Presunrise spread F at Fortaleza

J. W. MacDougall,^{1,2} M. A. Abdu,^{3,4} P. T. Jayachandran,^{1,2} J.-F. Cecile,¹
and I. S. Batista³

Abstract. At Fortaleza, Brazil, in the equatorial zone about 400 km south of the magnetic equator a presunrise (secondary) maximum of spread F occurrence is observed during sunspot minimum and, in particular, during December solstice. The spread F takes the form of patches of irregularities that are convecting eastwards at $\sim 50 \text{ m s}^{-1}$. Most of the patches are collocated with bottomside bulges of the ionosphere. Our measurements indicate that these bottomside bulges are unstable due to a gradient-drift instability that is slowly growing and produces the spread F . The bulges themselves seem to be evidence of a Rayleigh-Taylor instability process.

1. Introduction

Equatorial spread F is detected as diffuse echoes on ionograms and indicates that various plasma instability processes are causing ionospheric structuring [see Kelley, 1989]. There have been many recent experimental as well as theoretical investigations of the onset, growth, and dynamics of the equatorial spread F (see references below). From these investigations it is known that various combinations of electric field, neutral wind, and gravity waves play a role in triggering the spread F . Most studies have concentrated on the explosive development of evening spread F associated with plasma bubbles. There have been relatively few studies of the postmidnight/presunrise spread F .

For most equatorial stations, spread F has an evening onset, usually associated with a bubble resulting from a Rayleigh-Taylor instability [e.g., Woodman and LaHoz, 1976]. After the spread F onset there is an occurrence maximum, within ~ 2 hours of onset, then the typical nighttime pattern is a gradual decrease of spread F probability, or intensity, during the rest of the night, with an abrupt decrease to ~ 0 probability at sunrise (assuming that the probability was still > 0 just before sunrise) [Kil and Heelis, 1998; Abdu et al., 1981; Chandra and Rastogi, 1972]. This same pattern is seen for South American stations [Abdu et al., 1992; Rastogi, 1980], and at the station used for this study, Fortaleza, this same pattern of spread F occurrence is seen during high sunspot number years.

In this paper we show that during sunspot minimum there is an additional presunrise maximum of spread F occurrence at Fortaleza. While there have been a lot of studies of the postsunset spread F development, there have been relatively few studies of presunrise spread F [see Bowman, 1978; Rastogi,

1977; Sastri, 1979]. The reason for the paucity of presunrise studies is probably because most stations show relatively weak spread F at this time as compared to the postsunset interval spread F .

In this study we will show that the presunrise spread F takes the form of eastward convecting patches of irregularities. These convecting patches are seen during all night hours. Therefore, in order to have a second maximum near dawn, some process that amplifies or creates more irregularities in the convecting patches is needed. We will be assuming that the production process is independent of longitude so that a presunrise maximum could not be due to a preferred creation region west of Fortaleza. We discuss ionospheric conditions at Fortaleza during the presunrise period and will suggest that the irregularities are amplified/created by a two-stage gradient-drift instability process.

2. Observations

A Canadian Advanced Digital Ionosonde (CADI) [see Grant et al., 1995] has been in operation at Fortaleza (4°S , 322°E , dip -9°) since October 1994. The operating mode was set to record a 200 frequency ionogram every 5 min, and to sample eight “fixed” frequencies (for convection measurements) every 30 s. There are small gaps in the sequence of fixed frequency sampling when the ionograms are recorded. Most of our plots show time in UT. Local time is UT minus 3 hours.

We will also be showing some ionospheric motions deduced by the digital ionosonde. The method for doing this is described by Grant et al. [1995]. Briefly, the ionosphere often behaves like a cloud of scatterers, particularly under spread F conditions, and for each scatterer the angular location and the Doppler shift is measured using a spaced-antenna receiving array. From these location and Doppler measurements the ionospheric motion is determined by doing a leastsquares fit of a uniform vector motion to fit the measured Doppler velocities.

It should be noted that the measured vertical component of the velocity should be corrected if one wants to obtain the actual motion of the ionosphere [Krishnamurthy et al., 1990]. The correction is because the recombination causes a change in the phase path, and this shows up as a Doppler velocity. The correction is of the order of 7 m s^{-1} and is downward. Since this is a small relatively constant correction during nighttime and we are interested only in velocity fluctuations, our vertical

¹Department of Physics, University of Western Ontario, London, Ontario, Canada.

²Department of Electrical and Computer Engineering, University of Western Ontario, London, Ontario, Canada.

³Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos, Brazil

⁴Currently at the Department of Physics, University of Western Ontario, London, Ontario, Canada.

measurements that will be shown have not been corrected for this effect.

