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MULTICOMPONENT DIFFUSION AND ENERGY CHARACTERISTICS OF PARTIALLY IONIZED PLASMA IN THE IONOSPHERE OF A PLANET

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Annotation

The paper considers the problem of energy and multicomponent ambipolar diffusion of plasma in the lower ionosphere of a planet with a weak magnetic field. Energy and diffusion equations are derived for three-temperature plasma in which heat and mass transfer processes are taking place jointly with chemical reactions in a form which is convenient for calculating models of the composition of a multicomponent ionosphere. Unlike in some early formulations of the problem [1-4], it is shown that the coupling effect of the electric polarization field on the motion of charged particles in the ionosphere is such that the diffusion rates of individual ion components are determined in terms of number density gradients of all ion components of the mixture. The proposed approach generalizes the known description of ambipolar diffusion derived earlier as part of the theory of a traditional ternary mixture (e,i,n) [5-9] to the case of an atmosphere composed of many charged components. Energy interactions among components are analyzed, in particular, thermal energy losses or electrons (ions, neutral particles) due to elastic and inelastic collisions, which allowed to obtain energy equations for each component of the system.

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Introduction */4

The transfer of charged particles by means of diffusion, which along with the photochemical process controls the vertical distribution of ionosphere components is an important factor in all diverse aeronomy processes taking place in the ionosphere of a planet. The diffusion of charged particles in weakly charged multicomponent plasma of the lower ionosphere differs from diffusion of small components in the conditions of a neutral atmosphere. This is related, in the first place, to the necessity of taking into account electrostatic forces not only during the collision of charged particles, but also during the collision of charged and neutral particles, when an electric dipole moment is induced in the latter, and in the second place, to the necessity of taking into account the electric field effect of a space charge formed during the fast diffusion movement of electrons compared with the motion of ions, impeding the relative diffusion of charged particles.

In the case of three-component plasma (e,i,n), the electron-ion plasma undergoes joint (ambipolar) diffusion under the effect of an electric polarization field $\vec{E}$ with a common diffusion coefficient and common velocity $\vec{V}_e = \vec{V}_i$. Problems of plasma diffusion in the ionosphere assuming a ternary mixture are discussed in detail in a number of studies (see for example [5,8], and also the joint authorship study [9]).

For weakly ionized ionosphere plasma, consisting of electrons, various kinds of ions and neutral particles, the diffusion rates of individual charged components are not equal to each other and are

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*Numbers in the margin indicate pagination in the foreign text.

determined from the condition which states that the longitudinal electric current is approximately zero. Few studies discuss the ambipolar diffusion problem in the general case of a multicomponent ionosphere (see for instance, [1-4, 9-11]), while several studies along these lines do not use equivalent expressions for diffusion rates of individual ion components of the gas mixture (for instance [1] and [4].

The purpose of this study is to derive energy equations for multi-temperature plasma of the lower ionosphere and also general diffusion equations for determining diffusion flows for types of ions isolated in the mixture of atmospheric ions using the concept /5 of effective ambipolar diffusion coefficients. Another objective of the study is to eliminate a number of inaccuracies in the description of ambipolar diffusion of a multicomponent conductive medium which occurred in some early formulations of the problem [1,3,4].

1. Stefan-Maxwell Relations for Multicomponent Diffusion

For a quantitative analysis of multicomponent diffusion processes in ionosphere plasma, we will consider the Stefan-Maxwell relations derived in classical kinetic theory of multicomponent gaseous mixtures of monoatomic gases of moderate density as part of a first approximation for multicomponent diffusion coefficients and a second approximation for thermal diffusion coefficients [12]

$$\vec{d}_s = \sum_{k=1}^{N} \frac{x_s x_k}{\mathcal{D}_{sk}(1)}(\vec{V}_k - \vec{V}_s) + \nabla \ln T \sum_{k=1}^{N} \frac{x_s x_k}{\mathcal{D}_{sk}(1)}\left[\frac{D_k^T(2)}{\rho_k} - \frac{D_s^T(2)}{\rho_s}\right], \quad (s=1,2,\ldots N) \qquad (1.1)$$

Here m_s, ρ_s, n_s is the molecular weight, mass density and number density of the s-th component, respectively, $\vec{V}_s$, $x_s=n_s/n$ is the diffusion velocity and molar concentration of the s-th component, n, ρ, T is the total number density, mass density and temperature of the gas mixture and D_s^T, D_{sk} are respectively the thermal diffusion coefficients and binary diffusion coefficients for all pairs of components. The vectors of diffusion forces $\vec{\alpha}_s$ are defined as

$$\vec{d}_s = \nabla x_s + (x_s - c_s)\nabla \ln p - \frac{c_s}{p}\left(\rho \vec{F}_s - \sum_{k=1}^{N} \rho_k \vec{F}_k\right), \qquad (s=1,2,\ldots N) \tag{1.2}$$

where $c_s = \rho_s/\rho$ is the mass concentration of the s-th component, p is the pressure of the gas mixture and F_s is the force acting on the s-th component. The order of approximation $\xi=1,2,\ldots$ with which the transfer coefficents are determined in (1.1) corresponds to the number of first terms in a series expansion of the coefficients of perturbed distribution functions of components in terms of Sonine's polynomials.

Until recently, relations (1.1) for diffusion rates were only derived in first approximation in the kinetic theory of gases. Usu- /6
ally such approximation is considered to be adequate, however in ionized gases, the admissible error may turn out to be considerable. The necessity of taking into consideration higher order approximations in calculations of transfer coefficients in an investigation of flows of ionized mixtures of gases in the ionosphere ($\xi=3$ and higher [12,13]), when not only the temperature and pressure but also the elementary chemical composition [14] of the flow undergoes changes, makes the Stefan-Maxwell equations in form (1.1) inapplicable in aeronomy in the general case.

However, study [15] gave very recently a derivation of relations (1.1) from the kinetic theory of gases in any approximation for transfer coefficients using the Chapman-Enskog method, and study [16] derived relations (1.1) for the case of imperfect (perfect) mixtures of gases by methods of thermodynamics of irreversible processes, while demonstrating the symmetry of the matrix of resistance to diffusion, in complete agreement with the latest results of the kinetic theory of gases.

Let us make some transformations. Henceforth we will consider as external forces electric, magnetic and gravitational forces

$$\vec{F}_s = \vec{G} + \frac{e_s}{m_s}\left(\vec{E} + \frac{1}{c}\vec{V}_s \times \vec{B}\right), \qquad (1.3)$$

where $\vec{G}$ is acceleration due to gravity, e_s is the electric charge of the s-th component (for neutral components we will assume $e_s \equiv 0$), $\vec{E}$ is the electric field intensity vector, $\vec{B}$ is the magnetic induction vector, which in the general case includes the unperturbed magnetic field of the planet and a small induced field. Using the relation $p_s = x_s p$ for the partial pressure of the s-th component, we have $\nabla x_s = \nabla p_s / p - x_s \nabla \ln p$, from which we obtain

$$\vec{d}_s = \frac{1}{p}\left\{\nabla p_s - n_s e_s\left(\vec{E} + \frac{1}{c}\vec{V}_s \times \vec{B}\right) - c_s \nabla p + \frac{c_s}{c}\vec{J} \times \vec{B}\right\}, \qquad (1.4)$$

where $\vec{J} = \Sigma_s e_s n_s \vec{v}_s$ is the density of the total conduction current in the plasma.

Expression (1.4) takes into account the quasineutrality of ionosphere plasma

$$\sum_{s=1}^{N} e_s n_s \simeq 0 \qquad (1.5)$$

Using formula (1.4) and also the full equation of motion (without the viscous term) for the continuum which models the mixture of gases as an entity, we rewrite the Stefan-Maxwell equations (1.1) in the form of equations of motion for individual charged components of the ionosphere[1]. /7

$$\rho_s \frac{d\vec{V}}{dt} + \sum_{j=1}^{N'} n_s n_j \nu_{sj}(\vec{V}_s - \vec{V}_j) = -\nabla p_s + n_s e_s\left(\vec{E} + \frac{1}{c}\vec{V}_s \times \vec{B}\right) - K n_s \alpha_s \nabla T + \rho_s \vec{G}, \qquad (1.6)$$

In the above, $\nu_{sj} = KT/nD_{sj}$ are the coefficients of friction which are either determined experimentally or from a detailed investigation of the dynamics of particle collisions using the kinetic theory of gases, K is Boltzmann's constant, N' is the number of charged components

[1]The viscosity of the system is almost completely determined by the neutral component of the ionosphere [7].

of the gas mixture, and α_s is the thermal diffusion factor defined by

$$\alpha_s = \sum_{j \neq s}^{N'} \frac{n_j}{n \mathcal{D}_{sj}} \left[\frac{D_s^T}{\rho_s} - \frac{D_j^T}{\rho_j} \right] \qquad (1.7)$$

which constitutes a measure of the relative importance of thermal diffusion and ordinary diffusion. In the general case, the thermal diffusion factor is a complicated function of temperature, concentration, and molecular weights depending parametrically on the laws obeyed by intermolecular forces [12]. According to available estimates, thermal diffusion for principal components of the ionosphere is a negligibly small quantity due to the small difference in molecular weights, which essentially should only be taken into account in light gases (hydrogen and helium [17]).

