УДК 551.510.413.7 : 519.8

Numerical modeling of the ion temperature influence on the plasmasphere 3D structure formation

M.G. Botova, O.V. Martynenko, A.A. Namgaladze
Polytechnic Faculty of MSTU, Physics Department

Abstract. The formation of three-dimensional structure of the "plasmasphere – ionosphere" system under the influence of ionization / recombination, charge exchange reactions and field-aligned (along the geomagnetic field lines) diffusion of ions O^+ and H^+ has been investigated by the numerical simulation method using the global upper atmosphere model (UAM). A few large-scale structural features: 3 night-time ionospheric electron density maxima – sub-auroral, mid-latitudinal and near-equatorial, and corresponding peaks of n(O^+) in the outer plasmasphere and n(H^+) in the mid-latitudinal plasmasphere have been obtained. The geometry of the geomagnetic field and the spatial non-homogeneity of the ion temperature give a determinative contribution to the formation of these features.

Аннотация. Методом численного моделирования с использованием глобальной модели верхней атмосферы Земли (UAM) исследовано формирование трехмерной структуры системы "плазмосфера-ионосфера" под влиянием процессов ионизации/рекомбинации, зарядообмена и продольной диффузии ионов O^+ и H^+. Показано формирование нескольких крупномасштабных структурных особенностей: три ночных ионосферных максимума электронной концентрации – приавроральный, среднеширотный и приэкваториальный, и соответствующие им максимумы концентрации ионов O^+ во внешней плазмосфере и концентрации ионов H^+ в среднеширотной плазмосфере. Существенный вклад в формирование этих особенностей вносит геометрия магнитного поля и пространственная неоднородность ионной температуры.

Ключевые слова: ионосфера, плазмосфера, амбиполярная диффузия, геометрия магнитного поля, ионная температура
Keywords: ionosphere, plasmasphere, field-aligned ion diffusion, the geometry of the magnetic field, ion temperature

1. Introduction

The Earth's atmosphere is exposed to the fluxes of the solar radiation and the high-energy particles. As a result, a significant part of the atoms and molecules of the upper atmosphere is ionized. The principal factor determining the behavior of the charged atmospheric components is the geomagnetic field. The Lorentz force does not allow charged particles motion across the field lines, creating the magnetic traps for the plasma. So, regions of the high content of the charged particles appear in the Earth's space environment – the ionosphere and the plasmasphere. Plasma density and ion composition here are influenced by many regular and irregular physical and chemical factors: the spectra of the ionizing radiation and high-energy particles, temperature, density and chemical composition of the neutral atmosphere, the spatial and temporal variations of the electric and magnetic fields, the local time and latitude etc. As a result, there are the complex spatial and temporal variations of the physical and chemical parameters of the near-Earth plasma, which are known as the "space weather". The forecasting of the "space weather" presents the problem of the great practical importance.

The plasmasphere was discovered by satellite and radio measurements in the 60s (*Gringauz et al*., 1961; *Carpenter*, 1963; 1966). Its coupling with the ionosphere through different plasma transport processes (field-aligned diffusion, electromagnetic drift, neutral wind dragging) was modeled by many researchers, e.g. the excellent monograph of (*Krinberg, Tashchilin*, 1984). But our research has shown that many of the known ionosphere-plasmasphere interaction features can be explained using a very simple model, taking into account extremely limited set of physical factors.

In the work the formation of the Earth's plasmasphere-ionosphere system has been reproduced by the numerical simulation method in a completely symmetrical 3D statement of the problem with accounting of a minimal set of physical processes: ionization / recombination, charge exchange $O^+ \leftrightarrow H^+$ reactions and the field-aligned ion diffusion. These processes are the most important for the Earth's plasma shell formation. Their detailed understanding grounds the base for the determination of the contribution of other factors. It allows enhancing reliability of the space weather forecasting.

2. The physics to be modeled – basic sketch

Three basic processes constitute the formation of the ionosphere and the plasmasphere: the appearance and disappearance of charged particles and their spatial redistribution.