We noted that spread F was commonly observed in the presunrise hours. A typical ionogram sequence that illustrates this is seen in Figure 1. This shows only every third ionogram at 15 min intervals. Figure 1 shows quite clean ionospheric echo traces at the beginning and end of the sequence. Clean traces had been seen for the 2 hours before this sequence. On the 0445UT ionogram an additional trace appears below the second hop F echo. This additional trace progressively decreases in range until it merges with the F region trace around 0600UT. It can be shown (see below) that this additional trace was due to a patch that moved in from west of Fortaleza. Note that the maximum echo frequencies in the patch (about 10 MHz) are somewhat higher than the critical frequency at Fortaleza (about 5 MHz). This is shown by part of the patch clearly projecting above the critical frequency around 0600UT. The ionospheric echo from ~0530 to 0700UT would obviously be classified as range type spread F . During later times the appearance of the ionospheric trace evolves toward appearing as frequency spread and then disappearing at the time of sunrise, around 0815UT. Note that the F region critical frequency was ~6 MHz at the beginning of the sequence but dropped to ~4 MHz just after the time when the patch of spread F reached overhead at 0630UT.

On other nights the spread F development is usually similar to this example in most respects, although the details vary. In general, the spread F does not suddenly develop overhead but moves in from the west in the form of one or more patches. As seen for this example, often there are decreases in the ionospheric critical frequency about the time spread F patches pass overhead, and often the maximum densities in the spread F patches are larger than the ambient electron density. However, a decrease in critical frequency and/or higher patch densities are not always observed.

The initial spread F would invariably be classified as range spread, and it does not always evolve to frequency spread as it did for this example. Sometimes the spread F would still be classified as range spread at time of sunrise disappearance.

Before looking at more details of the individual spread F patches, we first present some statistical results about the occurrence of presunrise spread F at Fortaleza during sunspot minimum conditions. Figure 2 shows the percentage occurrence of spread F in postmidnight (local time) hours from November 1994 to October 1995. The percent occurrence of spread F was calculated by assigning, visually, to each hour an index: 0 is no spread, $\frac{1}{2}$ is barely detectable spreading, and 1 is obvious spreading. From these assigned indices the percent occurrence was calculated. Figure 2 shows that except during the March equinox presunrise spread F is quite common at Fortaleza. The occurrence reaches near 100% for a few hours in December. The pattern is obviously semiannual with maxima in solstices. This same pattern for Fortaleza during the prior, 1985–1986, sunspot minimum can be seen in the work of *Abdu et al.* [1998]. During that earlier sunspot minimum the December occurrence of presunrise spread F reached 85–90%. The occurrence during 1985–1986 June solstice was significantly lower. Spread F occurrence studies for sunspot maximum by *Abdu et al.* [1992, 1998] did not show the presunrise increase for any of the seasons at Fortaleza. Thus this presunrise spread F phenomenon is only clearly seen during sunspot minimum.

We also examined the magnetic activity to see if this affected the occurrence of presunrise spread F . There was no obvious

association of high/low spread F days with high/low magnetic activity days. Also, numerical cross correlation of the number of hours of spread F with the A_p index showed no significant correlation. This lack of correlation was found with no lag between the A_p day and the spread F day and also with A_p leading (or lagging) by 1 (or more) day(s). This lack of magnetic dependency of spread F occurrence showed up when we selected spread F samples to study in more detail. We randomly selected about the same number of samples that had presunrise average $K_p > 3$ (disturbed) as had quiet K_p .

Other properties of the ionosphere which some studies show to be related to spread F occurrence are the ionospheric height and height changes [*Farley et al.*, 1970]. The interest in ionospheric height changes is because a steep bottomside gradient and an upward motion (due to an eastward electric field) tend to be unstable. Also, a greater layer height reduces the damping of instabilities by recombination and, by reducing the ion-neutral collision frequency ν_{in} , enhances the gravity growth term for the Rayleigh-Taylor instability. In our studies we did not note that height was an obvious factor, provided it was above 200 km. Most of the spread F occurred when the F region bottomside was around 250 km, a very typical value for the nighttime F region. We did note that when the bottomside of the F region was as low as ~200 km, then there was little spread F . The low F region heights were found during equinox, the seasons when Figure 2 shows there to be a minimum occurrence of spread F .

We did not find that spread F was obviously more common during upward layer motion than during downward motion. The motion that we are discussing here is the general up or down motion of the layer over intervals of the order of an hour or more. As will be described below, shorter-period vertical velocity perturbations were commonly associated with the spread F that we observed.