Equation (1.6) did not take into account the possible anisotropy of coefficients of friction in the magnetic field, which is related to not having taken into account the effect of the magnetic field in Stefan-Maxwell equation (1.1). At the same time, it is clear that in strongly magnetized plasma ($\Omega_e \gg \beta_{ei}$, $\Omega_e = \frac{e\beta}{cm_e}$), in particular, such as the ionosphere in the F region of the Earth's ionosphere, the collision term must be anisotropic. In simple cases (for example for completely ionized two-component plasma), in ionosphere conditions, this effect can be estimated by the order of magnitude [18]. We also note that although the presented derivation of equations of motion (1.6) is only valid in a single-temperature approximation, the form of the equations remains unchanged also in the case of multi-temperature plasma [19].

Directly in the ionosphere of the planet, neutral molecules are much more numerous than charged particles: $n_n \gg n_e, n_i$. Therefore in describing physical processes in the lower ionosphere, one can /8
often restrict the analysis to the theory of a weakly ionized gas. In this case, we can assume that the hydrodynamic velocity coincides with the velocity of the neutral gas $\vec{V} \approx \vec{V}_n$, all components of which

have the same velocity $\vec{V}_n$ (assuming gravitational-diffusion equilibrium in the thermosphere). Then the general equation of motion for the plasma component of the gas mixture, obtained by summing equations (1.6) over all charged gas components, assumes the form

$$\rho_L \frac{d\vec{V}}{dt} + \sum_{s=1}^{N'} n_s n_n \tilde{\nu}_{sn} (\vec{V}_s - \vec{V}) = -\nabla P_L + \frac{1}{c} \vec{J} \times \vec{B} + K \sum_{s=1}^{N'} n_s \alpha_s \nabla T_s + \rho_L \vec{G}, \tag{1.8}$$

$$\tilde{\nu}_{sn} = \sum_{j=1}^{N(n)} n_j \nu_{sj} / n_n , \quad n_n = \sum_{j=1}^{N(n)} n_j , \quad \rho_L = \sum_{s=1}^{N'} m_s n_s , \quad P_L = \sum_{s=1}^{N'} P_s . \tag{1.9}$$

Here $\tilde{\nu}_{sn}$ is the total coefficient of friction of the s-th charged component with the neutral component of the ionosphere; n_n is the total number density of neutral components of the gaseous mixture, ρ_L, n_L, P_L are respectively the mass density, number density and pressure of the plasma component of the ionosphere. The upper index "n" in a sum denotes summation over neutral components of the system. The general equation of motion for the neutral component of the ionosphere

$$\rho_n \frac{d\vec{V}}{dt} + \sum_{s=1}^{N'} n_s n_n \tilde{\nu}_{sn} (\vec{V} - \vec{V}_s) = -\nabla P_n + \nabla \cdot \overline{\overline{\Pi}}_n + K \sum_{s=1}^{N(n)} n_s \alpha_s \nabla T_s + \rho_n \vec{G}, \tag{1.10}$$

$$\overline{\overline{\Pi}}_n = -\eta_n \left[\nabla \vec{V} + (\nabla \vec{V})^T - \frac{2}{3} (\nabla \cdot \vec{V}) \overline{\overline{I}} \right], \quad P_n = \sum_{s=1}^{N(n)} P_s , \quad \rho_n = \sum_{s=1}^{N(n)} m_s n_s \tag{1.11}$$

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follows from equation (1.8), and the full equation of motion for the continuum modeling the gaseous mixture as a whole entity $\rho\, d\vec{V}/dt = -\nabla p + \nabla\cdot\overline{\overline{\Pi}} + \frac{1}{c}\vec{J}\times\vec{B} + \rho\vec{G}$

where $\overline{\Pi}_n$ is a tensor of viscous stresses of the gaseous mixture, η_n is the viscosity coefficient and ρ_n, p_n are the mass density and pressure of the neutral component of the ionosphere.

2. Collision Effects

Detailed calculations of various transfer processes in the ionosphere of a planet require a rigorous treatment of the problem of collisions among various particles. The collision term $\mathcal{M}_k = \sum_{j\neq k} n_k n_j \nu_{kj} (\vec{V}_j - \vec{V}_k)$ in equation (1.6) represents the velocity with which a unit of volume of the k-component loses momentum as a result of collisions of its particles with other components. Introducing the mean collision frequency $\beta_{ks} = n_s \nu_{ks} m^{-1}{}_{ks}$, we express the collision term $\vec{M}_{ks}$ in the form /9

$$\vec{\mathcal{M}}_{ks} = n_k n_s \nu_{ks} (\vec{V}_s - \vec{V}_k) = n_k m_{ks} \beta_{ks} (\vec{V}_s - \vec{V}_k). \tag{2.1}$$

In the above $m_{ks}=m_k m_s/(m_k+m_s)$ is the reduced mass, $\beta_{ks}=n_s g_{ks}\overline{Q}_{ks}$ is the mean collision frequency with momentum transfer between particles of type k and s, $g_{ks}=[8KT_R/\Pi m_{ks}]^{1/2}$ is the mean relative speed of particles with Maxwell velocity distributions, $T_R=m_{ks}(\frac{T_k}{m_k}+\frac{T_s}{m_s})$ is the reduced temperature and $\overline{Q}_{ks}$ is the mean collision cross-section with momentum transfer. We shall present some estimates: The scattering cross-section $\overline{Q}_{ks}$ is determined from an experiment or by means of gas kinetics calculations [12,18,19], when the law governing the interaction between particles is known sufficiently well. Kinetic theory gives the following expression for $\overline{Q}_{ks}$ in the case of collision of ions with a neutral gas [19]

$$\overline{Q}_{in}=\frac{4}{3}\left(\frac{m_{in}}{2KT_n}\right)^3\int_0^\infty Q_{in}(g)\exp[-(m_{in}/2KT_n)g^2]g^5dg, \qquad (2.2)$$

where $Q_{in}(g)$ is the momentum transfer cross-section between particles of type i and n, having relative thermal speed g and equal macroscopic velocities of motion $\vec{V}_i=V_n$. A more exact expression for Q_{in} taking into account differences in the velocities of motion of components i and n is presented in study [20]. Rigorous analysis shows that as a charged particle approaches a neutral particle, an electric dipole moment is induced in the latter and the collision cross-section between the particles is determined to a considerable degree by the resultant electrostatic forces. For ions with neutral particles, Banks [21,22] proposes the following semi-empirical expression

$$\overline{Q}_{in}=17{,}7\cdot 10^{-4}\alpha_0^{1/2}\left[m_{in}\left(\frac{T_i}{m_i}+\frac{T_n}{m_n}\right)\right]^{-\frac{1}{2}}, \mathrm{cm}^2 \qquad (2.3)$$

where the atomic polarization $\alpha_0(=10^{-24}\alpha'\ \mathrm{cm}^3)$ for the principal neutral components of Earth's ionosphere has the following values: $\alpha'_{O_2}=1.60$, $\alpha'_{N_2}=0.82$, $\alpha'_O=0.89$, $\alpha'_M=0.67$, $\alpha'_{He}=0.21$, $\alpha'_N=1.13$ [23,24].

It is assumed that the ions and the gas obey a Maxwell distribution. In this case, the collision frequency is independent of the temperature and is determined from relation [21,2]

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$$\vartheta_{in} = 2.6\cdot 10^{-9} n_n \left(\alpha_0/\mu_A\right)^{1/2}, \ \sec^{-1} \quad (2.4)$$

where $\mu_A = \frac{A_1 A_n}{A_1 + A_n}$ and A_s is the mass of the particle in atomic units. /10

The resonance charge transport reaction plays an important part in the diffusion of ions of some type in the same type of gas. The frequency of collisions for this process can be approximately represented in the form[1]

$$\vartheta_{in} = \vartheta_{in}^{0} \cdot n_n \left(T_i + T_n\right)^{1/2}, \ сек^{-1} \quad (2.5)$$

where the constants β_{in}^{o} ($=10^{-12}\beta'_{in}$ cm^2/sec·deg.$^{1/2}$) for the principal components of the Earth's ionosphere have the following values: $\beta'_{O^+,O}=1.6$, $\beta'_{O_2^+,O_2}=1.1$, $\beta'_{H^+,H}=1.0$, $\beta'_{He^+,He}=3.0$, $\beta'_{N_2,N_2}=2.1$, $\beta'_{N^+,N}=1.6$ [29].

While considering the collision frequency of electrons with a heavy particle, we will use the condition $m_e \ll m_n$; then $m_{en} \approx m_e$, $T_R \approx T_e$, and we obtain for the mean collision frequency

$$\vartheta_{en} = \frac{4}{3} n_n \left(\frac{8KT_e}{\pi m_e}\right)^{1/2} \left(\frac{m_e}{2KT_e}\right)^{3} \int_0^\infty Q_{en}(g) \exp\left[-\frac{m_e g^2}{2KT_e}\right] g^5 dg = n_n \left[\frac{8KT_e}{\pi m_e}\right]^{1/2} \bar{Q}_{en} \quad (2.6)$$

For the principal neutral components of the Earth's ionosphere, the mean collision cross-sections with momentum transfer have the values: $\bar{Q}_{e,n_2} = (3.76-4.54\cdot 10^{-4}\ T_e)\ T_e^{1/2}\cdot 10^{-17}$, cm^2, $\bar{Q}_{e,O_2} = 2.93\cdot 10^{-16}(1+3.6\cdot 10^{-12}\cdot T_e^{1/2})$, cm^2; $\bar{Q}_{e,O} = (4.53-1.3)\ 10^{-16}$, cm^2; $\bar{Q}_{c,M} = (72.9-9.93\cdot 10^{-3} T_e)$, cm^2; $\bar{Q}_{e,He} = (7.46-0.8)\ 10^{-16}$ cm^2 [21,22].

The total collision frequency of an electron in multicomponent

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[2] In all formulas applied in practice, the temperature is expressed in degrees Kelvin and all other magnitudes in CGS units.

plasma is equal to the sum of collision frequencies with different components $\beta_e = \Sigma_s \beta_{es}$.

