TRANSPORT PHENOMENA AND ABUNDANCE ANOMALIES IN COSMIC PLASMA

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Abstract. Hydrodynamical equations for a fully ionized hydrogen-helium plasma are derived by the Chapman–Enskog method. The electron and ion transport coefficients are found as the functions of electron and ion temperatures and number densities as well as of the magnetic field strength. The presented equations are needed for describing transport phenomena in laboratory and cosmic plasmas. It is shown that transport phenomena can produce abundance anomalies; e.g., a sound wave propagating through a homogeneous plasma may be accompanied by the oscillations of chemical composition. Various astrophysical consequences of the theory are discussed.

It is well known that astrophysical as well as laboratory plasma may often be chemically inhomogeneous. For instance, the spots of peculiar chemical compositions have been observed in the surface layers of Ap-stars (see, e.g., Pikel'ner and Chochlova, 1972; Preston, 1974; and Kitamura, 1980). The abundances of certain elements in these spots are many times different from normal. The number of the spots as well as their sizes, may be very different but all of them are stable enough (no considerable variation of the spot geometry has been detected). The abundance anomalies have also been observed in the interstellar space (see, e.g., Kaplan and Pikel'ner, 1980). Up to now the processes producing such anomalies and the conditions necessary for these processes to occur, have not been thoroughly analysed.

For detailed investigation of the abundance anomalies one must derive the hydrodynamical equations describing the behaviour of each chemical element in a moving plasma in the presence of the electrical and magnetic fields as well as of the gradients of temperatures and number densities. Under astrophysical conditions, the abundances of heavy elements are usually rather small; this means that these elements may be considered as impurities in a hydrogen-helium plasma. The most interesting case is that of a hydrogen-helium plasma with the He/H ratio by number ~0.1. In this case He cannot be considered as impure because the behaviour of H is strongly affected by the collisions with the He ions (especially if He is fully ionized). Furthermore, the collisions between helium ions can affect the behaviour of the helium plasma component as strongly as the hydrogen-helium collisions. Because of the extremely complicated character of this problem, the accurate magnetohydrodynamical equations for astrophysical conditions have not yet been derived up to now.

This paper presents magnetohydrodynamic equations for a fully ionized hydrogen-helium plasma. The dependence is found of the electron and ion transport coefficients on the electron and ion temperatures and number densities as well as on the magnetic field. We show the transport phenomena in cosmic plasma may lead to the appearance...
of abundance anomalies. In conclusion, we briefly discuss the possible astrophysical consequences of the theory. The transport properties of the species heavier than hydrogen and helium in a cosmic plasma will be analysed elsewhere.

1. The Transport Equations

The electron and ion distribution functions $f_a$ in the presence of the electric and magnetic fields, $E$ and $B$, are governed by the kinetic equations

$$\frac{\partial f_a}{\partial t} + \mathbf{v} \cdot \nabla f_a + \left[ \frac{F_a}{m_a} + \frac{e_a}{m_a} \left( E + \frac{\mathbf{v}}{c} \times \mathbf{B} \right) \right] \times \frac{\partial f_a}{\partial \mathbf{v}} + \sum \beta S_{ab}(f_a, f_b) = 0,$$

where $e_a$ and $m_a$ are the charge and mass of particles, $\mathbf{v}$ is their velocity and $F_a$ is an external force acting on them; the Greek subscripts label the tip of particles, hereafter the subscript 'e' will be also used to refer to electrons, and '1, 2' to ions. The collision integrals $S_{ab}$ may be taken in the form suggested by Landau (1937)

$$S_{ab} = \frac{2\pi \lambda e_a^2 e_b}{m_a} \frac{\partial}{\partial v_i} \left[ f_a(v) \frac{\partial f_a(v')}{\partial v_j} - f_b(v') \frac{\partial f_b(v)}{\partial v_j} \right] V_{ij}(v - v') \, dv', \quad (2)$$

where $\lambda$ is the Coulomb logarithm. We assume that $\lambda$ is independent of the tip of the particles. For a hydrogen-helium plasma such an approximation is quite satisfactory see, e.g., Sivukhin (1966). In Equation (2) the indices $i, j = x, y, z$ and summation is carried out over on the repeated indices. The effect of the magnetic field on the collision integrals (2) is unimportant and, thus, ignored because we consider a non-quantizing magnetic field.

A set of the transport equations for a fully ionized two-component plasma with equal electron and ion temperatures, $T_e = T_i$, was derived by Fradkin (1957). Using the modified Chapman-Enskog method (cf., Chapman and Cowling, 1939), Braginskii (1957) generalized these result to the case $T_e \neq T_i$. Let us make use of the Braginskii technique and obtain the transport equations for a plasma with two types of ions. We shall not assume that $T_e = T_i$, because under astrophysical conditions, the electron and ion temperatures may be essentially different (e.g., in an optically thin plasma layer in which the characteristic time of radiative energy loss is shorter than the time of energy exchange between electrons and ions). However, we shall assume that ions of all the types have the same temperature $T_i$.

The hydrodynamical parameters of the particles (the number density $n_a$, the mean velocity $V_a$ and the temperature $T_a$) are determined by

$$n_a = \int f_a \, dv, \quad n_a V_a = \int v f_a \, dv, \quad 3k n_a T_a = \int m_a (v - V_a)^2 f_a \, dv.$$