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Space Weather Phenomena in the Equatorial Ionosphere

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Abstract. Our increasing dependence on space-based technological systems requires that we understand the factors that determine "space weather," which affects the operation of satellites as well as space-based communication and navigation systems. The latter are particularly vulnerable to conditions in the dip equatorial ionosphere where geometry of the geomagnetic field creates conditions for the growth of certain plasma instabilities, which produce sub-kilometer scale structure in the ionospheric plasma that are capable of scattering VHF and higher frequency radio waves. The phenomenon of the equatorial plasma bubble (EPB) that occurs in the postsunset equatorial and low latitude ionosphere is therefore an important component of space weather in this region. Forecasting of this space weather phenomenon involves not only the identification of ambient conditions responsible for the day-to-day variation in its occurrence and spatial structure during magnetically quiet periods but also understanding the influence of solar variability on these conditions. This paper discusses briefly our present understanding of the role played by certain parameters of the equatorial ionosphere in the development of EPBs and the influence of solar activity on the equatorial ionosphere, in the context of its role in the generation of ionospheric irregularities that may be detrimental to the operation of space-based communication and navigation systems.

Keywords: Space weather, equatorial ionosphere, equatorial spread F irregularities, ionospheric scintillations, magnetic storms.
PACS: 94.05Sd, 94.20dt, 94.20Vv, 94.20Wf, 94.20ws, 52.35Py

EQUATORIAL SPREAD F

Earth's ionosphere, created through partial ionization of its upper atmosphere by EUV and X-ray emissions from the sun, is to lowest order stratified into horizontal layers. In the dip equatorial region, where the geomagnetic field is horizontal, a steep upward density gradient present on the bottomside of the ionospheric F layer in the postsunset hours, on account of rapid destruction of the E region below due to recombination, creates a condition that is basically unstable to the growth of the Rayleigh-Taylor (RT) instability. Equatorial spread F (ESF) is the generic name used to describe the irregularities generated in the equatorial F region by the growth of plasma instabilities. This name was originally introduced by Berkner and Wells [1] to describe the phenomenon that gave rise to the spread in ionograms obtained by sounding the ionosphere using radio waves (Figure 1).

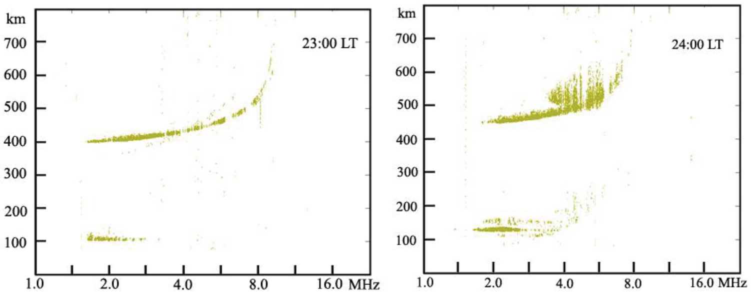

FIGURE 1. Ionograms obtained from ionosonde observations at an equatorial location (Trivandrum, India) show that around local midnight on this day the pattern of echoes develop a "spread" in range.

Plasma density irregularities associated with ESF span a large range of scale sizes extending from about 0.1 m to hundreds of kilometers, of which the irregularities with scale sizes in the range 100 m to a few tens of kilometers are attributed to the growth of a generalized version of the RT instability, which includes the destabilizing effects of not only gravity but also an eastward ambient electric field in the postsunset equatorial ionosphere as well as the prevailing neutral wind. As shown in Figure 2, in the presence of a horizontal, northward magnetic field, as in the equatorial ionosphere, a small disturbance on the bottomside of the postsunset equatorial F region causes the eastward gravitational current to give rise to accumulation of charges and resultant perturbation electric fields, which are so directed as to raise the depleted region to higher altitudes.

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In the nonlinear phase of the growth of the RT instability, the density depletion referred to as an equatorial plasma bubble (EPB) may rise to the topside of the equatorial F region and also develops smaller scale structure [2]. The plasma bubbles are geomagnetic field-aligned structures, highly elongated along the field lines, as the instability involves the interchange of magnetic flux tubes containing low- and high-density plasma. This is a postsunset phenomenon because geomagnetic field-aligned currents that connect the equatorial F region with the off-equatorial E regions, at the feet of the field line, flow through a conducting ionospheric E region during daytime to short-circuit the F region perturbation electric fields.