The elastic collision dynamics of two charged particles are described by a well known potential, which allows to derive an expression for the mean momentum transfer cross-section [18].

$$\bar{Q}_{ei} = \frac{e^4 \ln \Lambda_{ei}}{24\pi(\hat{\varepsilon} K T_e)^2} = 5{,}85 \cdot 10^{-16} \ln \Lambda_{ei}/T_e^2 \quad , \text{ cm}^2 \quad (2.7)$$

where $\hat{\varepsilon}$ is the dielectric permeability coefficient of the plasma and $\Lambda_{ei} = 1.24 \cdot 10^7 \sqrt{T_e^3/n_e}$ is the Coulomb logorithm (ni). The corresponding mean electron collision frequency with momentum transfer is

$$\vartheta_{ei} = n_i g_{ei} \bar{Q}_{ei} = n_i \frac{4\sqrt{2\pi}}{3} \left(\frac{m_e}{KT_e}\right)^{3/2} \left(\frac{e^2}{4\pi\hat{\varepsilon} m_e}\right)^2 \ln \Lambda_{ei} \approx \frac{4{,}55 n_i \ln \Lambda_{ei}}{T_e^{3/2}}, \text{ sec}^{-1} \quad (2.8)$$

For ion-ion collisions, according to [21,22], the cross-section /11 can be expressed in the form

$$\bar{Q}_{ij} = 4{,}4 \cdot 10^{-6} \ln \Lambda_{ij}/T_R^2 \text{ ., cm}^2 \quad (2.9)$$

where the parameter Λ_{ij} is defined as $\Lambda_{ij} = 2E\, R_D/e^2$, E is the mean energy of the relative motion of two ions and $R_D = 4\pi e^2/K\hat{\varepsilon}\ (\bar{n}i/Ti + nj/Tj)^{-1/2}$ is the Debye radius. It is assumed that both gases have a Maxwell velocity distribution. Then the corresponding frequency of ion-ion collisions is

$$\vartheta_{ij} = n_j g_{ij} \bar{Q}_{ij} = 8{,}4 \cdot 10^{-2} n_j \frac{\ln \Lambda_{ij}}{\mu_A^{1/2} T_R^{3/2}} \quad . \quad (2.10)$$

3. Ambipolar Diffusion of Ionosphere Plasma in the Absence of External Electromagnetic Forces

We will now consider diffusion processes in a multicomponent ionized gas in the ionosphere of a planet with a weak magnetic field $\vec{B} \approx 0$, on the assumption that all different types of particles participating in this motion have a different temperature. Because of the smaller mass, electrons undergo faster diffusion than ions, however the space charge formed in the process gives rise to an electric field $\vec{E}$ which tends to slow down their motion. The electric field acts in the opposite direction on ions and accelerates them. Ignoring the magnetic field induced by the separation of charges, the Stefan-Maxwell relation (1.6) for a charged ionosphere component s can be expressed as follows

$$KT_s\vec{\Lambda}_s - e_s n_s \vec{E} = \sum_{k=1}^{N} \nu_{sk}\left(n_s\vec{J}_k - n_k\vec{J}_s\right), \quad (s=1,2,\ldots N') \qquad (3.1)$$

$$\vec{\Lambda}_s = \frac{n_s m_s}{KT_s}\frac{d\vec{V}}{dt} + \nabla n_s - \frac{n_s}{H_s}\vec{i}_g + \frac{n_s}{T_s}(1+\alpha_s)\nabla T_s \qquad (3.2)$$

Here $\vec{J}_s = n_s(\vec{V}_x - \vec{V})$ is the diffusion flow (flow of the number of particles of type s with respect to the mean mass velocity $\vec{V} = \rho^{-1}\sum_s \rho_s \vec{V}_s$); $\vec{i}_g = \vec{G}/g$ is the unit direction vector $\vec{G}$ and $H_s = KT_s/m_s g$ is the local altitude scale of the s-th component. Introducing the diffusion movement coefficients C_s and the diffusion coefficients D_s of charged particles of type s

$$b_s = e_s\left[\sum_{k=1}^{N}\nu_{sk}n_k\right]^{-1} = e_s\left[\sum_{k=1}^{N} m_{sk}\zeta_{sk}\right]^{-1}, \quad D_s = \frac{KT_s}{e_s}b_s \qquad (3.3)$$

relations (3.1) can be written in the form /12

$$\vec{J}_s = \frac{b_s}{e_s}\sum_{k=1}^{N}\nu_{sk}n_s\vec{J}_k - D_s\vec{\Lambda}_s + b_s n_s \vec{E}, \quad (s=1,2,\ldots N') \qquad (3.1^*)$$

Relation (3.3) between D_s and C_s is the Einstein relation, known earlier for a ternary mixture of neutral components, ions and electrons.

Let us write down the expression for the electric current density $\vec{J} = \sum_{s=1}^{N} e_s\vec{J}_s$. Taking into account (1.5) and (3.1), we have

$$\vec{J} = \sigma\vec{E} - \sum_{s=1}^{N} e_s D_s \vec{\Lambda}_s + \sum_{s=1}^{\hat{n}}\sum_{k=1}^{N} b_s n_s \nu_{sk}\vec{J}_k, \qquad (3.4)$$

where the conductivity of the plasma (longitudinal conductivity in the presence of a magnetic field) is determined from the expression

$$\sigma = \sum_{s=1}^{N} e_s b_s n_s = \sum_{s=1}^{N} e^2 n_s \left[\sum_{k=1}^{N} \nu_{sk} n_k \right]^{-1} = \sum_{s=1}^{N} e^2 n_s \left[\sum_{k=1}^{N} m_{sk} g_{sk} \right]^{-1}. \quad (3.5)$$

Since a minute vertical separation of electrons with respect to positive ions leads to the formation of a strong electric polarization field in the ionosphere impeding the relative diffusion of charged particles, ultimately a stationary state is established in ionosphere plasma, in the presence of which ions and electrons move in such a way that a space charge does not arise. In this case, only small deviations from equilibrium can occur and any vertical electric current must be negligible. Setting in expression (3.4) $_h=0$, we shall find the electric polarization field E_h under the action of which ambipolar diffusion is taking place in the ionosphere. Next, eliminating this field from relations (3.1) and omitting the subscript h in the vertical component of vector quantities, we write the Stefan-Maxwell relations in the form

$$KT_i\Lambda_i - \frac{e_i n_i}{\sigma} \sum_{s=1}^{N} KT_s b_s \Lambda_s = \sum_{s=1}^{N} \nu_{is}^{(a)} (n_i J_s - n_s J_i), \; (i=1,2,\dots N') \quad (3.6)$$

So-called ambipolar coefficients of friction $\nu_{is}^{(a)} = \nu_{is} - e_i \sum_k b_k n_k \nu_{ks} / \sigma$ were introduced here. In deriving formula (3.6), for symmetry of the final relations, the zero term $e_i J_i \sum_s \sum_k b_s n_s n_k \nu_{sk} / \sigma = 0$ (by virtue of the quasilinearity of (1.5) and relations (3.3)) was added to the right member of (3.1).

Relation (3.6) can be simplified. For atmospheres of planets, electron mobility exceeds many times ion mobility $|C_e| >> C_i$ [25]. /13
Consequently, the following approximate relations are valid

$$\sigma = -e b_e n_e \left[1 - \sum_{j \neq e}^{N'} b_j n_j / b_e n_e\right] \simeq -e b_e n_e,$$
$$\frac{K e_i n_i}{\sigma} \sum_{s=1}^{N} T_s b_s \Lambda_s = -\frac{K n_i}{n_e b_e} \left[T_e b_e \Lambda_e + \sum_{s \neq e}^{N'} T_s b_s \Lambda_s\right] \simeq -\frac{n_i}{n} K T_e \Lambda_e$$

and equation (3.6) for vertical diffusion of type i ions can be expressed as follows

$$K T_i \Lambda_i + \frac{n_i}{n_e} K T_e \Lambda_e = \sum_{K=1}^{N'} \nu_{iK}^{(a)} (n_i J_K - n_K J_i), \quad (i=1,2,\dots N')$$
$$\nu_{iK}^{(a)} = \nu_{iK} + \nu_{eK} + \sum_{s \neq e} \theta_s n_s \nu_{sK} / \theta_e n_e \simeq \nu_{iK} + \nu_{eK} \tag{3.7}$$

In the case when electrons and ions have the same temperature ($T_e = T_i = T$), it is convenient to rewrite relation (3.7) in terms of ambipolar binary diffusion coefficients

$$\mathcal{D}_{iK}^{(a)} = \frac{KT}{n \nu_{iK}^{(a)}} = \left[\frac{1}{\mathcal{D}_{iK}} - \frac{e}{e} \sum_{s=1}^{N} \frac{\theta_s n_s}{\mathcal{D}_{sK}} \right]^{-1} \simeq \frac{\mathcal{D}_{iK} \mathcal{D}_{eK}}{\mathcal{D}_{iK} + \mathcal{D}_{eK}} \tag{3.8}$$

in the form

$$\Lambda_i + \frac{n_i}{n_e} \Lambda_e = \sum_{K=1}^{N} \frac{n_i J_K - n_K J_i}{n \, \mathcal{D}_{iK}^{(a)}}, \quad (i=1,2,\dots N'-1) \tag{3.9}$$

In investigating the composition of the atmosphere of a planet, relations (3.9) together with differential continuity equations for the concentrations n_i of ion components of the atmosphere

$$\frac{d}{dt}(n_i/\rho) + \nabla_h J_i = \sum_{r=1}^{R} (\gamma_{ir} - \eta_{ir}) \left[K_r \prod_{i=1}^{N} n_i^{\eta_{ir}} - K_r' \prod_{i=1}^{N} n_i^{\gamma_{ir}} \right], \quad (i=1,2,\dots N') \tag{3.10}$$

and the plasma quasilinearity condition

$$n_e \simeq \sum_{j \neq e}^{N'} n_j \tag{3.11}$$

allow to calculate the vertical distribution of charged components in the lower ionosphere of the planet at a given temperature profile. Here η_{ir}, γ_{ir} are the stoichiometric coefficients in the r-th (r=1,2, ...,R) aeronomic reaction, $\eta_{1r}[1] + \eta_{2r}[2] + \dots \underset{K_r'}{\overset{K_r}{\rightleftarrows}} \gamma_{1r}[1] + \gamma_{2r}[2] + \dots$; R is the number of reactions, Kr, Kr' are the constant velocities of the direct and reverse reaction respectively.

