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ROLE OF EQUATORIAL IONIZATION ANOMALY IN THE INITIATION OF EQUATORIAL SPREAD F

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Abstract. A comparative study is made of the changes in the latitudinal structure of the F region electron density at fixed altitudes in the Indian equatorial region on days with and without postsunset onset of equatorial spread F, using (N-h) profile data of Ahmedabad (dip latitude 18.6°N), Waltair (dip latitude 10.6°N), and Kodaikanal (dip latitude 1.5°N). It is found that on spread F days the ratio of the electron density in the altitude region 270 - 300 km between Ahmedabad and Waltair showed a sudden enhancement starting at 1700 LT by a factor of 8 to 30 (at 1900 LT) from a near-constant value of about 2 during the daytime. No such enhancement of the density ratio was evidenced on days without spread F. The enhancement of the electron density ratio prior to the onset of spread F is interpreted as an intensification of the northern crest of the equatorial anomaly, with the ionization in the bottomside F region as far north as 9° from the dip equator participating in the crest intensification process. The rapid intensification of the ionization anomaly engenders a similar augmentation of the neutral anomaly around sunset hours. This in turn creates a localized cell of altitude dependent equatorward neutral wind that aids further intensification of the crests of both the anomalies and augmentation of ionization in the magnetic field line tube passing through the height of maximum plasma density of the F_2 layer over the equator. The net result of these coupling processes is a weakening of the ambient transequatorial wind (particularly during northern winter months) and reduction of the north-south asymmetry of the ionization anomaly crests, a condition favorable for the onset of spread F (Maruyama and Matuura, 1984). The present study thus indicates a significant role of the anomaly intensification at altitudes much below the F region peak and associated neutral dynamics in the initiation of spread F.

Introduction

Extensive experimental as well as theoretical efforts made in the recent past (see reviews of Kelley and McClure [1981], Basu and Basu [1981], and Ossakow [1982] led to noteworthy advances in the understanding of the apparently complex phenomenon of equatorial spread F (ESF). Several questions nevertheless remain unresolved, and the fundamental one among them concerns the physical conditions necessary and/or sufficient for the generation of ESF irregularities. Recent studies of ionosonde data demonstrated a significant influence of local ionospheric parameters in the generation and sustenance of spread F, and it is inferred that the collisional Rayleigh-Taylor (R-T) instability [Haerendel, 1974] plays a prominent role in the initiation of spread F [Abdu et al., 1982, 1983; Sastri, 1984]. A new dimension to the discussion of the nature of the physical mechanism(s) underlying the onset of spread F has been added by the inference of a large-scale quasi-periodic ionization structure in the evening equatorial ionosphere [e.g., Rottger, 1978; Woodman and La Hoz, 1976; Tsunoda and White, 1981]. The relative role of plasma instabilities and dynamical processes in the neutral atmosphere in the generation of spread F irregularities thus remains an unsettled question. Local ionospheric conditions and large-scale distortions in the east-west distribution of ionization have only been considered thus far in assessing the physical mechanism(s) responsible for the generation of spread F irregularities. In this paper, we present and discuss the first ever experimental evidence of a systematic relationship of the changes in the latitudinal distribution of electron density at fixed altitudes in the equatorial bottomside F region (i.e., equatorial ionization anomaly, EIA) to the postsunset onset of ESF (spread F).

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Results and Discussion

The study is based on true height profiles of electron density reduced by the well-known Budden [1954] matrix method from the bottomside ionogram data obtained at Kodaikanal (10°14'N, 77°28'E, dip latitude 1.5°N), Waltair (17°43'N, 83°18'E, dip latitude 10.6°N), and Ahmedabad (23°01'N, 72°36'E, dip latitude 18.6°N) during two observational campaigns. The first campaign covered and period December 28, 1981, through February 23, 1982, and the second campaign of shorter duration covered a major portion of March 1984. Simultaneous data were available at the three stations for a total of 33 days for which further analysis was attempted. Postsunset onset of spread F in ionograms at Kodaikanal and Waltair was seen on 17 days out of the total 33 days (ESF occurrence was rather rare at Ahmedabad). At Kodaikanal and Waltair the occurrence of spread F was well correlated on a day-to-day basis although the onset of ESF was not always at the same local time at the two stations.

