LOW LATITUDE IONOSPHERIC STUDIES USING SATELLITE MAGNETIC DATA

Archana Bhattacharyya

Indian Institute of Geomagnetism, Kalamboli Highway, New Panvel, Navi Mumbai 410218, India,
Email: abh@iigs.iigm.res.in

ABSTRACT

One of the important phenomena associated with the electrodynamics of the low latitude ionosphere is that of the equatorial plasma bubbles (EPBs), which on occasion cause disruptions in the operation of space-based communication and navigation systems. The day-to-day variability in occurrence and characteristics of EPBs is yet to be understood. In recent times, observations of magnetic field fluctuations associated with EPBs have led to new theories, and provided a new tool for studying the spatial evolution of EPBs both under magnetically quiet and disturbed periods. In two case studies presented here, magnetic field fluctuations observed during the post midnight period indicate the generation of fresh EPBs due to the occurrence of an eastward electric field in the equatorial ionosphere in response to geomagnetic activity.

1. INTRODUCTION

Geometry of the Earth's magnetic field plays an important role in the electrodynamics of ionospheric plasma. In the equatorial and low-latitude ionosphere it gives rise to phenomena such as equatorial electrojet, equatorial ionization anomaly, and equatorial plasma bubbles (EPB). Of these, the EPBs associated with plasma density variations or irregularities, of spatial scales extending over several orders of magnitude (usually referred to as equatorial spread F (ESF)), which include intermediate scale (100 m to few kilometers), irregularities, pose a practical problem in that VHF and higher frequency radio wave signals propagating through the low latitude ionosphere are scattered by the intermediate scale irregularities. Movement of the irregularities across the path of a signal recorded by a ground receiver causes the amplitude and phase of the recorded signal to fluctuate or scintillate. Ionospheric scintillations may cause considerable degradation of radio wave signals that propagate through a layer of irregularities, due to deep fading of the signal and rapid phase fluctuations, which may sometimes result in loss of lock for a receiver. In some seasons, particularly for high solar activity periods, there may be severe disruptions in the operation of communication systems and navigation systems such as GPS. The regions of the globe, which are most susceptible to such disruptions, are the auroral/polar cap regions and the equatorial and low latitude regions.

In the post-sunset equatorial ionosphere, a steep upward gradient in the plasma density exists on the bottom side of the F-region. This is basically an unstable situation with the horizontal geomagnetic field in the equatorial region supporting the heavier fluid on top, and amenable to the growth of the Rayleigh-Taylor (R-T) instability. Ionospheric plasma is associated with a low value of β ($< 10^{-4}$), where β is the ratio of particle pressure to magnetic field pressure. Hence, models for the development of EPBs have been generally based on quasi-neutral plasma fluid equations in the electrostatic limit [1], [2], [3], [4]. However, recent observations of magnetic field fluctuations associated with EPBs call for an electromagnetic version of the R-T instability or some other explanation. These observations also provide a new tool to understand the generation and evolution of EPBs.

The first observations of magnetic field fluctuations associated with EPBs were based on Dynamic Explorer 2 (DE-2) satellite data obtained at an altitude of around 400 km [5]. Simultaneously observed electric and magnetic field perturbations associated with an EPB updrafting at supersonic speed led the authors of [5] to suggest that the magnetic field fluctuations were produced by field-aligned currents (FACs) carried by Alfvén waves generated in the equatorial F region at the leading edge of the updrafting EPB. Electromagnetic plasma waves have also been detected within and around density depletions in the topside equatorial F region mostly at altitudes between 400 and 500 km, by electric and magnetic field sensors of the Extremely Low Frequency Wave Analyzer (ELFWA) instrument on the Combined Release and Radiation Effects Satellite (CRRES) [6]. These observations have yielded an amplitude (~ 0.3 nT) for magnetic field fluctuations associated with EPBs, which is much smaller than those reported in [5]. On account of the elliptic orbit of CRRES, lower limit of the ionospheric region accessible to the CRESS orbit, during the 15 months of observation, was such that in the 2100 to 2400 LT period, observations were mostly made above an altitude of 600 km. Hence most of the EPB related magnetic field fluctuations reported in [6] are observed during post-midnight periods. Reference [7] reported in-situ observations of night-time low latitude F region currents at an altitude of around 400 km, coupled with the presence of EPBs, on the basis of scalar magnetic field and electron density measurements made by instruments on board the CHAMP (Challenging Minisatellite Payload) satellite. Recently, results from the first comprehensive study of magnetic field fluctuations associated with EPBs derived from the vector magnetic field data obtained with CHAMP for the period 2001-2004, have been reported in [8]. The occurrence statistics of magnetic signatures of EPBs as a function of local time obtained by the authors of [8], shows maximum occurrence between 2100 and 2200 LT, with a gradual decrease to about 1% at 0400 LT. The significance of this finding in the context of theory shall be discussed in section 3.

