Ionospheric Plasma Effects for Geomagnetic LEO Missions at Mid- and Low-Latitudes

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Summary. Some of the main plasma characteristics are reviewed that a LEO satellite with high orbital inclination encounters during its travel across the terrestrial ionosphere of mid- and low-latitudes. It is the region of highest plasma density in the near-Earth environment. Its properties are predominantly ruled by the geomagnetic field. It will be shown how different ionospheric layers - first of all the E- and F-layer - contribute in different ways to the electrodynamic and thermodynamic behaviour of the highly interacting, complex system comprising the ionosphere, thermosphere, and plasmasphere. The physical description of its phenomena and data interpretation have nowadays to rely to a substantial part on numerical methods and models. New observational methods and space missions have essentially contributed to the recent progress in this field. The CHAMP mission takes part in this progress just as much as the IMAGE, TIMED, and other satellite projects as well as ground-based observation programs. The paper summarises recent developments in ionospheric studies as, e.g., the plasma transport at mid- and low-latitudes, the regular Sq-dynamo and the contribution of the F–region dynamo, the interhemispheric coupling by current systems and plasma flows, pulsations, the equatorial electrojet and the plasma fountain effect, the Appleton anomaly, the near-equatorial plasma bubbles, and further open issues.

Key words: mid- and low-latitude ionosphere, thermosphere, plasmasphere, electric fields, thermospheric winds and composition, equatorial effects, modelling

Introduction

The low-Earth orbiting (LEO) satellite CHAMP in its circular, near-polar orbit is a suitable platform for studying ionospheric plasma and electrodynamic phenomena on a global scale. With a cruising altitude from about 450 km at the begin of the mission to around 250 km at the end, it is just the ionospheric F-layer, i.e. the region of the highest plasma densities in the near-Earth environment, where its diagnostic instruments are operating. The high-precision measurements onboard CHAMP are therefore affected by this environment. For the correct data interpretation of, e.g., the vector magnetic field data with respect to the diamagnetic effect of the plasma [13] one needs to know the in-situ plasma parameters of the surrounding media where the measurements are performed. These high precision (and adjusted) magnetic field measurements, on the other hand, contribute together with the other diagnostic instruments to highly valuable insights into ionospheric electrodynamics and plasma physical processes which were inaccessible previously.

The ionosphere at mid- and low-latitudes has been explored for more than 80 years - first by ground-based ionosondes and later, beginning in the 1960-ies, by more improved radar techniques and early satellite missions. The general ideas about ionospheric physics, its global frame of the acting processes are supposed to be well-known now and the interest in ionospheric physics at mid- and low-latitudes declined. But during recent years, space based technologies have been developed that are sensibly dependent on more precise predictability of near-Earth conditions. Radio wave transmissions are disturbed, in particular, by small and medium scale phenomena in that region which need much more detailed studies. New experimental techniques appeared which allow more accurate and higher resolution measurements as well as global coverage. These are for instance remote sounding such as GPS occultation experiments as described, e.g., by [5], imaging techniques as onboard the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite [1] and various new in-situ explorations as, e.g., CHAMP and the Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) mission [8].

Ionospheric/plasmaspheric characteristics

The ionosphere is a multiconstituent plasma embedded in the high-altitude atmosphere [21, 7]. Traditionally, it is divided into several layers or regions (see Fig. 1, right panel) which are distinguished according to different main ionic constituents and different physical conditions. At F_2 region heights, the layer with the maximum plasma densities in near-Earth space, the portion of charged to neutral particles is of the order of 0.1% or less, i.e. the neutral gas and its motion and waves play an essential role in the plasma dynamic. The ionosphere is created by photoionization of solar extreme ultraviolet (EUV) radiations with wavelengths $<$102.7 nm and X-rays (see Fig. 1, left side). Ionization due to collisions, caused by precipitating high energetic particles, as the second important source, acts mainly at auroral and polar regions. Due to the absorption in the high-altitude atmosphere, solar EUV radiation is not observable by ground-based observatories. The large variability of radiation fluxes in the course of varying solar activity became obvious by extraterrestrial observations as, e.g., by the EIT instrument of the SOHO mission (see, e.g., http://sohowww.nascom.nasa.gov/). During solar flares, the X-radiation can increase by more than a factor of 200 while the EUV increase is more modest ($\approx$ 50%) which was shown, e.g. for the Bastille Storm Event in July 2000 [15], to resulting in an F–region plasma density enhancement of the order of 40%.

