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Equatorial Spread F and Plasma Bubbles: A Step Towards Prediction

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ABSTRACT

Equatorial spread F (ESF) and plasma bubbles are plasma irregularity phenomena that are known to occur in the equatorial- and low-latitude ionospheric F region at evening and nighttime. Those irregularities cause scintillation that disrupts trans ionospheric radio propagation, up to the GHz frequency range interfering on communication systems including the Global Positioning System - GPS. Although the general characteristics of spread F and bubbles, concerning their variation with season, solar cycle, and magnetic activity, are fairly well understood, we do not know much about the cause of the day-to-day variability, a crucial point when prediction is concerned. In this paper, we analyze ionospheric data from two low latitude stations in Brazil, in either presence or absence of bubbles, in order to try to establish the conditions under which bubbles shall occur. We conclude that the F layer critical frequency (f_oF_2) in the afternoon-sunset hours (or equivalently the F layer maximum density, N_mF_2) is a useful parameter to predict the occurrence of the bubble.

INTRODUCTION

Equatorial spread F are diffuse echoes on equatorial- and low-latitude ionograms that were first identified by Booker and Wells (1938). Since then, many researchers have investigated the occurrence of this phenomenon in order to try to determine its characteristics and variability with location, season, solar cycle and magnetic activity, mainly in the Indian and American sectors (Sastri and Murthy, 1975; Sastri and Sasidharan, 1980; Sastri et al., 1975, 1979; Rastogi and Woodman, 1978; Rastogi et al., 1981; Abdu et al., 1981a, b, 1983a, b, 1985; Batista et al, 1990).

Plasma bubbles are depletions in the F region plasma density that occur after sunset, following the rapid rise of the F region bottomside, owing to the enhancement of eastward electric field (or vertical drift), before its reversal (e.g. Rishbeth et al., 1972; Heelis et al., 1974; Batista et al., 1986). Theoretical and numerical simulation studies show that they are generated by the Rayleight-Taylor (R-T) gravitational instability process, the nonlinear evolution of which leads to field-aligned plasma depletions that rise up through the F region producing a cascade of irregularities from kilometer to centimeter scale sizes (Haerendel, 1973; Ossakow et al., 1979; Zalezak et al., 1982). Simultaneously with the rise to high altitudes above the dip equator the bubbles map along the Earth's magnetic field, extending thousands of kilometers to the north and south of the magnetic equator, making possible their detection in non-equatorial (low-latitude) locations.

One of the problems that remain unsolved is the day-to-day variability of the bubble occurrence. In outline, this work will discuss the use of spread F as indication of plasma bubble; show the analysis of ionograms from two low-latitude stations either in the presence or absence of bubbles; and establish some conditions under which plasma bubble can occur, that can be used to predict bubble occurrence some hours before it occurs.

THE USE OF ESF AS AN INDICATION OF PLASMA BUBBLE

Although plasma bubble events are always accompanied by range ESF, the converse is not true; that is, we can have ESF on equatorial ionograms that is not associated with bubble occurrence. By this reason, to monitor the bubble occurrence following only the spread F seen on ionograms does not seem to be a straightforward task, at a first glance. But this can be possible when an array of at least two ionosondes is set at the same longitude sector: the ionosonde close to the equator (dip latitude < 10^o) is used to detect ESF, and the ionosonde at low latitude (dip latitude between 10^o and 20^o) will detect spread F originated from the extended flux tube plasma bubble (Figure 1). The spread F simultaneously detected by the two equipments is a very good indication of plasma bubble occurrence. Abdu et al. (1991) successfully used that criteria to identify the presence of plasma bubble during a rocket launching campaign. Whalen (1997) used range spread F (RSF) on ionograms from stations located at the Appleton anomaly crest as signatures of equatorial plasma bubbles.

Other techniques such as *in situ* plasma density measurements on board of rockets and satellites can give direct observation of the plasma bubbles, but they do not give the long period of continuous time coverage as that provided by ionosondes. The optical techniques from conventional photometers and from all-sky imaging systems are very efficient in detecting plasma bubbles (Sobral et al., 1980; Sahai et al., 1994) but they are restricted to the dark-moon nights from non-cloud periods. Ionosonde data on the other hand can be obtained in a continuous basis, constituting a very useful tool for studying and predicting the ionospheric bubbles.

