A dynamical system approach to electric field fluctuations in equatorial plasma blubbles: CSES-01 observations

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One interesting feature of the equatorial ionospheric F region is the occurrence of plasma density irregularities, commonly referred to as "bubbles," which tend to form under specific conditions post-sunset. These ionospheric irregularities manifest as regions with significantly lower plasma density than the surrounding environment, extending vertically from the bottom of the equatorial F region upward, typically during nighttime. Within equatorial plasma bubbles, plasma density can be reduced by factors ranging from 10 to, in extreme cases, 1000. What adds to the intrigue is the power-law scaling behavior observed in the electron density energy spectra of these bubbles, reminiscent of the Kolmogorov power law in fluid turbulence theory. It is suggested that during nighttime, the ionospheric plasma conditions at high altitudes in the equatorial ionosphere may facilitate the emergence of two-dimensional turbulent processes, discernible through the characteristic energy cascade observed in inertial regimes. To account for the diverse turbulent scales observed, a hierarchical model of instabilities has been proposed. Specifically, if a gravitationally driven Rayleigh-Taylor instability may be responsible for the generation of large-scale equatorial plasma bubbles, the $\vec{E} \times \vec{B}$ gradient drift instability may cause the unstable steep density gradients that form on the sides of equatorial plasma bubbles. This process results in irregularities spanning from hundreds of meters to a few kilometers. Subsequently, as density gradients become steeper, kinetic drift instabilities come into play, giving rise to irregularities ranging in size from tens of centimeters to a few meters. Naturally, not only the electron density within plasma bubbles exhibits a turbulent nature, but also other physical quantities display similar characteristics, such as the magnetic and electric fields.

Here, we examine the spectral and dynamical characteristics of turbulent fluctuations in the electric field within equatorial plasma bubbles, utilizing data from the Electric Field Detector (EFD) aboard the Chinese Seismo-Electromagnetic Satellite-01 (CSES-01). Launched in February 2018, this satellite orbits at an altitude of about 500 km on a 97.4° inclined Sun-synchronous orbit, with descending and ascending nodes around 14:00 local time (LT) and 02:00 LT, respectively. In particular, thanks to the high resolution of the EFD, which allows to resolve spatial scales down to few meters, we applied a novel analysis method developed within the framework of dynamical systems. This method characterizes the system's persistence in a specific state and the local dimension of fluctuations [1, 2, 3]. Grounded in the extreme value theory and Poincaré's recurrence theorem, it is particularly useful for characterizing dynamical changes in out-of-equilibrium systems, revealing the occurrence of dynamical transitions. Results on the extremal index θ, a measure of the local persistence of the system in a state, and the instantaneous dimension d, providing information on the active degrees of freedom, indicate a significant increase in dimension during plasma bubbles/depletions, while persistence decreases. These findings are discussed in connection with the turbulent nature of electric field fluctuations in plasma bubbles.

References

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