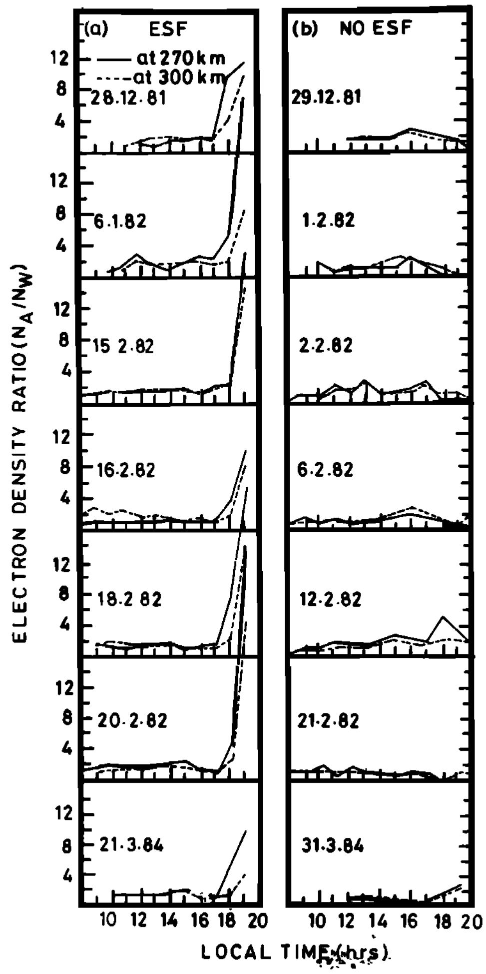

Fig. 1. The variation of electron density ratio N_A/N_W, between Ahmedabad (N_A) and Waltair (N_W), with local time on days of (a) ESF and (b) no ESF.

Figures 1a and 1b depict the diurnal variation of the electron density ratio at 270 and 300 km between Ahmedabad and Waltair typical of days with and without spread F, respectively. It is quite evident from Figure 1 that on spread F days the density ratio at 270 km as well as 300 km shows an almost steady value of about 2 until 1700 LT and then increases sharply to a high value in the range 8 to 30 by 1900 LT, which is only a few minutes earlier than the onset time of spread F. Although the enhancement in the density ratio is evident at both 270 km and 300 km, its magnitude is often greater at the lower altitude, as may be seen from Figure 1. It is observed that the maximum value of the ratio of electron densities between Ahmedabad and Waltair occurs at an altitude in the region 270 to 300 km and tapers off at higher altitudes around h_{max}, the height of maximum electron density (N_m). It is obvious from Figure 1b that such a conspicuous enhancement of the electron density ratio does not manifest on days without spread F. The evidence obtained here thus suggests that an intensification of the anomaly crest region is a necessary condition for the initiation of spread F in the evening equatorial ionosphere. It is to be mentioned here that we have analyzed the ionogram data up to only 2000 LT on days without spread F and up to 1900 LT on spread F days.

