terr Phys* (*GB*), **2** (1952) 66.

3 Bhargava B N, *Indian J Meteorol Hydrol & Geophysics*, **9** (1958) 35.

4 Lyon A J, Skinner N J & Wright R W H, *J Atmos & Terr Phys* (*GB*), **19** (1960) 145.

5 Chandra H & Rastogi R G, *Ann Geophys* (*France*), **28** (1972) 37.

6 Chandra H & Rastogi R G, *Ann Geophys* (*France*), **28** (1972) 209.

7 Rastogi R G, *J Atmos & Terr Phys* (*GB*), **43** (1980) 593.

8 Rastogi R G, Mullen J P & McKenzie E, *J Geophys Res* (*USA*), **86** (1981) 3661.

9 Wright R W, Koster J R & Skinner N J, *J Atmos & Terr Phys* (*GB*), **8** (1956) 240.

10 Koster J R, *J Atmos & Terr Phys* (*GB*), **12** (1958) 100.

11 Bhargava B N, *J Inst Telecommun Eng* (*India*), **10** (1964) 404.

12 Bandyopadhyay P & Aarons J, *Radio Sci* (*USA*), **5** (1970) 931.

13 Chandra H, Vats H O, Sethia G, Deshpande M R, Rastogi R G, Sastri J H & Murthy B S, *Ann Geophys* (*France*), **35** (1979) 145.

14 Rastogi R G & Woodman R F, *Ann Geophys* (*France*), **34** (1978) 31.

15 Rastogi R G & Aarons J, *J Atmos & Terr Phys* (*GB*), **42** (1980) 42.

16 Rastogi R G, *Indian J Radio & Space Phys*, **11** (1982) 159.

17 Rastogi R G, Chandra H & Deshpande M R, *Indian J Radio & Space Phys*, **11** (1982) 240.

18 Pasricha P K, Reddy B M & Mitra A P, *Indian J Radio & Space Phys*, **11** (1982) 64.

19 Rastogi R G, *Proc Indian Acad Sci Sect A*, **93** (1984) 83.

20 Whitney H E, Buchau J, Johnson A L, Mullen J P & Weber E J, *AFGL-7 rep. No. R-77-0282, Air Force Geophysical Laboratory, Hanscomb, Massachusetts, USA*, 1977.

21 Martyn D F, *J Geophys Res* (*USA*), **64** (1959) 2179.

22 Rastogi R G, *J Geophys Res* (*USA*), **85** (1980) 722.

23 Clemmow F C, Johnson M A & Weekes K, *The Physics of the Ionosphere* (Physical Society, London, UK), 1955, 136.

24 Lowan A N, *J Geophys Res* (*USA*), **60** (1955) 421.

25 Serbu G P, Bordeau R E & Donley J L, *J Geophys Res* (*USA*), **66** (1961) 4314.

26 Calvert W, *J Geophys Res* (*USA*), **68** (1963) 2591.

27 Whitehead J D, *J Geophys Res* (*USA*), **76** (1971) 238.

28 Beer T, *Planet & Space Sci* (*GB*), **21** (1973) 297.

29 Klostermeyer J, *J Geophys Res* (*USA*), **83** (1978) 3753.

30 Prakash S & Pandey R, *Proc Indian Acad Sci Sect A*, **88** (1979) 229.

31 Dungey J W, *J Atmos & Terr Phys* (*GB*), **9** (1956) 304.

32 Balsley B B, Haerendel G & Greenwald R A, *J Geophys Res* (*USA*), **77** (1972) 5625.

33 Haerendel G, *Preprint Max-Planck Institute fur Physik and Astrophysik Munich* (*Germany*), 1974.

34 Hudson M K, Kennel C F & Kaw P K, *Trans Am Geophys Un* (*USA*), **54** (1973) 1147.

35 Scannapieco A J & Ossakow S L, *Geophys Res Lett* (*USA*), **3** (1976) 451.

36 Woodman R F & La Hoz C, *J Geophys Res* (*USA*), **81** (1976) 5447.

37 Kelley Mc, Haerendel G, Keppler H, Valenzuela A, Balsley B B, Carter D A, Ecklund W L, Carlson C W, Hausler B & Torbert R, *Geophys Res Lett* (*USA*), **3** (1976) 448.

38 McClure J P, Hanson W B & Hoffman J H, *J Geophys Res* (*USA*), **82** (1977) 2650.

39 Reid G C, *J Geophys Res* (*USA*), **73** (1968) 448.

40 Cunnold D M, *J Geophys Res* (*USA*), **74** (1969) 5709.

41 Rastogi R G & Woodman R F, *Ann Geophys* (*France*), **34** (1978) 31.

42 Rastogi R G, *J Geophys Res* (*USA*), **85** (1980) 722.

43 Rastogi R G, *J Atmos & Terr Phys* (*GB*), in press.