2. THEORETICAL DEVELOPMENTS

In order to explain the observations reported in [5], a transmission line analogy for the development of EPBs, shown schematically in Figure 1, was proposed [9]. In this model, the field-aligned currents (FACs) are carried by oppositely propagating Alfvén waves that are launched in the equatorial F region when an EPB starts to grow. These FACs provide the coupling between E and F regions, which makes the EPB/ESF an exclusively post-sunset phenomenon. During daytime, a large E region conductivity shorts out the perturbation electric field, thereby inhibiting the growth of the R-T instability. An important result, which came out of the transmission line analogy, was that growth of EPBs requires that the field-line integrated Pedersen conductivities in the two conjugate E regions at the feet of the field-lines joining the equatorial F-region to these E-regions, should have small and nearly equal values; i.e. $\Sigma_{PN}^{E} \approx \Sigma_{PS}^{E} \approx 0$. This condition implies that a small angle between the solar terminator and magnetic meridian is an important factor for growth of EPBs as was suggested in [10] on the basis of observed seasonal and longitudinal occurrence patterns of equatorial scintillations. The importance of this condition has been brought out more recently in two studies. The first is of the seasonal/longitudinal variations in EPB occurrence based on electron density measurements made by DMSP satellites at an altitude of about 840 km, during the period 1989 to 2002 [11], while the second study looked at the seasonal/longitudinal variations in the occurrence rates of CHAMP magnetic signatures of EPBs at an altitude of around 400 km for the period between 2001 and 2004 [8]. It is the departure of these results from the criterion suggested in [10], which need to be understood now.

The basic condition for the growth of R-T instability exists every day during post-sunset hours. However on many occasions, depending on the season, the instability produces only bottom-side irregularities [12], which are confined to a limited altitude extent of thickness 50-100 km on the bottom-side of the equatorial F region, and there is no development into EPBs. The linear theory for the growth of EPBs, based on the transmission line analogy, has been extended to explore the role of E-region conductivity in the non-linear development of EPBs [13]. This weakly non-linear

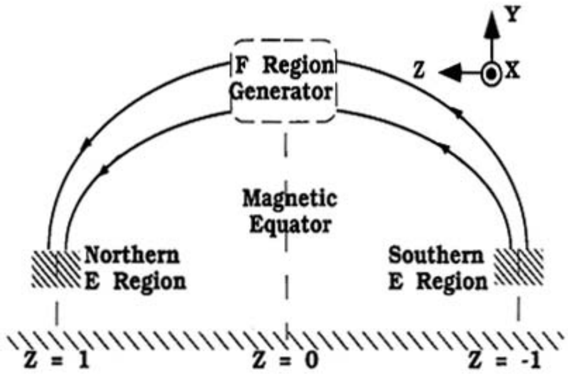

Figure 1. Schematic of the transmission line analogy for the development of EPBs with the equatorial F region generator coupled to the conjugate E regions through field aligned currents carried by Alfvén waves.