The main source of charged particles in the upper atmosphere is the photo-ionization of the neutral atoms and molecules by the solar extreme ultraviolet and X-ray radiation ($\lambda \leq 134$ nm). The main ionospheric ion is O^+, which appears as the result of consecutive photo-dissociation and photo-ionization reactions:

$$O_2 + h\nu \rightarrow O + O; \; O + h\nu \rightarrow O^+ + e^-.$$

It is important to note that O atoms produced by the photodissociation act are lighter than the O_2 molecules, and they rise upward becoming in the upper atmosphere the main neutral component and a source of the major O^+ ion.

The big part of the lower ionosphere consists of heavy molecular ions which are generated by the photoionization of molecules of the main atmospheric gases:

$$O_2 + h\nu \rightarrow O_2^+ + e^-,$$
$$N_2 + h\nu \rightarrow N_2^+ + e^-.$$

The photoionization is the main cause of the ionosphere forming.

Due to the limitation by the energy and momentum conservation laws, the direct recombination of O^+ ions is very slow (only through the triple collisions or radiative recombination). Therefore, the main mechanism for the disappearance of the ionosphere charged particles is the dissociative recombination – recombination of the molecular ions:

$$XУ^+ + e^- \rightarrow (XУ)^* \rightarrow X^* + У^*.$$

Thus, the disappearance of the main ionospheric ion O^+ goes through the charge exchange reaction with the neutral biatomic molecule, NO, O_2 and N_2:

$$XУ + O^+ \rightarrow XУ^+ + O.$$

Therefore, the recombination goes intensively at low altitudes, where the density of the heavy molecules is high.

In the lower ionosphere, where the collisions with neutral molecules are frequent, the transfer processes can be ignored because of the short ion lifetime. The ionosphere structure and composition here are completely determined by the photoionization and recombination. Higher, in the O^+ populated area, where the ion lifetime is longer, the ions can go far from their place of the birth. The most important relocation is upward along the magnetic field lines. The ions rise into the more rarefied atmosphere and, accordingly, to longer lifetime and accumulate there during the day.

In the upper ionosphere the charge exchange reactions are important.

$$H + O^+ \leftrightarrow H^+ + O.$$

In the daytime resulting light H^+ ions rise further upward and accumulate in a magnetic trap near the magnetic tube tops forming the plasmasphere. In the nighttime the ions from the plasmaspheric reservoir return back down and maintain the ionosphere plasma density.

Ion field-aligned motion occurs as a result of the ambipolar diffusion. In contrast to the diffusion of neutral particles, ions and electrons can not diffuse independently of each other: it would have violated the plasma quasi-neutrality. Light electrons tend to up in the gravitational field and drag ions upward too through the internal polarization field. Therefore, the velocities of the ions and electrons are close (*Brunelli, Namgaladze*, 1988).

The ambipolar diffusion velocity depends on the spatial distribution of ions and electron temperature and density. The vertical component of the ambipolar diffusion velocity of the one-component plasma ($m_e \ll m_i$, we neglect the ion inertia and the thermal diffusion) is given by:

$$\left(V_d\right)_z = -D_\alpha \sin^2 I \left(\frac{1}{H_p} + \frac{1}{n_i}\frac{\partial n_i}{\partial z} + \frac{1}{T_p}\frac{\partial T_p}{\partial z} \right),$$

where the usual designations H_p and T_p are used – respectively, the plasma height scale and the plasma temperature:

$$H_p = kT_p / m_i g,$$
$$T_p = T_i + T_e.$$

Here, m_i – the ion mass, n_i – the ion density, D_α – the ambipolar diffusion coefficient, I – the magnetic field inclination, g – the gravity acceleration, k – the Boltzmann constant.

In the daytime when lower parts of the tubes are in active ionization area, diffusion fluxes are directed upward from the ion source, and in the nighttime when the recombination dominated there – downward.

These are the basic physical and chemical processes forming the Earth ionosphere and plasmasphere. They were reproduced in our simulations.

3. Modeling task description

The study was conducted by the mathematical modeling method using the global numerical model of the Earth's upper atmosphere UAM (Upper Atmosphere Model) (*Namgaladze et al.*, 1998), which describes the upper atmosphere, ionosphere and plasmasphere of the Earth as a coupled system.

The UAM calculates physical parameters of the Earth's upper atmosphere at the altitude range between 80 and 100 000 km depending on latitude, longitude, altitude and time for any helio-geophysical conditions (time, season, levels of solar and magnetic activity, etc.).