DATA RESULTS AND DISCUSSION

Ionosonde data from Fortaleza – FZ (3.8° S, 38° W; -3° dip latitude) and Cachoeira Paulista – CP (22.5° S, 45° W; -15° dip latitude), Brazil, were used in this study. The parameters f_oF_2, the F layer critical frequency, and h'F, the F layer virtual height, were analyzed for March 1981, a period of high solar activity, with mean flux at 10.7 cm, $F_{10.7}$, of the order of 200 Joules/s.cm^{-2}.Hertz. The bubble events are identified as those periods when spread F occurs simultaneously over FZ and CP (see Figure 1 and the explanation related to it).

Figure 2 (a and b) shows the monthly mean of f_oF_2 and h'F over FZ and CP, either in the presence or absence of bubbles. As we can see from Figure 2a, the bubble periods are characterized by an intensification of the Appleton anomaly, in relation to the non-bubble days; that is, a decrease in f_oF_2 over FZ and an increase of the same parameter over CP. Figure 2b shows the well known local time behavior of h'F around sunset, during bubble and non-bubble periods (see, for example, Abdu et al., 1983b). The F layer base is higher during the period bubble occurrence at both locations. During the periods of non-occurrence of bubbles the F layer base height still shows a significant increase over FZ, around sunset, although it does not reach the same height as during the bubble periods.

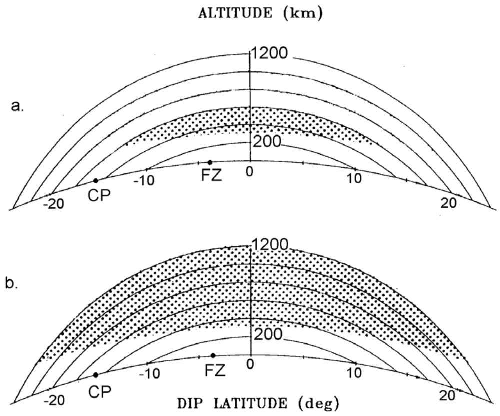

Figure 1 – Schematic representation of the ESF (shaded region) not associated (a) and associated (b) with plasma bubbles. In (a) there was no bubble formation so only the ionosonde closer to the equator will detect the ESF; in (b), after the bubble rise to high altitudes, extending to higher latitudes, ESF can be detected also at the low latitude station.

The electrodynamic processes that control all this behavior is well described considering the coupling between equatorial F region and the low-latitude conjugate E-regions along the same field line (Batista et al., 1986; Heelis et al., 1974; Rishbeth, 1971; Eccles, 1998). The daytime equatorial F-layer ionization moves upward due to ***ExB*** drift arising from eastward electric field induced by E-region dynamo. This electric field is reversed at night causing also a reversal in the ionization drift velocity to downward. Before its reversal, however, the vertical drift undergoes a rapid enhancement giving rise to a prereversal maxima, caused by the build up of the F-region polarization electric field, or the F-region dynamo field produced by thermospheric winds, that arises from the decrease in E-layer conductivity following sunset (Rishbeth, 1971). This scenario can favor the growth of instabilities, such as the gravitational R-T, according to the instability growth rate factor (see, for example, Zalezak et al., 1982)

$$\gamma = \left(\frac{\boldsymbol{ExB}}{B^2} - \boldsymbol{U_n} - \frac{\boldsymbol{g}}{\nu_{in}} \right) \cdot \frac{\nabla n}{n} - \beta \qquad (1)$$

where ν_{in} is the ion-neutral collision frequency, β is the recombination rate, $\boldsymbol{U_n}$ is the neutral wind velocity, $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic field, $\boldsymbol{ExB}/B^2$ is the plasma drift velocity, $\boldsymbol{g}$ is gravity, and $\nabla n/n = (1/n)dn/dz$ is the scale length of electron density distribution (n). In the non-linear theory, the instability is proportional to $e^{\gamma t}$ and consequently, a combination of ionospheric conditions that yield $\gamma > 0$ in Eq. 1 will lead to the growth of the instability and to bubble and spread F developments. The same factors that favor the growth of the instability and bubble generation also enhance the