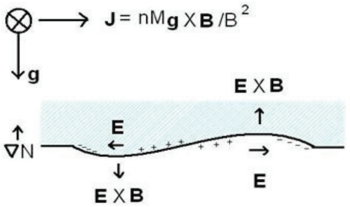

FIGURE 2. Development of EPB on the bottomside of the postsunset equatorial ionospheric F region due to growth of the Rayleigh-Taylor instability.

The intermediate scale length (100 m to a few km) irregularities generated by the growth of the RT instability are capable of forward scattering VHF and higher frequency radio signals transmitted from a satellite as they propagate through the ionosphere on their way to a ground receiver. Movement of the irregularities across the signal path causes the spatial pattern of intensity variations on the ground to drift past the receiver, which records temporal fluctuations or scintillations of the amplitude and phase of the signal. While amplitude scintillations can cause deep fades leading to loss of signal, rapid phase scintillations may cause loss of receiver lock. The signature of an EPB is seen in the total electron content along the signal path estimated using a dual frequency GPS receiver, as seen in Figure 3, which also shows scintillations of the signal intensity [3].

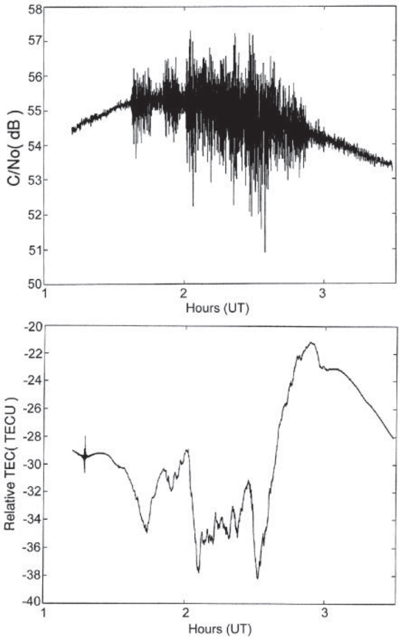

FIGURE 3. *(top)* Intensity scintillations on a 1.6 GHz GPS signal due to irregularities of scale sizes of about 300 to 400 m. *(bottom)* Simultaneously present variations in total electron content (TEC) along the signal path due to the occurrence of EPBs, as estimated from dual frequency GPS measurements. TECU = 10^{16} electrons / m^2.

As such, the basic condition for growth of the RT instability, viz., an upward density gradient, is present every night, but the day-to-day variability in the occurrence pattern of EPBs and their spatial structure is yet to be understood. In situ observations of the irregularities with instruments on board rockets and satellites have provided information about one-dimensional spectral characteristics of the irregularities and associated electric field fluctuations in the vertical and horizontal directions, respectively [4]. In recent years, magnetic field fluctuations associated with EPBs have also been observed [5]. An example of magnetic field fluctuations observed in the region of EPBs at an altitude of around 400 km, by instruments on board the CHAMP satellite, which was in a near polar orbit with inclination of 87.3°, is shown in Figure 4. There are significant fluctuations only in the components transverse to the main geomagnetic field, which is directed along the z-axis.

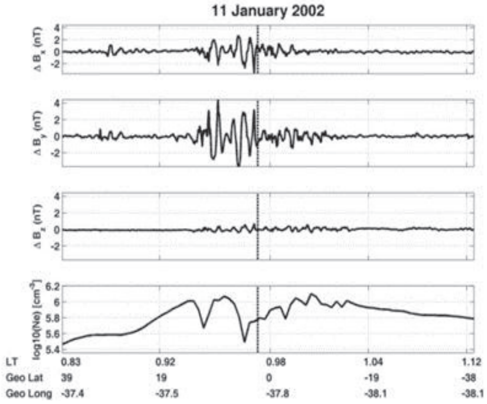

FIGURE 4. The top three panels show fluctuations in the three components of the magnetic field measured by magnetometer on board the CHAMP satellite. The dip equator is indicated by a dashed line in each panel. In the bottom panel are simultaneous measurements of electron density by CHAMP, which show structures associated with EPBs.

Radars have been used to study meter and sub-meter scale irregularities, which coherently backscatter VHF radio waves transmitted upward from the ground. These signals undergo Bragg scattering by ionospheric irregularities of appropriate wavelengths. Height-time-intensity maps of the backscattered radar signals provide information about the nonlinear evolution of the RT instability [6]. For instance, it is seen from Figure 5 where such maps are given for a 53 MHz signal transmitted vertically upward and coherently backscattered by 2.8 m scale-size irregularities that on some nights the RT instability evolves into EPBs extending into the topside of the ionosphere, and on other nights irregularities are confined to a thin bottomside layer.

