Fundamentals of Ionospheric Plasma Dynamics

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Today, society relies more and more on radio-navigation and communication systems deployed in near Earth space for a variety of industries and important systems, providing safety-of-life navigation services to aviation, maritime, and land-based users. The satellite-to-Earth radio links passing through the Earth's ionosphere can be impacted by different scales dynamical processes in the ionospheric plasma. The ionospheric dynamic processes have a great variety of spatial and temporal scales, with various physical drivers and sources of energy. This lecture will provide an overview of the fundamental processes responsible for ionospheric plasma dynamics during both quiet and geomagnetically disturbed conditions.

Even under quiet conditions, the ionospheric plasma has large scale dynamics with altitude, local time, latitudinal/longitudinal dependances, seasons and solar activity variations. Here, we will review the fundamental features in the Earth's ionosphere formation with a combination of processes of ionization, recombination, and transports. We will discuss on how the ionospheric plasma is structured from altitudes of ~80 km up to the plasmasphere, day-night plasma dynamics, and the global distribution of the peak ionization and total electron content in polar, middle latitude, and equatorial zones. Particular focus will be placed on the development of the equatorial ionization anomaly caused by the vertical plasma drift at the equator and plasma diffusion along geomagnetic field lines. We will also discuss the formation of equatorial plasma bubbles caused by Rayleigh-Taylor instability and plasma irregularities under quiet time conditions.

Geomagnetic storms represent distinguished space-weather phenomenon. During these events, the ionosphere is affected by other sources of energy, rather than just solar radiation. This energy coming from the magnetosphere in the form of plasma convection and energetic particle precipitation lead to increased ionization, Joule and particle heating, disturbed neutral wind dynamo, and penetration of electric field from high latitudes to middle/low latitudes. These physical processes disturb the quiet-time ionosphere plasma dynamics by producing the large-scale ionospheric structures, plasma density gradients, and plasma irregularities. Ionospheric storms can have many large-scale effects, including Storm Enhanced Density (SED) and Large-scale Traveling Ionospheric Disturbances (LSTIDs). SED represents a continental-size ionospheric plasma density enhancement related with electric fields uplift the dayside equatorial plasmas to higher altitudes causing equatorial ionization anomaly expands to mid/high latitudes. LSTIDs are disturbances with wavelength greater than 1000 km that can propagate from high to low latitudes and even into the opposite hemisphere with high speed. LSTIDs are driven by the combination of magnetospheric

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energy inputs - Joule heating and particle precipitations, and we will discuss the physics of these phenomena.

Ionospheric plasma density irregularities are a specific feature of the ionosphere dynamics induced by geomagnetic storms. Under quiet conditions, the mid-latitude ionosphere is generally free of ionospheric plasma irregularities. Geomagnetic storms lead to an occurrence of intense high latitude ionospheric irregularities due to an increase in auroral particle precipitation and high latitude electric fields. Intense ionospheric irregularities typically expand equatorward from the auroral/subauroral latitudes and can reach the midlatitudes. At the same time, the midlatitudes can be also affected by a poleward expansion of the equatorial irregularities. When storm-induced penetration electric fields superimpose on the normal pre-reversal enhancement in the dusk sector of the equatorial ionosphere, it triggers the formation of very intense equatorial plasma bubbles that extend to low and middle latitudes. We will use representative cases to illustrate the physical mechanisms of global dynamics of ionosphere plasma irregularities.

This review brings together the sequence of important physical processes and events which explain the plasma dynamics of the ionosphere in both quiet and geomagnetically disturbed conditions. Some of these phenomena are still puzzling, and more observations and simulation efforts are necessary to better understand the physical processes in the Earth's ionosphere.

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