Figures 2a and 2b show the height variation of the constant electron density contours at the three stations during the day of spread F occurrence, December 28, 1981, and on the following day of no ESF occurrence, respectively. The variations of the height h_m at the three stations are also shown in the figures. The density contours at Kodaikanal and also at Waltair on December 28 show the typical behavior of the ionosphere close to the trough region of the anomaly on a day of strong development of the anomaly, which is further strengthened in the afternoon hours, in particular after 1700 LT by the upward rise of ionization not only at Kodaikanal but also at Waltair, which is 9° north of the dip equator. The upward speeds as revealed by the lower contour movement are 55 and 13 m/s at those two stations, respectively. Part of this motion, though it may be small, is not real, as it is contributed by the fast recombination of ionization underneath the F_2 layer during the near-sunset hours. It is clear from the isoionic contours shown in Figure 2a that the ionization at these two stations has been lifted up in association with a rapid steepening of the layer on the bottomside around sunset, while at Ahmedabad the contours are maintained nearly at the same height level, in spite of the fact that recombination is expected earlier at this northernmost station than at the other two during the winter solstice. This pattern indicates accretion or retention of ionization density at a rate faster than the chemical recombination rate is operative over this station. It can be seen from Figure 2b that at Kodaikanal the contour movement on the day without spread F is similar to that on the day with spread F, while at Waltair the upward movement is severely inhibited in the afternoon hours and even reversed at 1900 LT. This feature of plasma motion and the variation of h_m at Waltair indicate that there is no upward depletion of plasma, unlike on the spread F day. The behavior of plasma density contours at Waltair on the day of no spread F is more like that at Ahmedabad on the spread F day.

It is well known that the strength of the ionization anomaly undergoes a conspicuous enhancement in the postsunset hours during years of high sunspot activity [e.g., Lyon and Thomas, 1963; Rao and Malhotra, 1964] and an apparent renewal of the "fountain" process is considered to be the cause of this evening enhancement [Rishbeth, 1977]. The renewal of the fountain process is widely believed to be due to an enhancement of the eastward electric field brought about by the F region dynamo mechanism [see Rishbeth, 1981 and references therein]. Incoherent scatter radar observations of the F region vertical drift at Jicamarca [Woodman, 1970; Woodman et al., 1977] and analysis of ionosonde data [Rao, 1963; Sastri, 1982] lend support to this understanding. The rapid upward motion of the F_2 layer over Ko-

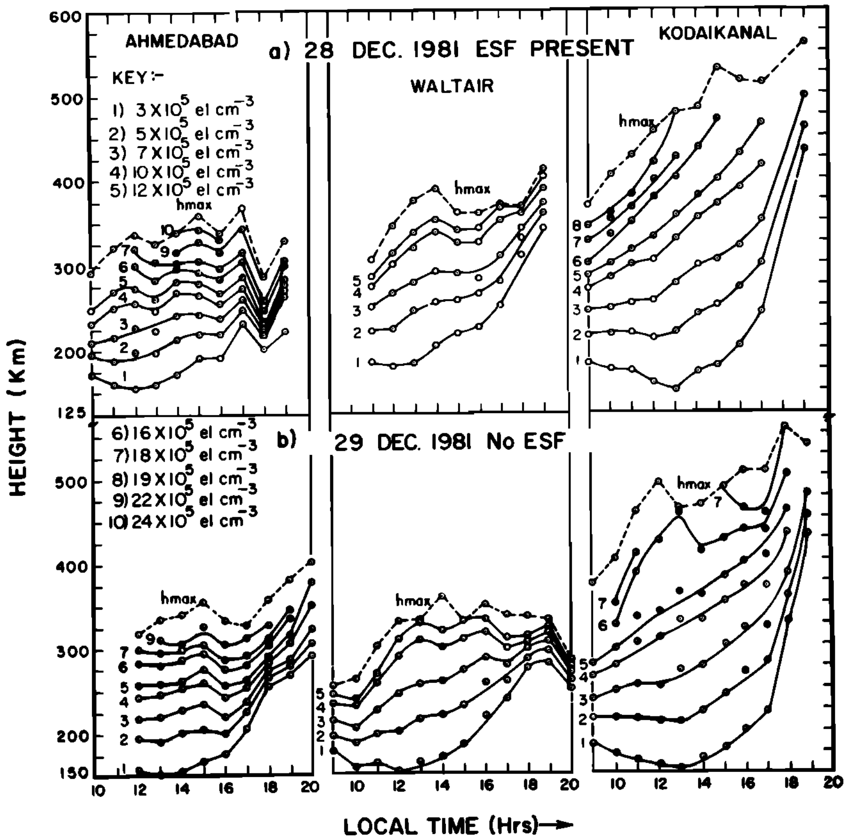

Fig. 2. Height variation of constant electron density contours (solid lines) and h_mF_2 (dashed lines) during daytime at the three stations on (a) ESF and (b) no-ESF days.