theory has yielded the following condition for the evolution of bottom-side perturbations into EPBs:

$$\nu_i + \frac{\mu_0 V_A^2 \Sigma_P^E}{l} < \sqrt{\frac{g}{2L}} \qquad (1)$$

where ν_i is the ion-neutral collision frequency, V_A is the Alfvén speed, Σ_P^E is the field line integrated Pedersen conductivity of the E region in either hemisphere (Σ_{PN}^{E} and Σ_{PS}^{E} have to be equal for the growth of the instability in this theory), l is the length of the field line from the equatorial F region to E region, and L is the vertical plasma density gradient scale length. This condition for the first time, introduces a time scale for the discharge of the bubbles through the E region conductivity, in the non-linear evolution of EPBs. If this time scale is short compared to the inertial growth period for the R-T instability, currents flowing through the E region short the perturbation electric field associated with the instability before the EPBs can develop, and only bottomside irregularities may result. This condition also supports the observations that height of the post-sunset equatorial F layer is a key parameter in the generation of EPBs [14], [15].

In another recent study of the characteristics of electromagnetic Rayleigh-Taylor modes in the nighttime equatorial F-region [16], which assumes the parallel conductivity to be finite, it has been shown that magnetic field fluctuations of a few nT associated with shear Alfvén waves could arise from fluctuating parallel current density. The apex altitude of the field line has been taken as 300 km in this study, and ion inertial currents have been ignored. At the altitude of CHAMP satellite or the proposed SWARM constellation, ion inertia is expected to play a role. From this point of view, the models used in [9], [13], which retain ion inertial effects, seem to be more suitable for explaining the observed magnetic field fluctuations associated with EPBs.

3. EPB GENERATION DURING MAGNETICALLY DISTURBED PERIODS

An important aspect of the impact of solar variability on Earth's environment, which is emphasized by programmes such as the International Living With a Star (ILWS) program, is how it affects the performance of space-based communication and navigation systems. As mentioned earlier, height of the post-sunset equatorial F layer has been identified as a key parameter in the generation of EPBs [14],[15]. Hence disturbances in the eastward electric field in the equatorial F region due to magnetic activity are expected to affect the generation of EPBs.

One of the problems encountered in studies of the effect of magnetic activity on the generation of EPBs using observations such as ionospheric scintillations and radars, which are related to electron density fluctuations, is that it is not known whether the observed scintillations or radar echoes are produced by freshly generated irregularities or by irregularities that were generated several hours earlier to the west of the observation point and then later drifted into the path of the radio wave signal. A solution to this problem has been found using spaced receiver observations of equatorial scintillations. It has been reported in [17] that scintillations on a VHF signal caused by ESF irregularities and recorded at an equatorial station by two receivers spaced along a magnetic east-west baseline, show strong de-correlation between the two signals in the initial phase of EPB development, generally up to 2200 LT. This de-correlation has been attributed to the electric field fluctuations that arise due to the growth of the R-T instability, and which decay about 2 hours after the EPBs are generated. This characteristic of the EPBs may be used to estimate the 'age' of the EPB's, which is crucial for establishing a cause-effect relationship between magnetic storms/ substorms and generation of EPB's due to eastward turning of the ambient electric field as a result of magnetic activity [18]. In this context, it is pertinent to note that the local time occurrence pattern of EPB associated magnetic field fluctuations observed by CHAMP [8] is close to the local time occurrence pattern for electric field fluctuations associated with EPBs found from spaced receiver observations of nighttime equatorial scintillations [17]. It is expected from theory [9], [13] that electric and magnetic field fluctuations associated with EPBs would be present simultaneously, and hence they would decay at the same time. Thus post midnight magnetic field fluctuations associated with EPBs indicate that the bubbles encountered by the satellite are freshly generated. This makes the magnetic signature of an EPB observed in post-midnight satellite magnetic data, an important tool for studying EPB generation due to electric field disturbances in the equatorial ionosphere caused by magnetic activity.

There are two major sources of large scale, low latitude ionospheric electric field disturbances during magnetically disturbed periods: (a) prompt penetration of high latitude electric field during periods when the high latitude convection pattern undergoes large changes and there is either 'undershielding' or 'overshielding'; (b) ionospheric disturbance dynamo set up by storm time winds due to deposition of enhanced energy at high latitudes. A few cases of prompt penetration of high latitude electric field into the low latitude ionosphere in different longitude zones, have been studied recently using incoherent scatter radar data from Jicamarca (11.9º S, 283.1º E, 0.8º dip lat.) [19] [20], and electrojet ΔH from the Peruvian, Philippine, and Indian ground stations [20]. The latter study has shown that prompt penetration effects may be seen in ΔH form Philippine and Indian longitude sectors when this takes place during daytime in these sectors, even while night time incoherent scatter radar data from Jicamarca shows such effects.