Returning now to the more detailed examination of spread F patches, Figure 3 shows the “fixed” frequency ionosonde recording for the spread F sequence shown in Figure 1. Figure 3 is for the 4.1 MHz fixed frequency, which is the frequency from the set of eight fixed frequencies that usually gives the best continuity in the data. The dashed trace intersecting from the left at a virtual height (group range) of about 300 km, in the top plot, is the unperturbed F region echo from overhead. The gaps in the traces are when the ionograms were recorded. The diffuse traces of the spread F patch can be seen converging (from above) on the overhead trace and merging with it after about 0600UT. The echo disappears after about 0720UT when the ionospheric critical frequency drops below 4.1 MHz and reappears (along with a few bursts of interference) at sunrise around 0815UT.

The lower plots of Figure 3 show the convection calculated for these hours. The bottom plot shows the number of reflectors on the sky maps [see *Grant et al.*, 1995]. We find that we get reliable convection measurements when there are ≥ 50 reflection points on the sky maps. Therefore the measurements before about 0500UT and after about 0700UT are not reliable. In the interval from 0500 to 0700UT it may be seen that the zonal motion is eastward at about 50 m s^{-1} (second plot) and that the meridional motion is close to 0 m s^{-1} (third plot). Both 50 m s^{-1} eastward and 0 m s^{-1} north-south are very typical values during the time of night when we see presunrise spread F . The vertical velocity (fourth plot) is initially about 0 m s^{-1} at 0500UT. It then decreases to a minimum of about 20 m s^{-1} downward just after 0600UT and then increases to a maximum just before 0700UT.

Figure 1. Spread F ionogram sequence 0400-0900 UT for Fortaleza, December 4, 1994. The frequency scale is 1-20 MHz (logarithmic). Below 10 MHz the frequencies are marked each 1 MHz.

Figure 2. Percent occurrence of spread *F* (both types) over Fortaleza between November 1994 and October 1995 for the postmidnight period. Sunrise is between 0800 and 0900 UT. We show only the postmidnight data because strong interference during evening hours made it difficult to get good spread *F* statistics.

We find that this pattern of velocity inflection is commonly seen during passes of spread *F* patches over Fortaleza.

Another way of using the digital ionosonde data to study the spread *F* is to project the measured echo locations (echo ranges and angles of arrival) onto a horizontal surface. Of course, the echo ranges that are used are the virtual ranges, and the angles of arrival are not corrected for ionospheric refraction, but nevertheless, the projection may show us something about the patch locations as a function of time. We will call such a plot a "displacement" plot. Figure 4 shows the displacement plot for the data of Figures 1 and 3. The top plot is the east-west displacement versus time, and the bottom plot is the north-south displacement. For this sample there are echoes from overhead (near 0 km displacement) before about 0600 and after 0800 UT. Starting about 0430 UT a patch of echoes is seen west of Fortaleza, and this patch converges on Fortaleza and transits overhead between 0600 and 0700 UT. The convergence speed is close to 300 km hr^{-1} or 83 m s^{-1} which is compatible with the measured eastward convection from plot 2 of Figure 3 at the time the patch transits overhead. The patch actually appears to be composed of two patches separated by about $\frac{1}{2}$ hour, and there seems to be a third patch about $\frac{1}{4}$ hour later. These patches are not seen very far to the east of Fortaleza. This is at least partly due to the decrease in ionospheric densities after the patch was overhead, but tilting of the patch structures could make it easier to see the patch when it is west of Fortaleza. Many patches can be seen both to the west and, after traversing overhead, to the east of Fortaleza.

Note that the bottom plot on Figure 4 shows that the patch does not have any appreciable north-south (magnetic coordinates) displacement. The lack of measured magnetic north-south displacement may just mean that the irregularities that compose the patch are strongly aligned along the magnetic

field, and because ionosondes mostly see specular reflections, a digital ionosonde would have difficulty detecting north-south displacements of such irregularities.

3. Discussion

We summarize the above results as follows: (1) Presunrise spread *F* at Fortaleza during sunspot minimum takes the form of eastward convecting patches moving eastward at (typically) 50 m s^{-1} . (2) There is no clear magnetic activity association. (3) When spread *F* patches are overhead, the time is often near the time of a downward inflection minima in vertical motion. (4) Spread *F* maximum occurrence is during December solstice, and there are minima of occurrences in equinox.

We will now discuss the items on this list. The spread *F* was in the form of eastward moving patches. Since, as shown by Figure 2, the percentage occurrence of spread *F* increases from a low number around local midnight to a maximum just before sunrise, the patches are not just transporting spread *F* that was formed earlier in the night. As mentioned in the introduction, we assume that there is no preferential longitude, about 1000–2000 km west of Fortaleza, where patches of spread *F* would have formed. Therefore one would not produce a presunrise maximum merely by transport. We examined displacement plots for the presunrise period (see Figure 4 example) for several months of our Fortaleza data in an attempt to select samples that showed formation of presunrise spread *F* over Fortaleza. We looked for patches that showed displacement motion starting at Fortaleza and moving away only. We found only three possible examples, and in two of these there was a reversal of the east-west motion that gave a confused pattern of patch motion. Therefore essentially every one of our spread *F* occurrences was associated with a patch of irregularities that we saw move in

Figure 3. Ionospheric data on 4.1 MHz "fixed" frequency for December 4, 1994. The top plot shows the virtual height versus time, and the plots below show eastward motion (Plot 2), northward motion (Plot 3), upward motion (Plot 4), and number of sources on each sky map (bottom plot). The number of sources on a sky map should be ≥ 50 for a good motion measurement.