daikanal observed from 1700 LT as seen in Figures 2a and 2b is mostly due to the renewal of the fountain effect. The consistent and significant increase of the electron density ratio between Ahmedabad and Waltair in the altitude region 270-300 km prior to the onset of spread F noticed in the present study cannot, however, be attributed entirely to the usual renewal of of the fountain effect. This is because while the postsunset enhancement of the anomaly is fairly common in occurrence and manifests on days with as well as without spread F (see Figures 2a and 2b), the conspicuous presunset increase in N_A/N_W reported here is apparent only on spread F days and that too in a narrow altitude range of 270-300 km. Besides, if the usual evening enhancement of the eastward electric field is only responsible for the upward drift of the bottomside F region both at Kodaikanal and Waltair, then the upward drift of the layer at Waltair ought to have been much higher (50 m s^{-1}) than the 13 m s^{-1} actually observed. We propose two plausible mechanisms in order to explain the results qualitatively. Both the suggested mechanisms depend on the structure of the neutral winds in the E and F dynamo regions at low latitudes. In view of the lack of simultaneous observations on the latitudinal and the vertical structure of neutral winds and electric fields in the equatorial ionosphere, both mechanisms seem applicable.

1. The enhancement of the electron density ratio (N_A/N_W) in the lower part of the bottomside F layer prior to the onset of spread F may be due to redistribution of ionization brought about by the latitudinal variation in the planetary eastward electric fields. Aggson et al. [1987] have recently showed evidence, for the first time, that such latitudinal gradients exist in the vertical component of the planetary electric field in the evening twilight sector. The E field vertical component is known to be significantly larger (2 to 6 mV/m) than the zonal component (0.3 to 1 mV/m) during sunset time. According to Aggson et al., the accuracy of measurements made by a polar-orbiting satellite-borne E field measuring probe is about ± 2 mV in the equatorial region. Hence the latitudinal gradient in the vertical electric fields could be measured, and not those in the zonal electric fields. Since the E fields at sunset twilight time, both vertical and eastward components, are primarily of F region dynamo origin and not due to the E region dynamo around the heights of 80-120 km where the ionization quickly recombines in the evening hours, one can expect that similar latitudinal gradients in the zonal field component may exist and may cause the redistribution of bottomside F_2 region ionization so as to produce the N_A/N_W ratio enhancement in the 270 to 300 km region. Raghavarao et al. [1984, 1987] have reported experimental evidence for

the presence of large-scale gradients in the vertical and horizontal motion of plasma around the height region of 200 km observed on two occasions over Sriharikota Rocket Range(5.5°N dip latitude). Out of the four barium cloud releases at different altitudes on each occasion the one released around 200 km only produced two ion clouds which moved with different velocities, while the releases at other altitudes produced only one ion cloud for each barium release as normally expected in the presence of uniform electric fields. These experiments were conducted during the evening twilight time when the equatorial spread F occurred. Raghavarao et al. [1984] also have shown that at F region altitudes an equatorward wind in the meridional plane engenders an eastward electric field increasing with latitude on both sides of the dip equator. The presence of equatorward winds (converging toward the equator) in the evening hours has recently been reported by Biondi and Sipler [1985] from Natal (5.9°S, 35.2°W; 6.4°S dip latitude), Brazil, by the Doppler shift measurement on the 630.0 nm O I emission line. Such positive gradients with latitude in the eastward electric fields on either side of the dip equator at the altitudes just beneath the F_2 layer as observed by us can effectively redistribute the plasma to result in the enhancement of the observed ratio (N_A/N_W) in a limited altitude region. However, knowledge of the meridional wind structure with height and latitude is important for attributing the resultant eastward field gradients in order to explain the observed results, and we donot yet have this knowledge.