Equations (3.9) generalize to the case of diffusion of various types of ions and electrons in a mixture composed of many components the well known diffusion equations introduced by Kolegrov et al [26] for determining the densities of individual components used in many /14 studies during calculations of models of the composition of a neutral atmosphere.

Ignoring for simplicity the inertial term in expression (3.2) for Λ_s, and restricting ourselves to a consideration of stationary movement of a neutral atmosphere, we write relation (3.7) in terms of the gradients of principal hydrodynamic quantities in the following final form

$$\frac{T_i}{T_e+T_i}\nabla_h \ln n_i + \frac{T_e}{T_e+T_i}\nabla_h \ln n_e + \frac{1+\alpha_i}{T_e+T_i}\nabla_h T_i + \frac{1+\alpha_e}{T_e+T_i}\nabla_h T_e + \frac{1}{H_i} = \sum_{k=1}^{N} \nu_{ik}^{(a)}(n_i J_k - n_k J_i) / K n_i (T_e+T_i), \quad (i=1,2,\dots N'-1) \qquad (3.12)$$

where $H_i = K(T_i+T_e)/m_i g$ is the altitude of the homogeneous atmosphere of the i-th ion component. The influence of the thermal diffusion effect on the altitude distribution of ion components of the atmosphere is only considerable for minor components [27]. Equations (3.12) for diffusion flows of ion components are fundamental in a descritpion of ambipolar diffusion and generalize the results obtained earlier [5-10] for three-component plasma to the general case of weakly ionized multicomponent plasma in the lower ionosphere.

Finally, assuming that collisions among ions and neutral particles play a greater part than collisions among charged particles (which is valid for the lower ionosphere in the E and F regions), and also taking into account the fact that in the thermosphere the neutral components are in a state of gravitational-diffusion equilibrium ($J_i \approx 0$), we obtain from equations (3.7) an expression for the diffusion rate of the j-th principal plasma component

$$V_j = V - D_j^{(\alpha)}\left[\frac{T_j}{T_e+T_j}\nabla \ln n_j + \frac{T_e}{T_e+T_j}\nabla \ln n_e + \nabla \ln (T_e+T_j) + \frac{1}{H_j}\right], \qquad (3.13)$$

where the ambipolar diffusion coefficient $D_j^{(a)}$ is defined by the relation

$$D_j^{(a)} = \left[\sum_{k=1}^{N^{(n)}} \frac{n_k \nu_{jk}^{(n)}}{K(T_e+T_j)}\right]^{-1} = \frac{D_j D_e (T_e+T_j)}{T_j D_e + T_e D_j} = \frac{K(T_e+T_j)\, b_j b_e}{e(b_e - b_j)} \qquad (3.14)$$

The index n in the sum denotes summation over neutral components of the system. Thus, on the strength of relation (3.11), the drift velocity of each ion component depends on the gradients of all ion components of the ionosphere.

In the special case of three-component plasma ($n_e = n_i = n$), formulas (3.13) and (3.14) become the well known relations for the coefficient and ambipolar diffusion rate of plasma in a coordinate system /15 moving with the velocity of the entire substance

$$V_i = V - D_i^{(a)}\left[\nabla_h \ln p_i + \frac{1}{\mathcal{H}}\right], \quad D_i^{(a)} = \frac{K(T_e+T_i)}{m_{in}\nu_{in}}, \quad p_i = Kn(T_e+T_i) \qquad (3.15)$$

4. Ambipolar Diffusion in Proper Magnetic Field of Planet

In discussing the problem of diffusion in the ionosphere of a planet with its own magnetic field $\vec{B}$, we will limit ourselves to the case in which it suffices to consider the interaction of charged ionosphere components only with neutral particles (friction with neutral gas) which are in a state of diffusion equilibrium, without taking into account collisions of charged particles among themselves. In this case, the equation of motion (1.6) for each type of charged particle will be represented in the form

$$\vec{J}_s = \frac{b_s}{c}\vec{J}_s \times \vec{B} + b_s n_s\left(\vec{E} + \frac{1}{c}\vec{V}\times\vec{B}\right) - D_s \vec{\Lambda}_s, \quad D_s = \frac{K T_s}{\sum^{(n)} m_{is}\nu_{is}}, \quad b_s = \frac{e_s}{\sum^{(n)} n_i \nu_{si}} \qquad (4.1)$$

Denoting by $\vec{A}_{\parallel}$ and $\vec{A}_{\perp}$ the components of an arbitrary vector along and across the line of force of the magnetic field $\vec{B}$ / $\vec{A}_{\parallel}=(\vec{A}\cdot\vec{h})\vec{h}$, $\vec{A}_{\perp}=\vec{h}\times(\vec{A}\times\vec{h})$, $\vec{h}=\vec{B}/B$), we write the longitudinal and transverse component of equation (4.1) in the form

$$\vec{J}_{s\parallel}=b_s\left(n_s\vec{E}_{\parallel}-\frac{KT_s}{e_s}\vec{\Lambda}_{s\parallel}\right),\ \vec{J}_{s\perp}=b_{s\perp}\left(n_s\vec{E}'_{\perp}-\frac{KT_s}{e_s}\vec{\Lambda}_{s\perp}\right)+b_{s\wedge}\left(n_s\vec{E}'-\frac{KT_s}{e_s}\vec{\Lambda}_s\right)\times\vec{h}, \qquad (4.2)$$

$$b_{s\perp}=\frac{c}{B}\sum_{k=1}^{N}{}^{(n)}\frac{\vartheta_{sk}}{\Omega_{sk}}\Big/\left[\sum_{k=1}^{N}{}^{(n)}\frac{\vartheta_{sk}}{\Omega_{sk}}\right]^2+1,\quad b_{s\wedge}=\frac{c}{B}\Big/\left[\sum_{k=1}^{N}{}^{(n)}\frac{\vartheta_{sk}}{\Omega_{sk}}\right]^2+1, \qquad (4.3)$$

where $\Omega_{sk} = e_s B/m_{sk}C$ is the generalized gyromagnetic frequency of the s-th component, and $\vec{E}' = \vec{E} + \frac{1}{c}\vec{V} \times \vec{B}$ is the electric field in a coordinate system moving at the velocity of the neutral gas in the ionosphere.

Using formulas (4.2), let us write down the expressions for the density of the flow along and across the magnetic field

$$\vec{J}_{\perp}=\sigma_{\perp}\vec{E}'_{\perp}+\sigma_{\wedge}\vec{E}'\times\vec{h}-\sum_{s=1}^{N}b_{s\perp}\vec{\Lambda}'_{s\perp}-\sum_{s=1}^{N}b_{s\wedge}\vec{\Lambda}'_s\times\vec{h}, \qquad (4.4)$$

$$\vec{J}_{\parallel}=\sigma\vec{E}_{\parallel}-\sum_{s=1}^{N}b_s\vec{\Lambda}'_{s\parallel},\quad \vec{\Lambda}'_s=KT_s\vec{\Lambda}_s,$$

where the transverse and Hall conductivity is determined from the expressions /16

$$\sigma_{\perp}=\sum_{s=1}^{N}e_s n_s b_{s\perp},\quad \sigma_{\wedge}=\sum_{s=1}^{N}e_s n_s b_{s\wedge} \qquad (4.5)$$

In Earth's lower ionosphere (F-region) $B \approx 0.3$ gauss, $\beta_{in}\sim 1\,sec^{-1}$; $\beta_{an}\sim 35\,sec^{-1}$; $\beta_{ei}\sim 1500\,sec^{-1}$; $m_e= 9.108\cdot 10^{-28}$ g, $e= 1.602\cdot 10^{-20}$ e.m.u. and the following estimates

$$\vartheta_{ek}/\Omega_{ek}\ll\vartheta_{ik}/\Omega_{ik}\ll 1,\quad |b_e|\gg|b_i| \qquad (4.6)$$

are valid in a considerable range of altitudes. Using these estimates, we obtain the following approximate relations

$$b_{s\perp} \simeq \frac{c}{B} \sum_{k=1}^{N^{(n)}} \frac{\beta_{sk}}{\Omega_{sk}} , \quad b_{s\wedge} \simeq \frac{c}{B} , \quad \underset{=}{d} \simeq -e b_e n_e , \quad d_\wedge \simeq 0 \tag{4.7}$$