On April 17, 2002, Jicamarca radar data and ΔH calculated from the equatorial station, Jicamerca and off equatorial station Piura, showed prompt penetration of high latitude electric fields [19], [20]. However, since the period when prompt penetration took place is evening/nighttime in the Indian and Phillipine sectors, signatures of it in the electrojet ΔH from these regions could not be seen. CHAMP observations provided the opportunity to see if the prompt penetration of an eastward electric field due to either 'undershielding' or 'overshielding', into the nighttime equatorial ionosphere in any longitude zone produced EPBs on this day. Vector magnetic field data from CHAMP averaged over 1s is used in this investigation. The electron density data from CHAMP is sampled every 15 s. The interplanetary electric field (IEF) $\mathbf{E} = -\mathbf{V}_{SW} \times \mathbf{B}_{IMF}$, is calculated from the solar wind velocity, $\mathbf{V}_{SW}$, and $\mathbf{B}_{IMF}$, the interplanetary magnetic field (IMF) obtained from ACE satellite data, and time-shifted to the magnetopause location. The time-shifted y and z components of the IEF $\mathbf{E}$ in the Geocentric Solar Ecliptic coordinates, E_y (dawn-to-dusk component of the IEF) and E_Z, on April 17 and 18, 2002 are shown in Fig. 2. In order to obtain the magnetic signatures of EPBs from CHAMP observations, the modeled main field, linear secular variation and external field contributions have been removed from the 1s averaged vector magnetic data using the CO2 model. Further the magnetic data was high-pass filtered with a cut-off period of 30s. The magnetic field components are displayed in a mean-field-aligned (MFA) coordinate system, in which the B_Z component is aligned with the mean magnetic field. Fig. 3 shows an example of EPBs encountered by

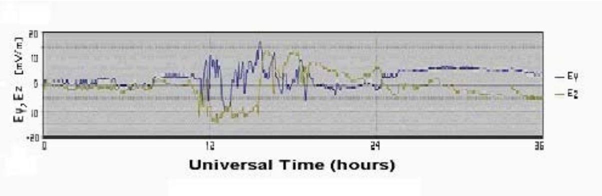

Figure 2. E_Y, the dawn-to-dusk component, and E_Z, the component perpendicular to the ecliptic plane, of the IEF on April 17 and 18, 2002.

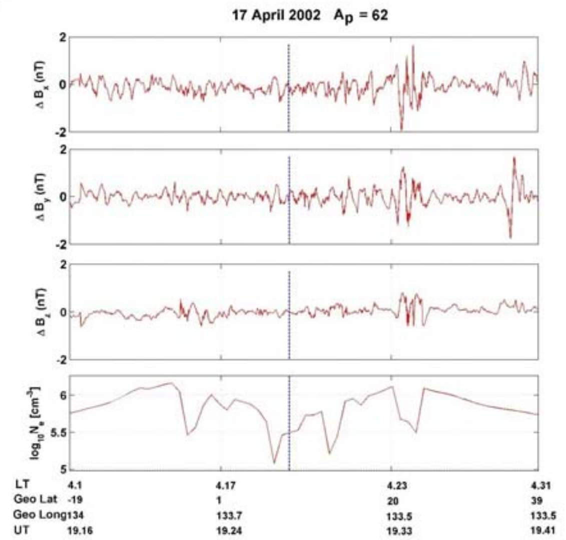

Figure 3. High-pass filtered vector magnetic field data from CHAMP in MFA coordinates and corresponding electron density data measured by PLP on April 17, 2002. The dashed line indicates the location of the dip equator.