The mid- and low-latitude ionosphere is closely connected, via the Earth's magnetic field, to the plasmasphere above. During magnetically quiet condi-

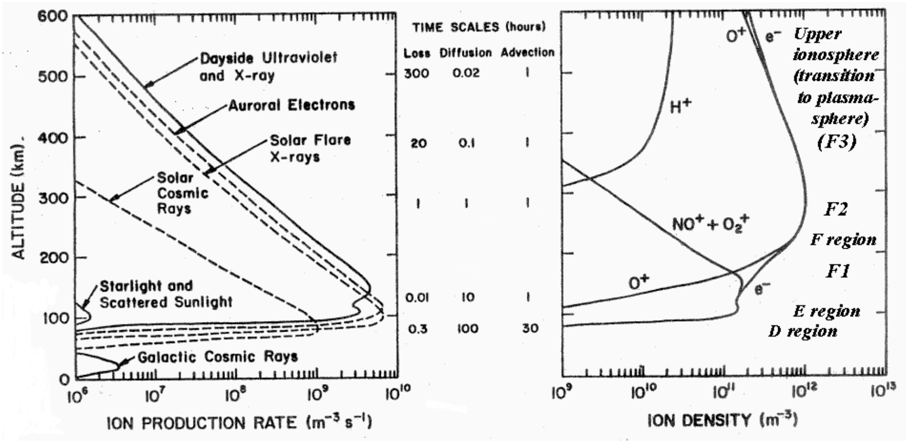


Fig. 1. Ionisation rates (left) and typical ion densities of the n(h) profile (right). Adapted from: A. Richmond and Gang Lu, CEDAR Workshop 1999, tutorial lecture.

tions, the plasmaspheric flux tubes are filled up from the ionospheric source region as they corotate together with the upper atmospheric layers. The outer boundary of the plasmasphere, the plasmapause, is established as the equilibrium between corotation and global magnetospheric convection electric fields. Its projection into the ionosphere marks the transition between mid-latitudes and subauroral (or ionospheric trough) latitudes which corresponds to an average McIlwain L-shell position of L=4 during undisturbed conditions. During geomagnetically disturbed days it can come as close as L=2 or less for very strong storms [6, 10, 3].

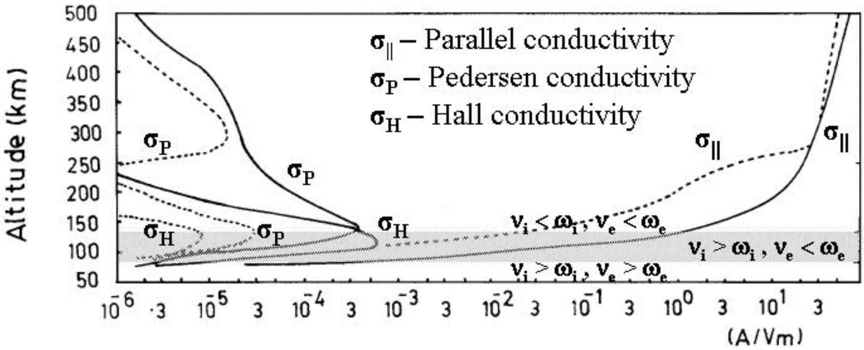


Fig. 2. Typical daytime conductivity profiles for the ionosphere with the parallel conductivity $\sigma_{\|}$, the Pedersen σ_P and the Hall conductivity σ_H; dashed lines indicate nighttime conditions. After: [22, Figure 1].