Figure 4. “Displacement” plot for hours 0000-0900 UT on December 4, 1994. The top plot shows the apparent ionospheric reflector location east or west of Fortaleza, and the bottom plot shows the north or south location. The spread *F* shows as the slanting bands in the top plot.

from the west and which we usually saw continuing to move toward the east after transiting overhead. As can be seen in Figure 4, we could usually see these patches for on the order of an hour during their travel time from the west to Fortaleza and usually for a similar time after transiting Fortaleza and moving to the east. During the approximately 2 hours that we could see most patches the intensity of the patches usually did not show dramatic changes. Therefore we assume that the growth times of irregularities is of the order of an hour. If growth time was very much faster, then we would have expected to see obvious changes in the strength of the echoes as they traveled to Fortaleza, and if the growth rate was very much slower then we would not get the presunrise enhancement in spread *F* that is seen in Figure 2. We therefore associate the presunrise spread *F* with moving patches of irregularities that are slowly growing. We will show below that a growth time of the order of an hour is compatible with ionospheric conditions for the patches.

This slow growth means that the patches would probably need to have some initial structuring during earlier hours. The obvious question is whether these patches were associated with bubbles or backscatter plumes during evening hours. To answer this, we would need data from the region about 1000-2000 km west of Fortaleza, which is presently not available. Therefore we cannot say whether these patches have any association with bubbles or plumes.

We thought that possibly ionospheric currents might play some part in the irregularity growth. However, result 2, the lack of magnetic activity association, infers that in a statistical sense currents do not seem to be involved. Of course, it is local ionospheric currents rather than those that determine the planetary magnetic indices that are more likely to be important, so we also examined the magnetometer data for Fortaleza and also for a nearby equatorial station to see if there was any evidence of detailed magnetic variations that might be associated

with the spread F . While some of the magnetometer records from disturbed intervals showed a lot of variations and one could often find a variation at about the time that spread F patches were over Fortaleza, many of the magnetometer records showed absolutely no variations larger than 1 or 2 nT during spread F times and for several hours around spread F times.

There could be some enhancement of the spread F occurrence if the magnetic disturbances become large enough. Previous studies [Batista *et al.*, 1990; Sastri and Sasidharan, 1980] found positive correlation of presunrise spread F with magnetic activity at selected stations and selected months. There is some evidence from these studies and our own observations that for large K_p values (~ 7) there is an increased probability of presunrise spread F . Since large K_p values are quite rare at sunspot minimum (the interval for this study), magnetic disturbances are not an important factor in this study.

Property 3 of the presunrise spread F is that there was often (usually) an inflection of vertical motion at the time the spread F patches were over Fortaleza. This did not always occur, but it occurred frequently enough that we will use it as a condition for spread F development. The question then became as follows: In what way is the vertical motion perturbation involved in the patch enhancement? There are several possible answers: (1) The vertical motion, combined with a vertical gradient, could be unstable. (We examined this possibility in detail but were unsuccessful in showing that the irregularities were seen at the times of both high vertical gradients and large upward motions. In fact, the irregularities were commonly seen at times of downward motion which is not the expected direction for instability.) (2) The vertical motion, since it was a transient variation, might have finite vertical wavelengths or time delays that would enhance the instability by increasing the vertical gradients. (We later discounted this effect because we were able to study the motion at different heights using our several fixed frequencies and often found negligible velocity differences at the different heights.) (3) The vertical velocity perturbation seen over Fortaleza might not be the same as when the spread F formed or intensified at an earlier time, so the association is irrelevant. (As shown by Figure 4, the patches are seen moving in from west of Fortaleza, so a velocity perturbation observed when the patches are over Fortaleza may not be the same perturbation as when the patches formed. We have no data from the formation region west of Fortaleza (the South America west coast stations, Huancayo, etc., are much too far west). In studying the movement of the spread F patches, we note that the movement usually appears to be at a constant speed which turns out to be the convection speed that we measure when the patch is over Fortaleza. This was seen for the data shown in Figure 3. We therefore make the assumption that the patch and the convection pattern usually move in synchronism toward the east. We do not require exact synchronism but enough synchronism so that the convection pattern seen when the patch is over Fortaleza is approximately the convection pattern that accompanied the patch from the time of formation. We therefore assume that the vertical velocity perturbation is somehow associated with the spread F development.) (4) The vertical velocity perturbation causes a downward bulge of the ionosphere, and it is this bulge that is unstable. (This is the mechanism that we are proposing, so we discuss it further in the following paragraphs.) This instability on the sides of the bulges is essentially the same as the instability on a tilted ionosphere

during postsunset spread F development that has been discussed in several papers [Kelley *et al.*, 1981, 1986; Kelley, 1985].