Eliminating the longitudinal electric field $\vec{E}_{\parallel}$ from relations (4.2) and (4.4) and ignoring terms which are small compared to unity, we obtain the following expression for the longitudinal diffusion flow of ions

$$\vec{J}_{s\parallel} = \frac{b_s n_s}{d} \vec{J}_{\parallel} + \sum_{j=1}^{N} \frac{b_s b_j}{d\, e_s} \left(n_s e_s \vec{\Lambda}'_{j\parallel} - n_j e_j \vec{\Lambda}'_{s\parallel} \right) \simeq -\frac{b_s n_s}{e b_e n_e} \vec{J}_{\parallel} - \frac{b_s}{e} \Big(\vec{\Lambda}'_{s\parallel} + \frac{n_s}{n_e} \vec{\Lambda}'_{e\parallel} \Big) = -\frac{b_s n_s}{e b_e n_e} \vec{J}_{\parallel} - D_s^{(a)} \left[\frac{1}{K(T_s+T_e)} \left(\nabla_{\parallel} P_s + \frac{n_s}{n_e} \nabla_{\parallel} P_e \right) - \frac{n_s}{\mathcal{H}_s} \vec{\zeta}_{g\parallel} \right] \quad (s = 1, 2, \ldots N'-1) \tag{4.8}$$

The term involving $\vec{J}_{\parallel}$ can be omitted. Indeed, $C_s n_s / C_e n_e \sim 10^{-3}$; $J_{\parallel} \sim 10^{-12}$ e.m.u. [28], which together with $n_s \sim 10^6$ cm, gives $|\vec{J}_{\parallel}/e n_s| \sim 10^2$ cm/sec. Since $|\vec{V}_{s\parallel}|$ in the ionosphere is probably of the order of magnitude 1 m/sec, the term involving $\vec{J}$ in relation (4.8) is small, so that we can assume

$$\vec{J}_{s\parallel} \simeq -D_s^{(a)} \left[\frac{1}{K(T_e+T_s)} \left(\nabla_{\parallel} P_s + \frac{n_s}{n_e} \nabla_{\parallel} P_e \right) - \frac{n_s}{\mathcal{H}_s} \vec{\zeta}_{g\parallel} \right] \tag{4.9}$$

in complete accordance with formula (3.13).

To obtain the transverse component of the diffusion ion flow in ionosphere conditions (4.7), we proceed as follows: Using the full equation of motion of the plasma component of gas mixture (1.8) in the form

$$\sum_{s=1}^{N'} \vec{\Lambda}'_s \equiv \rho_L \frac{d\vec{V}}{dt} + \nabla P_L - \rho_L \vec{g} - K \sum_{s=1}^{N'} n_s \alpha_s \nabla T_s = \frac{1}{c} \vec{J} \times \vec{B} - \sum_{s=1}^{N'} \frac{e_s}{b_s} \vec{J}_s , \tag{4.10}$$

we write the last term in the right member of expression (4.4) for $\vec{J}_\perp$ as follows

$$\sum_{s=1}^{N} b_{s\wedge}\vec{\Lambda}'_s\times\vec{h} = \frac{c}{B}\sum_{s=1}^{N}\vec{\Lambda}'_s\times\vec{h} = -\vec{J}_\perp - \frac{c}{B}\sum_{s=1}^{N}\frac{e_s}{b_s}\vec{J}_s\times\vec{h}. \qquad (4.11)$$ /17

Then from (4.4) we obtain for the transverse component of the electric field $\vec{E}'_\perp$

$$\vec{E}'_\perp = \frac{1}{\sigma_\perp}\sum_{s=1}^{N} b_{s\perp}\vec{\Lambda}'_{s\perp} - \frac{c}{B\sigma_\perp}\sum_{s=1}^{N}\frac{e_s}{b_s}\vec{J}_s\times\vec{h}. \qquad (4.12)$$

Next, eliminating $\vec{E}'_\perp$ from relations (4.2) and (4.12) and omitting terms which are small by virtue of conditions in the ionosphere [4.6], we obtain for the transverse diffusion ion flow the following final expression

$$\vec{J}_{s\perp} = -n_s\vec{V}_\perp + \frac{c}{B}\left[n_s\vec{E} - \frac{1}{e_s}\vec{\Lambda}'_s - \frac{b_{s\perp}n_s}{\sigma_\perp}\sum_{k=1}^{N'}\frac{e_k}{b_k}\vec{J}_k\right]\times\vec{h} \qquad (4.13)$$

in which the last term in brackets is eliminated using the full equation of motion of the neutral gas mixture component (1.10)

$$\sum_{s=1}^{N'}\frac{e_s}{b_s}\vec{J}_s \equiv \sum_{s=1}^{N'}\sum_{j=1}^{N(n)} n_s n_j \nu_{sj}(\vec{V}_s-\vec{V}_j) = \rho_n\frac{d\vec{V}}{dt} + \nabla p_n - \nabla\cdot\overline{\overline{\Pi}}_n - k\sum_{s=1}^{N} n_s\alpha_s\nabla T_s - \rho_n\vec{g}. \qquad (4.14)$$

Formula (4.13) generalizes to the general case of weakly ionized multicomponent plasma the results obtained earlier for three-component plasma [6,7]. Ignoring for simplicity the inertia of particles and also the effect of thermal diffusion in equation (4.14), we obtain from (4.13) in the special case of a ternary mixture ($C_{i\perp}n_i/\delta_\perp \approx 1/e$) the following standard expression for the transverse diffusion rate of electrons (ions) [6].

$$\vec{V}_{e\perp} \simeq \frac{c}{B}\left(\vec{E} + \frac{1}{e n_e}\nabla P_e\right)\times \vec{h} . \qquad (4.15)$$

If Γ_s denotes the rate at which the s-th component of the ionosphere is formed as a result of all aeronomic reactions, a good approximation of the continuity equation for the s-th ionic component is the following equation

$$\frac{d}{dt}\left(n_s/\rho\right) - \nabla_\perp \cdot \vec{J}_{s\perp} - \nabla_\parallel \cdot \left\{\frac{D_s^{(a)}}{K(T_e+T_s)}\left[\nabla_\parallel P_s + \frac{n_s}{n_e}\nabla_\parallel P_e - n_s m_s \vec{g}_\parallel\right]\right\} = \Gamma_s \qquad (4.16)$$

where $\vec{J}_{s\perp}$ is determined from formula (4.13), which allows to calculate the distribution of charged components in the lower ionosphere of a planet with a magnetic field when the temperature profiles in /18
the ionosphere and also the dynamics of the neutral gas are given. The degree of complexity of the right member of equation (4.16) depends on which reactions and components are acknowledged to be necessary for a description of properties of the ionosphere at the given altitude. Equations (3.12) and (4.16) derived in this study are promising for a description of ambipolar multicomponent diffusion of individual types of ions in plasma in the lower ionosphere. Numerical modeling of the vertical structure of the ionosphere based on these equations is of considerable interest.

5. Deviations from Local Thermodynamic Equilibrium in the Ionosphere Of a Planet

A characteristic peculiarity of the ionosphere of a planet is the absence of thermal equilibrium, which is reflected, for example, in a difference in kinetic temperatures of electrons, ions and neutral particles. The basic reason for the absence of local thermodynamic equilibrium in the ionosphere is the circumstance that in the general case, the energy of solar photons or charged space particles is greater than the energy necessary for ionization. A great portion of this energy is carried away by photoelectrons. Their initial energy spectrum

$$\mathcal{E}_e = h\nu - \Sigma_j D_j^{(ion)} - \Sigma_j \Sigma_\alpha D_j^\alpha \qquad (5.1)$$

is a complicated function of an incoming photon $h\nu$, the ionization potential $D_j^{(ion)}$ of an atom subjected to the effect of radiation and also the degree of excitation (D_j^α is the excitation energy of the j-th component to the α level) of the positive ion that is being formed. The energy of fast photoelectrons goes partially into heating the electron gas thermalized by elastic collisions, into excitation of electronic vibrational and rotational energy levels of molecules and the fine structure $O(^3P)$, and partially into formation of excited ions and secondary electrons, which in turn are capable of exciting electronic and vibrational energy levels of atmospheric particles and elastic interactions with thermalized electrons. The heating of electron gas in the ionosphere during collisions with photoelectrons and secondary electrons leads rapidly to a Maxwell distribution of velocities characterized by the electron temperature T_e (sometimes "tails" of high-energy superthermal electrons may /19 exist in the upper ionosphere and protosphere, since collisions at high altitudes are rare, so that during their existence the electrons are not able to undergo thermalization). The heated electron ionosphere gas which is generated is cooled on account of elastic and inelastic collisions with neutral particles having temperature T_n and also during Coulomb interaction with ions in the surrounding medium having temperature T_i. In principle, different ion components may have different temperatures (for example, in the Earth's ionosphere, the temperatures of light and heavy ions may differ by 100°K [30,31]); however in the general case, the latter is impeded by the Coulomb interaction between them. Heated ionosphere ions are then cooled in elastic collisions with neutral particles.

We will present a quantitative description of the process of equalization of the temperatures of ions and electrons in the ionosphere, while limiting ourselves for simplicity to the case of two-component plasma. We denote by T_{ee} the time at which the Maxwell distribution of electrons is established (thermalization time), which occurs as a result of internal interactions among the elections proper. The analogous quantity for ions will be denoted by T_{ii}. Finally T^{ε}_{ei} will denote the energy exchange time between electrons and ions (time in which local thermodynamic equilibrium is established within the system).