CHAMP in the 134°E longitude sector, at around 1920 UT (~ 0400 LT), which could have resulted from prompt penetration of a dusk-to-dawn electric field around 19 UT on April 17, 2002. This is consistent with the abrupt decrease seen in the eastward electric field at Jicamarca, on the dayside, in response to a sudden decrease in the y- component of the IEF [19]. Magnetic field fluctuations in this case have an amplitude of ~ 2 nT. No ionospheric scintillations were seen on a VHF signal recorded at the equatorial station, Tirunelveli (8.7ºN, 77º E, 0.6º dip latitude), in the Indian region, in association with the prompt penetration electric field on April 17, 2002.

January 11, 2002, was a day with weak magnetic disturbances, with SYM-H reaching its lowest value of around – 80 nT at 8 UT (Fig. 4). On this day also

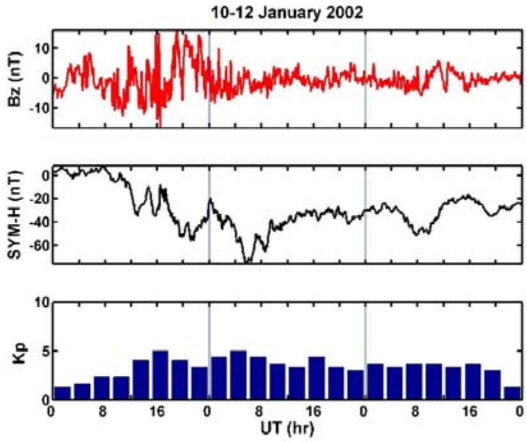

Figure 4. The IMF northward component B_Z, SYM-H and Kp indices for 10-12 January, 2002.

fresh EPBs were generated in the post-midnight period as seen from the associated magnetic field fluctuations shown in Fig. 5. The occurrence of fresh EPBs at this time may be attributed to magnetic activity [21]. Amplitude of magnetic field fluctuations associated with these EPBs, in the 322º E longitude region, is ~ 4 nT, which is much larger than that observed on April 17, 2002, in the 134º E longitude sector, although the strength of density fluctuations is nearly the same in both cases, as seen from Fig. 3 and Fig. 5. This may be due to the lower strength of the main magnetic field in the 322º E longitude region.

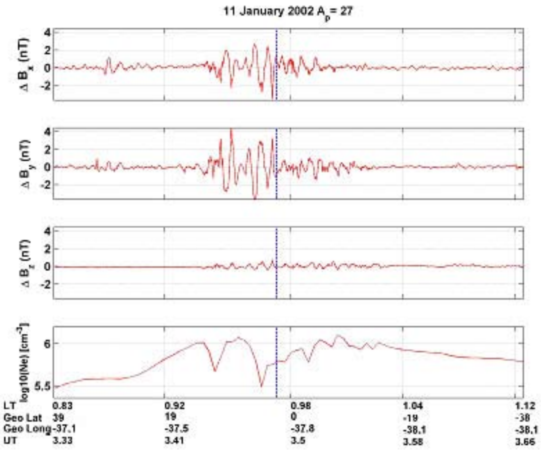

Figure 5. Same as Fig. 3 for January 11, 2002

In a recent model calculation, it has been shown that storm time vertical drift and reduced off-equatorial E region shorting during the post midnight period, may lead to a different pattern of evolution of EPBs compared to quiet times, with EPBs reaching much greater heights compared to quiet periods [22].