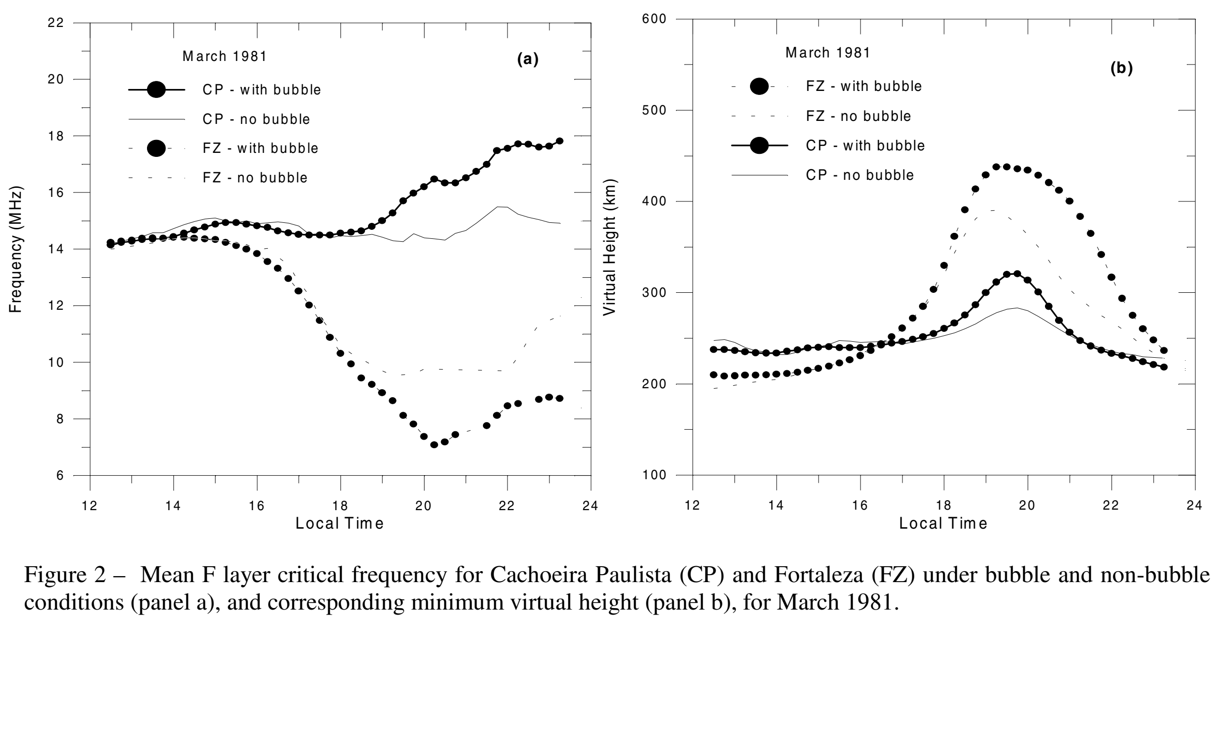

Figure 2 – Mean F layer critical frequency for Cachoeira Paulista (CP) and Fortaleza (FZ) under bubble and non-bubble conditions (panel a), and corresponding minimum virtual height (panel b), for March 1981.

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fountain effect that generates the equatorial anomaly. That is the reason for the good correlation between the anomaly development and the bubble formation (Figure 2a).

Thermospheric winds also play an important role in irregularity development. Using a numerical model Maruyama (1988) showed that large transequatorial wind significantly reduces the instability growth rate, independently of its direction. Following Mendillo et al. (1992), this can be understood referring to Eq. 1. A northward meridional wind will contribute to increase γ along that portion of a flux tube that is in the southern hemisphere, since the wind component perpendicular to $\boldsymbol{B}$, ($\boldsymbol{U_{\perp}}$) is in the same direction as the $\boldsymbol{g}$ component perpendicular to $\boldsymbol{B}$. The opposite effect occurs along the northern portion of the flux tube. The interhemispheric motion of plasma from south to north, via $\boldsymbol{U_{\parallel}}$ component (parallel to $\boldsymbol{B}$), results in more plasma experiencing the stabilizing effect in northern hemisphere than plasma experiencing the growth effect in the southern hemisphere, with the net result being the stabilization over the entire flux tube. The same stabilizing effect would occur for a southward transequatorial wind. The conclusion, as in Maruyama (1988) is that it is the existence of a strong meridional wind, and not its direction that decreases the instability growth rate, contributing to instability inhibition.