Rigorous theory [32] gives the following expressions for the times T_{ee}, T_{ei}

$$\tau_{ee}=\frac{3\sqrt{m_e}\,(KT_e)^{3/2}}{4\sqrt{2\pi}\,e_e^4 n_e \ln\Lambda}\ ,\quad \tau_{ii}=\frac{3\sqrt{m_i}\,(KT_i)^{3/2}}{4\sqrt{\pi}\,e_i^4 n_i \ln\Lambda}\ . \qquad (5.2)$$

Here ln Λ is the Coulomb logorithm (which varies from 10 to 20 for typical conditions in the ionospheres of planets). If both electrons and ions have approximately a Maxwell distribution with respect to velocities with temperatures T_e and T_i, the process of equalization of the electron and ion temperatures is described by the relaxation equation [33] (see also equation (6.11))

$$\frac{dT_e}{dt}=-\frac{T_e-T_i}{\tau^{\varepsilon}_{ei}}\ ,\quad \tau^{\varepsilon}_{ei}=\frac{3}{8\sqrt{2\pi}}\,m_i m_e\frac{\sqrt{K^3}}{n_i e_i^2 e_e^2 \ln\Lambda}\left[\frac{T_e}{m_e}+\frac{T_i}{m_i}\right]^{3/2} . \qquad (5.3)$$

The expression for T^{ε}_{ei} can be simplified by taking advantage of the smallness of the ratio m_e/m_i. If condition

$$T_i \ll m_i T_e/m_e\ , \qquad (5.4)$$

is satisfied, formula (5.3) implies /20

$$\tau_{ei}^{\varepsilon} \simeq 3m_i(KT_e)^{3/2}/8\sqrt{2\pi m_e}\, n_i e_i^2 e_a^2 \ln\Lambda. \tag{5.5}$$

In the general case, by order of magnitude

$$\tau_{aa} : \tau_{ii} : \tau_{ai}^{\varepsilon} = 1 : (m_i/m_e)^{1/2}(T_i/T_e)^{3/2} : m_i/m_e. \tag{5.6}$$

Thus, when condition (5.4) is satisfied, which holds nearly always in ionosphere conditions where the temperature of ions is lower than the temperature of electrons $T_{ee} \ll T_{ei}^{\varepsilon}$ is valid. If, in addition, the condition

$$T_i \ll (m_i/m_e)^{1/3} T_e \tag{5.7}$$

is satisfied, (which is valid in the ionosphere), $T_{ii} \ll T_{ei}^{\varepsilon}$ also holds. In the case when $T_e = T_i$, then for example, for fully ionized plasma consisting of electrons and protons, we have

$$\tau_{ei}^{\varepsilon} \approx 22\,\tau_{ii} \approx 950\,\tau_{ee}.$$

Thus, local thermal equilibrium within each plasma component of the ionosphere is established faster than among all components of the system. As a result, a quasi-equilibrium state arises, which, in general is characterized by three temperatures: an electron T , ion T_i and neutral T_n temperature. This circumstance allows to derive macroscopic transfer equations with various temperatures in a description of physicochemical processes taking place in the ionosphere of a planet.

Elaborate thermal equilibrium of the ionosphere, and individually the electron and ion temperature, depends on sources and sinks of thermal energy of ionosphere particles which will be discussed in the next section.

6. Equations of Heat Balance in Ionosphere

One of the main difficulties of planetary aeronomy is an adequate description of inflow of heat to the upper atmosphere. By analogy with Earth's thermosphere, we start out with the fact that the energy balance of large-scale dynamic systems in the upper atmosphere of a terrestrial planet is essentially determined by absorption of short wave solar radiation by atmospheric components, absorption (emission) of thermal radiation from the surface of the /21 planet and atmosphere, aeronomic reactions, dissipation of particular types of waves (acoustic, gravitational and magnetohydrodynamic), dissipation of turbulent energy (in lower thermosphere) and Joule dissipation of ionosphere current heated by corpuscular flows having different characteristics and also dynamic processes resulting in a redistribution of heat from nonuniformly distributed sources. The general form of the intrinsic energy balance equation of a laminar flow of a multicomponent gaseous mixture in the upper atmosphere can be written as follows [12]

$$\rho \frac{d\varepsilon}{dt} + p\nabla\cdot\vec{V} = -\nabla\cdot(\vec{q}+\vec{q}_R) + \bar{\bar{\Pi}}:\nabla\vec{V} + \sum_{s=1}^{N} m_s \vec{J}_s \vec{F}_s + Q_d. \qquad (6.1)$$

Here $\varepsilon = \sum_s \frac{n_s \varepsilon_s}{\rho}$ is the thermodynamic intrinsic energy per unit volume of the gaseous mixture, ε_s is the intrinsic energy per one molecule of type s, $\vec{q} + \vec{q}_k$ is the heat flow, $\vec{q}_k$ is the inflow of energy due to radiation and Q_d are possible local heating sources of the atmosphere. The last term in the right member of equation (6.1) for the external mass force (1.3) is equal to $\vec{J}\cdot\vec{E}'$ and corresponds to Joule heating of the atmosphere by ionosphere electric currents. In the general case the energy inflow $\vec{q}_R$ due to radiation consists of an infrared radiation flow from the Sun and the atmosphere near the planet ($\vec{q}_{IR}$) and a flow of ultraviolet and X-ray radiation from the

Sun, leading to heating of the atmosphere during photoionization, photodissociation and the following aeronomic reactions. In the case of a two-dimensional model of the atmosphere, we have for the amount of short wave solar radiation absorbed per unit volume of the medium per unit time the expression

$$A_{\odot}=-\nabla\cdot\vec{q}_{UR}=\sum_{s=1}^{N} n_s \int_0^{\infty} h\nu\,\delta_s(\nu) F_{\nu\infty} \exp\left[-\sum_{i=1}^{N}\int_z^{\infty} \sec\theta_{\odot}\, n_i\,\delta_i(\nu)\,dz\right] d\nu \qquad (6.2)$$

where $F_{\nu\infty}$ is the amount of incident flow of solar photons on the upper boundary of the atmosphere, $\Theta_{\odot}$ is the Sun's zenith angle and $\delta_s(\nu)$ is the radiation absorption cross-section of the s-th component of the atmosphere.

The absence of thermal equilibrium in the ionosphere of a planet, in the general case, does not allow using only equation (6.1) written in terms of a single kinetic temperature of the gas during calculation of the heat balance. Separate heat balance equations must be used for electrons, ions and neutral particles whose temperatures differ sharply under ionosphere conditions. In the monograph by Ivanovskiy et al [34], the equations of motion for the energy of electrons and ions are derived on the basis of kinetic theory. In this study we will derive these equations heuristically, considering the gas as a continuum. Using the definition of intrinsic energy of a medium ε and continuity equation (3.10), we write (6.1) in the form /22

$$\sum^{N}\left[\frac{d}{dt}(n_s\varepsilon_s)+n_s h_s \nabla\cdot\vec{V}+\nabla\cdot\vec{q}_s-\gamma_s A_{\odot}-e_s\vec{J}_s\cdot\vec{E}'_s\right]=-\nabla\cdot\vec{q}_{IR}+\overset{=}{\Pi}:\nabla\vec{V}+Q_{\psi} \qquad (6.3)$$

where $h_s=\varepsilon_s+p_s/n_s$ is the enthalpy per one molecule of the s-th component, the coefficients γ_s indicate the portion of absorbed short wave solar radiation converted directly into intrinsic energy of the s-th component, $\sum_s\gamma_s=1$, $e_s\vec{J}_s\cdot\vec{E}'$ is the rate at which the thermal energy of component s increases per unit volume because of the electromagnetic field.

Assuming that viscous energy dissipation and radiant heat exchange are essentially determined by the neutral component of the thermosphere, using the energy equation form (6.1) for the entire plasma, we will set up an equation which is analogous in structure, expressing the law of conservation of individual charged components of the ionosphere

$$\frac{d}{dt}(n_s \mathcal{E}_s) = -\nabla\cdot\vec{q}_s - n_s k_s \nabla\cdot\vec{V} + e_s \vec{J}_s\cdot\vec{E}' + \gamma_s A_{\odot}^{(ion)} + Q_{\alpha_s} - \sum_{\substack{k=1\\k\neq s}}^{N} E_{sk} \qquad (6.4)$$

where the last additional term in the right member of the equation represents the exchange rate of energies between the isolated s-th and all other components (this term drops out from the full energy equation (6.3), $\sum_{\substack{k=1\\k\neq s}}^{N} E_{sk} = 0$). This term takes into account, for instance, the energy lost by component s (per unit time per unit volume) due to elastic and inelastic collisions leading to rotational, vibrational and electron excitation of neutral particles with other one-component media, having in the general case a temperature which is different from T_s.

The thermal energy losses of electrons per unit volume due to elastic collisions with heavy and neutral particles can be determined using formula

$$\sum_{j=1}^{N} E_{ej} = \sum_{j=1}^{N} \delta_j \frac{2m_e}{m_j} \frac{3}{2} k (T_e - T_j) \nu_{ej} n_e . \qquad (6.5)$$ /23

In fact, it is known that during a collision of a light particle with a heavy particle at rest, the portion of transferred energy may be on the order of magnitude of the ratio of the masses m_e/m_j. For example, during isotropic scattering, the average portion of transferred energy is $2m_e/m_j$. Thus, the mean energy lost by one electron in one elastic collision can be expressed in the form

$$\Delta \bar{\varepsilon}_{ej} \simeq \frac{2m_e}{m_j} \frac{3}{2} K (T_e - T_j).$$

The energy transfer rate E_{ej} for an electronic gas interacting with particles of component j is determined from the formula

$$E_{ej} = \frac{2m_e}{m_j} \frac{3}{2} (T_e - T_j) \vartheta_{ej} n_e = 3 n_e n_j \frac{m_e}{m_j} K \left(\frac{8KT_e}{\pi m_e} \right)^{1/2} \bar{Q}_{ej} (T_e - T_j). \qquad (6.6)$$

Because of the factor $2m_e/m_j$ in the right member of (6.6), this specific electron cooling rate (electrons undergo cooling when $T_e > T_j$; when $T_j > T_e$, the reverse process takes place) associated with elastic collisions is rather small (in the ionosphere $2m_e/m_j \sim (2-3)\cdot 10^{-5}$). Electron energy losses occur much more rapidly as a result of inelastic collisions, which were taken into account by introducing the inelastic collision energy loss coefficient δ_j in equation (6.5) which may differ from unity by several orders of magnitude. In the general case, calculation of δ_j requires a knowledge of the cross-sections of all inelastic collision processes existing in the ionosphere (vibrational, rotational and optical energy level excitation processes).