The most fundamental equation in any ionospheric theory is the continuity equation (1):

$$\frac{\partial n_i}{\partial t} + B\nabla\left(\frac{n_i\ \mathbf{v}_{i\|}}{B}\right) + \nabla\ (n_i \mathbf{v}_{i\perp}) = P_i\ - L_i\, n_i \qquad (1)$$

with P_i as the source (or production) terms of the individual species n_i, L_i their loss function, B is the ambient magnetic field, and $\mathbf{v}_i = \mathbf{v}_{i\perp} + \mathbf{v}_{i\|}$ the particle's bulk flow velocity. All these terms contribute differently to the plasma density distribution at different altitudes; Fig. 1 gives in its middle part some estimation of the characteristic times for the different terms. At altitudes up to the F_1–layer the right-hand terms of (1) dominate; during daytime they balance each other and during sunset the plasma density at this altitude range falls quickly by several orders of magnitude.

Dynamics: neutral winds, electric fields, and currents

In the F_2–layer, the upper ionosphere and plasmasphere the transport terms (diffusion and advection, left side of equation 1) are the most important. Any physical description of the plasma behaviour there depends on nonlocal physical processes as the diffusion (fluxes) along the magnetic flux tubes, the plasma drift induced by ion drag with the neutral air, and the electromagnetic drift perpendicular to the magnetic field. These processes are described by the equations of motion and energy or by kinetic equations for the suprathermal particles [3, and references therein].

The collisions between neutrals and various charged particles play an important role in the partially ionized ionospheric plasma. They determine the electrodynamical behaviour of this medium (see Fig. 2). At E–region altitudes, there exists a region (indicated in grey in Fig. 2: from about 80 km to 130 km), where the electrons are more tied to the geomagnetic field than the ions. Electrons and ions are subject to different forces and, consequently, charge separations occur and electric polarization fields are built up. This process is well-known for a long time as the atmospheric dynamo resulting in the Sq (i.e. solar quiet) electric fields (see, e.g., [14]) and the corresponding current system (Fig. 1 in [14]). This generator was originally described by a 2–D dynamo model that could explain at that time nearly all observational facts of the mean Sq currents found from ground-based magnetometer observations. It is interesting to note that these electric fields, which are due to neutral wind modes at a restricted height range in the E–region and which reflect planetary, tidal, and gravity waves propagating upward from the lower atmosphere, map along the geomagnetic field lines up to the upper ionosphere and plasmasphere because of the high parallel conductivity (cf. Fig. 2).

With new observations in the late 60-ies and 70-ies, summarized in the first global mid-to-low latitude electric field model by [18], it became clear

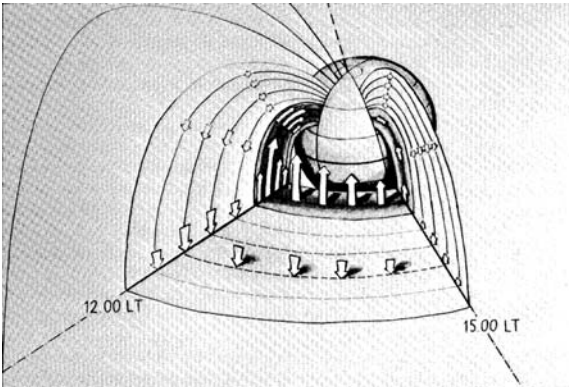
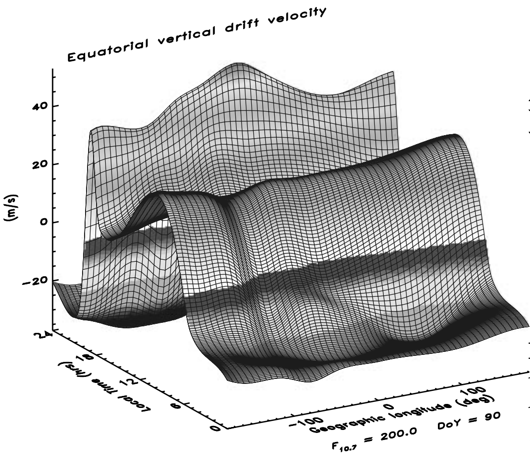