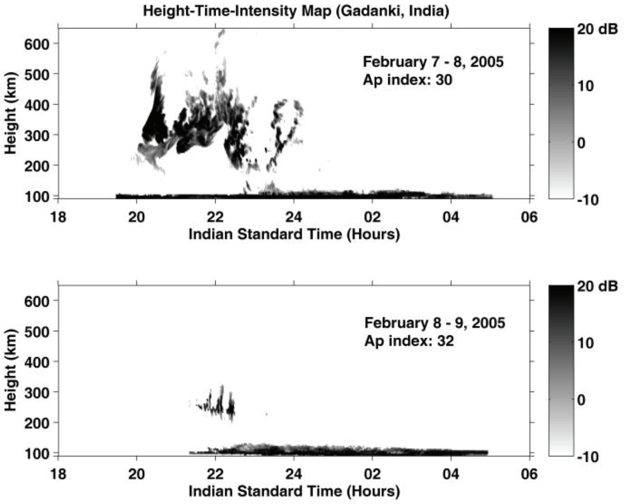

FIGURE 5. Height-time-intensity maps obtained with a 53-MHz coherent scatter radar operating at Gadanki (dip latitude 6.3°N) in India.

ELECTROMAGNETIC INTERCHANGE MODE

In view of the possible detrimental effects this space weather phenomenon may have on the performance of satellite-based communication and navigation systems, there have been innumerable studies to identify the factors that influence the evolution of the RT instability in the postsunset equatorial ionosphere. Radar studies had identified the height of the postsunset equatorial F layer as one of the key parameters [7]. Although in a seminal study in which Hudson and Kennel [8] had pointed out the fundamental electromagnetic nature of the interchange mode, they found that the coupling to Alfvén mode has a stabilizing effect for finite parallel wavelengths, and hence traditionally the RT instability was treated as an electrostatic instability. Thus, most simulations of the development of EPBs were two-dimensional dealing with field-line integrated entities. Although postsunset development of EPB requires that the growth period of the instability be shorter than the time taken to discharge the bubble through conducting E regions, field-aligned currents that couple the equatorial F region with the conjugate E regions at the two ends of the geomagnetic field lines (Figure 6) could not be considered in the 2D simulations. Keeping this in mind, an electromagnetic RT instability was considered in a 3D model, where shear Alfvén waves generated as the EPB starts to grow and carries field-aligned currents that couple the equatorial F region with conjugate E regions [9].

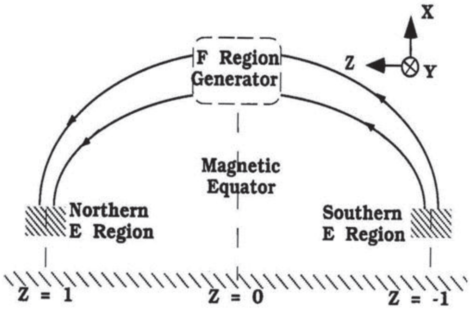

FIGURE 6. A transmission line model for the development of EPBs.

According to this theory, a condition for nonvanishing density perturbations to exist in the equatorial F region is that the field-line integrated E region Pedersen conductivities in the two hemispheres should be identical. This requires that the magnetic meridian must be aligned with the sunset terminator. Thus, the declination of the geomagnetic field at the dip equator at a given longitude would determine the season with the most frequent occurrence of EPBs in that longitude region. Based on the observed seasonal pattern of scintillation occurrence at equatorial locations in different longitude zones, Tsunoda [10] had earlier arrived at this conclusion, which was later ratified by long term (1989–2002) data obtained from electron density measurements by DMSP satellites at an altitude of 840 km [11]. This study showed that to lowest order, the alignment of the magnetic meridian with the sunset terminator determined the seasonal occurrence pattern of the EPBs at any longitude. The next question that arises is, How small does the E region conductivity have to be for the evolution of the RT instability into an EPB? To answer this question, a three-mode system was considered to describe the weakly nonlinear evolution of EPBs, which yielded a condition for development of topside structure. This condition required that in a region where ion-neutral collisions are not very frequent, the time required for the EPB to grow (inverse of the linear growth rate $\sqrt{g/2L}$, where L is the density gradient scale length) should be shorter than the time required for the E region conductivity to short-circuit the perturbation electric field associated with the RT instability, which is given by $d/\mu_0 V_A^2 \Sigma_P^E$, where d is the length of the geomagnetic field line connecting the equatorial F region with the conjugate E region in either hemisphere, V_A is the Alfvén speed, and Σ_P^E is the field line integrated E region Pedersen conductivity [12]. The latter time increases with increasing height of the equatorial F region, which causes d to increase. This establishes the role of the height of the equatorial F region as well the E region conductivity in the development of the EPB. In a situation where the above condition is not met, the RT instability evolves into structures that are confined to the bottomside of the equatorial F region. The bottomside irregularities do not have a large latitudinal extent because of their low height above the dip equator, and they have a steeper spectrum indicating the dominance of a central wavelength of about 1 km and absence of irregularities of a few hundred meter scale sizes. Thus, the bottomside irregularities may cause scintillations on VHF signals but not on L-band and higher frequency signals.