When the temperature of electrons is not high ($T_e \lesssim 10^3$K), the main part is played by excitation of molecular rotational energy levels. According to [35], for nonpolar N_2 and O_2 molecules, we have as the portion of energy δ lost to excitation

$$\delta_{eN_2} = 6{,}5 (1 + 0{,}027 T_e^{1/2}) / T_e^{3/2}, \quad \delta_{eO_2} = 2{,}9 / (1 + 0{,}036 T_e^{1/2}) T_e \qquad (6.7)$$

At $T_e > 10^3$K, the excitation of vibrational energy levels and at $T_e \gtrsim (3\cdot 10^3 - 10^4)$°K, the excitation of optical energy levels already plays an important part. In particular, according to [36], the optical energy losses in atomic oxygen are

$$\delta_{eo} = 82.5/T\, T_e^{1/2} \tag{6.8}$$

and owing to excitation of transitions between fine structure levels, they become noticeable at temperatures which are characteristic for ionospheres of planets ($T_e \lesssim 10^3$ °K).

For a mixture of gases, δ is determined according to formula /24

$$\delta = \sum_{s=1}^{N} \delta_{es} \cdot \beta_{es} \Big/ \sum_{s=1}^{N} \beta_{es}, \tag{6.9}$$

where β_{es} and δ_{es} are the collision frequencies and the portion of transferred energy for a gas of type s. Mention should be made of the fact that the method of taking into account the inelastic collision energy loss during collisions of electrons with molecules in terms of the coefficient δ is approximate even in the case of considerably high energy transfer rates between rotational and vibrational degrees of freedom on one hand and translatory degrees of freedom on the other hand. A detailed calculation is necessary when the relationship is weak [37].

In the case of interaction of heavy particles i and n we have [18]

$$\overline{\Delta\mathcal{E}_{in}} \simeq \frac{2m_{in}^2}{m_i m_n}\left[\frac{3}{2}K(T_i - T_n) - \frac{1}{2}m_n(\vec{V}_i - \vec{V}_n)^2\right]$$

from which follows the energy transfer rate for an ion colliding with neutral particles n

$$E_{in} = 3n_i n_n K \frac{m_i m_n}{(m_i+m_n)^2}\left(\frac{8K}{\pi}\right)^{1/2}\left(\frac{T_i}{m_i}+\frac{T_n}{m_n}\right)^{1/2}\overline{Q}_{in}\left[(T_i - T_n) - \frac{m_n}{3K}(\vec{V}_i - \vec{V}_n)^2\right] \tag{6.10}$$

Let us now write down the energy balance for an electron gas in the case of three-temperature plasma. For electrons we have $\varepsilon_e = 3/2KT_e$ and $h_e = 5/2KT_e$, so that equation (6.4) after formula (6.2) has been taken into account assumes the form

$$\frac{d}{dt}\left[n_e\frac{3}{2}KT_e\right] = -\nabla\cdot\vec{q}_e - \left[n_e\frac{5}{2}KT_e\right]\nabla\cdot\vec{V} - e\vec{J}_e\cdot\vec{E}' + \eta_e\sum_{s=1}^{N} n_s\int_0^{\infty} \sigma_s^{(i\nu)}(\nu) F_{\nu\infty}\exp\left[-\sum_{i=1}^{N}\int_z^{\infty} n_i \sec\theta_0\,\sigma_i(\nu)\,dz\right]d\nu - \sum_{s=1}^{N(\nu)}\frac{2m_e}{m_s}\frac{3}{2}K\beta_{es}n_s(T_e-T_n) - \sum_{j=1}^{N'}\frac{2m_e}{m_j}\frac{3}{2}K\beta_{ej}n_j(T_e-T_i) + Q_{de} - L_e \qquad (6.11)$$

where $Q_{de} \approx 2\cdot 10^{-12}\,\frac{ne}{E}\,\phi_e$ [eV/cm^2$\cdot$sec] (ϕ_e represents a flow of fast electrons with energy E) is the inflow of heat to the thermalized electron gas of the ionosphere from high-energy particles which fell out into the atmosphere [38], L_e are the heat losses of electrons during rotational excitation of nonpolar molecules, during vibrational excitation of molecules, and during excitation of transitions between levels of the fine structure of atomic oxygen [39]. Since Joule heat is essentially released in electron gas, to emphasize this fact, it is convenient to represent the term $-e\vec{J}_e\cdot\vec{E}'$ in the form $\vec{J}_e\cdot\vec{E}' = \vec{J}\cdot\vec{E}' - e\vec{J}_i\cdot\vec{E}'$, $\vec{J}_i = \sum_{i=1}^{N'}\vec{J}_j$, где $\vec{J}$ .. where $\vec{J}$ is the current flowing in the ionosphere as a result of the action of an electric field (for example auroral current or an equatorial electrojet in the Earth's ionosphere).

An additional source of heat for the ionosphere of a planet, especially in the case of nonmagnetic planets, may be hot solar wind plasma, the interaction of which with the planet constituting an obstacle leads to generation of hydromagnetic and acoustic energies. Another heating source in the topside ionosphere of a planet is the turbulent heat conductivity of hot solar wind plasma. We will present some estimates: /25

The energy transfer rate $E_{e,n}$ for an electron colliding with neutral particles, for the principal neutral components of the

Earth's ionosphere has the following values:

$$E_{e,N_2}=1.77\cdot 10^{-19} n_e n_{N_2}/1-1.21\cdot 10^{-4}T_e/T_e\,(T_e-T_n)\ \text{eV/cm}^3\cdot\text{sec}\quad E_{e,N_2}=1.21\cdot 10^{-18} n_e n_{O_2}/1+3.6\cdot 10^{-2}T_e^{1/2}/T_e^{1/2}(T_e-T_n);\quad E_{e,O}=3.74\cdot 10^{-18} n_e n_O T_e^{1/2}(T_e-T_n);\quad E_{e,H}=9.63\cdot 10^{-16} n_e n_H\cdot /1-1.35\cdot 10^{-4}T_e/T_e^{3/2}(T_e-T_n);\quad E_{e,He}=2.46\cdot 10^{-17} n_e n_{He} T_e^{1/2}(T_e-T_n)\,[21,22].$$

The rate at which an electron gas loses energy which is transferred to a mixture of positive ions, for example O^+, He^+ and H^+, is defined in [40] as

$$\text{в}[40]\ \sum_{j\neq e}^{N'} E_{ej}=\frac{5\cdot 10^{-7}(T_e-T_i)}{T_e^{3/2}} n_e\left[n_{O^+}+4n_{He^+}+16n_{H^+}\right],\ \text{eV/cm}^3\cdot\text{sec} \tag{6.12}$$

According to [40] cooling of electron gas by rotational excitation of N_2 and O_2 molecules can be written in the form

$$L'_{e,N_2}=2.9\cdot 10^{-14} n_e n_{N_2} T_e^{-1/2}(T_e-T_n),\quad L'_{e,O_2}=6.9\cdot 10^{-14} n_e n_{O_2} T_e^{-1/2}(T_e-T_n) \tag{6.13}$$

At $T_e > \sim 1500°K$, vibrational excitation [41] is more effective for N_2 and O_2

$$L''_{e,N_2}=2.99\cdot 10^{-12} n_e n_{N_2} \exp\left(g\,\frac{T_e-2000}{2000\,T_e}\right)\left[\exp\left(-f\,\frac{T_e-T_n}{T_e T_n}\right)-1\right],\ \text{eV/cm}^3\cdot\text{sec} \tag{6.14}$$

$$g=1.06\cdot 10^4+7.51\cdot 10^3\, th\left[1.10\cdot 10^{-3}(T_e-1800)\right], \qquad /6.14/$$

$$f=3300+1.233(T_e-1000)-2.056\cdot 10^{-4}(T_e-1000)(T_e-4000);$$

$$L''_{e,O_2}=7.45\cdot 10^{-13} n_e n_{O_2} \exp\left(g'\,\frac{T_e-700}{700\,T_e}\right)\left[\exp\left(-3000\,\frac{T_e-T_n}{T_e T_n}\right)-1\right],$$

$$g'=3.902\cdot 10^3+4.38\cdot 10^2\, th\left[4.56\cdot 10^{-4}(T_e-2400)\right].$$

Losses by excitation of the fine structure of the O atom ground level and the first excited metastable ^1D level of the same atom can be written respectively in the form

$$L'_{e,0} = -3{,}4\cdot 10^{-12} n_e n_0 \left(1 - 7\cdot 10^{-5} T_e\right)\left(T_e - T_n\right) T_n^{-1}, \quad \text{eV/cm}^3\cdot\text{sec}$$

$$L''_{e,0} = -1{,}07\cdot 10^{-10} n_e n_0 T_e^{1/2} \exp\left(-2{,}27\cdot 10^4/T_e\right)\Big\{0{,}406 + 0{,}357\cdot 10^{-4} T_e - (0{,}333 + 0{,}183\cdot 10^{-4} T_e)\exp\left[-\frac{1{,}37\cdot 10^4}{T_e}\right] - (0{,}456 + 0{,}174\cdot 10^{-4} T_e)\exp\left[-\frac{2{,}47\cdot 10^4}{T_e}\right]\Big\}.$$