Fig. 3. Scheme of the 3-D interhemispheric current system for Northern summer conditions, looking into the afternoon plasmasphere region with cuts at the geomagnetic equator, the 15 LT and the noon meridian. (After: [22, Figure 20]).

that a 3–D model which includes the interhemispheric coupling for asymmetric (e.g. seasonal) conditions is necessary (see, e.g., [22] and references therein). One of those models is schematically shown in Fig. 3 showing a concentrated region of FACs near local noon at L≈1.5 flowing steadily into the summer hemisphere and more diffuse FAC current regions toward the morning and evening side and at other latitudes with the opposite flow direction.

While the dynamo described above is mainly confined to daytime hours (because of E–region conductivity), during nighttime hours further generator mechanisms at F–region heights contribute the major part to mid-latitude currents. One is associated with the gravitational equilibrium of the plasma, in which the ions drift eastward and electrons westward (i.e. an east-west current), and the other with the dynamo action of the neutral wind circulation at F–region heights [19, and references therein].



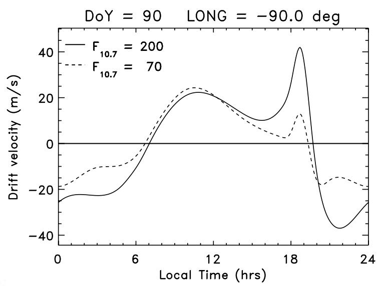


Fig. 4. Scherliess' model of equatorial upward drift [20]: perspective view for high solar activity (left) and comparison of low and high solar activity (right).

Considering the equatorial ionosphere, it is quite a modelling challenge up to now, to describe the complicated current circuit situation adequately owing to the many coupled processes operating in a complicated geometrical situation [19]. The drift peculiarities near the equator like the fountain effect which results in the Appleton anomaly and the post-sunset upward drift maximum [21, 7] are well-known empirically for long time. The most advanced empirical model of the equatorial zonal electric field component (upward drift) was published by [20] and Fig. 4 illustrates this vertical drift behaviour.

Disturbed conditions and geospheric storms

Large perturbations of the Earth's space environment result from solar events and perturbations in the solar wind with the subsequent coupling of their energy and mass to the magnetospheric-ionospheric-thermospheric domain [6]. The ionospheric storm response manifests itself in dramatic variations of plasma densities at the F_2 region electron density peak [17, and references therein]. Those variations can exceed 100% from averages and involve enhancements (positive storm phases) and depletions (negative storm phases). A part of these variations result from disturbances of the high atmosphere like composition changes, generation of planetary waves, and additional neutral gas heating mainly in the auroral regions. Other important factors are the disturbance dynamo, transient prompt penetration electric fields [2], and the transport of plasma with enhanced electron density caused by particle precipitation. New techniques and recent satellite missions like IMAGE and TIMED brought about much progress in their study, as was demonstrated with event analyses like, e.g., for the large storm of 15 July 2000 [9, 15, 24].