EPB OCCURRENCE AND SOLAR VARIABILITY

Variability of the sun influences the height of the postsunset equatorial F region. During magnetically quiet periods, the ambient eastward electric field in the equatorial F region immediately following sunset undergoes a pre-reversal enhancement (PRE) before it turns westward. The PRE depends on the season, being a maximum during the equinoxes. It also depends on the level of solar activity, which determines the solar UV flux involved in heating the upper atmosphere, thereby giving rise to motions of the neutral component. The neutral particles have collisions with electrons and ions that compose the ionosphere, and thus the motion of the neutrals causes a conducting fluid to move across the geomagnetic field lines, resulting in electric fields in an Earth-fixed frame. Hence the PRE is generally largest during solar maximum and lowest during solar minimum [13]. EPBs are thus most likely to occur during solar maximum, and this is borne out by observations of ionospheric scintillations in the equatorial and low latitude regions [14].

The other way in which solar variability influences the generation of EPBs is through transient events such as a geoeffective coronal mass ejection (CME) that happens more often close to the peak of the solar cycle, or a high speed stream of charged particles coming from a coronal hole, which occurs during the declining phase of a solar cycle. The CMEs evolve as interplanetary coronal mass ejecta (ICME) as they travel through interplanetary space to the edge of Earth's magnetosphere. The high-speed streams emanating from solar coronal holes interact with lower speed solar wind, creating regions of compressed magnetic fields: the corotating interaction regions (CIRs). Orientation of the interplanetary magnetic field (IMF) associated with these when they finally impinge on Earth's magnetosphere plays a key role in their geoeffectiveness in producing a magnetic storm or substorm. A southward oriented IMF reconnects with the geomagnetic field to create "open" magnetic field lines in the polar regions, which are connected to the IMF at the other end. Reconnection on the nightside of these magnetic field lines swept back to that side by the solar wind causes energized plasma to flow back in the sunward direction. As this plasma encounters an increasing geomagnetic field, the electrons and ions drift in opposite directions to form a westward ring current around Earth at a distance of about $4R_E$ in the magnetosphere. An index derived from measurements of geomagnetic field variations at midlatitude stations gives the strength of the ring current and is an indicator of magnetic storms. At a time when the north-south component, B_Z, of the IMF suddenly undergoes a change from northward to southward, the equatorial and low-latitude ionosphere, which lie in regions with closed magnetic field lines, are not shielded from the penetration of an electric field of magnetospheric origin into this region. Subsequently, a shielding electric field develops to cancel out this electric field. On the nightside this shielding electric field is eastward. Now if the IMF B_Z suddenly changes from southward to northward, the magnetospheric convection field disappears, and the shielding electric field gives rise to an eastward electric field in the nighttime equatorial ionosphere, when the ambient electric field had already reversed to westward. If this results in a net eastward electric field, then the height of the equatorial F region may be increased to create conditions conducive to the development of EPBs. A similar situation may arise after several hours of geomagnetic activity with enhanced currents in the auroral ionsphere. Joule heating produced by these currents give rise to a disturbance dynamo, which may generate an eastward electric field in the nighttime equatorial ionosphere [15].

Prediction of the occurrence of an EPB in the equatorial ionosphere, and its latitudinal extent, therefore require not only identification of magnetically quiet period ambient conditions, which are the precursors of an EPB, but also an understanding of the response of the equatorial ionosphere to geoeffective transient events on the sun, under different conditions.

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