2. The origin of the height dependent poleward gradients in the planetary eastward electric field invoked here is not the only one that can explain the observed results. Alternatively, a strong transequatorial wind can also cause the increase in N_A/N_W on days with spread F, and this appears plausible because a majority of our data pertain to local winter months when such a wind pattern can be expected to prevail. The wind field nevertheless ought to possess an intricate latitude - altitude structure because the increase in N_A/N_W occurs preferentially in the range of 270 - 300 km. Since direct experimental information is available neither on the spatial structure of the electric field nor on the wind field simultaneous with the ionosonde results presented here, the question of the physical processes responsible for initiating the enhancement of N_A/N_W remains an open one for further study and elucidation.

The rapid intensification of the northern crest of the anomaly around sunset on spread F days and the absence of such a feature on days without spread F revealed by the results of our study indicate a role of plasma as well as neutral dynamics in the initiation of spread F particularly during the winter solstice. A marked asymmetry of the amplitudes of the northern and southern crests of the anomaly can be created in winter by a strong transequatorial wind acting in association with the usual E x B vertical plasma drift around the dip equator. Such conditions are unfavorable for the initiation of spread F as demonstrated by Maruyama and Matuura [1984], and this is seen to be the situation prevalent on days without spread F in our data sample. The insignia of the usual enhanced vertical upward drift at Kodaikanal around sunset and the lower height of the F layer (inhibition of upward drift) at Waltair on days without spread F (in comparison with days of spread F) evident in our data (see Figures 2a and 2b) corroborates this understanding. In contrast, the sudden and prominent intensification of the northern crest region of the anomaly noticed on spread F days engenders a fast development of neutral pressure ridges characteristic of the equatorial neutral anomaly [Hedin and Mayr, 1973]. These in turn lead to the establishment of an equatorward wind pattern which can effectively lift the bottomside F region at locations in between the crest and trough regions of the anomaly, such as the location of Waltair in the present analysis. The intensification of the neutral anomaly crests can be expected to occur very fast because the ion drag force, dominant at F region altitude, can impart the ion (zonal) drift velocity to the neutrals with a time constant of only a few minutes [Dougherty, 1961]. The higher altitude of the F layer at Waltair on spread F days (in comparison with that on days without spread F) evidenced in our data and the recent observations of Biondi and Sipler [1985] on the presence of equatorward winds at the evening twilight time on certain nights and Meriwether et al. [1985] that equtorward neutral wind can cause appreciable vertical transport of plasma close to the dip equator (around 10° dip) support the explanation made here. The upward motion of the F_2 layer over Waltair (dip angle = 20°) observed on December 28 shown in Figure 2a can be caused by an equatorward wind of about 40 m/s, and the winds observed by Meriwether et al. [1985] and Biondi and Sipler [1985] on magnetically quiet days are in the same range (50 to 100 m/s). These observations are, however, made immediately after sunset. The localized equatorward wind pattern created by the intensified neutral anomaly crests will, as soon as that pattern is set up, weaken the ambient transequatorial wind and reduce the north-south asymmetry of the anomaly crest regions. Such a condition is favorable for the initiation of spread F, as demonstrated by Maruyama and Matuura [1984]. It is to be stressed here that the relationship between the changes in the latitudinal distribution of electron density in the bottomside F region and the onset of spread F reported here is rather different from that discussed by Maruyama and Matuura [1984]. Our results show the changes in the ionization anomaly to be confined to a narrow altitude region below the F region peak, while the changes illustrated by them pertain to the entire F region well above the peak as observed from the topside of the F_2 layer. We envisage here that the preferential mass loading or filling up of a particular magnetic field line tube, revealed by the altitude-limited increase in N_A/N_W, renders it unstable for the R-T instability, which is widely considered to be responsible for the initiation of spread F. We feel it important therefore to attempt further analysis similar to the present analysis of the neutral anomaly as well, using satellite data (neutral mass spectrometer) from the Atmospheric Explorer series, and also numerical simulations on the interaction of realistic ionization crests with the neutral winds to study the possible changes in the neutral atmospheric dynamics and their consequences for the occurrence of the equatorial spread F.

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