Global first principle numerical modelling offers the possibility to study theoretically the complex behaviour of the whole system: the thermosphere, ionosphere, plasmasphere, and its electrodynamics (as performed by, e.g., [4, 16, and references therein]. Fig. 5 shows an exemplary model result of a

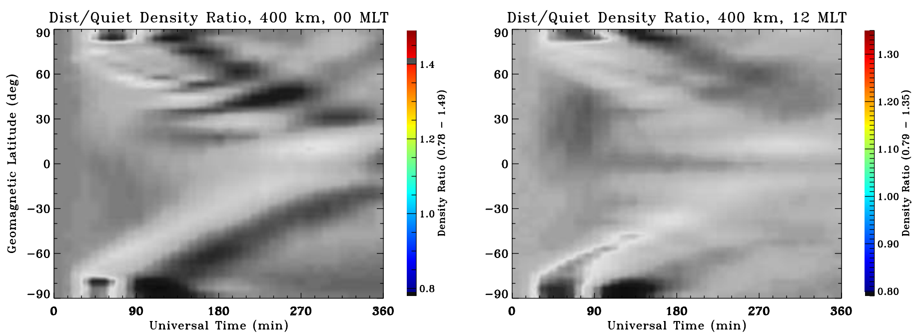


Fig. 5. Numerical simulation study of global TAD propagation (see text).

storm event: the propagation of a Travelling Atmospheric Disturbance (TAD) wave due to a moderate auroral energy input which corresponds to a 20-min increase of the cross-polar potential drop up to 155 kV or an AE index of about 1000 nT followed by the subsequent relaxation to the quiet (Namgaladze 1998, private communication). A numerical storm study during the preparation phase of the CHAMP mission [11, 16] pointed to the unique possibility to combine high-resolution accelerometer and magnetometer measurements to investigate density variations and neutral wind responses to geomagnetic forcing. The simulations showed that it even should be possible to resolve TADs (gravity waves) and to draw conclusions about the validity of thermospheric models.

Equatorial anomaly, plasma bubbles and instabilities

The post-sunset near-equatorial ionosphere undergoes dramatic changes due to eastward electric field variations (see Fig. 4) and is therefore the realm of several interesting plasma processes [23]:

- the Appleton anomaly which is characterized by upward plasma motion followed by diffuse downward transport at both sides of the equator,
- spread F echoes as a plasma instability process causing irregularities at the bottomside F region, and
- plasma bubble generation due to rapid upward plasma motion causing turbulent conditions in the F–region and upper ionosphere.

CHAMP can contribute a lot for further elucidating these processes and first results have already been published [12, 13]. In combination with plasma measurements, the high precision magnetic field sensors can be used to detect ionospheric F–region currents. The global occurrence of F–region currents and their spatial confinement to the near-equatorial region bounded by the Appleton anomaly was found with a predominant appearance in the premidnight sector [12]. Fig. 6 shows an example of geomagnetically quiet time records at about 20 LT together with the DIDM plasma density measurements. The deep density trough at the equator is due to the large post-sunset

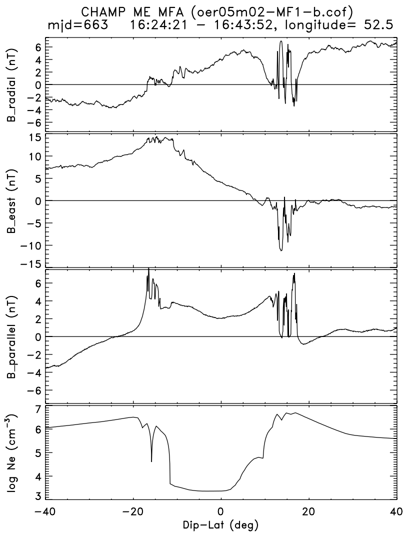


Fig. 6. Measurements of magnetic variations (deviations from a model in MFA coordinates, upper three panels) and DIDM plasma density (bottom panel, log. scale) onboard CHAMP for an equator crossing on the geomagnetically quiet day 25 Oct 2001.