If there is reasonable synchronism between the spread F patch and convection variations, then a downward vertical velocity perturbation will gradually produce a downward bulge. Figure 5 shows a good example of this phenomena. The top plot shows downward bulges on the bottom of the virtual height versus time plot; the third plot shows the vertical velocity perturbations that appear to be producing the bulges. The bottom plot shows the east-west displacement plot of the spread F patches. It can be seen that the times when the patches transit over Fortaleza (marked by vertical lines) are closely coincident with the times the bulges are seen over Fortaleza. Times of the overhead transits, as are marked by the vertical lines, were our best estimates after examining the displacement plots for a number of the eight fixed frequencies. The vertical velocity perturbations seen here (~ 30 m s⁻¹ peak to peak) would produce bulges comparable with those seen on the top plot of the figure (~ 30 km peak to trough) in about 17 min. Since we usually can see the patches for about an hour before they transit Fortaleza, 17 min seems to be too short for the bulge growth time. However, this time estimation neglects various factors such as lack of exact synchronism between perturbations and convection and dissipation processes such as normal recombination. We therefore assume that an uncorrected growth time of 17 min gives reasonable agreement between the observed size of the bulges and the observed vertical velocity perturbations.

The instability process that acts on the bulges to produce smaller-scale structuring is the gradient-drift instability with the gradient and the drift being in the horizontal direction. The bulges convert the vertical bottomside ionospheric gradient L_v into a horizontal component $L_h = L_v / \sin \theta$, where θ is the tilt of the isodensity contours. For the example shown in Figure 5, the maximum layer tilt is about 15°, and taking the vertical gradient length to be $L_v = 15$ km (this was our typical measured bottomside vertical gradient scale length) and $V_{east} = 100$ m s⁻¹ (the eastwards velocity was higher than usual for this example), the basic instability growth rate [see e.g., Linson and Workman, 1970], $\gamma = V_{east} / L_h = 100 \sin 15^\circ / 15 \text{ km} = 1.7 \times 10^{-3} \text{ s}^{-1}$ or about 10 min. Thus the basic, simplified, growth rate estimation of irregularities on the downward bulges is faster than the inferred ~ 1 hour growth time for this phenomenon.

The more detailed instability growth rate formula is $\gamma = (V_{east} - U_{east}) / L_h - \beta$ where U_{east} is the eastward neutral speed, and β is the recombination coefficient. If the eastward plasma speed is equal to the neutral speed, then there is no instability growth. It is commonly accepted that the neutral atmosphere and plasma will move approximately together during nighttime hours when there is little E region conductivity, in which case $V - U = 0$, and there would be no growth. However, a satellite measurement of V and U [Coley *et al.*, 1994] showed that there can be systematic differences between equatorial V and U . The typical difference that Coley *et al.* showed for the postmidnight period is about $V - U = +25$ m s⁻¹ (eastward). This speed difference might not be appropriate for Fortaleza and for the bottomside ionosphere, since it averages all longitudes and does not clearly separate heights. For Fortaleza we show in Figure 6 the neutral wind speed from the horizontal wind model - 90 (HWM-90) [Hedin *et al.*, 1991] for Fortaleza in December 1994 (marked U) and our average measured ionospheric convection for Fortaleza in November and December 1994 (marked V). It can be seen that

Figure 5. Data sample from December 24, 1994 hours 0000-0900. The top plot shows virtual height versus time and several bottomside downward bulges can be seen. These are identified by the vertical lines that show (third plot) the associated vertical velocity perturbations (bulges are located at the end of downward motion perturbations), and (bottom plot) the bulges are coincident with the passage of bands of irregularities over Fortaleza. The second plot shows that the horizontal velocity was around 100 m s^{-1} eastward during most of this sample.

the plasma speed is systematically greater than the neutral speed, and again, about 25 m s^{-1} would be typical for $V - U$.