Therefore, the meridional wind is an important parameter in the day-to-day variability of ESF and bubble developments. However, meridional wind measurements are not available at many locations and the measurements are generally restricted to nighttime periods, because they are based on optical techniques. Without knowing the meridional wind it is not possible to calculate correctly the instability growth rate, emphasizing the need to use the ionospheric parameters, themselves, such as those regularly measured by ionosondes, in an attempt to predict ESF and plasma bubbles.

Based on the relative mean behavior of f_oF_2 over FZ and CP during bubble and non-bubble periods, shown in Figure 2a, we investigate the ratio between the critical frequencies at the two stations, $(f_oF_2)_{CP}$ / $(f_oF_2)_{FZ}$, during bubble and non-bubble periods, for March 1981. The results for some typical days on the month are shown in Figure 3. As we can see, on the days with plasma bubble development (Figure 3a) the ratio between critical frequencies remains almost constant until a local time between 1630 and 1800, after which a rapid increase is observed on the ratio. On the days with no occurrence of bubbles (Figure 3b), the ratio remains low, generally not exceeding 1.3-1.4. A ratio greater than 1.5 gives an indication of plasma bubble occurrence. We have examined other events during September 1989, and the same tendency is observed for that period.

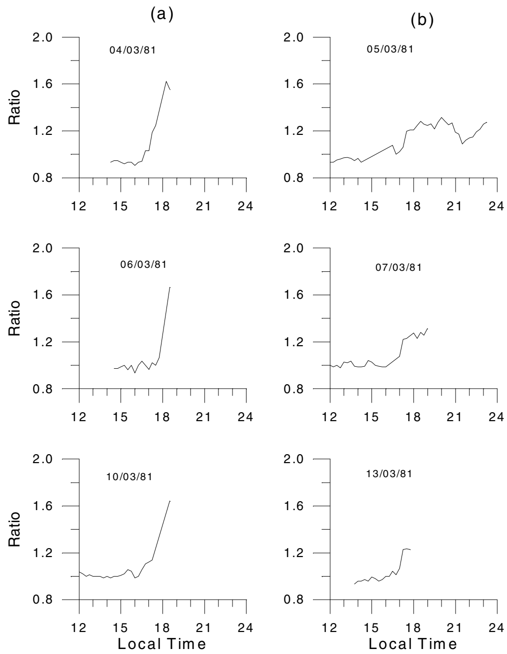

Figure 3 – Ratio between F layer critical frequency at CP and at FZ, $(f_oF_2)_{CP}$ / $(f_oF_2)_{FZ}$, for days with (a) and without (b) bubble formation.

The behavior of the frequency ratio above described is similar to that observed by Raghavarao et al. (1988), using three low-equatorial-latitude stations in India. They showed that the electron density ratio (at a fixed height) between two low latitude locations is much higher during the days with ESF, than on days without spread F. Rama Rao et al. (1997), also using ionospheric data over Indian stations conclude that a well-developed ionization anomaly is one of the conditions for the generation of ESF.

CONCLUSIONS

According to the results shown in this work, and also based on previous studies, it is clear that the simultaneous monitoring of f_oF_2 at the magnetic equator and at a low latitude station, close to the equatorial anomaly crest, at the same longitude sector, can be very helpful for plasma bubbles predictions. The ratio between f_oF_2 at the two locations being greater than 1.5 at the local times just preceding the ESF occurrence gives a clear indication of the development of irregularities that will lead to plasma bubble formation. This is a first step for prediction because the study was restricted to a period of equinox, high solar activity. Data analysis for all seasons and for various levels of solar activity is now under development in an attempt to generalize the present criteria.

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