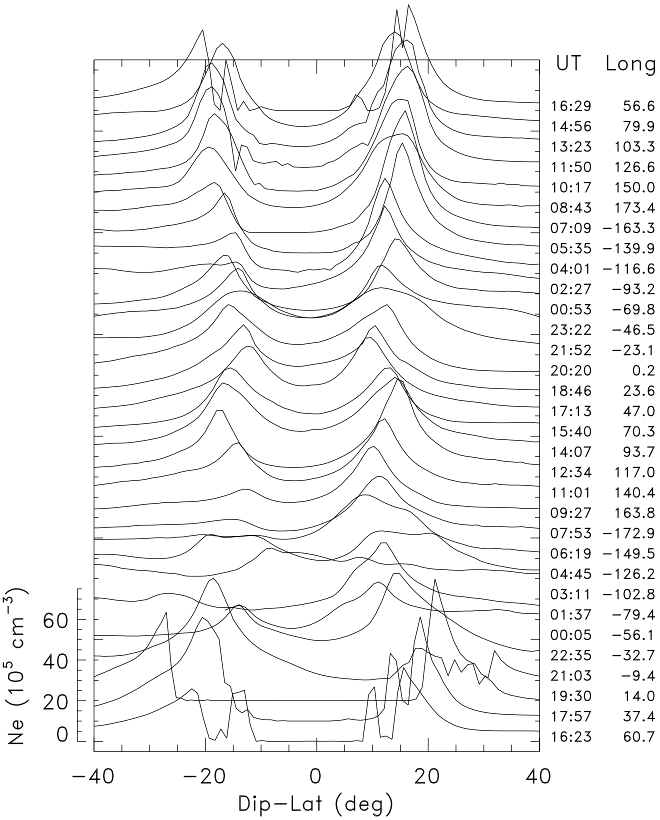


Fig. 7. Stack plot of DIDM plasma density measurements (from bottom up, offset 10^6 cm^{-3}) during successive orbits during the geomagnetic storm of 21-23 Oct 2001. Equatorial crossings (UT and geogr. long.) of each orbit are indicated on the right.

upward plasma drift (Fig. 4) with the subsequent diffusive transport to the crest regions (Appleton anomaly). The small-scale magnetic fluctuations observed there are interpreted as the appearance of F region currents, coupled with the presence of plasma bubbles (see density fluctuations in the bottom panel, Fig. 6).

Fig. 7 displays the near-equatorial density changes during a two-day storm interval on 21-23 Oct 2001 with Kp values up to 8- and a minimum Dst of -187 nT on Oct 21, 22 UT. The shift of the crests toward higher latitudes in the first few hours of the storm is probably due to penetration electric fields while they move back and forth during the later storm development. The depth of the equatorial trough flattens which is due to the combined effect of disturbance dynamo and neutral wind action.

Summary

During recent years, new LEO missions like the CHAMP and TIMED satellites have provided new and much more refined data about the near-Earth space concerning the electromagnetic, ionospheric and high-atmospheric environment. They brought about a wealth of new data for interesting studies which were not possible previously. These studies serve a dual purpose: they allow on the one side new insights into the complex physical processes of the ionospheric plasma and current systems at all latitudes during quiet and disturbed conditions. On the other side, they are the prerequisite for precise modelling of the Earth's magnetic field as well as the high atmosphere and the ionosphere itself from space. They allow novel science with important new and interesting studies. Among these are:

– investigations on the role of the diamagnetic effect and its relation to measured or modelled ionospheric plasma parameters;
– detailed analysis of the influence of the ionosphere on magnetic field modelling from space;
– systematic survey of plasma bubble signatures and of other plasma instabilities using global search algorithms and elucidation of their generation and development;
– fine-tuned ionospheric current studies at mid- and low-latitudes including the equatorial electrojet and the 3-D dynamo current system;
– case studies of storm events and the accompanying change of high-atmospheric, ionospheric and electrodynamic properties including travelling atmospheric disturbances, planetary waves as well as disturbance dynamo and penetration electric fields;
– large-scale pulsation studies from space simultaneously with ground observations of magnetometer networks to test theoretic ideas and models and aiming at remote control of the near-Earth plasma environment.

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