It should be noted that the digital ionosonde convection measurements are made on fixed frequencies that are reflected from the bottomside of the layer at $\sim 250 \text{ km}$. For the presunrise intervals the bottomside gradients were quite high, so that the

echo height for all our fixed frequencies was $\sim 250 \text{ km}$. Thus our V is for a typical bottomside height of $\sim 250 \text{ km}$. The V from incoherent scatter radars (the nearest is Jicamarca) is from heights above the bottomside and generally shows faster speeds than what we measured on the bottomside [see Fejer *et al.*, 1991]. This upward height gradient of V may play a role in this

Figure 6. Zonal velocities for neutrals (*U*) and plasma (*V*). The neutral velocity is from the horizontal wind model-90 and the plasma velocities are from Fortaleza measurements. Positive velocity is toward the east.

instability process. First, it will steepen the backside tilt on bottomside bulges thus making them more unstable. Second, the speed difference, $V - U$, becomes height dependent. Since the HWM-90 model for neutral winds also gives an upward height gradient for *U*, it is not clear whether $V - U$ is increasing or decreasing with height. For a discussion of some of the expected effects on instability growth with velocity variations (shear) see *Satyanarayana et al.* [1984]. For this study we will assume that $V - U$ doesn't vary much with height and has a typical value 25 m s^{-1} .

For the horizontal scale length L_h in the growth equation we will use $L_h = L_v / \sin \theta$. The value $L_v = 15 \text{ km}$, used above, was very typical (based on examining true height profiles for a number of nights). However, the value of $\theta = 15^\circ$ that we used for the data from the example shown in Figure 5 is an underestimation of the typical maximum θ . The typical θ (maximum slope) is $\sim 41^\circ$ using 30 km for the maximum-to-minimum height variation, using 40 m s^{-1} for the typical speed, and using 45 min for the typical period (and assuming a sinusoidal variation). Using $L_v = 15 \text{ km}$ and $\theta = 41^\circ$ gives $L_h = 22.8 \text{ km}$ (minimum value of L_h). Using this value for L_h and 25 m/s for $V - U$ in the growth rate calculation, we obtain $\gamma = 1.1 \times 10^{-3} \text{ s}^{-1}$ or 15 min (with $\beta = 0$).

Next, examining the recombination coefficient β , we used two different calculations for this. A simplified formula for β from *Ratcliffe et al.* [1956] which is given by *Rishbeth and Garriott* [1969, formula 506] yields $\beta = 2.7 \times 10^{-4} \text{ s}^{-1}$ for 250 km height. A more detailed formula $\beta = N_e (K_1/[O_2] + K_2/[N_2]) / (N_e + (K_1/C_1)[O_2] + (K_2/C_2)[N_2]) \text{ s}^{-1}$, where K_1 , K_2 , C_1 , and C_2 are reaction coefficients given by *Anderson and Rusch* [1980] and

other required values are taken from the MSIS-90 and IRI models, yields a value of $3.8 \times 10^{-4} \text{ s}^{-1}$. Therefore the two estimations of β yield very similar values, and we use the mean of these, $\beta = 3.3 \times 10^{-4} \text{ s}^{-1}$.

Replacing the $\beta = 0$ value in the growth rate calculation with this value gives $\gamma = 7.7 \times 10^{-4} \text{ s}^{-1}$ or 22 min for the growth rate. Since we are not looking for a very fast growth, this value seems to be compatible with the slow presunrise growth of spread *F* that we earlier estimated to be of the order of an hour.

We next turn to the following question: What causes the vertical velocity perturbations that seem to create the bottomside bulges? As noted earlier, these are not usually associated with any synchronous magnetic disturbance, although a few perturbations might have had an associated disturbance. We noted that these perturbations tended to have a periodicity of the order of an hour (one very clean example had several cycles of an oscillation with a period near 45 min). A prior equatorial study of gravity waves [*Rama Rao et al.*, 1997] also found that about 1 hour was a common gravity wave periodicity for Indian equatorial stations. A limited spectral analysis of daytime gravity waves over Fortaleza by one of us found a periodicity around 45 min to be very common. Therefore there is an indication that gravity waves may be involved in the spread *F* process.

Although the velocity perturbations that we observe are unlikely to be directly induced by gravity waves (most equatorial gravity waves have relatively small amplitudes compared to these perturbations), the gravity waves may initiate a disturbance in vertical velocity. This disturbance could then grow as a Rayleigh-Taylor (R-T) instability on the bottomside.

The basic growth rate for long-wavelength R-T instabilities is $\gamma = g/(L_v v_{in}) - \beta$. Using $g = 9.1 \text{ m s}^{-2}$, $L_v = 15 \text{ km}$ (from above), $v_{in} = 0.7 \text{ s}^{-1}$ (from Figure B.2 of Kelley [1989] for sunspot minimum and height 250 km), and $\beta = 3.3 \times 10^{-4} \text{ s}^{-1}$ (from above), one obtains $\gamma = 5.4 \times 10^{-4} \text{ s}^{-1}$ or 31 min growth time. Therefore the bottomside bulges should be growing slowly because of the R-T instability process. If the bottomside bulges result from an R-T instability, then this explains why the vertical velocity perturbation would stay synchronized with the plasma convection.