The UAM calculates the densities of the main neutral and charged components of the Earth's upper atmosphere, temperatures of the neutral, ion and electron gases, electric potential and electric field's vector components.

The UAM basic configuration (theoretical self-consistent) is the first-principles-based physics model with the already adjusted system of physical interrelations, which numerically integrates the systems of time depended 3D equations of continuity, motion and heat-balance for neutral, ion and electron gases jointly with the equation for potential of the electric field.

But the UAM includes also the set of alternative empirical models of separate atmospheric regions and processes, such as NRL MSISE (*Picone et al.*, 2002) – the model of neutral composition and temperature, HWM (*Hedin et al.*, 1996) – the model of horizontal wind, *Volland* (1978) and Heppner-Maynard-Rich electric potential models (*Heppner, Maynard*, 1987) etc. Each included model calculates the certain set of physical parameters of the modeling object and can be used instead of theoretical equations solving. These sub-models exchange data using the unified interface.

Such modular structure allows arbitrarily to take into account or to eliminate any physical processes, or to modify their characteristics in order to study selectively the effects generated by each of them. This UAM ability was used in our research.

In order to select exclusively the field-aligned ion diffusion effects we eliminated all other transfer processes in this calculation. The convection drift and neutral wind were set completely absent. The Earth' geographic and geomagnetic axes were superposed in order to eliminate the longitudinal variation. The equator-symmetrised neutral temperature and composition distributions were stated as stationary in solar-magnetic frame. Model calculations were conducted for the equinox moment, i.e. the solar illumination conditions were identical for both bases of any magnetic tube. Thus, the problem statement was completely symmetrical.

In our simulation we have reproduced the first 5 days of the plasmasphere filling under low solar activity conditions ($F_{10.7}$ = 70) starting from the very low initial density of charged particles in the ionosphere and plasmasphere (~10^{-3} m^{-3}). In order to smooth the sharp changes the calculation started in pre-midnight hours (2200 MLT) for each longitude (night-time ionization by scattered radiation), and to the sunrise time the ion distribution became more natural.

We have investigated in the presented work the formation of the large-scale spatial distributions of O^+ and H^+ ions and their diurnal variation and the influence of the spatial inhomogeneity of ion temperature on these processes.

4. Modeling results and discussion

The overall picture after 5 days of simulation time is fairly realistic: the repetitive diurnal variation in the ionosphere and the plasmasphere which is virtually uniform in the longitudinal direction. The plasmasphere filling rate in our simulation also corresponds with the known satellite and other data. The characteristic filling time is a few days at the tubes with L~4 (L is the parameter of McIlwain). At geostationary orbit height our filling rate agrees with GEOS-2 data (*Song et al.*, 1988) – about 25 cm^{-3} per day. For L~4.5 in our modeling the electron density in the equatorial plane increases by approximately 80 cm^{-3} per day, which is consistent with (*Carpenter et al.*, 1993). At short tubes with L<3 the clear diurnal variation was formed already after the first day, which corresponds to (*Green, Reinisch*, 2003).

Thus, we can assume that the model with all above listed simplifications is still physically appropriate, and smaller structural features of the ionosphere-plasmasphere system can also be considered as physically meaningful.

There are large-scale inhomogeneities in the spatial distribution of ion composition and temperature of the plasma. At the ionosphere level these structural details are most evident in the night sector. There are 3 latitudinal areas (symmetrical in both hemispheres) with increased plasma density: sub-auroral (latitudes 60-65º), near-equatorial (near 10º) and mid-latitudinal (30-40º) and corresponding peaks of $n(O^+)$ in the outer plasmasphere and $n(H^+)$ in the mid-latitudinal plasmasphere (Fig.). Physical mechanisms of their formation will be discussed below.

An arched area of constant high O^+ density appears in the near-equatorial region during the first modeling day and practically does not change further. It is expressed most clearly in the night time and during the day it disappears in the dense ionosphere. The tubes, in which it is formed, have a small length and small cross-section in the near-equatorial part. On the other hand, the "productivity" of the ionosphere source which "fills" this "reservoir" is greater than on other tubes, because the big part of this near-horizontal tube is located in the active ionization area. Therefore, a significant number of ions O^+ has been produced here during the day and accumulated to the saturation state in the upper part of tubes where the recombination is almost absent. The gravity force in this area does not "drag" the ions back to the dense atmosphere (and to the fast recombination) because tubes are horizontal. Efficiency of O^+ losses in the charge exchange reaction is also lesser than in the longer tubes: H^+ ions can not leave these tubes and recycled back to the O^+.