Calculations of γ'_e during high and low solar activity were carried out in [43-45]. According to [45], we have for γ'_e /26

$$\gamma'_e = \begin{cases} 1 + 9\,\dfrac{z - 120}{480} & \text{eV for} \quad 120 \le z \le 600\,\text{km}, \\ 10 & \text{eV for} \quad z \ge 600\,\text{km}. \end{cases} \tag{6.16}$$

We will write the intrinsic energy transfer equation for the ion component of the atmosphere ignoring viscous dissipation of ions as follows

$$\frac{d}{dt}\left[n_i\left(\frac{3}{2}KT_{ion} + \mathcal{E}_i^{ch}\right)\right] = \nabla\cdot(-\vec{q}_i) - \left[n_i\left(\frac{5}{2}KT_{ion} + \mathcal{E}_i^{ch}\right)\right]\nabla\cdot\vec{V} + e\vec{J}_i\cdot\vec{E}' + L_i \tag{6.17}$$

$$\sum_{j=1}^{N'} \frac{2m_e}{m_j}\frac{3}{2}K\beta_{ej} n_j\left(T_e - T_{ion}\right) + \sum_{j=1}^{N'}\sum_{K=1}^{N} {}^{(n)}\frac{2m_{jK}}{m_j + m_K}\beta_{jK} n_j\left[\frac{3}{2}K\left(T_n - T_{ion}\right) + \frac{m_K}{2}\left(\vec{V}_j - \vec{V}_K\right)^2\right] + Q_{d_i}$$

where

$$n_i\left[\frac{3}{2}KT_{ion} + \mathcal{E}_i^{ch}\right] = \sum_{j=1}^{N'} n_j\left[\frac{3}{2}KT_{ion} + \mathcal{E}_j^{ch}\right]$$

is the intrinsic energy per unit volume of the ion component of the ionosphere. Heating of ions takes place during Coulomb interaction with electrons, in this case, the rate at which heat arrives in the ion gas $\sum_j^{N'} E_{je} + L'_i$ is equal to the cooling rate of electrons in equation (6.11). The ions undergo cooling during elastic collisions with heavy particles. In this case the heat transfer rate is either determined by the difference between the temperatures of the ion and neutral gases or by the possible difference in the directed velocities $\vec{V}_i$ and $\vec{V}_n$ (frictional heating). Effective cooling of ions in the "parental" gas takes place during resonance transfer of the charge; in this case, the expression for β_{in} is changed by the factor $(T_n+T_{ion})^m$, where $0.3 \lesssim m \lesssim 0.4$ for most atmospheric gases [46]. For the Earth's ionosphere, the heat losses consist of elastic collision losses of O^+, He^+, H ions (taking into account resonance recharging) [21,22]

$$
\begin{aligned}
&L_{O^+n}+E_{O^+n}=[6{,}6\cdot 10^{-14} n_{N_2}+5{,}8\cdot 10^{-14} n_{O_2}+2{,}8\cdot 10^{-14} n_{He}+3{,}3\cdot 10^{-11} n_H+\\
&2{,}1\cdot 10^{-15} n_O (T_{ion}+T_n)^{1/2}](T_n-T_{ion}) n_{O^+};\quad L_{He^+n}+E_{He^+n}=[5{,}3\cdot 10^{-14} n_{N_2}+5{,}8\cdot 10^{-11} n_O+10\cdot 10^{-11} n_H+\\
&4{,}5\cdot 10^{-14} n_{O_2}+4{,}0\cdot 10^{-15} n_{He} (T_{ion}+T_n)^{1/2}](T_n-T_{ion}) n_{He^+};\quad L_{H^+n}+E_{H^+n}=[3{,}1\cdot 10^{-14} n_{N_2}+\\
&3{,}5\cdot 10^{-14} n_O+2{,}8\cdot 10^{-14} n_{O_2}+5{,}5\cdot 10^{-14} n_{He}+1{,}4\cdot 10^{-14} n_H (T_{ion}+T_n)^{1/2}](T_n-T_{ion}) n_{H^+};
\end{aligned}
\tag{6.18}
$$

The inflow of heat to the ion gas from photoionization is small and it is not taken into account in equation (6.17). Usually the ion temperature is determined from the equilibrium form of this equation, while the effect of the thermal conductivity of ions compared with the thermal conductivity of electrons (in view of the smaller thermal conductivity rates of ions) can also be ignored, since $\lambda_e/\lambda_j \sim \sqrt{m_e/m_i} >> 1$ [18].

Kinetic theory of multicomponent gaseous mixtures of single-atom gases of moderate density in any approximation obtained by the Chapman-Enskog method leads to the following expressions for heat flows transferred by electrons and ions [18,29] /27

$$
\vec{q}_e = -\hat{\lambda}\nabla T_e - \sum_{i=1}^{N'} \hat{\lambda}_{ei}\nabla T_{ion} - \hat{\mathscr{x}}_e \vec{J}_e - \sum_{i=1}^{N'} \hat{\mathscr{x}}_{ei}\vec{J}_i , \tag{6.19}
$$

$$
\vec{q}_i = -\hat{\lambda}_{ie}\nabla T_e - \sum_{\substack{j=1\\ j\neq i}}^{N'} \hat{\lambda}_j \nabla T_{ion} - \hat{\mathscr{x}}_{ie}\vec{J}_e - \sum_{j=1}^{N'} \hat{\mathscr{x}}_j \vec{J}_j , \tag{6.20}
$$

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where $\hat{\lambda}_e$, $\hat{\lambda}_i$ and $\hat{\lambda}_{ei}$, $\hat{\lambda}_{ie}$ are the thermal conductivity and mutual thermal conductivity tensors for electrons and ions, $\hat{\mathscr{H}}_e$, $\hat{\mathscr{H}}_i$ and $\hat{\mathscr{H}}_{ei}$, $\hat{\mathscr{H}}_{ie}$ are thermoelectric force tensors. Usually the contribution of cross-effects to the total rate of the process is smaller by one order of magnitude in comparison with the direct effect [12]. Moreover, at a moderate degree of ionization of ionosphere plasma, when collisions with neutral particles play a crucial part, the reciprocal heat conductivity tensors $\hat{\lambda}_{ei}$ and $\hat{\lambda}_{ie}$ and thermoelectric force tensors $\hat{\mathscr{K}}_{ei}$ and $\hat{\mathscr{K}}_{ie}$ are insignificant [29]. The second simplification is related to the circumstance that the heat flow is mainly determined by the thermal conductivity $\lambda\Delta t$, since on the strength of the quasilinearity of plasma, the ion and electron diffusion flows have the same order of magnitude and thermal conductivity, not coupled by quasilinearity conditions proceeds much faster ($\sqrt{m_i/m_e}$ times faster).

Thus, when $\vec{B}=0$, formula (6.19) for a heat flow transferred by electrons has the form [18]

$$\vec{q}_e = -\lambda_e \nabla T_e , \quad \lambda_e = \frac{2,4}{1+\vartheta_{ei}/\sqrt{2}\vartheta_e} \frac{K^2 n_e T_e}{m_e \vartheta_e} \qquad (6.21)$$

where λ_e is the total electron thermal conductivity of the gaseous mixture and β_e is the total mean collison frequency of electrons with all heavy particles. When $\vec{B}\neq 0$, formulas (6.21) are valid for a heat flow which is parallel to the magnetic field. There formulas take on a different form for the perpendicular component of the heat flow. [18].

In the topside ionosphere of planets with a magnetic field, heat transfer in electron gas occurs only along the lines of force of the magnetic field (the ratio $\lambda_\perp/\lambda_\parallel$ is an extremely small quantity, and essentially, it depends on electron-ion collisions. In this case, thermal conductivity is the same as that for a completely ionized gas [30, 47]

$$\lambda_{ei} = 3,203 \frac{K^2 n_e T_e}{m_e \vartheta_{ei}} = 0,236 \frac{64\sqrt{\pi K}\,(2KT_e)^{5/2}}{e^4 \sqrt{m_e}\ \ln \Lambda_{ei}} \qquad (6.22)$$

Since the atmospheres of planets represent incompletely ionized /28 plasma, especially at low altitudes, where considerable collisions occur between electrons and neutral particles, in the general case expression (6.22) is not valid and formula (6.21) must be used which, taking into account (6.22), can be represented in the form

$$\frac{1}{\lambda_e} = \frac{1}{\lambda_{ei}} + \sum_{k=1}^{N(n)} \frac{1}{\lambda_{ek}}, \qquad (6.23)$$

where λ_{ek} is the thermal conductivity of electrons in a neutral gas composed of various components (collisions of charged particles are ignored). This quantity is given by

$$\lambda_{ek} = \frac{8}{9}\left(\frac{n_e}{n_k}\right) K \left(\frac{8KT_e}{\pi m_e}\right)^{1/2} \frac{1}{\bar{Q}_{ek}}. \qquad (6.24)$$

The thermal conductivity coefficient of type i ions is

$$\lambda_i = 5,95 \cdot 10^{-8}\, T_i^{5/2} / m_i^{1/2} \, (\text{эв}\,\text{см}^{-1}\,\text{сек}^{-1}\,\text{град}^{-1}), \qquad (6.25)$$

Using the full energy equation and heat balance equation for an electron and ion gas, an energy equation can be derived for a neutral atmosphere with heat sources (sinks) because of the interaction with the plasma component of the planet's ionosphere. These equations permit to investigate thermal conditions in a neutral atmosphere and ionosphere plasma, while taking into account the mutual effect of components of the system.

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