A further implication of the bulges being an R-T instability is that if the bottomside height becomes lower (as it did in equinox) then both v_{in} and β would increase and the instability would vanish. This seems to explain why we observed less spread F during equinox. Also, v_{in} increases during sunspot maximum [see Kelley, 1989, Figure B.2], so that, again, the R-T instability would not be unstable at 250 km heights. Thus the seasonal and sunspot variation of presunrise spread F at Fortaleza seems to be a consequence of the changes in R-T growth rate with height and sunspot number changes. Note that what appear to govern the spread F occurrence pattern are variations of the growth rate for the bottomside bulges, rather than changes in the growth rate of the gradient-drift instability that structure the bulges into spread F .

One should note that not all the spread F patches had an associated bottomside bulge. Some patches seemed to be just associated with a horizontal gradient (a sharp decrease) in the electron density, this also being unstable because of the same gradient-drift mechanism. Since these alternate gradients were only occasionally observed and had no obvious association with other ionospheric properties at the time we observed them, we will not speculate further about them in this paper.

A prior study of presunrise spread F by Bowman [1978] showed that the spread F was associated with traveling ionospheric disturbances (TIDs). There is also a theoretical study [Booker and Fergusen, 1978] connecting TIDs and spread F . As mentioned above, at least part of the spread F development sequence that we are proposing (the bottomside bulges) seems to have a TID connection. Also, we can often see discrete traces embedded in the diffuse "cloud" of spread F echoes. For an example see the ionograms in Figure 1 around 0600UT. These are similar in appearance to some of the TID traces that Bowman [1990, 1991] analyzed. We did not note any significant difference in speed of movement of these discrete traces as compared to the measured ionospheric convection speed. Thus we infer that in our spread F the discrete traces that resemble TIDs are just reflections from larger clumps (scale sizes) of ionization. Our results are thus not incompatible with the earlier studies mentioned above in that we also see TID like echoes, but we do not believe that these are genuine TIDs.

4. Conclusion

We observe a presunrise maximum in spread F occurrence during sunspot minimum in Brazil during solstices (particularly December solstice). The spread F takes the form of eastward moving patches that must be slowly growing in intensity of irregularities. The majority of these patches are associated with downward bulges on the bottomside of the ionosphere, and it seems likely that gradient-drift plasma instability is operating on these bulges to produce the irregularities.

The bulges appear to be caused by synchronous vertical velocity perturbations that we observe, and it seems likely that a R-T instability process is associated with the velocity perturbations that create the bulges. Changes in the R-T growth rate with ionospheric height and with sunspot number seem to explain some of the temporal behavior of the spread F .

Acknowledgements. The CADI program is supported by the Communications Research Centre, Ottawa, Canada.

The editor thanks R. Sekar and another referee for their assistance in evaluating this paper.

References

- Abdu, M. A., I. S. Batista, and J. A. Bittencourt, Some characteristics of spread F at the magnetic equatorial station Fortaleza, *J. Geophys. Res.*, **86**, 6836-6841, 1981.
- Abdu, M. A., I. S. Batista, and J. H. A. Sobral, A new aspect of magnetic declination control of equatorial spread F and F region dynamo, *J. Geophys. Res.*, **97**, 14897-14904, 1992.
- Abdu, M. A., J. H. A. Sobral, I. S. Batista, V. H. Rios, and C. Medina, Equatorial spread F occurrence statistics in the American longitudes: Diurnal, seasonal and solar cycle variations, *Adv. Space Res.*, in press, 1998.
- Anderson, D. N. and D. H. Rusch, Composition of the nighttime ionospheric F1 region at the magnetic equator, *J. Geophys. Res.*, **85**, 569-574, 1980.
- Batista, I. S., M. A. Abdu, and R. A. Medrano, Magnetic activity effects on range type spread F and vertical plasma drifts at Fortaleza and Huancayo as studied through ionosonde measurements and theoretical modeling, *Ann. Geophys.*, **8**, 357-364, 1990.
- Booker, H. G., and J. A. Fergusen, A theoretical model for equatorial ionospheric spread F echoes in the HF and VHF bands, *J. Atmos. Terr. Phys.*, **40**, 803-829, 1978.
- Bowman, G. G., The occurrence of post-midnight spread F associated with TIDs, *J. Atmos. Terr. Phys.*, **40**, 713-722, 1978.
- Bowman, G. G., A review of some recent work on mid-latitude spread F as detected by ionosondes, *J. Geomagn. Geoelectr.*, **42**, 109-138, 1990.
- Bowman, G. G., Ionospheric frequency spread F and its relationship with range spread at mid-latitude regions, *J. Geophys. Res.*, **96**, 9745-9753, 1991.
- Chandra, H., and R. G. Rastogi, Equatorial spread F over a sunspot cycle, *Ann. Geophys.*, **28**, 37-44, 1972.
- Coley, W. R., R. A. Heelis, and N. W. Spencer, Comparison of low-latitude ion and neutral zonal drifts using DE 2 data, *J. Geophys. Res.*, **99**, 341-348, 1994.
- Farley, D. T., B. Balseley, R. F. Woodward, and J. P. McClure, Equatorial spread F : Implications of VHF observations, *J. Geophys. Res.*, **75**, 7199-7210, 1970.
- Fejer, B. G., F. R. DePaula, S. A. Gonzales, and R. F. Woodman, Average vertical and zonal F -region plasma drifts over Jicamarca, *J. Geophys. Res.*, **96**, 13901-13906, 1991.
- Grant I. F., J. W. MacDougall, J. M. Ruohoniemi, W. A. Bristow, G. J. Sofko, J. A. Koehler, D. Danskin, and D. André, Comparison of plasma flow velocities determined by the ionosonde Doppler drift technique, SuperDARN radars, and patch motion, *Radio Sci.*, **30**, 1537-1549, 1995.
- Hedin, A. E., et al., Revised global model for thermospheric winds using satellite and ground based measurements, *J. Geophys. Res.*, **96**, 7657-7688, 1991.
- Kelley, M. C., Equatorial spread F : recent results and outstanding problems, *J. Atmos. Terr. Phys.*, **47**, 745-752, 1985.
- Kelley, M. C., *The Earth's Ionosphere*, Academic, San Diego, Calif., 1989.
- Kelley, M. C., M. F. Larsen, C. LaHoz, and J. P. McClure, Gravity wave initiation of equatorial spread F : A case study, *J. Geophys. Res.*, **86**, 9087-9100, 1981.
- Kelley, M. C., et al., The Condor equatorial spread F campaign: Overview and results of the large-scale measurements, *J. Geophys. Res.*, **91**, 5487-5503, 1986.