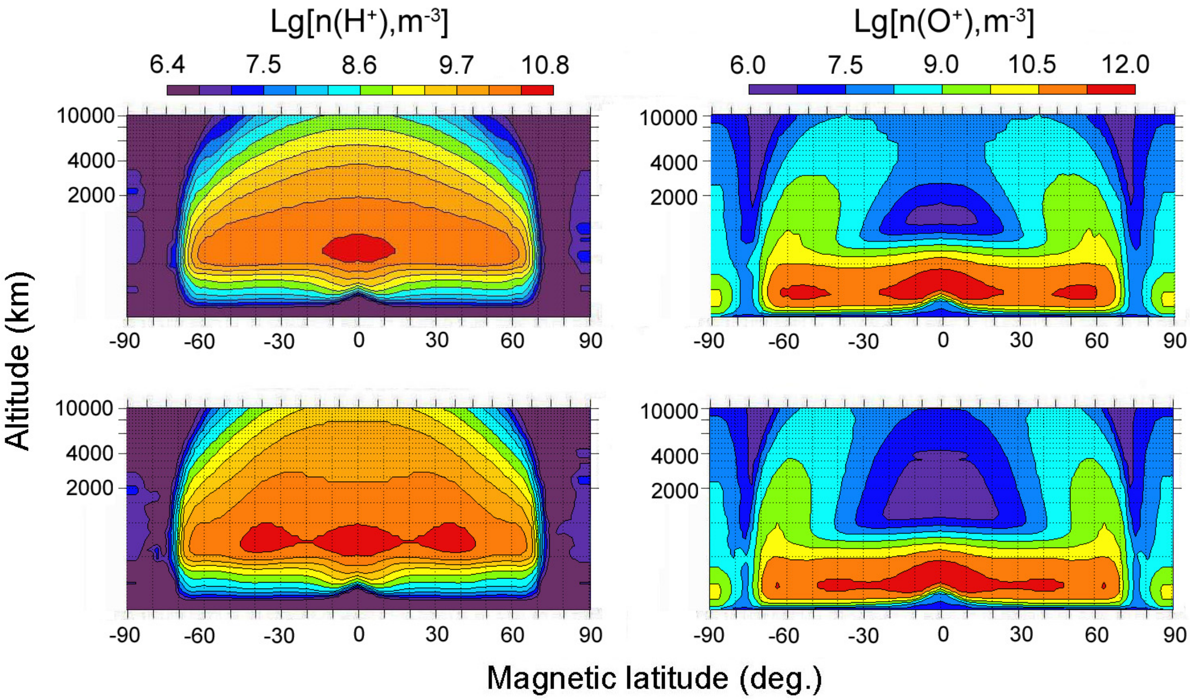

Fig. Vertical sections $n(O^+)$ (right column) and $n(H^+)$ (left column) along the midnight meridian after 1st (upper line) and 5th (lower line) days of modeling time

As a result, a significant concentration of O^+ ions is formed here and remains through all the night. Shorter tubes are located entirely in the denser neutral atmosphere, and longer ones inclined stronger and the ions "roll" to the dense atmosphere under the force of gravity. Therefore in both shorter and longer tubes the night recombination goes faster, and the maximum appears between them.

Another maximum forms during 3rd-5th days of modeling time at the middle latitudes of the night ionosphere. It clearly corresponds with accumulation of H^+ ions in upper parts of these tubes (Fig.).

Such night mid-latitude areas of high electron content were observed in the experiments. Their existence was explained by (*Knyazeva, Namgaladze*, 2008) as the influence of the neutral wind. But our simulation shows that this structure can be generated by the diffusion process only.

In order to discover physical mechanism of its formation we ran another simulation, in which the ion temperature was set constant in whole space. In this modeling mid-latitudinal maximum did not appear. Therefore spatial inhomogeneity of T_i plays the main role in its generation.

