Sci. Bull.
DOI 10.1007/s11434-015-0749-4

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Review

Earth Sciences

Electric field penetration into Earth's ionosphere: a brief review for 2000–2013

Yong Wei · Biqiang Zhao · Guozhu Li · Weixing Wan

Received: 1 November 2014 / Accepted: 13 January 2015

Abstract Electric field penetration is a consequence of solar wind interaction with planetary magnetosphere and/or ionosphere. For both Earth with intrinsic magnetosphere and Mars/Venus without intrinsic magnetosphere, the penetration electric field causes various kinds of global and local electrodynamic response of the ionosphere to the solar wind electric field, especially the plasma motion in the ionosphere. Within the first 14 years of the twenty-first century, the cause and effect of the electric field penetration on Earth has been investigated extensively and understood more deeply. Here we review the progress acquired on the patterns and drivers of the penetration electric field, and its influences on the plasma distribution and the equatorial spread F in the mid- and low-latitude ionosphere. From the perspective of comparative study, we also shortly introduce the new results for Mars. What has become clear is that our understanding of electric field penetration has been significantly improved, but ultimately the crucial details of the global picture still remain unknown. Looking forward to the future research of the electric field penetration in Earth's ionosphere, the breakthrough relies on new instruments built up at different longitudes to improve the global coverage of the observation. An integrated network of instrument is necessary to reveal the longitude and local-time dependence of the electric field penetration and shed new light on the physical details of the global ionospheric processes driven by the electric field penetration.

Y. Wei · B. Zhao (✉) · G. Li · W. Wan
Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
e-mail: zbqjz@mail.igcas.ac.cn

Keywords Electric field penetration · Ionosphere · Magnetosphere

1 Introduction

The term "electric field penetration" refers to a phenomenon that a disturbed electric field, which has external origin, appears in the mid- and low-latitude ionosphere of the Earth or in the near-terminator ionosphere of the Venus and Mars. The disturbed electric field is usually called "penetration electric field" or "prompt penetration electric field (PPEF)". For Earth case, because the mid- and low-latitude ionosphere connects with the inner magnetosphere through closed magnetic field lines, an external electric field must propagate across the field lines to reach the equator. Therefore, it is named "penetration" to emphasize its difference from "mapping" of electric field along field lines. The external origin may refer to either the outer magnetosphere or the solar wind, considering that the magnetospheric electric field is ultimately driven by the solar wind. For the Venus and Mars, though they do not possess an Earth-like intrinsic magnetosphere, their induced magnetospheres can be an external origin of electric field. Certainly, the electric field within the induced magnetospheres also originates from the solar wind.

To study the Earth's electric field penetration, one has to first directly measure or indirectly infer the electric field in the mid- and low-latitude ionosphere, especially in the equatorial ionosphere. The incoherent scatter radar (ISR) at Jicamarca is the most powerful instrument to measure the electric field through the plasma vertical drift, and its database has been used to quantitatively determine the relationship between the interplanetary electric field (IEF) and PPEF. But a limitation of the ISR dataset is a lack of continuous observation; in other words, the dataset is too sporadic to fully meet the requirement of the PPEF-related studies. Another method is to use the geomagnetic ΔH to indirectly infer the overhead ionospheric electric field. The ΔH is the difference in the magnitudes of the horizontal (H) component between a magnetometer placed on the magnetic equator and one displaced 6°–9° away. At a given point on the dayside equator, the logic chain from the ΔH to the vertical drift is quite clear: The ΔH is linearly related to the strength of the equatorial electrojet (EEJ), the EEJ is linearly related to the electric field, and then, the electric field is linearly associated with the vertical drift ($\boldsymbol{V} = \boldsymbol{E} \times \boldsymbol{B}/B^2$). There are three pairs of stations widely used: Jicamarca (JIC, dip 0.8°N) and Piura (PIU, dip 6.8°N) at Peru, Yap (YAP, dip 1.6°N) and Okinawa (OKI, dip 19.5°N) at Japan, Tirunelveli (TIR, dip 0.5°S) and Alibag (ABG, dip 10°N) at India. One may identify PPEF through comparing the equatorial electric field with the external electric fields, e.g., IEF or magnetospheric electric field.