- Kil, H., and R. A. Heelis, Global distribution of density irregularities in the equatorial ionosphere, *J. Geophys. Res.*, **103**, 407-417, 1998.
- Krishna Murthy B.V., S. S. Hari, and V. V. Somayajulu, Nighttime equatorial thermospheric meridional wind from ionospheric h'F data, *J. Geophys. Res.*, **95**, 4307-4310, 1990.
- Linson, L. M., and J. B. Workman, Formation of striations in ionospheric plasma clouds, *J. Geophys. Res.*, **75**, 3211-3219, 1970.
- Rama Rao, P. V. S., D. S. V. D. Prasadd, P. Sri Ram, and P. T. Jayachandran, Effects of total solar eclipse on the low latitude ionosphere, *Terr. Atmos. Ocean Taiwan*, **34**, 342-350, 1997.
- Rastogi, R. G., Equatorial post midnight spread F and interplanetary magnetic field, *J. Geomagn. Geoelectr.*, **29**, 557-562, 1977.
- Rastogi, R. G., Seasonal and solar cycle variation of equatorial spread F in the American zone, *J. Atmos. Terr. Phys.*, **47**, 593-597, 1980.
- Ratcliffe, J. A., E. R. Schmerling, C. S. G. K. Setty, and J. O. Thomas, The rates of production and loss of electrons in the F region of the ionosphere, *Philos. Trans. R. Soc. London, Ser. A*, **248**, 621-642, 1956.
- Rishbeth, H., and O. K. Garriot, *Introduction to Ionospheric Physics*, Academic, San Diego, Calif., 1969.
- Sastri, J. H., Occurrence of post-midnight spread F over Kodaikanal, *Curr. Sci. India*, **48**, 12-18, 1979.
- Sastri, J. H., and Sasidharan, On the relationship between geomagnetic activity and spread F configuration at Kodaikanal, *Ann. Geophys.*, **36**, 247-250, 1980.
- Satyanarayana, P., P. N. Guzdar, J. D. Huba, and S. L. Ossakow, Rayleigh-Taylor instability in the presence of stratified shear layer, *J. Geophys. Res.*, **89**, 2945-2954, 1984.
- Woodman, R. F., and La Hoz, Radar observations of F region equatorial irregularities, *J. Geophys. Res.*, **81**, 5447-5466, 1976.
- M. A. Abdu and I. S. Batista, Instituto Nacional de Pesquisas Espaciais, Caixa Postal 515, 12201-970, Sao Jose Dos Campos, S. P., Brazil (email: abdu@dae.inpe.br)
- J.-F. Cecile, P. T. Jayachandran, and J. W. MacDougall, Department of Physics, University of Western Ontario, London, Ontario, Canada, N6A 5V9. (email: macdougall@uwo.ca)

(Received March 2, 1998, revised May 20, 1998;
accepted June 4, 1998.)