The formation of this maximum results from coincidence of two factors. Diffusional ion flux velocity increases with increasing T_i. On the other hand, the tube volume grows very rapidly with latitude. At the latitudes of 30-40° the diffusional fluxes are strong enough in order to fill relatively small volume of tubes during the daytime and to return the big part of accumulated ions back to the ionosphere at night. As a result the night maximum appears here. At shorter tubes the ion temperature and diffusion rate are too low, and longer ones have too big volume to fill it.

A noticeable feature of the forming structure is the sub-auroral night-time n(e) maximum and the "horns" of increased O^+ concentration above it (Fig.). It appears in the first modeling day and later "melts" gradually from the low-latitude side as the "constant reserve" of H^+ accumulates in the upper part of corresponding tubes. This maximum position and latitudinal extent coincides with strong O^+ fluxes area in the outer part of the plasmasphere.

Due to huge volume of near-auroral tubes the plasma density remains very low even after several days of filling, and daytime outward flow of O^+ does not meet any obstacles. Large quantities of O^+ still penetrate far into upper parts of the tubes even after 3-5 days, when at lower latitudes the accumulated H^+ stops O^+ flows. As a result, the ion composition in the near-auroral tubes differs significantly. The H^+ density is very low (the light-ion trough), but O^+ concentration is significantly increased as compared to the same heights on shorter tubes – the above described "horns". After sunset these heavy O^+ ions drop back into the ionosphere and support increased plasma density there. Downstream flow lasts whole night with weakening only before sunrise. The smaller tubes become empty faster.

The efficiency of O^+ returning into the ionosphere from high-altitude "store" is more than of H^+ ions: in the diffusional equilibrium state the concentration of heavy ions at lower altitudes is more than light ones if their total content in whole tube is equal. It results that thinner O^+ high-altitude plasma supports higher night F2-level density than more dense H^+ gas on shorter tubes of the inner plasmasphere.

In the real ionosphere this maximum maps on the area of convection which erodes it. But the areas of high n(O^+) at the outer edge of the plasmasphere which are genetically related with it are known (*Horwitz et al.*, 1986; *Roberts et al.*, 1987; *Guiter et al.*, 1995; etc.). In these studies a correlation was shown between the O^+ density at tube tops and latitudinal variation of electron temperature and the existence of this maximum was explained by the photoelectron heating.

Our simulation also confirms the importance the plasmaspheric T_e and T_i increase with height. It increases the height scale, and plasma distributes more uniformly along the whole tube, whereas at the tubes with lower T_i even H^+ ions accumulate in the bottom part of the tubes. As a result the "efficient volume" of tubes (which must be filled by H^+ ions in order to restrict O^+ propagation to ionosphere heights only) grows drastically – far more faster than their real geometric volume, and the tubes remain practically empty even after many days of filling.

In the simulations without photoelectron heating similar maximum appears in the first day of modeling time too but vanishes very fast in the following days.

Increasing plasma density at tubes with $L \geq 4$ was revealed also in modeling of (*Krinberg, Tashchilin*, 1984). But these authors got it at solstice conditions under high solar activity and explained its appearance by field-aligned plasma cross-flow from the summer hemisphere. We have got similar structure in completely symmetrical problem statement, and hence it should be generated by other physical mechanisms.

5. Conclusions

Thus, we have reproduced by the mathematical simulation method the process of diffusive filling of the plasmasphere in a completely symmetrical statement of the problem: equinox and the coincidence of magnetic and geographic axes. The field-aligned diffusion was the only transport process taken into account.

It has been shown that with all above listed simplifications main numerical parameters of the modeling plasmasphere refilling process agree with known nature data, and thus the model is still physically appropriate.

As a result of our simulations the spatially inhomogeneous and non-stationary plasma environment of the Earth with a number of large-scale three-dimensional structural features in the total plasma density and ion composition are generated. Most notable among them are three latitudinal areas (symmetrical in both hemispheres) with increased night-time plasma density: sub-auroral (latitudes 60-65º), mid-latitudinal (30-40º) and near-equatorial (near 10º) and corresponding peaks of n(O^+) in the outer plasmasphere and n(H^+) in the mid-latitudinal plasmasphere. Investigation of the mechanisms of their appearance has shown that along with the magnetic field geometry the spatial heterogeneity of the ion temperature determined by non-local photoelectron heating contributes greatly to the formation of these features.

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