The phenomenon electric field penetration was discovered by Nishida [1] through comparing the geomagnetic fluctuations and the interplanetary magnetic field (IMF) oscillations in its north–south component. Jaggi and Wolf [2] proposed a theoretical explanation for the prompt penetration mechanism through regarding electric field penetration as a consequence of the temporary failure of the so-called shielding mechanism. The "shielding" mechanism interprets electric field penetration as a result of some magnetospheric processes, especially the charge accumulation in the ring current region or the Alfven layer region. The convection electric field in the outer magnetosphere and the polarized electric field in the ring current region are described as the sources of PPEF and shielding electric field, respectively. They have opposite polarity and tend to cancel each other. Standing on this ground, the terms "undershielding" and "overshielding" denote two imbalance statuses: the convection electric field larger than the shielding electric field and the convection electric field smaller than the shielding electric field, respectively [3]. These magnetospheric electric fields communicate with the ionosphere through Region 1 (R1) and Region 2 (R2) field-aligned currents (FACs). As illustrated in Fig. 1, in the polar cap, the penetration electric field is associated with R1 FAC, while the shielding electric field is associated with R2 FAC. Therefore, the imbalance status of FACs can be used as proxies of magnetospheric electric fields to explain PPEF in the mid- and low-latitude ionosphere.

In the current frame of knowledge, those magnetospheric electric fields are ultimately driven by the solar wind and especially sensitive to IMF B_Z. Figure 2 depicts an oversimplified relation of PPEF and IMF B_Z. A rapid southward turning of IMF B_Z immediately causes the R1 FAC to increase, but the R2 FAC will take longer time (tens of minutes to several hours) to balance the enhanced R1 FAC, because the R2 FAC depends on the gradual charge accumulation in the ring current region. Hence, the duskward covection electric field will penetrate into the mid- and low-latitude ionosphere and remain eastward on the dayside before the R2 FAC is fully developed. This is the so-called undershielding. As to the so-called overshielding, the first evidence was presented by Kelley et al. [4]. An abrupt northward turning of IMF B_Z after a prolonged southward orientation may cause that the R2 FAC is stronger than the R1 FAC for a while, during which the dawnward shielding electric field can penetrate into the equator and be westward on the dayside. Note that the "northward turning" also includes significant decrease in the magnitude of southward B_Z (still remains southward). It is worth pointing out that the "overshielding" phenomenon cannot individually appear, and its appearance must follow an "undershielding" event. This is because shielding electric field develops during the time of "undershielding". The electric field penetration generally takes place during the geomagnetic storms. Considering a typical storm, the "undershielding" often appears during the main phase, while the "overshielding" generally appears (not always discernable) during the recovery phase.

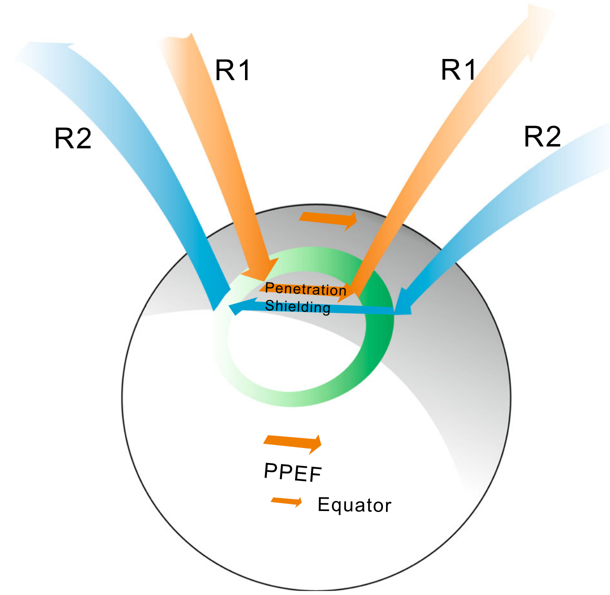

Fig. 1 Classical picture of the electric field penetration and shielding. The penetration electric field is associated with R1 FAC, while the shielding electric field is associated with R2 FAC. Both electric fields originate from the magnetosphere

According to the "shielding" theory, there should be a perfect shielding status if R1 and R2 FACs exactly balanced; i.e., they together do not produce disturbed electric