4. CONCLUSION

Magnetic signatures of EPBs observed in satellite data are now an accepted fact. These provide an important tool for the determination of the factors that control the generation and evolution of EPBs and ESF irregularities, which is an area of major concern in forecasting of space weather. In particular, the effect of transient solar events such as geo-effective coronal mass ejections that cause magnetic storms, in triggering the development of EPBs, continues to pose a challenge. The Swarm mission with its constellation of 3 satellites and array of instruments to measure, besides the magnetic field, the electric field, plasma density, air drag, ion and electron temperatures and ion drift velocity, would provide valuable inputs for such space weather studies. Three important areas, as far as EPBs are concerned, where the Swarm constellation would have significant contributions are: (1) It will provide information about the distribution of EPB magnetic signatures at two different heights for the same solar conditions, and hence the vertical extent of the bubbles under different conditions; which is of interest because the greater the vertical extent of the EPBs, greater is the latitudinal extent of the low latitude region where effects of the ESF irregularities are seen on communication and navigation systems. At present it is not clear what factors control the height to which the bubbles extend on any given night. (2) Another important contribution of the Swarm mission, with its two lower altitude satellites separated in longitude by 1 – 1.5°, would be the longitudinal variation in EPB characteristics at a given instant of time. This is important both in the context of evolution of spatial structure in EPBs during quiet times, and the longitudinal variation in electric field disturbances caused by magnetic activity. (3) As discussed in section 2, the post-sunset pre-reversal enhancement (PRE) of equatorial F region vertical drift is a very important factor in the generation and evolution of EPBs. Models of PRE require E region tides as input [23]. The tides would also play a role in the meridional current system of the equatorial electrojet during dusk, which has been derived from satellite magnetic field data [24]. The Swarm mission would provide an opportunity to explore the effect of this meridional current system on the day-to-day variability of EPB occurrence.

5. REFERENCES

1. Keskinen M. J. et al., *J. Geophys. Res*., Vol. 103, 3957-3967, 1998.
2. Sekar R and Kelley M. C., *J. Geophys. Res*., Vol. 103, 20735-20748, 1998.
3. Keskinen M. J. et al., *Geophys. Res. Lett*., Vol. 30 (No.16), 1855, doi: 10.1029/2003 GL 017418, 2003.
4. Retterer J. M. et al., *J. Geophys. Res.*, Vol. 110, A11307, doi: 10.1029/2002 JA009613, 2005.
5. Aggson J. L. et al., *J. Geophys. Res.*, Vol. 97, 8581-8590, 1992.
6. Koons H. C. et al., *J. Geophys. Res*., Vol. 102, 4577-4583, 1997.
7. Lühr H. et al., *Geophys. Res. Lett*., Vol 29(10), 1489, doi: 10.1029/2001/GL 013845, 2002.
8. Stolle C. et al., *J. Geophys. Res.*, Vol. 111, A02304, doi: 10.1029/2005 JA 011184, 2006.
9. Bhattacharyya A. and Burke W. J., *J. Geophys. Res.*, Vol. 105, 24941-24950, 2000.
10. Tsunoda R. T., *J. Geophys. Res*., Vol. 90, 447-456, 1985.
11. Burke W. J. et al., *J. Geophys. Res*., Vol 109, A12301, doi: 10.1029/2004 JA 010583, 2004.
12. Valladares C. E. et al., *J. Geophys. Res*., Vol. 88, 8025-8042, 1983.
13. Bhattacharyya A., *Geophys. Res. Lett*., Vol. 31, L06806, doi:10.1029/2003 GL 018960, 2004.
14. Jayachandran B. et al., *J. Geophys. Res*., Vol. 98, 13741-13750, 1993.
15. Fejer B. G. et al., *J. Geophys. Res*., Vol. 104, 19859-19869, 1999.
16. Basu B., *J. Geophys. Res*., Vol. 110, A02303, doi: 10.1029/2004 JA 010659, 2005.
17. Bhattacharyya A. et al., *Geophys. Res. Lett.,* Vol. 28(1), 119-122, 2001.
18. Bhattacharyya A. et al., *J. Geophys. Res*., Vol. 107 (A12), 1489, doi:10.1029/2002 JA 009644, 2002.
19. Kelley M. C. et al., *Geophys. Res. Lett*., Vol. 30 (4), 1158, doi:10.1029/2002 GL 016321, 2003.
20. Anderson D. et al., Proc. ILWS workshop on '*The Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects*", Goa, India, 2006 (in press).
21. Bhattacharyya A. et al., Proc. ILWS workshop on '*The Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects*", Goa, India, 2006 (in press).
22. Keskinen M. J. et al., *J. Geophys. Res.*, Vol. 111, A02303, doi: 10.1029/2005 JA011352, 2006.
23. Martinis C. et al., *J. Geophys. Res*., Vol. 108, A3, 1129, doi:10.1029/2002JA009462, 2003.
24. Olsen Nils, *J. Geophys. Res*., Vol. 102, A3, 4563-4576, 1997.